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Geology of the Mesozoic-Tertiary sedimentary basins in southwestern Somalia ☆

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Abstract

Two main sedimentary basins can be recognized in southern Somalia, the NE–SW trending Mesozoic-Tertiary Somali coastal basin, and the NNE–SSW Mesozoic Luuq-Mandera basin. The two basins are separated by the Bur region where the Proterozoic-Early Paleozoic Metamorphic basement of southern Somalia outcrops. The investigated area covers part of the Metamorphic basement of southern Somalia and of the Luuq-Mandera basin, although this basement is not described in details in this paper.

In the Bur region the basement outcrops discontinuously near inselbergs and monadnocks, which stand out of a blanket of recent sediments. Because of this patchy distribution and the limited areal extent of the outcrops, the structure of the metamorphic basement is difficult to reconstruct. A NW–SE trend of structures prevails and two metamorphic complexes (the Olontole and Diinsor complexes) can be recognized.

The Luuq-Mandera basin is a wide NNE–SSW synclinorium, delimited to the SE by the basement high of the Bur region, and to the west by the crystalline basement high of NE Kenya (Northern Frontier district). The extreme thickness of Triassic sediments in the axial part of the basin, and the thinner and younger succession on both sides of the basin suggest that the Luuq-Mandera basin was a subsiding elongated area that was invaded by the sea in the early Mesozoic, during the dismembering of Gondwana. The Jurassic–Cretaceous succession that followed comprises two main cycles of transgression and regression; the carbonate sediments that lie at the bottom pass up section into shales, evaporites and sandstone deposits.

Since late Cretaceous, continental contition prevaled, with a long phase of peneplanation, and then a general uplift, which brought about the creation of lake depressions and the capture of the Dawa river, with formation of the present Jubba valley.

The main tectonic events in the study area, and throughout SW Somalia, are represented by strike-slip movements along vertical faults in the Sengif and Garbahaarrey belt. Deformation is localized within a narrow belt that extends for more than a 100 km in a NE–SW direction. The near parallelism between the fold axes and the regional orientation of faults indicates a right-lateral movements along faults.

The structure of the Garbahaarrey belt consists of an anastomosing fault system that delimits elongated folded blocks, arranged in anticline–syncline structures, with subvertical axial surfaces and fold axes parallel to the main wrench faults. The orientation of folds and the typical "positive flower structure" profile of the anticlines indicate that shortening was perpendicular to the strike of the wrench, i.e. in a SE–NW direction. In the Garbahaarrey belt, strike-slip and shortening, therefore, occurred contemporaneously and led to a relative transpression between the NW and SE blocks.

The observed parallelism between fold and fault orientation cannot be explained with a simple rotation of pre-existing fold axes during transpression, but can be regarded as an example of folding and strike-slip movements that occurred simultaneously but independently along frictionless faults. The faults delimiting the anticlines accommodated the strike-slip component of transpression only, whereas the compressive component led to the generation of fold axes parallel to the wrench zone.

Results of the field work are summarized in two geological maps of the Gedo, Bakool, and Bay regions (1:250,000) which accompany this report (maps are attached with this issue).

Keywords: Southwestern Somalia; Sedimentary basins

1. Introduction

Research in SE Somalia began with the Bottego expeditions (De Angelis D'Ossat and Millosevich, 1900) and continued into the early 20th century mainly through

☆ This paper is dedicated to the memory of our friend and colleague Ali Kassim Mohamed.

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research by Stefanini (Stefanini, 1913; Stefanini and Paoli, 1916; Stefanini, 1931a,b, 1931c, 1931d, 1931e; Stefanini, 1936) and by those who studied the fossils and samples he collected (Artini, 1915; Manasse, 1916; Aloisi, 1927; D'Erasmo, 1931; Zuffardi Comerci, 1931a,b; Aloisi and De Angelis, 1938). In the early 20th century, the region west of the Jubba river was also studied by British geologists (Gregory, 1896; Gregory, 1900; Currie, 1925; Gregory, 1925; Weir, 1925; Weir, 1929).

In the years that followed, research continued, especially in the field of palaeontology (Venzo, 1942; Venzo, 1943a,b; Maccagno, 1947; Valduga, 1952). These authors made the first lithostratigraphic descriptions, the first paleontological studies and first divided the succession into two series: the "Luuq" and "Bardheere" Series. The discontinuity of field data and the lack of detailed topographic maps made it impossible to gain an overall picture of the regional geology of the area; in fact, in the Geological Map of Eastern Africa (Dainelli, 1943) the "Luuq" Series, which more or less corresponds to the uppermost portion of the Jurassic–Cretaceous succession outcropping in the Jubba valley, was believed to be the oldest part of the succession and was thought to lie below the "Bardheere Series".

The results of all this early research and of more systematic studies done by the Italian oil company AGIP, mainly from 1936 to 1957, were summarized in the "Sheet Luuq" of the Geological Map of Somalia and of Ogaden, edited by AGIP Mineraria and by the Italian Research Council (CNR) (Azzaroli and Merla, 1957–59). This map first reported the main geological features of southern Somalia, and for some areas such as Mudug and the central Webi Shabeele, the adopted formations and cartographic units are still accepted. For the Jubba valley the contacts between formations were very approximate, and the large folds in the Garbahaarrey area were not reported; the mapped Formations remained those established by Stefanini, although the correct stratigraphic succession, with the "Luuq Series" on top of the "Bardheere Series", was recognized.

In the 1960s, the systematic use of aerial photo interpretation led to a new era in the geological mapping of the region. A series of petroleum geology surveys, with field mapping, seismic prospecting and aeromagnetic and gravimetric surveys, established the formational units (Barbieri, 1968, 1970; Beltrandi and Pyre, 1973) that are still generally accepted.

In 1973 oil well Hol N.1 was sunk, but was found to be non-productive; as a result, interest in the Upper Jubba valley declined (Beltrandi and Pyre, 1973; Barnes, 1976; Bignell, 1977; Kamen-Kaye and Barnes, 1979). From then on, geological studies on the region have been carried out by Italian researchers of the University of Florence (Merla et al., 1979; Abbate et al., 1993; Boccaletti et al., 1988), following a long-standing tradition of research in eastern Africa, and by researchers of the Geology Department at the Somali National University. Geophysical investigations were recently carried out by Rapolla et al. (1995a,b).

With the activities of the Faculty of Geology of the Somali National University and with founding of the Italian Cooperation with Developing Countries of the Italian Ministry for Foreign policies, between 1982 and 1990, Carmignani et al. (1983) has carried out geological investigations in southwestern Somalia, in collaboration with Somali and Italian researchers and students. These studies were suddenly interrupted in 1990 by the war events that have taken place in Somalia during that period. The present paper derives from geological investigations and field work carried out before 1990.

2. Regional geological setting

This section briefly describes the main geological features of southern Somalia. For further information and a more in-depth discussion of the geodynamic evolution of eastern Africa, see the numerous works on the subject (Norton and Sclater, 1979; Coffin and Rabinowitz, 1983; Rabinowitz et al., 1983; Bosellini, 1986; Piccoli et al., 1986; Coffin and Rabinowitz, 1987; Boccaletti et al., 1988; Coffin and Rabinowitz, 1988; Bosellini, 1989).

Two main sedimentary basins are recognized in southern Somalia (Fig. 1): the Mesozoic-Tertiary Coastal basin develops in a NE–SW direction, whereas the Luuq-Mandera basin, which formed during the Mesozoic, extends in a NNE–SSW direction. The two basins are separated by the Bur region, a vast area where the crystalline basement of southern Somalia outcrops. To the west, the Luuq-Mandera basin is bordered by the crystalline basement of northeastern Kenya (Northern Frontier district).

The axial zone of the Luuq-Mandera basin outcrops in the Gedo region, where boreholes indicate more than 4,400 m of sediment thickness. Evaporites and Permo-Triassic continental clastics are the deepest sediments found during drilling, and testify to the development of this basin during the initial break-up of Gondwana. The Triassic Luuq-Mandera basin should therefore be considered a part of the Karoo Rift system which develops in a NE–SW direction in eastern Africa, Madagascar and India (Bosellini, 1989). The Triassic successions are not found along the edge of the Luuq-Mandera basin where sedimentation only began in the early Liassic.

