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Stratigraphy, sedimentology and structure of the Numidian Flysch thrust belt in northern Tunisia

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ABSTRACT

The Oligo-Miocene Numidian Flysch of northern Tunisia has long been divided into three distinct lithostratigraphic units considered as vertically superimposed: the lower unit or the "Zouza member", the middle unit or the "Kroumirie member" and the upper unit or the "Babouch member". According to this reconstruction the two first members are mostly Oligocene in age and only the third member was assigned as early Miocene in age. In this study, we present new biostratigraphic data, based on planktonic foraminiferal analysis, demonstrating that both the Zouza and the Kroumirie members are Oligocene–early Miocene in age and are, therefore, coeval.

Four distinct facies associations have been identified within the Numidian Flysch including: (a) massive sandstones; (b) conglomerate; (c) an interbedded mudstone–sandstone association; and (d) a mudstone facies association. Slide-slump units and injectionite sands occur within the more mud-rich associations. The likely depositional setting is a muddy slope–apron system, cut locally by sand-rich channels, which fed channel-terminal lobe deposits. Paleocurrent data support strongly a flow from N and NW. Modal analysis, demonstrates that the Numidian sandstones are quartz-arenite type (QFL, 97.25:1.25:1.5) derived from middle to high grade-metamorphic and granitic rocks. Zircon geochronology, yielding ages of 514 ± 19 Ma from Tunisia and 550 ± 28 Ma from Sicily, would support the basement terrain that crops out along the Algerian coast and forms part of Calabro–Peloritani–Kabylian zone, as the most likely parental source of the Numidian Flysch for both Sicily and Tunisia. Zircon data from the Fortuna Formation yields ages of 1698 ± 67 Ma, which is more compatible with an African craton source.

Structural consideration of the basal contact of the Numidian Flysch with the underlying Tellian rocks, as well as newly interpreted seismic data; confirm the allochthounous position of the Numidian complex and its displacement southward.

Facies comparison with the equivalent Oligo-Miocene Bejaoua siliciclastic deposits outcropping towards the south shows that the Numidian complex is an "out-of-sequence thrust unit" and that the two Oligo-Miocene sedimentary systems are quite distinct and were sourced from wholly different source regions.

1. Introduction

The Oligo-Miocene Numidian Flysch forms part of an orogenic belt that stretches over 2000 km through the Western Mediterranean region. It outcrops from the Betic Cordilleras in southern Spain, along the North African margin to Tunisia, and eastwards to Sicily and the southern Apennines (Fig. 1) (Wezel, 1970; Hoyez, 1989; Dewey et al., 1989; Guerrera et al., 1993). Recent worldwide discoveries of hydrocarbons in thrust-fold systems, together with recognition that the Numidian Flysch is a proven gas play in Sicily, have revived exploration activity in this deep-water turbiditic system both onshore and offshore northern Tunisia. However, despite several works devoted to the Numidian Flysch complex in northern Tunisia, there is still considerable debate about the stratigraphic relationship between its constituent members (Fig. 2), the environment of deposition and sandstone provenance, and the overall structural context especially regarding its relationship with the underlying succession and the coeval Bejaoua group, which lies immediately to the south.

Stratigraphically, the Numidian Flysch was first sub-divided into three members by Rouvier (1977) (Fig. 2): the Zouza shales

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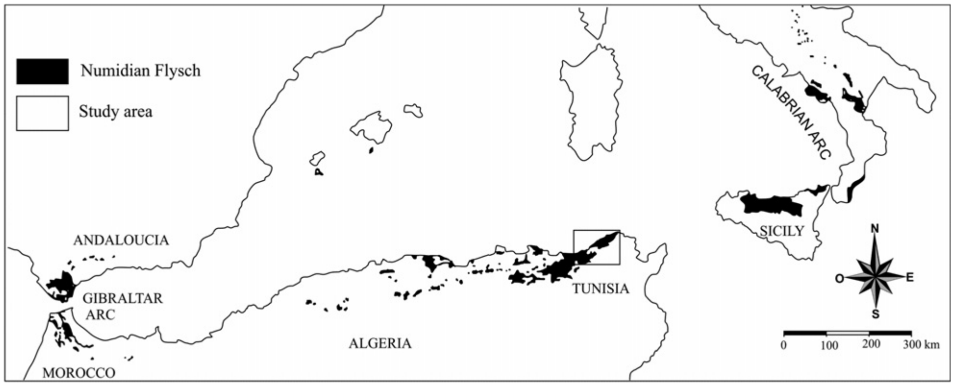

Fig. 1. Location map of Numidian Flysch orogenic belt, Western Mediterranean region (Hoyez, 1989).

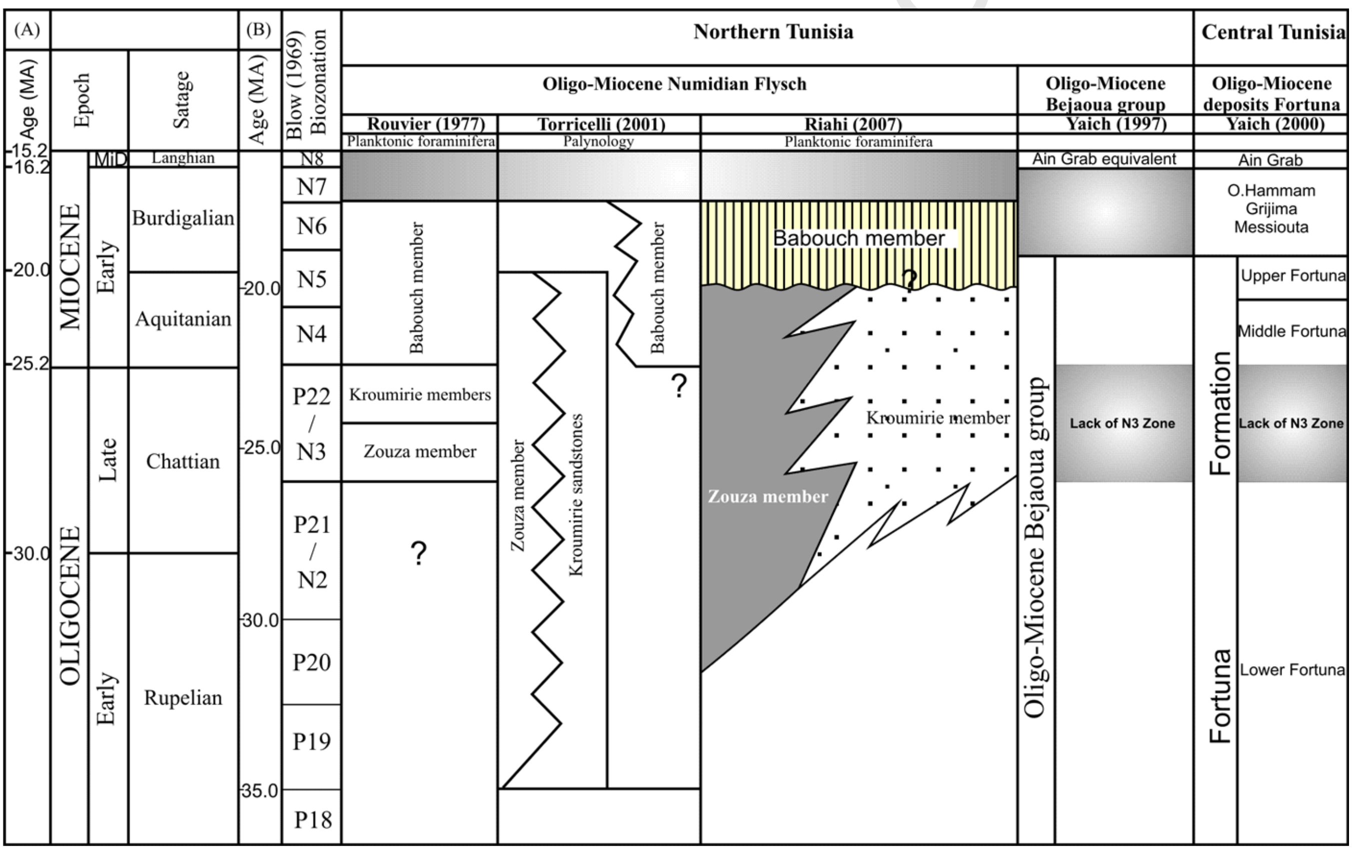

Fig. 2. Stratigraphy of the Oligo-Miocene deposits in northern Tunisia, mainly drawn after Rouvier (1977), on the basis of Torricelli (2000) and Yaich (1997).

(1500–2000 m thick) at the base, the Kroumirie sandstones (1000–1200 m thick) in the middle and the Babouch shales (300 m thick) at the top. In this stratigraphic scheme the two lower members were attributed to the Upper Oligocene (N3 zone), whereas a Lower Miocene age was inferred for the third member (N4–N6 zone). More recently, on the basis of a detailed palynological investigation, Torricelli et al. (2000) and Torricelli and Biffi (2001) have suggested that Zouza and Kroumirie members are age equivalent rather than stratigraphically superimposed (Fig. 2).

Regarding the sedimentology, significant advances have been made on documenting the principal sedimentary facies of all three members (Beaudoin et al., 1986; Parize, 1988; El Maherssi, 1992; Yaich, 1997), but no comprehensive depositional-environmental model has yet been developed.

According to several previous studies (Gottis, 1953, 1962; Wezel, 1968; Kujawski, 1964, 1969; Crampon, 1973; De Jong, 1975; Alouani, 1996; Dlala, 1996) the Numidian complex is considered as transgressive over the underlying deformed Tellian Cretaceous to Eocene rocks, with an hiatus occurring between the two units during the middle to late Eocene (Priabonian time). Consequently, the Numidian Flysch and the Bejaoua group are both considered to belong to a linked sedimentary system through which material was supplied from a continental-to-deltaic succession in the south (the Nubian sandstone and Fortuna formation) to the Numidian Flysch basin in the north (Wezel, 1968).

The alternative view considers the Numidian Flysch as a complex thrust unit displaced from North to South and now resting in different areas on older rocks, which themselves are allochthonous or para-autochthonous units with variable detachment levels represented either by Triassic evaporites or Tertiary shales (Rouvier, 1977; Caire et al., 1971; Carr and Miller, 1979; El Euchi et al., 2004; Ould Bagga et al., 2006).