The Mesozoic series of the Luuq-Mandera basin gently dips to the NW in the southeastern part of the basin, whereas the strata dip SE in the northwestern

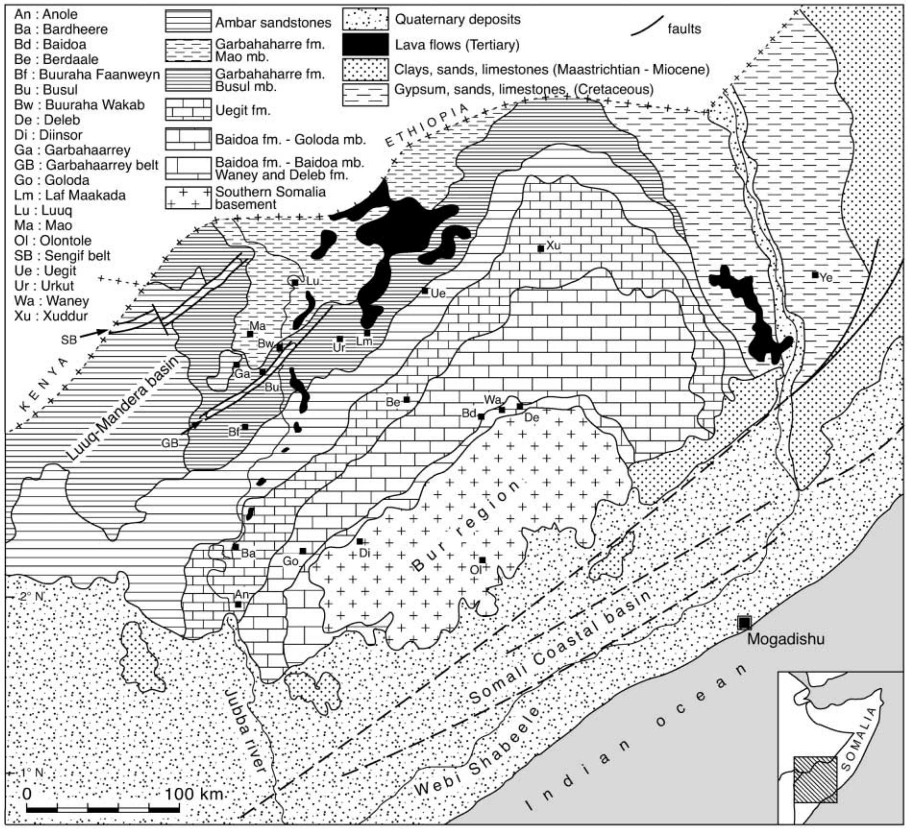

Fig. 1. Geological sketch map of southern Somalia (after Abbate et al., 1993, modified).

area. The basin therefore can be described as a large syncline, with limbs dipping only a few degrees. The mapped syncline in the central part of the basin is called the Tomalo syncline. Two deformation zones, which extend for more than 100 km and are parallel to the axis of the basin, modify this regular structure: the Sengif belt and the Garbahaarrey belt. Both these deformed areas are characterized by antiforms that allow the Jurassic limestones of the Uegit Formation to outcrop. The Jurassic limestones are comparatively more resistant to erosion than the Cretaceous succession, and the Sengif belt and the Garbahaarrey belt are the highest areas in the region, whose highest peak is at an altitude of 482 m (Buurraha Sardheer), and are the most important morphological features of the area.

The area lies in a region with a semi-arid climate, characterized by morphological maturity, with wide, flat or slightly inclined plains. The slight height differences in the area are highlighted by the thalweg of the Jubba valley, which is 160 m above sea level in Luuq (in the northern part of the study area), whereas 170 km further south, in Baardheere, it is about 100 m above sea level. The average altitude of the area is about 200–300 m a.s.l. and alluvial deposits are found at altitudes of 150–200 m.

3. Stratigraphy

3.1. The crystalline basement of southern Somalia

The Precambrian basement of southern Somalia outcrops for about 30,000 km between the Jubba valley and Mogadishu, in a highly peneplaned area, where it is only locally exposed in isolated inselbergs, locally called "Bur". For this reason, this metamorphic basement is also known in literature as the "Bur Crystalline Basement" or "Basement of the Bur region". The rest of the area is covered by residual soils (1–30 m thick) and alluvial deposits. Given that there are few outcrops, data and field observations derive from isolated outcrops that are sometimes quite distant from one another, and from a few boreholes.

The metamorphic rocks of this area were described by geologists who first became interested in the geology of southern Somalia (Stefanini and Paoli, 1916; Aloisi and De Angelis, 1938), and investigations continued through the years (Azzaroli and De Angelis, 1965; Borsi, 1965; Daniels, 1965; Ilyin, 1967; Bellieni et al., 1980; Haider, 1983; Warden and Horkel, 1984; Dal Piaz and Sassi, 1986; Haider, 1993).

Two high-grade metamorphic complexes can be distinguished in the Crystalline Basement of southern

Somalia: the Olontole Complex and the structurally overlying Diinsor Complex; their relationships have not been fully understood due to the extreme discontinuity of outcrops. Granitoids intruded both complexes that underwent migmatization.

1. *The Olontole Complex:* The complex consists of migmatite, paragneiss with subordinate amphibolite, quartzite and calc-silicate fels.
2. *The Diinsor Complex:* It consists of paragneiss, migmatite, quarzite (sometimes banded and rich in iron) and marble.
3. *The Intrusive Complex:* Foliated granites intrude both complexes. Rb–Sr whole rock isochrons indicate that these rocks are 500–550 Ma (early Palaeozoic), although older ages are reported by Bosellini (1989: 615 Ma) and Borsi (1965: 604 Ma).

Relationships among these three complexes are illustrated in Fig. 2. Development of a series of km-scale synforms and antiforms dislocated by Mesozoic and Tertiary NW–SE trending faults can be observed on a regional scale. Two fold systems can be recognized at outcrop scale. The first is a system of isoclinal folds that refold a schistosity developed during high-grade metamorphism. This folding event occurred before granite emplacement. The second is a system of open folds which developed in the entire Bur region and produced a foliation also in the granite bodies. This event therefore occurred after the granites were emplaced.

The nature of the contact between the Olontole Complex and the Diinsor Complex it is still a matter of debate; it could either be an original stratigraphic contact or a tectonic contact. In both cases its nature has been completely obliterated by the episode of high-grade metamorphism. Transposition during deformation further complicates the tectonic setting. The metamorphic grade in the two complexes is similar, but on the basis of available data, it is difficult to establish whether this is to be attributed to (a) a single metamorphic event which

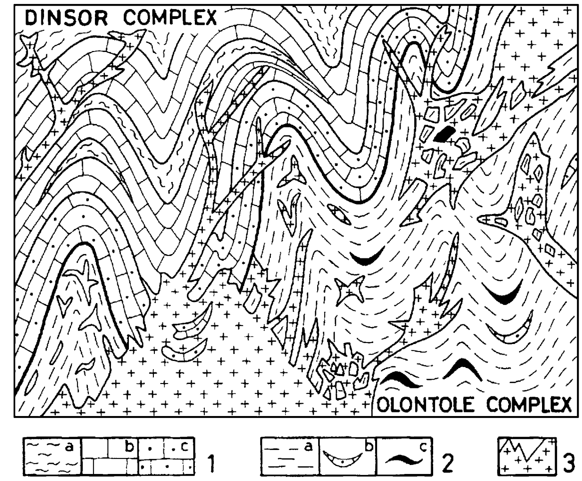

Fig. 2. Sketch cross-section showing structural setting of the metamorphic basment of southern Somalia before the second tectonic event (after Dal Piaz and Sassi, 1986). (1) Diinsor complex: (a) paragneisses, migmatites, (b) marbles, (c) iron bearing quartzites; (2) Olontole complex: (a) paragneisses, migmatites, (b) quartzites, (c) anfibolites; (3) granites.

involved both complexes, or to (b) two diachronous events which developed under similar petrologic conditions.

Assuming an early Paleozoic age for the granites, the last tectonic events involving the crystalline basement of southern Somalia may be ascribed to the last phases of the Pan-African cycle, whereas the major tectonometamorphic event could date back to the Precambrian.

3.2. The Luuq-Mandera basin

The area we investigated includes the eastern portion of the Luuq-Mandera basin, a large synclinorium of Jurassic and to Cretaceous sedimentary rocks outcropping between the Bur region and the "Northern Frontier District" crystalline basement outcropping in Kenya (Figs. 1 and 3). The outcropping succession consists of

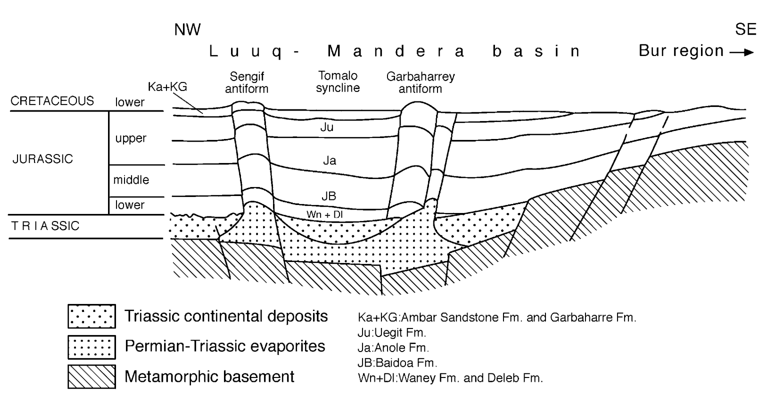

Fig. 3. Schematic section of the Luuq-Mandera basin (after Beltrandi and Pyre, 1973, modified).

carbonate sediments at the base, passing to evaporitic/terrigenous deposits up section. Continental deposits, probably of Tertiary age, lie unconformably above these sediments and are covered by younger basalts.

Based on surface data, the Jurassic–Cretaceous succession is estimated to be 2500–2900 m thick (Beltrandi and Pyre, 1973), but the Hol. 1 well, located in the central part of the basin (3°35′23″N, 42°02′58″E) (Burmah Oil Co., 1973) reported more than 4400 m of sedimentary rocks without reaching the metamorphic basement. In the central portion of the Luuq-Mandera basin, Bosellini (1989) estimates that the succession is more than 9000 m thick based on the interpretation of seismic data, or about 13,700 m thick based on aeromagnetic surveys. The detrital, carbonate and evaporite formations in the axial zone of the Luuq-Mandera basin do not outcrop. It is assumed that deposition in this part of the basin began early, perhaps in the Permo-Triassic, whereas the transgression reached the edge of the basin only in the early Jurassic.

The Jurassic–Cretaceous series of the Luuq-Mandera basin outcropping in the study area has been investigated in many works (Stefanini, 1931d; Barbieri, 1968; Beltrandi and Pyre, 1973; Angelucci et al., 1983; Canuti et al., 1983; Buscaglione et al., 1993), which can be consulted for a more detailed lithologic description and a complete list of fossil contents. The succession includes the following formations (from bottom to the top):

- The Deleb Formation;
- The Waney Formation;
- The Baidoa (Baydhabo) Formation;
- The Anole (Caanoole) Formation;
- The Uegit (Waajid) Formation;
- The Garbaharre (Garbahaarrey) Formation;
- The Ambar (Cambar) Sandstone Formation.

The entire succession deposited in an epicontinental sea during two main transgressive/regressive cycles (Fig. 4). The transgression on the Bur crystalline basement started with few meters of conglomerates and quartz arenites of uncertain age (the Deleb Formation), which pass to shales, marls and limestones with Toarcian ammonites (Waney Formation). Above these basal members lie 600–700 m of bioclastic, detrital and oolitic limestones that correspond to the Baidoa Formation. The maximum extent of the marine ingression is marked by the deposition of marls, dark shales and marly limestones with belemnites of the Anole Formation. The regression begins with the platform limestones of the Uegit Formation and continues with the evaporite deposits of the Garbahaarre Formation. During the late Jurassic–early Cretaceous regression, the Ambar Sandstone Formation was deposited in the western part of the basin. Detrital sediments intercalate the evaporite facies in the final stages of the regression.

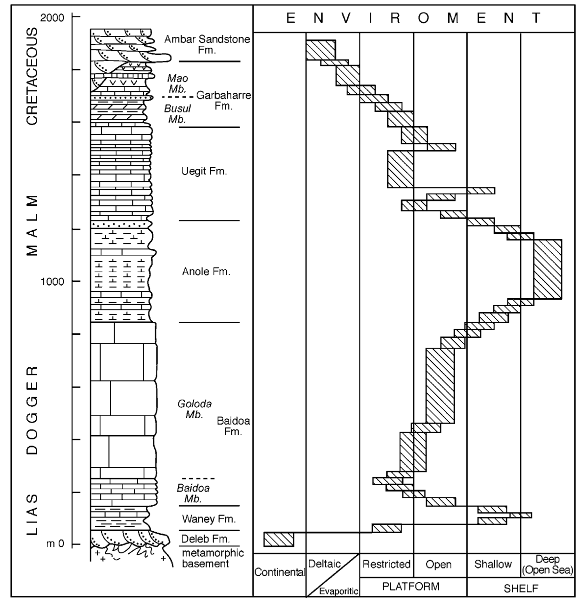

Fig. 4. Stratigraphy and environmental interpretation of the Luuq-Mandera basin (after Bruni and Fazzuoli in Ali Kassim et al., 1987).

3.2.1. The Deleb Formation

The early Jurassic sedimentation on the peneplaned crystalline basement begins with quartz-bearing conglomerates, which pass up section to poorly cemented quartz arenites rich in pyrite and mica. Thickness for this formation varies from 12 m at the type locality in Deleb, to 30 m, 100 km SW of Baidoa (Dominco, 1966; Buscaglione et al., 1993). The depositional environment varies from continental (fluvial) to transitional (delta). These deposits are also known in geological literature as "the Adrigat Sandstones" (Blandford, 1870; Hilal et al., 1977). The age of this formation is not determined; based on the age of the above-lying formation, it is inferred to be early Liassic.

3.2.2. The Waney Formation

Near Baidoa this formation is divided into three members (Canuti et al., 1983; Buscaglione et al., 1993). The basal member, which contains no fossils, consists of gray marly limestones and marls bearing quartz clasts. The intermediate member is composed of thick beds of gray, bioclastic calcilutites that are often bioturbed, marls and marly limestones alternated with calcarenitic beds in the upper part of the succession. The calcarenite beds, tens of cm thick, are composed of bioclastic and peloidal packstone–grainstones. The top of the formation consists of marls and red fossiliferous shales, calcilutites and calcarenites. There is a strong bioturbation of the basal carbonate sediments, which have a nodular aspect, and were affected by recrystallization. In the upper calcilutite and calcarenitic beds, graded bedding, cross bedding and breccia beds are common, along with pellets, peloids and coprolites. The replacement of grains by iron oxide is common (ferruginous calcarenites). On the whole, the formation is about 70 m thick. The depositional environment varies from a lagoon environment with limited mass transport to an open shelf environment with periodic large influxes of clastic material. Based on the rich fossil association of bivalves, gastropods, brachiopods, benthonic foraminifers and ammonites, this formation can be attributed to the ?late Pliensbachian–late Toarcian.

3.2.3. The Baidoa Formation

This formation is divided into two members: the lowermost Baidoa Member and the uppermost Goloda Member.

3.2.3.1. The Baidoa Member. This member consists of well stratified calcarenites and dark gray bioclastic calcilutites, oolithic calcarenites and bioturbed calcilutites. Texturally the rocks consists of packstones/bioclastic grainstones, peloidal and oncoidal with frequent cross-bedding and oolithic grainstone beds (Buscaglione et al., 1993). Mudstones and bioturbed bioclastic wackestones prevail toward the top. The maximum thickness is about 100 m. The fossil content includes lamellibranchs, gastropods, echinoderms, foraminifers, ostracods, radiolarians and sponge spicules. The depositional environment varies from an open to a narrow continental shelf. The fossil association indicates an Aalenian to (?) early Bajocian age.