In order to shed further light on these controversies and to better understand the internal organization of the Numidian Flysch Formation as well as its sedimentary characteristics, architecture and its paleogeographic relationship with the underlying Tellian rocks and the Bejaoua group, a detailed interdisciplinary study has been undertaken, integrating biostratigraphy, sedimentology and structural geology. This study focuses on the Numidian rocks of the southern part of the orogenic belt in the Kroumirie range (Fig. 3). It aims to: (1) review the stratigraphy of different sections within the Zouza and Kroumirie members (sensu Glaçon et al., 1967; Rouvier, 1977) using planktonic foraminifera, (2) document the specific sedimentological characteristics, architecture and depositional setting of these members in their type locality, (3) to establish a comparison with the coeval Bejaoua group deposits and (4) to discuss the ultimate provenance of the Numidian Flysch sandstones.

2. Methodology

The study area is situated in northern Tunisia and represents the southern part of Kroumirie range (Fig. 3). The Oligo-Miocene deposits outcropping in this area are represented by the Bejaoua group in the south and the Numidian Flysch in the north. A series of sections were logged on a detailed bed-by-bed scale within the Numidian Flysch including, from east to west; Jebel Zouza (Tebaba and Gassa–Msid sections), Bougoutrane–Balta and Ben Metir sections. In addition, five sections were logged within the Bejaoua group, of which one is documented herein – the Jebel Hajra touila section. These sections form the basis of our sedimentological interpretations and were further sampled for biostratigraphy and petrographic analysis.

Over 102 samples were collected systematically from both the mudstone-rich units and isolated mudstone beds associated with sandstone units of the Numidian Flysch, and a further 62 samples were collected from the Bejaoua group deposits. All samples were processed for biostratigraphic study. Whereas parts of the mudstone-rich succession contain abundant planktonic foraminifera, the mudstones that are more closely associated with sandstone facies typically contain none or very few. Care was taken to look out for older reworked species eroded and re-deposited in turbidities. In many samples, there were significant numbers of benthic foraminifera, and in particular deep agglutinated forms.

Taking account of the stratigraphic variation in occurrence of some planktonic species as a result of geographical influence, we have mainly compared our results with the principal studies carried out in the Mediterranean basin by Bizon and Bizon (1972),

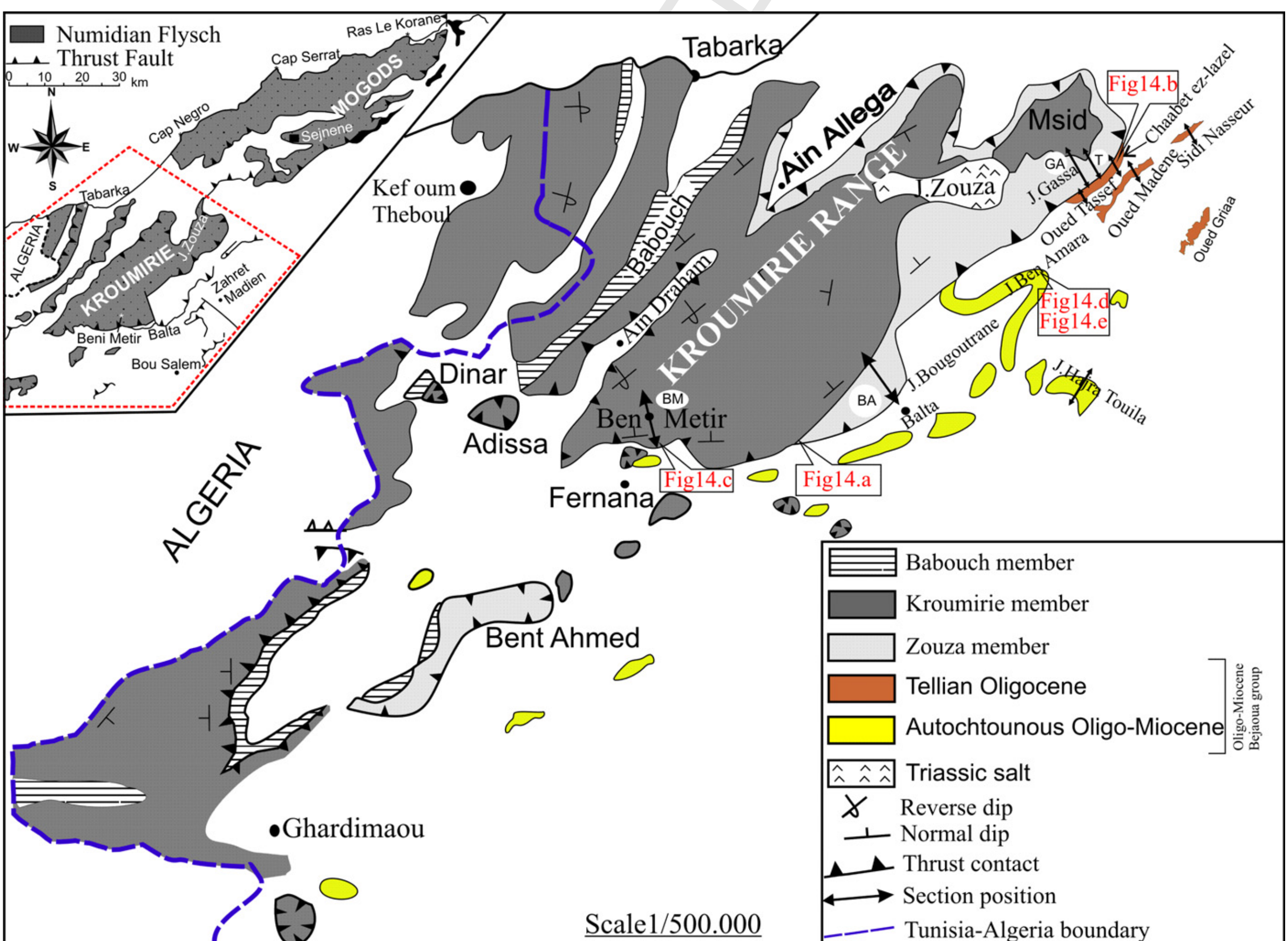

Fig. 3. Shematic map of the Kroumirie range showing the distribution of different members of the Numidian Flysch and the Oligo-Miocene Bejaoua group, near the main thrust front (Glaçon et al., 1967). T: Tebaba, GM: Gassa–Msid section, BA: Balta–Bougoutrane section, BM: Ben Metir section.

Ben Ismail-lattrache and Bobier (1984), Bolli et al. (1985) and Berggren et al. (1995).

3. Biostratigraphic results

3.1. Tebaba section (T)

This section was measured in the East of Jebel Zouza (Figs. 3 and 4), in approximately the same location as the type locality for the Zouza member as originally defined by Rouvier (1977), who considered it as the lowermost member of the Numidian Flysch. It consists of thick mudstone intervals (here designated MI1 to MI5) interbedded with massive sandstones and thin-bedded turbidite sandstones (designated SL1 to SL4).

Biostratigraphic investigations (Fig. 5) indicate that samples T1, T2, T3 and T5 are rich in a diverse planktonic foraminiferal assemblage including; *Globorotalia opima nana, Globigerina ampliapertura, Catapsydrax dissimilis* and *Globigerina sellii*. These species correspond to the *G. ampliapertura zone* (P20 zone) of early Oligocene (Upper Rupelian) age. Samples T11, T13, T16, T17, T18 and T19 include the same species, but *G. sellii* becomes rare and *G. opima–opima* becomes very abundant. These levels are attributed to the *G. opima opima* zone (P21 zone) characterising the late Oligocene (early Chattian). The samples T24 and T26 display a planktonic foraminifera association comprising *Globorotalia kugleri, Globigerina preabulloides, C. dissimilis and Globigerina ciperoensis angustiumbilicata*. This association dates *as* early Miocene (Aquitanian: N4 zone). The species identified within the uppermost mudstone interval (MI5, samples T30 and T31) also indicate a Lower Miocene age.

Together, these data demonstrate that the age of the Zouza member extends from early Oligocene to early Miocene. They also show the absence in this section of the N3 (P22) zone of late Oligocene age.

3.2. El Gassa–Msid section (GA)

This section forms the western prolongation of the Tebaba (T) section. It was partly studied by Torricelli (2000) and Riahi et al. (2007) and comprises the Zouza member and part of what is considered by Glaçon et al. (1967) and Rouvier (1977) to be the Kroumirie member (Figs. 3 and 4). Detailed mapping of the study area indicates that the lowermost sandstone unit encountered in the Tebaba section (SLT1) pinches out in the El Gassa area and is progressively replaced, to the west by a thick mudrock unit.

Samples GAS1, GAS2 and GAS3 collected from the lowermost exposed mudrock intervals contain an association of planktonic foraminifera characteristic of the *G. ampliapertura* zone of early Oligocene age (Rupelian: P20 zone) (Fig. 6). The presence of *G. opima opima* and the absence of *G. sellii* in GAS7 and GAS8 samples, suggest the Late Oligocene P21/N2 zone (Rupelian to late Chattian). The assemblage identified in the GAS14–GAS20 samples is characterized by the presence of *Cassigerinella chipolensis, Globigerina binanensis, G. opima–nana, G. kugleri, Globigerinoides primordius*