3.2.3.2. The Goloda Member. This member represents the thickest carbonate succession in southwestern Somalia. It consists of gray calcilutites, limestones and reddish-yellow dolomites, which at the top pass into yellow–brown calcarenites and bioturbed calcilutites. According to Buscaglione et al. (1993) this member presents different characteristics in the two areas where it typically outcrops: the Baioda area and the area east of Baardheere. In the outcrops east of Baardheere mostly calcilutites and dolomites outcrop in the basal portion, passing into calcilutites and yellowish and brown–gray calcarenites. In the Baidoa area the succession is mainly composed of gray calcarenites with subordinate calcilutites. It is about 600 m thick.

Fossils are generally abundant and include bivalves, gastropods, echinoderms, calcareous algae, foraminifers, corals, etc. The environment is that of a narrow platform for the basal portion, with a transition up section to an open platform environment. Based on paleontological data, this member is attributed to the late Bathonian–early Callovian.

3.2.4. The Anóóle Formation

This formation consists of gray or gray-green marls in beds more than 30 m thick, alternating with thin micritic, sometimes marly, limestone beds and calcarenites. Parallel- or cross-laminations are common. Brachiopods are often found in the marls, whereas foraminifers, ammonites, belemnites and structures such as burrows are found in the micrites. These are open sea sediments, deposited below the wave base and represent the phase of maximum ingression of the Jurassic sea. The formation is about 400 m thick. The deposition of this formation testifies to a phase of general subsidence which, from a geodynamic point of view, is linked with the separation of Africa from Madagascar, and the subsequent formation of oceanic crust (Coffin and Rabinowitz, 1987). Fossils indicate an early Kimmeridgian–late Callovian age.

3.2.5. The Uegit Formation

This formation consists of well bedded, coherent gray limestones divided by Barbieri (1968) into three members: the Cololio Member, the Curao Member and the Mugdile Member. The division into three members is mainly made possible by the intermediate clay-rich member that outcrops west of the Jubba river. We have found no lithological variations at the map scale which justify the partitioning of the formation into different members.

The base of the formation is represented by well bedded calcarenites, commonly oolitic. In the middle part of the formation, light gray fossiliferous micritic limestones prevail; less common are fine-grained calcarenites in m-thick beds, containing frequent mollusc remnants. The micrites are sometimes intercalated with dark gray marls. In the upper portion of the formation are found the characteristic calcarenite horizons containing cm-sized oncolites, coral colonies in growth position, large ostreids and large turricolate gastropods (Fig. 5). In some outcrops sandy limestones are present, containing a small percentage of quartz.

On the eastern limb of the Bussul Syncline, in the upper part of this formation is present a 3–4 m thick intercalation of quartz arenite similar to the one of the Ambar Sandstone Formation. These are the first terrigenous sediments of the regressive succession. According to Angelucci et al. (1983), the Uegit Formation is about 350 m thick.

The deposition environment varies from shallow shelf to lagoon. Fazzuoli (1985) carried out a detailed study of the Uegit Formation and he recognized three phases of deposition. A regressive phase is recorded at the base, with the transition from a shallow shelf to an open platform and then a narrow platform. The second phase is characterized by an increase in sea level and by the establishment agin of shallow shelf environment. During the third phase, the sea level decreased with transition from an open platform to a narrow platform environment.

Fig. 5. Bank rich in gastropods and ostreids remains ("lumachelle") in the Uegit Formation, road Garbahaarrey–Baardheere.

The fossiliferous association of bivalves, corals, calcareous algae and foraminifers allows this formation to be ascribed to the late Oxfordian–Titonian.

3.2.6. The Garbahaarre Formation

The formation outcrops in the northeastern portion of the study area and is divided into two members by Barbieri (1968): the Busul Member and the Mao Member.

3.2.6.1. The Busul Member. It mainly consists of yellow dolomites in dm-thick beds with characteristic intercalations of reddish, laminated quartz arenites and mollusc lumachelle. In the lower portion of the member the following prevails: finely laminated yellowish calcarenites in which the laminations are formed by thin beds rich in quartz grains; gray micritic limestones in thin beds containing mollusc remnants, in some cases so numerous that they form a characteristic finely laminated lumachelle; cm-scale, reddish quartzarenite intercalations, well cemented and sorted, with parallel laminations. In a few cases the arenaceous interbedding is up to 1 m thick. Yellowish calcarenites, finely laminated in dm-thick beds, dolomitic limestones and yellowish, well bedded crystalline dolomites, rarely containing m-thick marl intercalations, are typical in the upper portion. This member is about 300 m thick. The contact with the underlying Uegit Formation is well exposed in the anticline SE of Garbahaarrey, where it is concordant. The upper limit of the Busul Member is sharp and can either occur with the Mao Member, or with the Ambar Sandstone Formation. In the Luuq area, the upper contact with the Mao Member is easily recognizable because the base of the Mao Member is rich in evaporite layers, which can be easily distinguished from the underlying carbonate succession. Further south, the Mao Member contains evaporite intercalations and the contact between the two members is gradational. During field work in that area the contact between the two members was placed at the base of the first thick bed of green shales, which are characteristic of the lower portion of the Mao Member.

Many authors have suggested the presence of lateral transitions between the two members of the Garbahaarre Formation. In the study area this is not observed, because both in the field and on aerial photos the key-beds of the Busul Member can be followed for tens of kilometers with constant thickness. In the northwestern part of the study area, west of the Tomalo Syncline, the Busul Member contains thick beds of quartz arenites with cross-lamination. These beds are more common moving to the west. Probably westward, just outside the study area, there is a transition from the Busul Member to the Ambar Sandstone Formation (Fig. 6).

This member deposited in a shallow sea coastal environment, probably during a series of transgressive/regressive episodes, as the common cyclic alternation of sandstones, calcarenites and micritic limestones would suggest. Based on the presence of bivalves, this member can be ascribed to the Neocomian.

3.2.6.2. The Mao Member. The Mao member shows great lithostratigraphic variations, both vertical and lateral, as illustrated in Fig. 6. Based on lithological characters we distinguish an upper part of the member outcropping near Luuq, and a lower part, which contains two facies.

The lower portion of the member shows great lateral variations, and the following two successions can be distinguished:

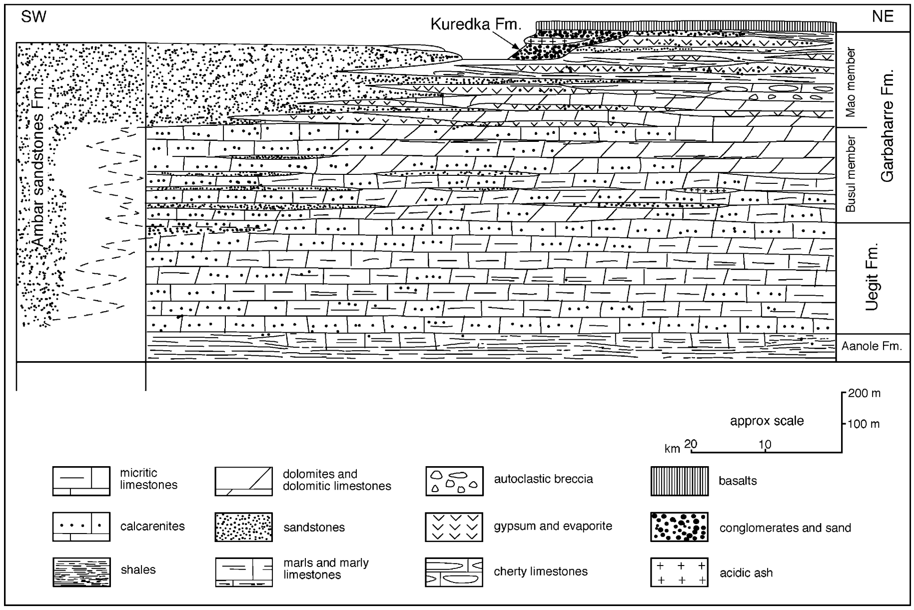

Fig. 6. Relationships between formations outcropping in the central part of the Luuq-Mandera basin.

(a) a succession that outcrops prevalently west of the Jubba river, in the core of the Tomalo Syncline. It is composed of a regular repetition of 3–6 m thick, commonly laminated beds of gypsum and anhydrite or gypsarenite with thin beds of green shale and carbonatic beds, from less than 1 m to several m thick, composed of laminated, often sandy calcarenites, marly limestones and dolomites (Fig. 7). Quartz sandstone intercalations are also common. The evaporites represent more than 70% of the succession that outcrops near the Macow well, north of Garbahaarrey, which gives its name to the member;

(b) a succession that outcrops east of the Jubba river characterized by the lack of evaporites. It is composed of dolomite and yellowish calcarenite, laminated, often sandy, well bedded, with intercalations of breccia with dolomitic elements containing traces of evaporites. A characteristic bed of chert-bearing calcarenites, 3–5 m thick, is present. Light-colored marls, gypsiferous green shales, with intercalations of light-colored quartzarenites similar to the arenites of the Ambar Sandstone Formation are commonly found near the base of the succession.

The upper portion of this member consists of green and red shales in beds up to 10 m thick, alternating with 4–5 m thick beds of finely laminated crystalline gypsum and laminated gypsiferous arenites commonly containing thin intercalations of green shales. The carbonate intercalations are limited to marls or light-colored, laminated marly limestones, or dolomitic limestones and laminated dolomites in thin horizons. Intercalations of several m of light-colored quartz sandstones, with a carbonate cement and evident cross-bedding very similar to the sandstones of the Ambar Sandstone Formation, are common in the Jubba valley, east and SE of Luuq.

Fig. 7. Evaporitic limestones in the Garbaharre Formation, NE of Garbahaarrey.

This member is about 300 m thick. The fossil content is low and only represented by bivalves. The entire Mao Member was deposited in an evaporitic environment

(Angelucci et al., 1983). The lower part shows a transition from SW to NE, from rocks richer in evaporites and terrigenous componenents to rocks poor in evaporites but still deposited in a narrow marine environment. The upper portion mainly consists of shales and evaporites, and probably deposited in a sabka environment; it marks the final regression of the sea from the entire area.

Given the poor fossil content, this member is uncertainly ascribed to the early Cretaceous (Neocomian–?Albian).

3.2.7. Ambar Sandstone Formation

This formation mainly consists of light-colored quartz arenites with a carbonate matrix, in beds of varying thickness, commonly >5 m (Fig. 8). The thicker beds have a lenticular shape, which would suggest channel deposits. Interbedded are yellowish sandy limestones and calcarenites, marls and green shales with evaporite are common mostly at the base of the formation. Cross-bedding is very common in the thicker arenaceous beds; the sets mainly dip NE; this further confirms that the formation has a NE progradation. Near Garbahaarrey the succession is no thicker than 200 m.

According to Barbieri (1968), the Ambar Sandstone Formation laterally passes to the Garbaharre Formation and the Uegit Formation. In the study area we found that the Ambar Sandstone Formation passes laterally to the Mao Member of the Garbaharre Formation. Very likely the Ambar Sandstone Formation passes to the Busul Member of the Garbaharre Formation just outside of the area we investigated, to the west. The only indication of such relationship between the Ambar Sandstone Formation and the Uegit Formation was found SE of Garbahaarrey; it is a bed of quartz arenites interbedded nearly at the top of the Uegit Formation. Lateral relationships between the Ambar Sandstone Formation and the Uegit Formation was also noted by other authors west of Baardheere (Angelucci et al., 1983), outside of our study area. Thickness of the Ambar Sandstone Formation increases from NE to SW (Fig. 6), near the Somalia/Kenya boundary it is reported to be about 600 m thick (Baker and Saggerson, 1958).

Fig. 8. Thick bedding in sandstones of the Ambar Formation, south of Garbahaarrey.

The heteropic contact of the Ambar Sandstone Formation with the Mao Member of the Garbaharre Formation is very well exposed along the southeastern limb of the Tomalo Syncline, between the Jubba river and Garbahaarrey. Near the Jubba valley, the slope just above the Busul Member is composed of the evaporite succession belonging to the Mao Member; further SW, in the Garbahaarrey area, the same slope, whose continuity is easily seen in aerial photos, mainly consists of the quartz arenites belonging to the Ambar Sandstone Formation, which lies directly above the Busul Member. There is a very gradual lateral transition; sandstone horizons typical of the Ambar Sandstone Formation are intercalated in the Mao Member at various levels up to the Luuq area. Interbedding is so common that in the map the contact between the Ambar Sandstone Formation and the Mao Member of the Garbaharre Formation has been conventionally placed at the base of the first thick gypsum and anhydrite intercalation.

The Ambar Sandstone Formation was deposited in a coastal-delta environment with an influx of continental terrigenous sediments. Toward the SW (in Kenya), these environments gradually pass to continental environments, from which the resedimented clastic material originated.

The formation is attributed to the Neocomian–?Albian because in the study area it is heteropic to the Busul Member of the Garbaharre Formation.

3.3. Tertiary continental deposits

3.3.1. The Faanweyn Formation

This formation consists of white siltstones and shales, with sandstones lenses. It is the oldest formation that lies uncomformably above the Jurassic–Cretaceous succession of the Luuq-Mandera basin, and occurs in isolated outcrops along the west side of the Jubba river.

Fig. 9. Outcrop of the Faanweyn Formation at top of hill, south of Garbahaarrey (Buuraha Faanweyn).

The maximum thickness of these sedimentary rocks is 10 m, and they are found at an altitude of 330 m a.s.l. (Fig. 9). The hill tops where this formation crops out have usually undergone silicification.

The isolated outcrops most likely represent remnants of a vast sedimentary cover that extended for almost 1000 km^2, in a lowered area between the Garbahaarraey Mountain Chain to the NW and the topographic relief of the outcropping Uegit Formation to the SE. The presence of finely laminated sediments and their exclusive occurrence in a lowered area suggest that this formation originated in a lacustrine sedimentary environment.

3.3.2. The Kuredka Formation

This formation was formerly called "Pre-basalt Continental Succession" (Carmignani et al., 1983), and outcrops near Luuq, where it lies uncomformably above the Jurassic–Cretaceous series and is capped by basalts.

This formation consists of conglomerates with basaltic and quartzitic pebbles and intercalations of quartzitic sands, showing both parallel- and cross-lamination (Fig. 10). Basaltic pebbles prevail towards the top of the succession. The quartzitic pebbles are well rounded and well-sorted by size, with a maximum diameter of 4–5 cm, whereas the basaltic pebbles are poorly rounded and sorted, with sizes ranging from a few mm up to dm. In the outcrops along the Jubba river, a m-thick intercalation of acidic volcanic ashes occurs towards the top of the formation (Aloisi and De Angelis, 1938), resedimented in a fluvial environment. Two 50–100 cm-thick layers of obsidian also occur at the top of the formation and indicate the presence of a nearby volcanic center. It is important to mention also the presence of silicified trees of some meter-size.

The typical occurrence of well rounded quartzitic pebbles indicates transport over long distances, because

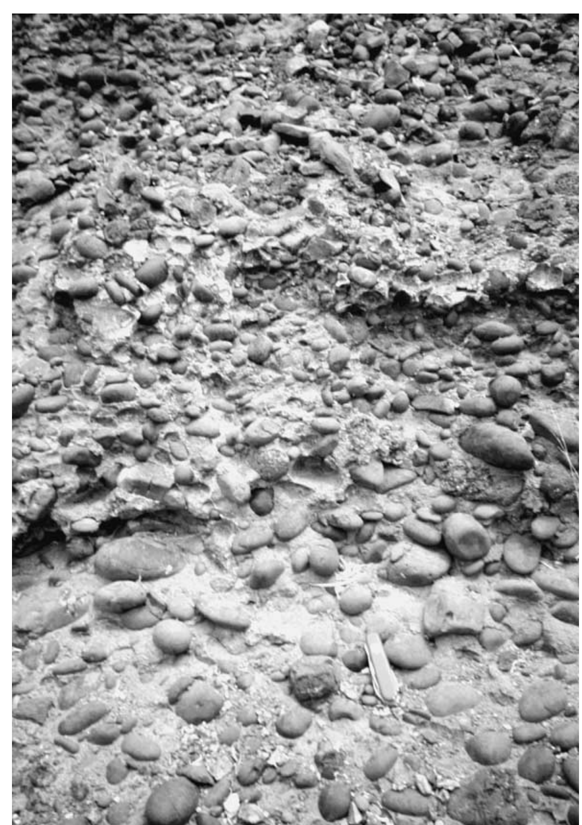

Fig. 10. The Kuredka Formation southeast of Luuq.

such lithologies do not outcrop in southeastern Somalia. The geochemical composition of the basaltic pebbles ranges from alkali basalt to phonolite (Ali Kassim and Fantozzi, 1985) and represents a magmatic event completely different from that which gave rise to the overlying basalts.