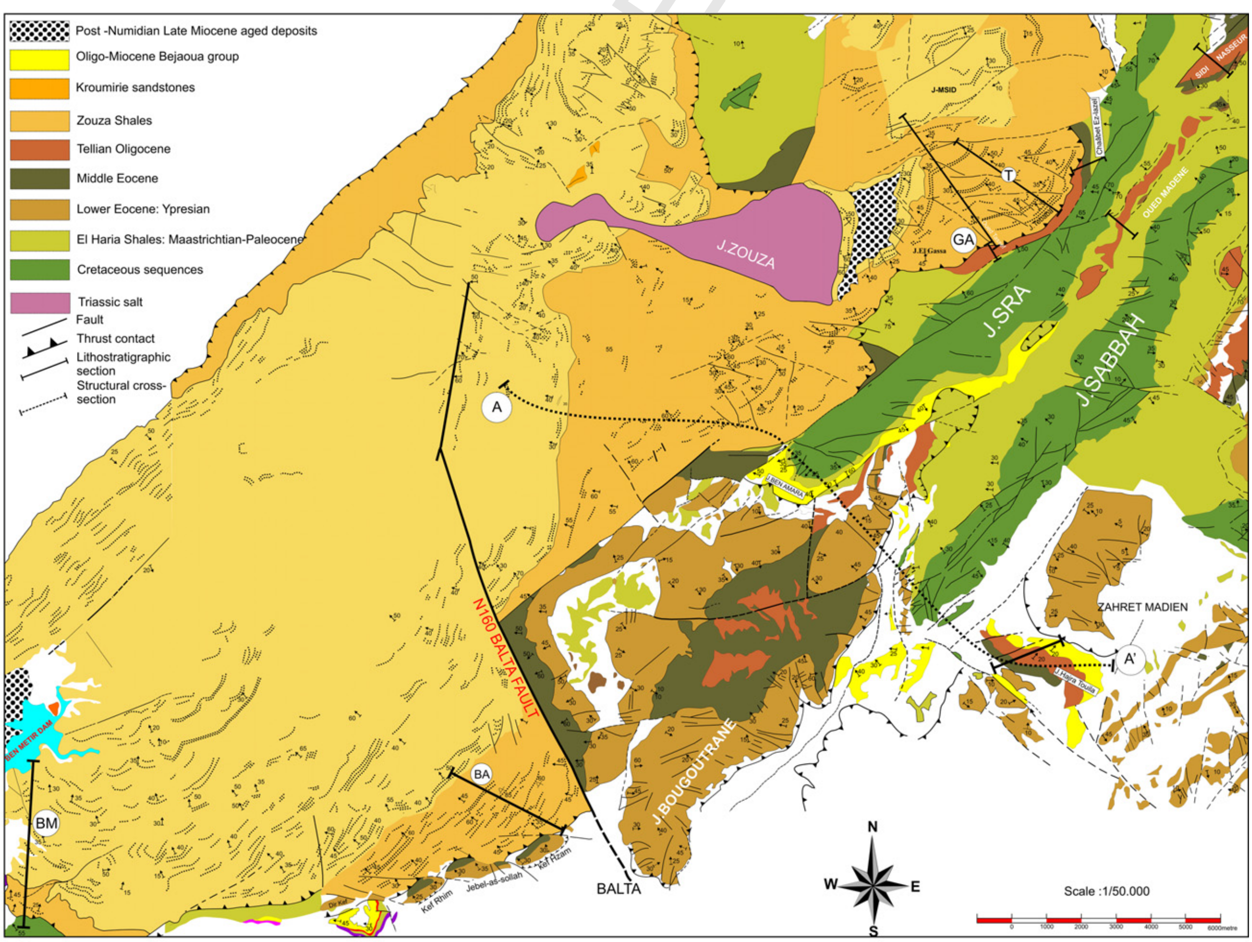

Fig. 4. Detailed geological map of the studied area with location of study area stratigraphic and structural cross-sections (Rouvier, 1977). T: Tebaba, GO: Gassa-Oued Tassef, BT: Balta, CZ: Chaâbet ez lazel, AA′: Structural cross-section location.

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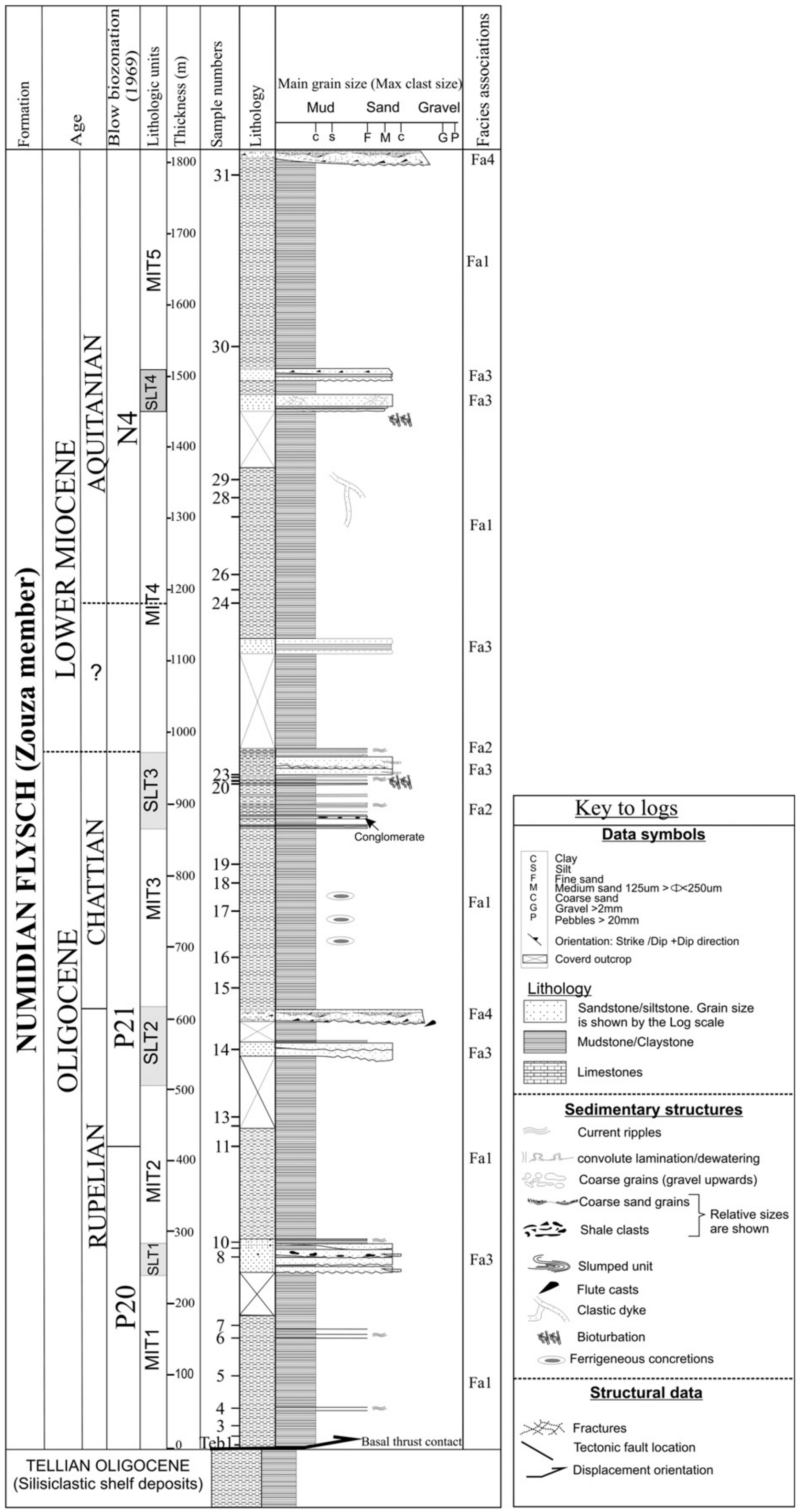

Fig. 5. Lithological succession, biostratigraphy and facies association of the Oligo-Miocene Numidian Flysch in Jebel Zouza (Tebaba section). MIT: Mudstone interval Tebaba; SLT: Sandy lens Tebaba.

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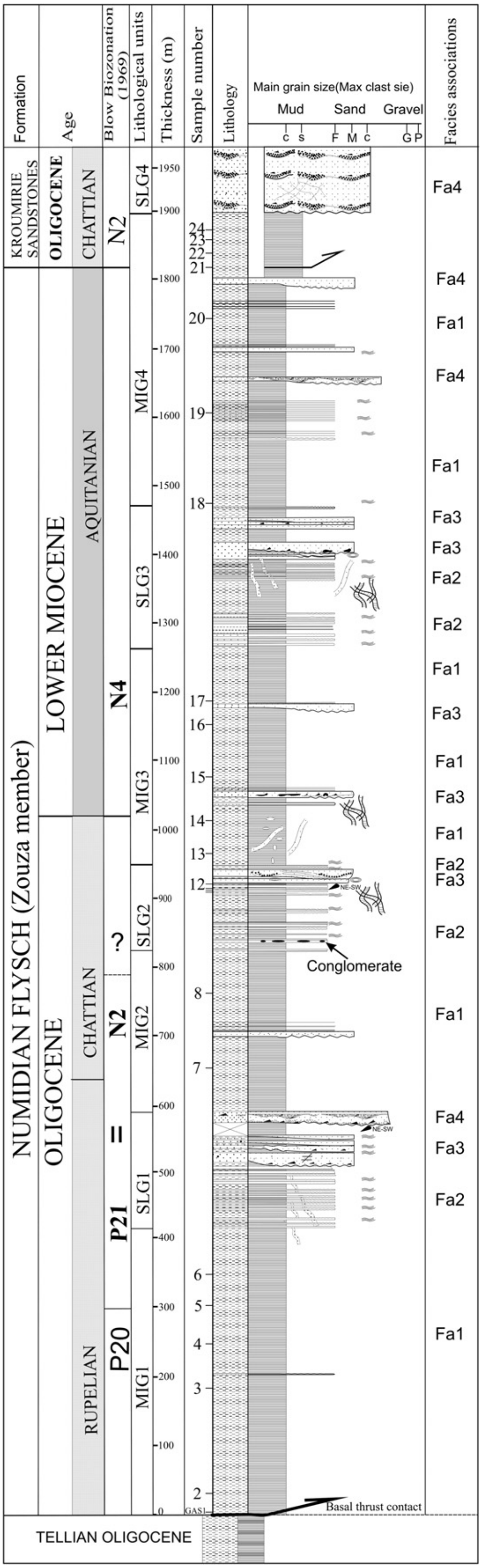

Fig. 6. Lithological succession, biostratigraphy and facies association of Oligo-Miocene Numidian Flysch in Jebel Zouza (Gassa–Msid section). MIG: mudstone interval Gassa, SLG: Sandstone interval Gassa.

cf., the appearance of *G. kugleri, Globogerinoides primordius* cf. and the absence of *G. opima opima*. This indicates an early Miocene age (N4 zone). Two samples collected from the uppermost mudstone interval (GAS22 and GAS23) show an association of planktonic foraminifera; including, *Globigerina angulisuturalis, G. ciperoensis, G. preabulloides, G. opima opima, C. dissimilis, C. chipolensis* characterising the *G. opima opima* zone of Late Oligocene age. This implies, therefore, the possibility of a tectonic (overthrust) contact within the mudstones of the uppermost part of the section (Fig. 6).

3.3. Balta-Bou Goutrane section (BA)

The geological map (Rouvier, 1977) indicates that the Numidian Flysch deposits outcropping in this area are formed by the succession of the Zouza and Kroumirie members (Fig. 4). The total section measured in this study is up to 2000 m thick, mainly comprising thick mudrock intervals (100–200 m thick) intercalated with thick amalgamated sandstone units (30–60 m thick).

Biostratigraphic analysis (Fig. 7) reveals that samples collected from the lower part of the section (B1, B2, B3, B4 and B5) contain planktonic foraminifera characterising the *G. opima opima* zone and indicating a Late Oligocene age (P21 zone). Nevertheless, all the rest of the section (B6, B7, B8, B9, B14, B15, B18, B19, B20, B21, B22, B23, B27 and B29) contain an Aquitanian fauna represented by *G. kugleri, G. preabulloides, C. dissimilis, G. ciperoensis angustiumbilicata, Globigerina binaiensis, G. primordius* and *Globorotalia mayeri*. This assemblage, therefore, dates most of the Numidian sequence (1500 m) in this area as early Miocene (Aquitanian: N4–N5 zone).

It is further important to consider that this great thickness (1500 m) of early Miocene sediments may in fact represent two or more structural units repeated by tectonics. New detailed mapping is necessary to check if there is repetition of the series within the Numidian Flysch of this area.

3.4. Ben Metir section (BM)

An excellent section through the "Kroumirie Member" is well exposed in the Ben Metir area (Figs. 3 and 4). It represents the original type locality for the "Kroumirie sandstones" (Rouvier, 1977; Gottis, 1953). Individual sandstone units are up to 20–25 m thick and consist of a series of graded to massive beds of coarse-grained quartz arenites. The intercalated mudstone intervals are generally partially covered by prolific vegetation, although they are better exposed towards the base of the section. The top of the original section, formerly dated as early Miocene on the basis of macrofossils (Gottis, 1953), is now completely obscured by the Ben Metir Dam.

Biostratigraphic analysis (Fig. 8) reveals that samples collected from the lower part of the section (BM1, BM2, BM3, BM4 and BM5) contain *Globigerina angulisuturalis, G. ciperoensis, G. preabulloides, G. opima opima, C. dissimilis, G. opima nana, G. primordius* and *Globigerina Tapuriensis* indicating the late Oligocene (P21 zone). However, all the rest of the section (BM6, BM7, BM8, BM9, BM10 BM11, BM12 BM13, BM14 and BM15) contains only arenaceous agglutinated foraminifera, so that precise dating is not possible.

As mentioned above the top of the section (the 300 m at the top) contain Gastropods, Echinoderms and Bivalves of lower Miocene age (Gottis, 1953).

3.5. Biostratigraphic discussion

As demonstrated above on the basis of planktonic foraminiferal analysis (Figs. 5–8) the basal part of Zouza member is dated as

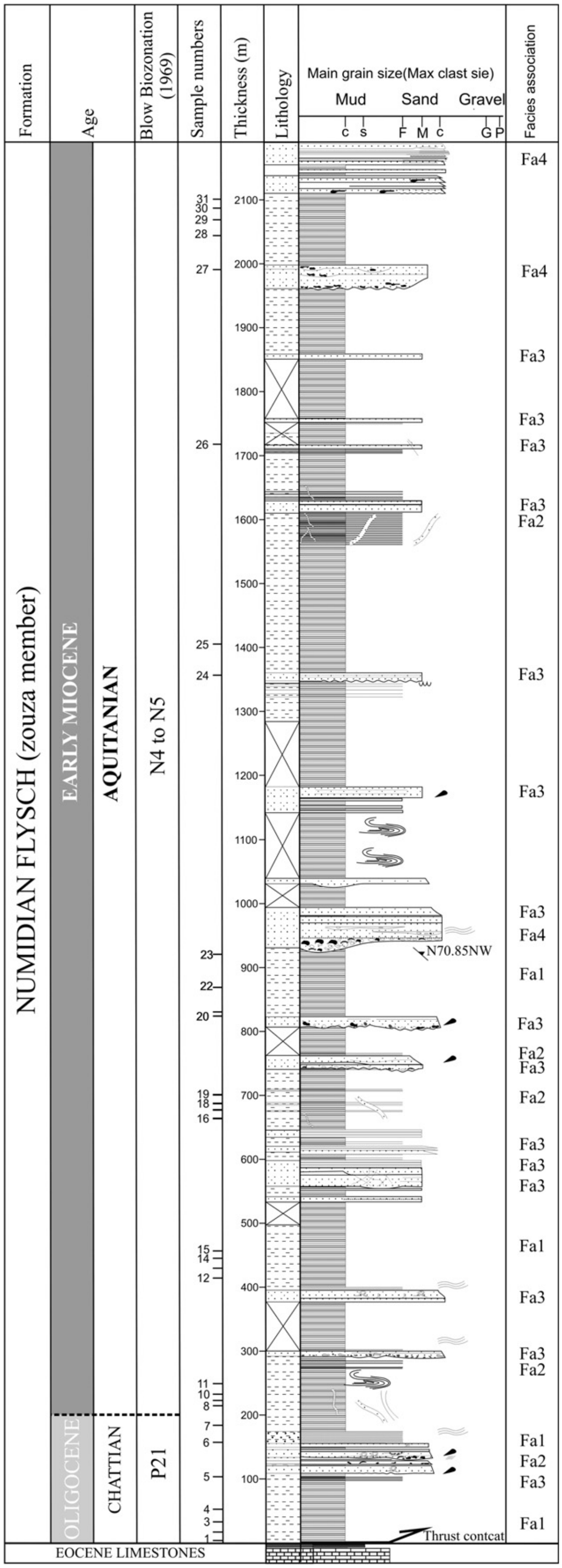

Fig. 7. Lithological succession, biostratigraphy and corresponding facies association of the Oligo-Miocene Numidian Flysch in Balta–Bougoutrane area.

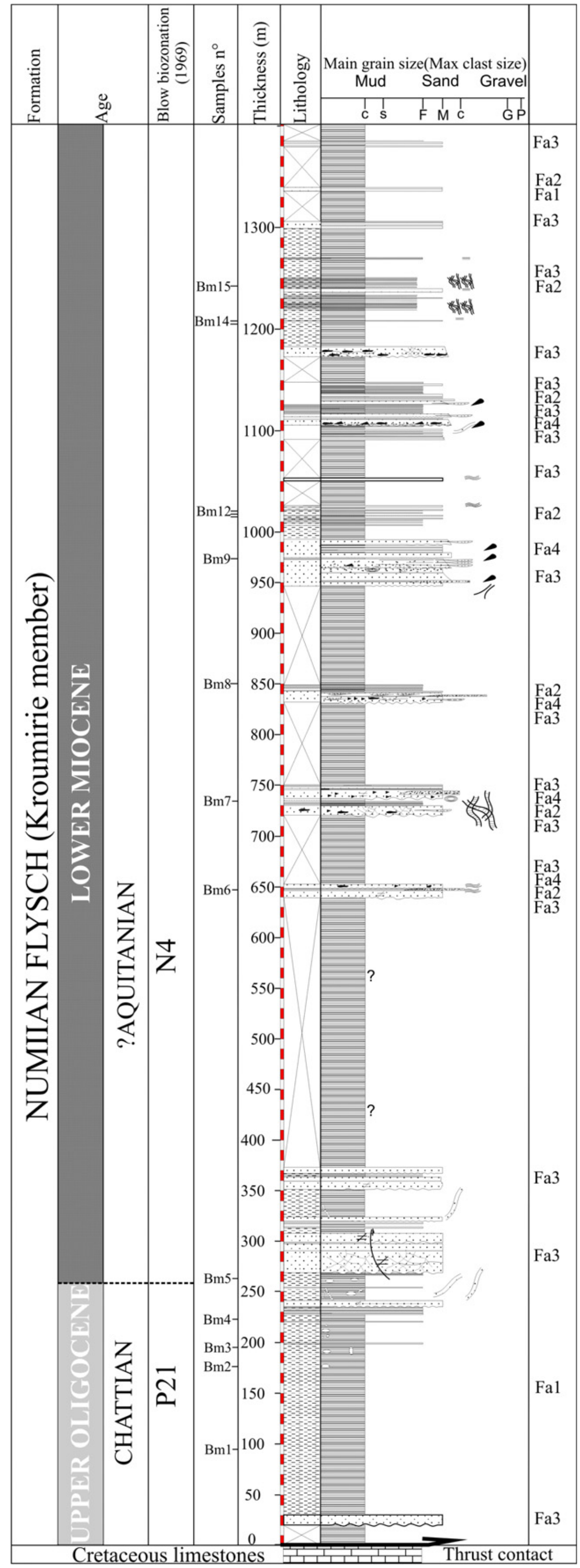

Fig. 8. Lithological succession, biostratigraphy and corresponding facies association of the Oligo-Miocene Numidian Flysch in Ben Metir area.

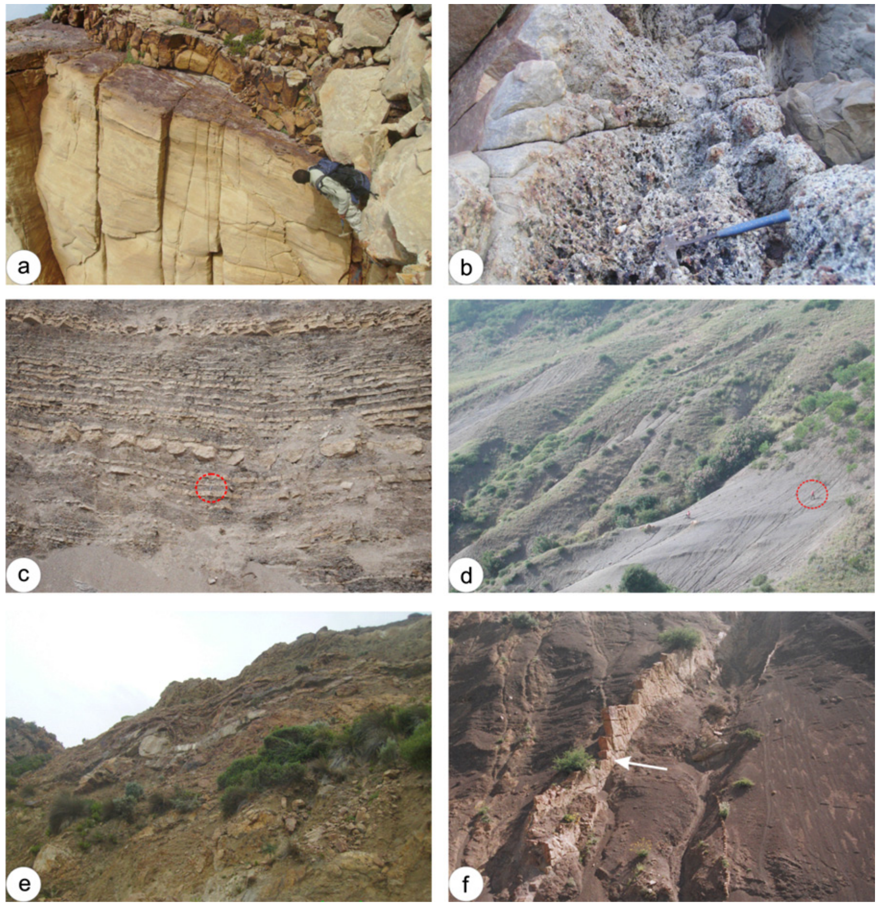

Fig. 9. Facies photographs. (a) Massive sandstone facies association (*FA3*). (b) Conglomerate, irregular to lenticular layer (*FA4*). (c) Thin-bedded sandstone–mudstone couplets (*FA2*). (d) Dark-grey mudstone (*FA1*). (e) Slump fold in shale-rich unit. (f) Sandstone dyke injected into dark-grey shale-rich unit adjacent to massive sandstone body near Oued Zouza and Tabouba, Sandstone dyke is 25 cm thick.