The thickness of this formation varies from 50 m NE of Luuq, to 15–20 m SE of Luuq. The thickness decreases to a few m at the base of the small basalt outcrops north of Urkut.

These fluvial deposits, which primarily crop out along the Jubba river, testify to a wide floodplain with meanders; the laminated sand deposits may represent sandbars along the river bed. Moving eastward, the thickness rapidly decreases until the Tertiary basalts lie directly above the Jurassic–Cretaceous series. The deposition of this formation very likely occurred in a river bed whose course was not very different from that of the present Jubba river.

The age of this formation is uncertain; nevertheless it is ascribed to the Tertiary on the basis of the presumed age of the overlying basalts and of the possible correlation with the Oligocenic Makadhuuf Sandstones. In the Webi Shabeeli valley the Makadhuuf Sandstones occupy the same stratigraphic position, unconformably overlying the Cretaceous succession and below basalts (Barbieri et al., 1979).

3.4. Tertiary volcanics

3.4.1. Basalts

In the study area, volcanic rocks occur in two distinct groups of outcrops: along the Jubba river, and NE of Urkut, in the Laf Maakada area. Along the Jubba river the outcrops of basaltic rocks are discontinuous, but they are distributed along the west side of the river and extend across the entire study area in a N–S direction. The Laf Maakada basalts outcrop in the northernmost part of the study area, and their areal extent is much larger. All these volcanic rocks have been studied both in the past (De Angelis D'Ossat and Millosevich, 1900; Manasse, 1916; Aloisi, 1927; Aloisi and De Angelis, 1938) and in more recent times (Ali Kassim and Fantozzi, 1985; Ali Kassim et al., 1993b).

Both the basalts of the Jubba valley and of Laf Maakada shows close similarities and consist of lavas, tuffs and sills. They are all fine-grained, aphyric or microporphyritic basalts with phenocrysts of plagioclase (An 80–60) and augite (Wo 42–39). The groundmass consists of plagioclase, clinopyroxene, partially altered olivine and opaque minerals. The Laf Maakada basalts differ due to the presence of iron-rich augite. The chemical composition of both basalts is consistent with transitional basalts of tholeiitic affinity, even if the Laf Maakada basalts represent more evolved magmas than those of the Jubba basalts, as inferred from the Mg content.

The basalts outcropping along the Jubba river have a maximum thickness of 32 m and columnar jointing is evident. At the base of the basalt flow, there is a layer of scoria several m thick. No other scoria layers or discontinuities of any kind are present in these outcrops, suggesting that one individual lava flow produced the Jubba river basalts. The Laf Maakada basalt bed is 15 m thick and the scoria layer at its base is only a few cm thick (west of Laf Maakada, Buur Samays). The top of the Laf Maakada basalt flow is blanketed by a soil bed up to 3–4 m thick, containing basaltic pebbles mixed with boulders and rounded fragments of limestones. These limestone fragments may represent the remnants of a sedimentary cover originally lying above the basalts. Through water prospecting surveys in the Xuddur area, Plio-Pleistocene calcareous and gypsiferous lacustrine sediments were found to overly basalts, which were then found, based on geophysical data, to be in continuity with those of Laf Maakada (Beltrandi and Pyre, 1973).

Since the arrangement of the Jubba river basalts is parallel to the actual Jubba valley, and since the Jubba basalts lie directly above fluvial sediments, it is likely that the basalt flow was channelled along a paleo river-bed.

The Jubba and Laf Maakada basalts must have an Oligocene to Plio-Pleistocene age if we assume (a) that all the basalts in this area have the same age, (b) a correlation between the Kureda Formation and the Makadhuud Sandstones, and (c) that the Plio-Pleistocene age of the sedimentary cover post-dating the lava flows of Xuddur is correct.

3.5. Quaternary deposits

The study area is characterized by widespread distribution of Quaternary deposits. In the geological maps only the most extensive, continuous and thickest outcrops are shown. All those areas in which the Quaternary formations outcrop discontinuously are reported on the map as outcrops of the bedrock. This is the case of the Tertiary basalt outcropping in the NE part of the map, where the basalts are almost entirely covered by residual soils and by extremely altered basalt pebbles. In the geological maps the following deposits are mapped: (a) caliche; (b) alluvial, colluvial, eluvial, eolian and beach deposits.

3.5.1. Caliche

Soils rich in calcium carbonate are usually cemented into a hard mass, which form extensive tabular areas. Mostly these outcrop in the northern portion of the study area, between the Xuddur and Berdaale. Water prospecting surveys in the Xuddur area have revealed that caliche covers Plio-Pleistocene lacustrine deposits (Beltrandi and Pyre, 1973).

3.5.2. Alluvial, colluvial, eluvial, eolian and beach deposits

Recent alluvial deposits are represented by sandy and silty sediments containing conglomerate and pebble intercalations. They are characterized by sedimentary structures such as ripples, cross bedding and parallel lamination. These deposits are mainly found along the course of the Jubba river, up to several hundred m distance from the present river-bed; their maximum height above the thalweg is 3 m at Luuq. The presence of ceramic artifacts above these recent deposits indicates that part of the Jubba alluvial plain was not involved in important flooding in recent times.

Terraced alluvial deposits are located above the recent alluvial deposits, and are separated by a fluvial escarpment of about 4 m. At Luuq they consist of cross-laminated and undulated sands with massive sand and horizontal siltstone and shale intercalations. The base is irregular and eroded (paleochannels), whereas the upper surface is generally subhorizontal and locally marked by channels that sometimes deepen down to the present level of the Jubba river. Prehistoric artifacts were found above these surfaces; their peneplanation and deposition therefore dates to the late Pleistocene (Coltorti and Mussi, 1987).

This group of deposits also includes the alluvial deposits at the base of slopes, the alluvial deposits of the tug and the red residual soils. The red residual soils occupy very widespread areas (NW of Luuq, NE of Garbahaarrey) and be up to 10 m (Buuraha Wakab).

4. Geomorphological evolution

The reconstruction of the geomorphological evolution of the area during the Tertiary is only based on a few continental formations, which outcrop discontinuously, and on a few geomorphological elements (Carmignani et al., 1983; Abdirahim et al., 1993). The proposed reconstruction is necessarily fragmented and incomplete.

The most evident morphological element of all of southern Somalia is an extensive peneplain at about 400 m a.s.l. (Fig. 11). On this horizontal erosion surface, now commonly covered by silcrete, calcrete and laterite soils, pebbles and well rounded grains are found; the latter suggest that the peneplanation phase was associated with fluvial erosion during a long period of tectonic stability. The extraordinary long stage of peneplanation, which would suggest the presence of an "ultiplain" (Twidale, 1983), makes it difficult to reconstruct the initial geomorphological setting in the area, and also makes it difficult to estimate the degree of erosion.

A long period of tectonic stability is necessary for an intense subaerial erosion. King (1976) mentions various phases of peneplanation in eastern Africa, among these the "Moorland planation", which corresponds to the "African planation", and occurred between the late Cretaceous and the late Miocene. This important phase of planation is said to be characterized by an extremely flat final morphology that develops over large areas, and by lateritic soils with calcrete and bauxite. These elements closely correspond to those we found in the study area. It would be natural, therefore, to correlate the peneplanation phase of southern Somalia with this event (African planation), which is recognized at even larger scales. After this phase of widespread horizontal planation a change in the landscape occurs, which is linked with the development of fluvial channels during a phase of general uplift, probably correlated with the development of the Rift valley (Nyamweru, 1980).

Fig. 11. Panoramic view of the Upper Jubba valley, note the peneplained top of the hill.