early to Late Oligocene (P20–P21 zone) and its uppermost part is of early Miocene age (Aquitanian: N4 zone). The faunal assemblage within the lower part of Kroumirie member also indicates a late Oligocene age (P21 zone), whereas the upper part is dated as early Miocene by Gottis (1953), in the Ben Metir area. Dating of the intervening section remains uncertain. This new dating of both the Zouza and Kroumirie members as Oligocene to lower Miocene in age leads us to question the validity of the vertical organization proposed for these two members of the Numidian Flysch in northern Tunisia. We have not independently dated the Babouch member, but note that this has been dated previously as lower Miocene (Glaçon et al., 1967; Rouvier, 1977).

The new biostratigraphic data presented here compare well with the palynologic associations found within the mudstones of both Kroumirie and Zouza members by Torricelli (2000). It therefore seems most likely that the Kroumirie and Zouza members are, in fact, coeval (Fig. 2). In some areas there is simply a natural lateral facies variation from mudstone-rich (Zouza) to sandstone-rich (Kroumirie). In other locations, the apparent vertical superposition is the result of thrust tectonics. Similar thrusting may also have affected parts of the mudstone dominated Zouza member in the Balta-Bou Goutrane section.

4. Numidian Flysch facies

The most easily accessible and well exposed parts of the Numidian Flysch outcrop along the northern coastline at Tabarka, Cap-Serrat and Ras El Koran. These have been the subject of most previous sedimentological studies (Beaudoin et al., 1986; Parize, 1988; El Maherssi, 1992; Yaich, 1997). Although some work has noted the tectonic complexity of the inland part of the Kroumirie range (Rouvier, 1977; Gottis, 1953, 1962; Wezel, 1968; Alouani, 1996), there has been very little sedimentological work carried out in this area.

This study, therefore, documents the nature and characteristics of the Numidian Flysch sedimentary facies in the inland region, on the basis of grain size, texture, sedimentary structures and bed thickness. The proposed facies as well as their associated depositional process and settings are based on descriptive schemes cross-referenced to Pickering et al. (1989) and Stow et al. (1996, 2000). The compilation of data collected from the vertical facies logging, the field mapping and the interpretation of sandstone bodies using aerial photographs have allowed some further comment on the internal organization and the geometry of these deposits. Four major facies association are identified (Fig. 9).

4.1. Facies associations

4.1.1. Facies association I (FA1): mudstones

This facies association is dominated by mudstones, ranging in colour from black, dark-grey, light-grey, brown to light green[1] Q6 (Fig. 9d and f). They generally display indistinct to massive bedding and some ellipsoidal yellow to brownish ferruginous concretions

[1] For interpretation of colour in Fig. 9, the reader is referred to the web version of this article.

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(septaria) of various size. Most of the mudstone contains no evident internal structures, although in some parts bioturbation and burrowing is evident, whereas other parts show fine-scale parallel lamination. Much of the succession has a more or less well-defined fissile or shale fabric. Locally there are very thin and thin-bedded siltstones and rare sandstones, showing grading and other sedimentary structures typical of fine-grained turbidites. Slump-slide units of fine sandstones and mudstones are locally intercalated (e.g. in the Balta–Bougoutrane area). The overall sand:mud ratio is <1:9.

Biostratigraphic studies show that many of the mudstones contain planktonic foraminifera, although they are not particularly high in $CaCO_3$ (generally <10–20%). Geochemical evaluation by El Mahersi et al. (2007) shows moderate enrichment in immature to early mature type II/III organic matter (TOC contents up to 1.1%), and a fair petroleum potential (up to 3.7 kg of HC/t of rock).

We interpret this facies association as the result of both hemipelagic and low-concentration turbidity current processes (Stow et al., 1996; Stow and Tabrez, 1998). In some areas they are associated with chaotic slump-slide units (Fig. 9e) and with injectionite sandstones (Fig. 9f) adjacent to thicker sandstone bodies.

4.1.2. Facies association II (FA2): mudstones and sandstones

This facies association is represented by thin and medium-bedded (7–40 cm thick), medium to fine-grained sandstones, interbedded with thin to very thick mudstone units displaying in some parts thin silty lamination (Fig. 9c). It generally occurs in units of 2–20 m thick. The sandstone beds show a variety of structures with normal and reverse grading, parallel lamination, and ripple cross-lamination, typical of medium-grained turbidites. Complete Bouma sequences are rare whereas partial sequences are commonly represented by Tab, Tabc, Tbc or Tc divisions. Sandstones beds show sharp basal contacts with groove marks. In some areas, trace fossils are common on the sandstone surfaces or within the mudstones. Locally the beds are tabular and can be traced over some hundred of metres. The overall sand: mud ratio is between 1:9 and 1:5. We interpret this facies association mainly as the result of low- to medium density/concentration turbidity currents, together with some hemipelagic input (Stow et al., 1996; Stow and Tabrez, 1998).

4.1.3. Facies association 3 (FA3): massive sandstones

This facies association comprises medium, thick and very thick-bedded massive sandstones (typically 1–8 m thick) with sharp to erosive bases and generally sharp tops (Fig. 9a). They commonly occur as an amalgamated series of beds in blocky sequences, of 10–35 m thick, with minor conglomerates, pebbly sandstones and structured sandstones. Generally, the massive sandstones are fine to medium grained, more rarely coarse-grained, and structureless except for water-escape features and diffuse parallel or rare cross-stratification. Shale-clasts are common especially near bed bases, and in some parts sufficiently common to be considered as a shale-clast conglomerate facies. The overall sand:mud ratio is between 9:1 and 4:1.

This facies association is very similar to the "structureless sandstones/pebbly sandstones facies" described in Numidian Flysch of Sicily (Johansson et al., 1998), interpreted as the product of high density turbidity currents (Lowe, 1982; Postma et al., 1988; Stow et al., 2000) and/or sandy debris flows (Stow et al., 2000; Shanmugam, 1996, 2000).

4.1.4. Facies association IV (FA4): conglomerates

This facies association is relatively rare in the Numidian Flysch sections of the Zouza area studied here, and is mainly present in the Balta-Bou Goutrane area within the medium and upper parts of the Tebaba and Gassa–Msid section sections. It is represented by massive pebbly to conglomeratic beds (1–5 m), completely structureless, mainly composed of very coarse-grained sandstone (Fig. 9b) grading upward to fine-grained sandstone. Layers with pebbly sandstones contain rip-up clasts of sandstones and mudstones (20 cm in diameter). These are associated with massive sandstones, structured sandstones and pebbly sandstones and locally with more chaotic shale-clast conglomerates and slurry sandstones (slurry flow sensu Lowe and Guy, 2000).

We compare this facies association to the "very thick to thin-bedded gravels and pebbly sands (>10% pebbles)" of the Stow classification scheme (Stow et al., 2000). They most likely represent deposition from high-concentration turbidity currents (Lowe, 1982; Postma et al., 1988; Stow et al., 2000).

4.2. Facies distribution and depositional setting

These facies and facies associations compare closely with those described previously from Numidian Flysch successions along the northern coastline at Tabarka, Cap-Serrat and Ras El Koran (Beaudoin et al., 1986; Parize, 1988; El Maherssi, 1992; Yaich, 1997) in Tunisia and elsewhere throughout the Western Mediterranean Numidian basin province, including the Numidian Flysch of northern Sicily (Braakenburg, 1994; Johansson et al., 1998). The massive sandstone facies association is also closely analogous to the *Deep-water Massive Sandstone* family described from many other parts of the world (Stow et al., 2000). While such facies are generally deposited in a deep-water setting, no specific depositional environment is implied. In the present study, benthic foraminifera are dominated by the deep agglutinated foraminifera including: *Ammodiscus cretaceous, Ammodiscus* cf. *pennyi, Ammobaculites* sp., *Bathysiphon latissimus, Glomospira charoides, Glomospira diffundens, Haplophragmoides impensus, Haplophragmoides walteri, Hyperammina* gp. *Subnodosiformis, Paratrochamminoides acervulatus, Paratrochamminoides heteromorphus, Reticulophragmium amplectens, Rhabdammina cylindrical, Rhizammina* cf. *indivisa, Saccammina grzybowski, Bathysiphon latissimus and Rhizammina* cf. *indivisa*. Such association lead us to interpret the Numidian Flysch as deep-water slope system. Ichnological investigation of the Numidian outcrops demonstrates that the Oligocene deposits, well recorded in the Zouza and at the base of Melloula–Tabarka sections are characterized by the frequency of meandering-like track of probably *Helminthoidea* types associated with a very frequent ramifications set in all directions left by the fucoids (*chondrites*). These ichnofacies are found in association with typical hexagonal cells of the *Paleodictyon* spp. This ichnofacies association would support bathyal sedimentation of the Numidian Flysch during the Oligocene.

Moving up the succession, the Aquitanian sediments occur in dominantly stacked channel fill complexes. Examination of the outcrops at the top of the Zouza and Tabarka areas indicate the presence of trace fossils dominated by Arenicolites ichnofacies, which favour a shallow to mid-depth channel fill environment and hence indicate a shallowing-upward trend through time during the Numidian Flysch deposition. This is accompanied by an overall tendency to become more sand-prone upwards.

The mudstone-rich sections (Zouza member) generally have between 10 and 20% sandstone facies as measured through a 1500–1800 m thick succession, occurring both as 2–20 m thick sandstone-rich units and as isolated thin sandstone beds. The massive sandstone and conglomerate facies associations typically occur in distinct sections with much higher sand: mud ratios (5:1–9:1); while in the Ben Metir section the overall sand: mud ratio through 1500 m of section is around 1:3. This dominance of mudstone facies, some of hemipelagic origin but much of fine-grained turbidity current origin, is typical of a mud-rich slope–apron depositional setting (Stow et al., 1996; Johansson et al., 1998). The thick, med-

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ium and coarse-grained sandstone-rich units, especially those with conglomerates and abundant shale-clasts, probably represent slope channel-fill deposits, whereas relatively thinner units of fine and medium-grained sandstones may have been deposited as channel-terminus slope lobes.

The comparison of the Numidian Flysch deposits along an East–West transect from Jebel Zouza to the Balta–Bougoutrane and Ben Metir area reveals some interesting thickness and facies variations that support these general conclusions. These changes are well illustrated in the grain size, thickness and the lateral continuity of the sandstone bodies and are clear evidence of marked lateral variability of facies in the Numidian Flysch. Some of the key observations include:

- Conglomerates facies tend to occur as thin lag horizons at the base of thicker sandstone units and may locally thicken and thin in relation to irregularities on the erosional base.
- Shale-clasts occur both as shale-clast conglomerates and as floating clasts (up to 30 cm diameter) in the massive sandstones facies association.
- Conglomerates, shale-clasts and massive sandstone facies tend to co-occur in distinctive coarse-grained units (5–25 m thick); showing blocky sequences within the mudstone facies. In some cases, they show a broad lenticularity over 500–1500 m laterally. These we interpret as slope channel deposits.
- Thick, medium and thin-bedded, structured sandstones (turbidites) typically occur together with thinner intercalated mudstones in distinct medium-grained units (3–15 m thick), that may also show some lenticularity over 1500–2500 m laterally. They commonly show thickening-up, thinning-up and mixed, asymmetrical sequences of bed thickness variation. These we interpret as lobe deposits (e.g. Oued Zouza location).
- Mass-transport facies (slide-slump units and other chaotic facies) are locally common within mudstone-dominant sections (e.g. in the North Ragoubet el Gasba part of the Balta area). Where mudstone facies are dominant, we infer a typical open slope–apron depositional setting.

4.3. Provenance

The Numidian Flysch outcrops in a "traceable" 2000 km belt extending from southern Spain through northern Africa, Sicily and into southern Italy. Such a broad descriptive statement implies, to a certain extent, a single unit and source area. However, it still a considerable conjecture over the ultimate source of the deep-water sandstone turbidites and associated facies that make up the Numidian Flysch with the interaction of various factors complicating process and paleogeographic reconstructions. Did the sediments of this late Cenozoic orogenic belt in the Western Mediterranean derive from a European (Caire, 1965; Broquet, 1968; Gottis, 1960, 1962; Delteil et al., 1971; Beaudoin et al., 1986; Parize, 1988; El Maherssi, 1992; Yaich, 2000) or African source (Wezel, 1968; Hoyez, 1970; Lorenz, 1978), or from a combi- Q8 nation of the two? Solving this problem has an important impact not only for the paleogeography of the Oligo-Miocene Numidian period but also for petroleum exploration activities in the Mediterranean basin, especially in terms of source rock potential and reservoir quality and distribution of this system.

The various hypotheses dealing with the ultimate source of the Numidian Flysch sandstones have been recently discussed in separate papers (Fildes et al., in press; Riahi et al., 2009). In the present work we present briefly additional new data supporting a northern provenance.

4.4. Paleocurrent data

Most of the investigated sand bodies of the Numidian Formation exhibit excellent sole markings with both flute casts and tool marks (Fig. 10). Measurements carried on outcrops along the coastline (Melloula–Tabarka, Citadelle and Cap Negro sections) gives dip-corrected flow ranging from 120° to 170° towards the SSE and SE (Fig. 11). These readings are closely comparable with previous works addressed to the same areas (Parize et al., 1986; El Mah- Q9 erssi, 1992; Yaich, 1997; Fildes et al., in press). Additional paleocurrents data collected from sole marking in Ben Metir, Balta

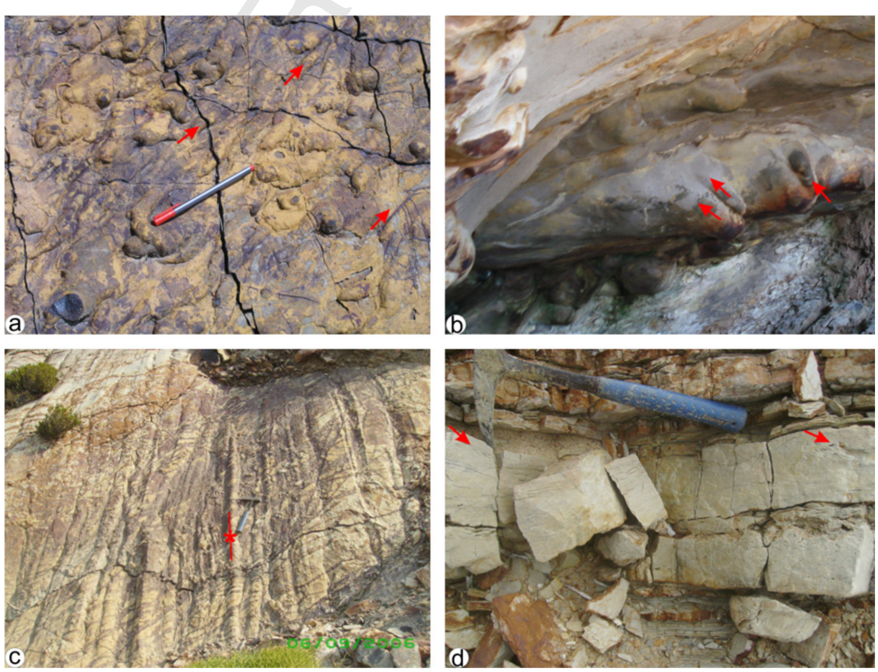

Fig. 10. Sole marking recorded at the base of thick massive sandstone units constituting the Numidian Flysch complex. Photos (a) and (b) show flute casts with a NW–SE (N12°–140°) direction which indicate a NW current direction (Tabarka area); (c) groove marks recorded at the base of massive sandstone units with a WNW–ESE direction (Melloula–Tabarka area) and (d) ripples on upper surface of thin to medium sandstone bed indicating a NE–SW flow direction (Cap-Serrat).

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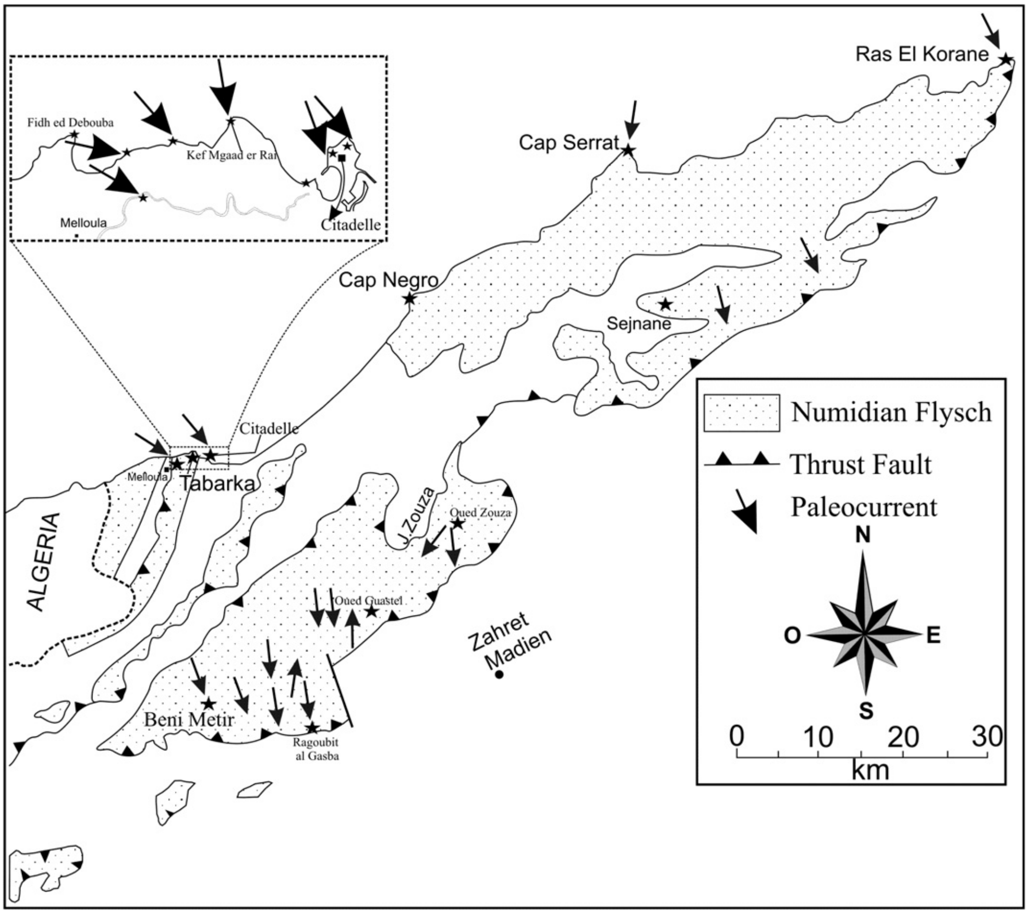

Fig. 11. Map showing pleocurrent directions based on flutes and ripples recorded from different outcrops of the Numidian Flysch in northern Tunisia.

and Sejnene areas support N to NW provenance (Fig. 11). At Balta and Oued Guastel areas, some readings recorded from both ripples and flutes measurements give much more varied readings with some supporting a current direction from South to North. The controversial reading in these localities may be explained by the greater degree of channel sinuosity that could be responsible of the variation in paleocurrent direction.