An abandoned fluvial valley more than 100 km long can be recognized between Garbahaarrey and Mandera in Kenya (see the sketch map "Geomorphological Evolution of the Upper Jubba valley" in the enclosed geological maps). This is supported by: (a) the presence of continuous Quaternary alluvial deposits; (b) two deep incisions in the rocks more resistant to erosion, the limestones of the Uegit Formation, in the major anticlines of the Garbahaarrey and Sengif mountain chains; and (c) by forest patterns and areas rich in vegetation. This fossil valley connects with the present course of the Dawa river just west of Mandera and can be interpreted as the ancient course of the Dawa before it was captured by the Jubba river; it is named "Paleo-Dawa" in the geomorphological sketch map.

The presence of lacustrine deposits (the Faanweyn Formation), now outcropping discontinuously between the Garbahaarrey mountain chain and the topographic higher area, which corresponds to the outcrops of the massive limestones of the Uegit Formation, strongly suggests the presence of a large lake (Faanweyn Lake) of which both the Paleo-Dawa and the Paleo-Jubba were tributaries.

A lowering of the hydrographic network followed, and the Faanweyn Lake dried-up. The water flowed along the Paleo-Jubba and along a water course located farther SE (Togga Dhuurta), as shown by the presence of fluvial conglomerates with basalt pebbles found in the Koora Farseed paleo-valley.

In the past, the course of the Paleo-Jubba between Luuq and Baardheere was not very different from the present course of the river, as highlighted by the alignment of outcrops of alluvial deposits of the Kuredka Formation and of the Tertiary basalts which flowed in its channel. The uplift of the area that followed, and the further incision of the previous deposits, created the current course of the Jubba river and the Quaternary alluvial terraces, which are easily recognizable in the Luuq area. The capture of the Paleo-Dawa by the Dawa near Mandera occurred during the latest stages of the geomorphological evolution of the area.

5. Tectonics

In the study area, the Mesozoic succession of the Luuq-Mandera basin dips gently northeastward for over 100 km, from the Crystalline Basement of the Bur region to the Garbahaarrey area (see the Tectonic Sketch Map of the Upper Jubba valley in the enclosed geological map). In the Garbahaarrey Chain and the Sengif Chain, bedding is folded developing anticlines and synclines with vertical axial planes, that in map view form two deformed zones about 10 km large and more than 100 km long. The two deformed zones correspond to the Garbahaarrey and the Sengif Chain. The Tomalo Syncline is found in the axial zone of the Luuq-Mandera basin, between the Garbahaarrey Chain and the Sengif Chain.

The Sengif Chain essentially consists of one single anticline with vertical axial plane and faulted limbs. This structure is less than 5 km wide and extends southeastwards for over 110 km from the Mandera zone (NW of Luuq) to Kenya; it runs only marginally through the study area. The structures of the Garbahaarrey Chain extend entirely within the study area and we investigate them in more detail. We named this elongated area where folding and faulting occurred the "Garbahaarrey Deformation belt".

The Garbahaarrey Deformation belt includes a N 40° E trending main fault, the Garbahaarrey Fault, which runs along almost the entire length of the deformed area. A series of minor parallel and oblique faults are associated with the main fault. In the Garbahaarrey belt the more deformed area is the central part of the belt, SE of Garbahaarrey. Deformation then reduces toward the southwest.

The northeastern portion of the Garbahaarrey Deformation belt, extending from the Buur Gran to the Buur Bakale area, is less deformed. In this area is exposed the northern part of the Garbahaarrey Fault and, an "en échelon" fold system with folds characterized by wide hinges and fold axes striking N 15° E and N 40° E (the Buur Guran Syncline, the Buur Guran Anticline and the Bur Bakale Syncline). Southwest of Urkut, two additional folds occur with a similar trend. They are symmetric folds with sub-vertical axial planes and gently inclined limbs. In detail, the dip of the limbs is about 5° at the pericline terminations of the Buur Guraan Anticline only, elsewhere the dips do not exceed 3°, thus indicating that this area underwent only a modest buckling.

The zone southeast of Garbahaarrey (see the Tectonic Sketch Map of the Upper Jubba valley in the enclosed geological map), underwent more intense deformation. In this area, the Garbahaarrey Fault is associated with other faults, always striking NE–SW, that bound open to tight folds: the Buuraha Wakab, Garbahaarrey and Busul Anticlines, the Busul Syncline. These are the most important folds in the entire area; the dip of their limbs is typically 10°, but commonly can reach 30–40°. Steeper (up to vertical) limbs only occur close to the faults. The fold profiles can be both symmetric or slightly asymmetric with vertical axial planes or steeply dipping toward SE. The hinge zone is generally wide and commonly a "box fold" profile occur. The main faults develop along limbs of the folds, originating flower structures geometries. The axes of the anticlines are subhorizontal and trend NE–SW, parallel to the main faults; however, deviations up to 40° commonly occur, and are generally associated with an abrupt axial dip, as in the Garbahaarrey Anticline. Further SW, deformation again decreases.

According to Beltrandi and Pyre (1973), folding in the Garbahaarrey and Sengif belt was produced by buckling near normal faults. Horsts would correspond to anticlines, whereas grabens would represent synclines. The transport of the pre-Jurassic evaporites or of the shales of the Anole Formation from the axial zone towards the limbs of the Tomalo Syncline would have given rise to differential uplift. However, this hypothesis does not satisfactorily explain all of the tectonic features of the Garbahaarrey Defomation belt. Beside the fact that it is difficult to accept the existence of as many horsts (all with the same wavelength) as anticlines, the folds of the northeastern segment of the belt are not separated by faults. Furthermore, folds are not always parallel to the faults; in one case a fault (the Garbahaarrey Fault) displaces the axial plane of an anticline (the Buur Guran Antlicline). The hypothesis by Beltrandi and Pyre (1973) does not account, therefore, for the systematic relationships between the faults and the the folds axes.

The deformation recognized in the Garbahaarrey Deformation belt can be better understood in the context of strike-slip tectonics. Typical features of a wrench zone are (Moody and Hill, 1956; Biddle and Christie-Blick, 1985; Sylvester, 1988): (a) deformation localized in zones that are narrow with respect to the their length; (b) main wrench faults, parallel to the deformed area; (c) "en échelon" folds, with axes oriented at low angle to the wrench fault; (d) both synthetic and antithetic conjugate strike-slip faults; they include both synthetic and antithetic faults oriented at low and high angles to the wrench fault, respectively.

An analysis of the geological maps allows us to recognize the typical features of a wrench zone tectonic features in the Garbahaarrey Deformation belt. The Garbahaarrey Fault, more than 100 km long, may represent the main wrench fault. The folds between Luuq and Urut show an "en échelon" arrangement; their orientation respect to the main wrench fault and the dislocation of their axial planes by faults indicate a right-lateral displacement along the main wrench fault. Minor faults, at both low and high angles to the Garbahaarrey Minor faults, occur throughout the area and represent conjugate systems consistent with the overall right-lateral movements along the main faults. The folds with axes striking N 50° E–N 60° E, occurring east of the Garbahaarrey fault in the proximity of the Jubba river, are bounded by faults that are interpreted as a system of conjugate dextral faults at low angles to the Garbahaarrey fault, similar to the R surfaces of the Riedel shear system. The distribution of the intensity of the deformation, which increases SE of Garbahaarrey (where most displacement occurs) and decreases to the NE and SW, confirms the hypothesis of a strike-slip tectonic regime, with deformation starting in the area SE of Garbahaarrey.

Some features suggest that the Garbahaarrey Deformation belt did not develop through simple strike-slip deformation, but that shortening occurred perpendicular to the deformation belt and thus gave rise to dextral transpressive movements (Harland, 1971; Wilcox et al., 1973; Sylvester and Smith, 1976; Sanderson and Marchini, 1984). Features indicating tectonic transpression are: (a) parallelism between fold systems and the major faults; (b) a difference of 20° between the orientation of the strike-slip zone and that of the associated "en échelon" folds.