4.5. Petrography and modal analysis

Modal analysis of the Numidian sandstones has revealed that all samples have a quartz arenite composition (Fig. 12a) with slightly different amounts of quartz and feldspar ($Q_{94–99}$, $F_{0–4.5}$, $L_{0.34–2.5}$). Most of the quartz grains are dominantly monocrystalline (90% of total quartz grains) showing non-undulose extinction (63% of the total monocrystalline quartz grains), whilst approximately 37% display undulose extinction. Polycrystalline quartz forms more than 6% and is present in different amounts depending on grain size. Feldspars occur in low amounts (average 1.25%), together with an even greater paucity of rock fragments and heavy minerals.

The quartz typology, including grain undulosity and polycrystallinity, has been investigated for the Numidian sandstones (Fig. 12b). Polycrystalline quartz was plotted versus undulatory (stained) to non–undulatory (unstained) monocrystalline quartz. This plot suggests that quartz grains of the Numidian Flysch are of metamorphic origin (Fig. 12b). The close approach of the plot to the boundary of plutonic provenance indicates the possibility of an igneous origin for some of the quartz grains. This supposition is reinforced by the presence of K-feldspar rather than plagioclase.

4.6. Zircon data

On the basis of the modal analysis and paleocurrent data obtained from the Numidian Flysch of northern Tunisia, a northern or northwestern provenance appears most likely. This conclusion is strongly supported by our further work on heavy minerals and zircon geochronology (Fildes et al., in press).

Zircon ages of 514 ± 19 Ma from Tunisia and 550 ± 28 Ma from Sicily can only have derived from rocks of European affinity. The original European provenance is most likely now represented by predominantly metamorphic rocks of the Kabylian belt in northern Algeria, whereas the Fortuna formation has a southern provenance from the African craton, confirmed by new zircon ages of 1698 ± 67 Ma (Fildes et al., in press).

5. Oligo-Miocene Bejaoua group

5.1. Para-autochthonous Tellian facies

These deposits are formed mainly by brown mudstones and siltstones containing rare sandy and/or glauconitic concretions. They occur as the substratum of the Numidian Flysch sections with a major tectonic contact (Chaâbet Ez Zlazel and Gassa areas) or outcrop discontinuously to the south of the main Numidian Flysch thrust front (Oued el Madene and Sidi Naceur areas). These sediments have been previously attributed to the lower Oligocene (Rouvier, 1977).

Our biostratigraphic study reveals that mudstones near the bases of the four studied sections are of lower Oligocene in age (Rupelian: P20 zone), as shown by the occurrence of *G. sellii*, *G.*

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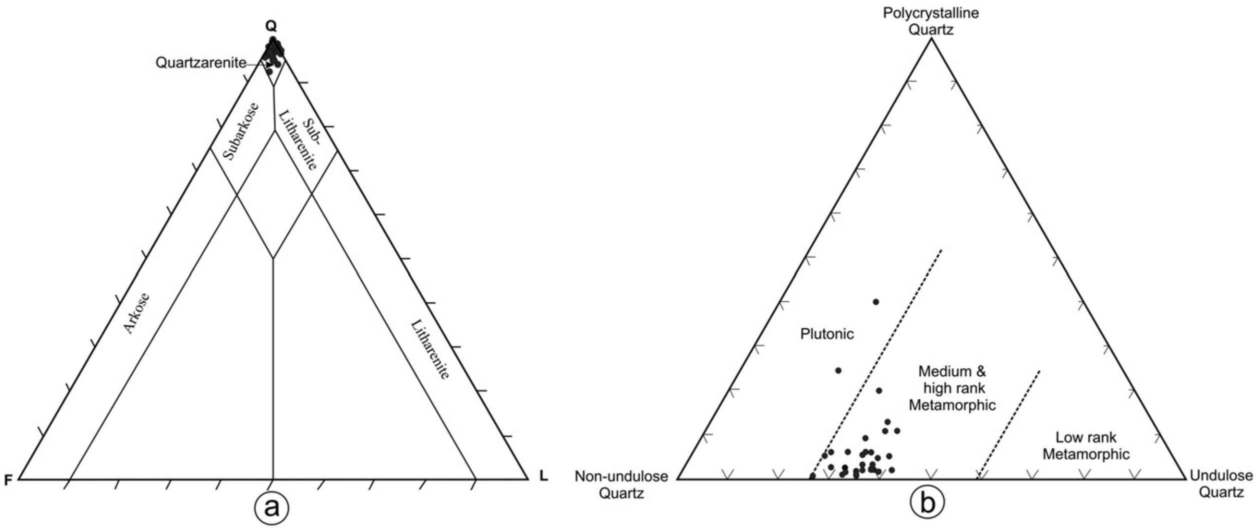

Fig. 12. QFL plots. (a) Classification of the Numidian sandstones: QFL plot (after Pettijohon et al., 1987). (b) Ternary plot of detrital quartz types of the Oligo-Miocene Numidian Flysch sandstones (after Basu et al., 1975). Filled circles represent the sandstone samples.

ampliapertura, Globigerina tripartita, Globigrina venezuelana, Globigerina yagaouensis, G. preabulloides and C. dissimilis. At the top of the all four sections, the mudstones are of late Oligocene age (Chattian: P21 zone), as evidenced by the co-occurrence of *G. opima opima* and *Globigerina angulusituralis*. The faunal assemblage is indicative of an outer shelf depositional setting.

5.2. Oligo-Miocene autochthonous facies

Jebel El Hajra Touila (Figs. 3 and 4) is situated a few kilometres West of Zahret Madien town. It provides one of the most complete and laterally extensive exposures of the Oligo-Miocene Bejaoua group in the so-called "autochthonous domain". The lowermost part of the section is made up of shales, glauconitic mudstones and fine-grained sandstones deposited within lower to middle offshore depositional environments, with episodic storm influences (Fig. 13). The middle part of the section is dominated by fine to medium grained, well sorted sandstones showing hummocky cross-stratification, rippled surfaces, flaser bedding, cross-stratification and bioturbation. These sedimentary structures are indicative of a foreshore to backshore environment. The uppermost part of the section corresponds to a sandy unit with large silicified wood debris, most likely deposited in a littoral setting with fluvial influences.

This succession is capped by a sandy limestone unit with a *Pectinides* fauna of probable Langhian age. This unit is well known from central Tunisia and correlative to the Ain Grab formation (Rouvier, 1977; Yaich, 1997).

5.3. Palaeogeographic relationships between Numidian Flysch and Bejaoua group

Sediment facies and biofacies characteristics of the Numidian Flysch sections studied in this work indicate a deep-water depositional setting with abundant input from turbidity currents and related downslope depositional process. These show an apparently more proximal facies aspect along the northernmost part of Tunisia (Tabarka area) and correspondingly more distal aspect southwards towards the thrust front (The Zouza, Balta and Sejnene areas).

Nevertheless, the sedimentological and biostratigraphic characteristics of the Tellian Oligocene succession, which outcrops in the Oued el Madene syncline and on which rests the Numidian Flysch, are generally indicative of an offshore, shallow-marine depositional environment. During that time, the "salt dôme zone" has acted as an emergent area with little sedimentary Oligo-Miocene record. Those of the Oligo-Miocene autochthonous Bejaoua group deposits (Hajra Touila section) are indicative of a shallow-marine shelf to shoreface depositional environment.

Taken together, these data exclude a direct derivation of the Numidian sandstone via the Fortuna Formation from the Saharan craton as previously supposed (Wezel, 1968), but suggests a N–S or NW–SE paleogeographic polarity for the Numidian Flysch sedimentary basin.

Furthermore, and as previously proposed (Yaich, 2000) there is a clear temporal difference in facies between the two sedimentary systems, in that detrital quartz pebbles appeared much later (since the Aquitanian) in the Fortuna Formation of central Tunisia (within a 'fluvial–deltaic' complex), than in the Numidian Flysch of northern Tunisia, where they occur in submarine channel facies of high density turbidites since the Oligocene time (Tebaba and Gassa sections). Paleocurrent data recorded in both coastal and interior outcrops of the Numidian Flysch are quite variable but, in general, further support a flow from N and NW rather than from the south. The controversial reading in some localities may be explained by the greater degree of channel sinuosity that could be responsible of the variation in paleocurrent direction. We therefore conclude that the Numidian Flysch and the Fortuna Formations have to be considered as two disconnected sedimentary systems which were supplied from north and south respectively. Their current juxtaposition has resulted from the thrusting of the Numidian Flysch southwards during the inversion phase that accompanied the convergence of Africa and Europe rather than sedimentary control. This has involved major sub-horizontal thrust emplacement from the north that induced their superimposition. The underlying system includes the Oligo-Miocene Bejaoua group and its more distal equivalent, the Tellian Oligocene, which actually wedges under the Numidian Flysch and outcrops further north within the Nefza window (Rouvier, 1977).

The displacement of the Numidian Flysch complex towards the south has allowed the covering of the Tellian series. During this emplacement, the Numidian Flysch was also deformed generating at the same time detached fold structures of NE–SW alignment affected later on by strike slip faults of NW–SE orientation (the N160 Balta fault). Structural observations made in the study area support this interpretation.