The difference in orientation (20°) between the Garbahaarrey fault zone and the "en échelon" folds between Luuq and Urkut indicates that transpression occurred in the area. This difference in orientation is found in the less deformed area, which corresponds to the northeastern termination of the Garbahaarrey Deformation belt. Because this area was only deformed during the final stages of the deformation phase, which produced the Garbahaarrey Deformation belt, the folds did not have time to rotate, and probably maintained their original orientation to the present. In a progressive simple shear deformation, there is usually a 45° angle between the principal axis of the incremental strain ellipsoid and the shear zone; this orientation brings about the formation of "en échelon" folds. In order to obtain a 20° angle, a shear strain with $\gamma = 2.4$ is necessary (Ramsay, 1967); this high value corresponds to shear angles of $\varphi = 68°$ and implies significant shortening (>60%) of the fold. This is in contrast with field observations; the dip of fold limbs is generally never greater than a few degrees. If transpression occurs during deformation, the folds form at smaller angles with respect to the shear zone. According to Sanderson and Marchini (1984), a shear strain with $\gamma = 0.2$ (corresponding to a $\varphi = 1°$ shear angle) and 20% shortening perpendicular to the shear zone is sufficient for the formation of folds at a 20° angle to the shear zone.

It is, however, difficult to explain the parallelism between folds and strike-slip faults, even through transpression: even if the first folds formed at 20° angles with respect to the shear zone, a large amount of strain is necessary to produce parallelism of fold axes and faults. Sanderson and Marchini (1984) further report that in order to have a small angle (<5°) between fold axes and shear zones, if the shear strain is $\gamma = 0.5$ (equivalent to a shear $\varphi = 27°$ angle), a shortening perpendicular to the shear zone of more than 50% is necessary. Evidence of such a shortening was not found in the field.

It must be noted that transpressive structures in the field are generally very different from theoretical models used to calculate the orientation of structural elements as a function of the degree of shear and shortening. Theoretical studies usually consider that the areas of transpression are regions of homogeneous deformation delimited by rigid, undeformed blocks in which most of the deformation takes place. In the field the presence of important vertical discontinuities (faults) often creates an irregular distribution of strain. When transpressive deformations are associated with vertical faults, the total stress has two components: one parallel to the strike-slip faults, the other perpendicular to it (Mount and Suppe, 1987). If movement along faults occurs frictionless, without dragging of the sedimentary cover, the stress component parallel to the faults is only responsible for the lateral displacement, i.e., of the slip, whereas the perpendicular component is responsible for the development of thrusts, anticlines and synclines striking parallel to the faults (Fig. 12). The relationship between the two components depends on the orientation of σ_1 with respect to the fault orientation.

For the development of the structures in the Garbahaarrey Deformation belt, the sedimentary rocks between the faults must not have been dragged. The area between the main faults must have been deformed mostly as a function of the compressional component of stress, and independently of the displacement along the fault. The abrupt change in orientation of the Garbahaarrey Anticline axis (east of Garbahaarrey) may have developed late and can be interpreted as a drag structure linked to a right-lateral strike during the final stages of deformation when the anticline had already formed.

Field data are scarce for the internal structure of the Sengif Deformation belt. Geological photointerpretation and field surveys have highlighted many similarities with the Garbahaarrey Deformation belt. The two belts are parallel and probably developed in the same tectonic event. As previously suggested by Beltrandi and Pyre (1973), development of the Garbahaarrey and the Sengif Deformation belt could be associated with the presence of a Triassic basin in the central part of the Luuq-Mandera basin: the two deformation belts coincide, both in terms of distance and strike, with the edge of the Triassic basin. It is more likely that deformation is not linked to movement of the deep-seated evaporites as suggested by Beltrandi and Pyre (1973), but that Triassic faults were reactivated as strike-slip faults involving the overlying sedimentary succession.

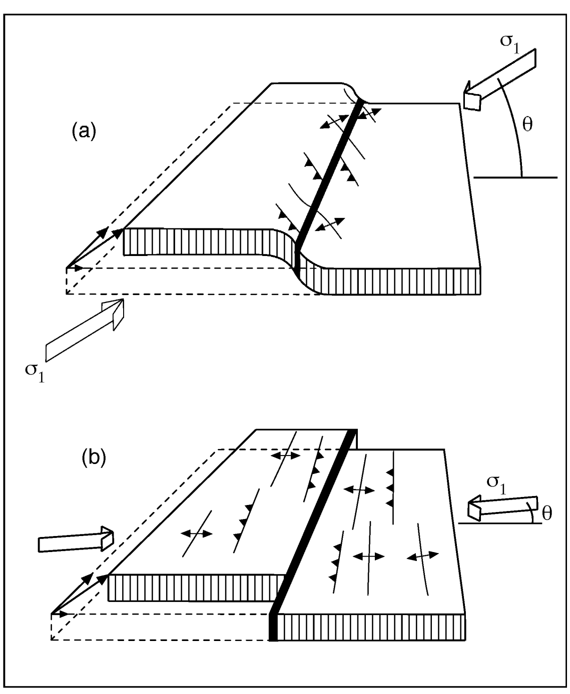

Fig. 12. Tectonic features developing in the case of (a) wrench deformation in zones of distributed shear; (b) decoupled strke-slip and thrust deformation along low-drag faults with little distributed shear (after Mount and Suppe, 1987).

The times of deformations in the Garbahaarrey and the Sengif Deformation belt are poorly constrained. The upper limit is represented by the age of the fluvial deposits and of the Tertiary basalts (Oligocene?) which, as previously mentioned, in adjacent areas lie discordantly and undeformed above the Jurassic–Cretaceous series; the age of the youngest sediment involved in deformation (the Ambar Sandstone Formation) indicates that the lower limit is early Cretaceous. Bosellini (1989) ascribes these movements to the late Jurassic–early Cretaceous, because the Ambar Sandstone Formation are assumed to discordantly overlie the folded Jurassic formations. We think that this hypothesis can be excluded because in the study area we did not found an unconformity at the base of the Ambar Sandstone Formation. Also according to other authors (Barbieri, 1968; Angelucci et al., 1983), the contact between the Garbahaarre Formation and the Ambar Sandstone Formation is heteropic and no unconformity is reported. Furthermore, the Ambar Sandstone Formation is folded in the Garbahaarrey Deformation belt.

According to Boccaletti et al. (1988), the tectonic events that deform the sedimentary succession of the Luuq-Mandera basin are late Cretaceous in age. This is based on the observation that outside of our study area, in central Somalia, the Ambar Sandstone Formation is folded and the Yesomma Sandstone Formation of late Cretaceous–Paleocene age (Altichieri et al., 1982; Guerrera, 1983; Arush and Basu, 1993) is not deformed. According to Ali Kassim et al. (1993a), these movements could be induced by the opening of the East African Rift. The differential rate of opening of different parts of the Rift might have created stress in the surrounding plate, resulting in the reactivation of the pre-Jurassic faults that border the Luuq-Mandera basin.

6. Conclusions

Investigations in southern Somalia have resulted in a better understanding of the stratigraphic succession that crops out in the eastern part of the Luuq-Mandera basin. The succession, which was deposited on the southern

Somalia metamorphic basement (Bur region), represents a major trangressive/regressive cycle. Transgression is marked by a few meters of conglomerate and quartz arenite (Deleb Formation), followed by shales, marls and limestones (Waney Formation). Above lie thick bioclastic, detrital and oolitic limestones (Baidoa Formation), in turn succeded by marls, shales and limestones (Anole Formation), which marks the maximum extent of the marine transgression. The regression phase began with deposition of the platform limestones of the Uegit Formation and continued with the evaporite deposits of the Garbahaarre Formation. The late Jurassic to early Cretaceous Ambar Sandstone Formation was deposited in the western part of the basin. Detrital sediments are intercalated with evaporite facies in the final stages of the regression.

Structural geological investigations were focused on the Garbahaarrey belt, previously interpreted as linked to normal faulting. We, however, suggest an origin in a dextral strike-slip deformation regime. This is supported by the localization of deformation to narrow zones, the development of wrench faults parallel to the deformed area, en echelon folds at low angle to the wrench faults and the presence of synthetic and antithetic conjugate strike-slip faults. Parallelism between folds axes and major faults suggests that the Garbahaarrey belt did not develop through simple strike-slip deformation, but that shortening occurred perpendicular to belt axis during dextral traspressive movements.

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