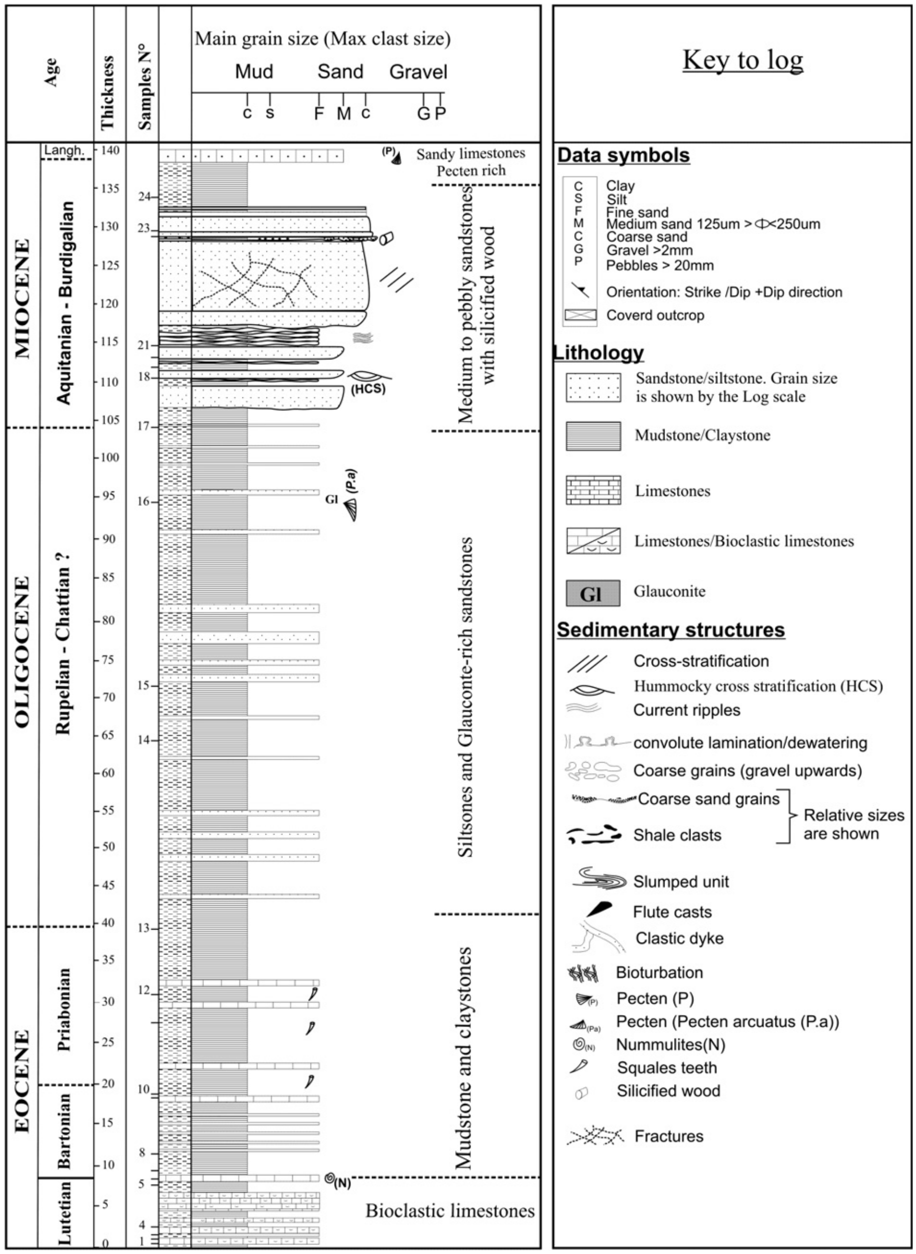

Fig. 13. Lithological succession, biostratigraphy and corresponding facies association of the Oligo-Miocene Bejaoua group in Jebel Hajra Touila.

6. Structural position of the Numidian Flysch

6.1. Surface data

The Numidian Flysch complex of the southern Kroumirie range overlies several different older series ranging in age from the late-Cretaceous to Paleocene–Eocene that are intensively deformed and folded. According to several authors, the contact between the Numidian Flysch and the underlying Tellian series is transgressive and the lack of the late Eocene (Priabonian time) deposits between the two units corresponds to a depositional hiatus (Gottis, 1962; Kujawski, 1964, 1969; Wezel, 1968; Crampon, 1973; Alouani et al., 1996). However, the presence of Triassic rocks along the basal contact of the Numidian Flysch, such as in the Hedil and Sejnene area, are considered in other works (Rouvier, 1973, 1977; Caire et al., 1971; Carr and Miller, 1979) as a strong argument in favour of a thrust displacement of the Numidian complex. In the Mogod domain Carr and Miller (1979) concluded, on the basis of a detailed mapping and structural analysis of both the Numidian Flysch complex and the Tellian rocks, that these two units are separated by a major thrust system.

Our detailed study of the area indicates that the contact between the Numidian Flysch and the underlying Tellian rocks is not outlined by Triassic rocks. Nevertheless, the abrupt truncation of the sandstone units of the Numidian Flysch is clearly evident in many localities. Such truncation is especially well documented in the Western Balta area where Eocene limestones (Kef Hzam, Kef Sollah and Kef Abiod) cut abruptly the Numidian Flysch deposits (Fig. 14a).

In Chaâbet ez Zlazel, the Numidian complex constitutes the highest structural unit, and its base, which is early Oligocene (Rupelian: P20 zone) in age, overhangs tectonically the late Oligocene Tellian shales (Chattian: P21 zone) (Fig. 14b). On the other hand, in this area the contact between the Tellian Oligocene deposits

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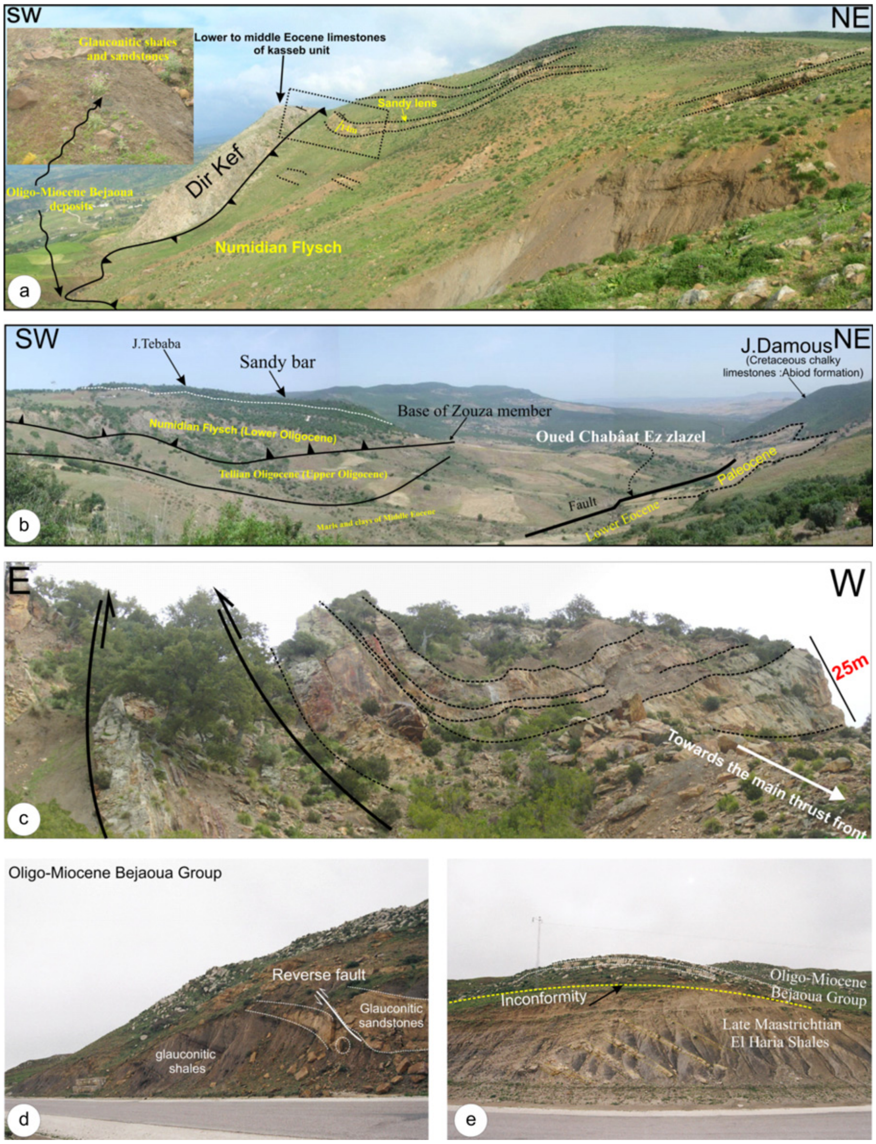

Fig. 14. Photographs showing stratigraphic and structural relationship between the Numidian Flysch and its substratum along the main thrust front. Photo (a): Field example of structural and sedimentologic evidences for tectonic emplacement of the Numidian complex. This photo shows the abrupt truncation of massive sandstone units at Sidi Bou Dali location (Western Balta area) which requires the emplacement of a sub-horizontal fault. This photo shows also, how rocks of the Numidian Flysch of deep-sea fan characteristics rest tectonically on shallow water facies represented by glauconite-rich sandstones of the Bejoua group. Photo (b): the Numidian complex constitutes the highest structural unit. Its base, which is early Oligocene (Rupelian: P20 zone) in age, overhangs tectonically the late Oligocene Tellian shales (Chattian: P21 zone). The contact is marked by a major sub-horizontal fault. Other faults can be traced in the depression separating the Tellian Oligocene from the middle Eocene–Paleocene shales. Photo (c): Deformed Numidian Flysch sandstone unit with Reverse faults type (Ben Metir area). Photo (d): Sedimentary transgressive contact between the Oligo-Miocene Bejaoua group and the underlying Cretaceous to Paleocene series dating the Pyrenean phase. Photo (e): Reverse fault affecting the Oligo-Miocene Bejaoua deposits.

and the late-Cretaceous to Tertiary series, corresponds to a major fault marked by discontinuous lower Eocene clays and black metric blocks of Eocene limestone that were rooted out during the displacement along the sole thrust. Therefore the contact between the Numidian Flysch and the underlying Tellian rocks is marked in the study area by a major sub-horizontal fault that can be traced in the depression separating the elevated Numidian unit to the North from the Maastrichtian chalky Abiod limestones anticline to the south (Fig. 14b).

Further to the south, the Tellian Oligocene shales facies (Chaâbet ez lazel, Oued Tassef, Sidi Nasseur and Oued Madene) are sandwiched between the Numidian Flysch and the Maastrichtian series of Amdouns folds and include locally several metric blocks of black limestones of Eocene age (Bou Dabbous Formation). Moreover, the structural organization of the Cretaceous rocks of Amdouns area shows detachment folds with ramping to duplex features locally marked by shear foliation in the Paleocene to Eocene shales.

Immediately to the South of the main thrust front (Jebel Ben Amara), the Oligocene Numidian Flysch overhangs the Oligo-Miocene terrigeneous sediments locally containing glauconite-rich sandstones horizons. The latter overlie, by means of an angular unconformity, the folded Cretaceous strata (Fig. 14d and e) that had been deformed during the major inversion phase of the late Eocene (Pyrenean phase of the authors (Rouvier, 1977; El Euchi et al., 2004). This major tectonic phase is well documented in several regions in surface as well as in subsurface in the Sahel and in offshore Tunisia (Rabhi et al., 2002; El Euchi et al., 2004; Khomsi et al., 2006). Similar glauconitic beds have also been recorded westward, to the north of Oued Bou Hartma (Sidi Bou Dali location), in front of the Numidian Flysch in Ben Metir (Fig. 14b). This juxtaposition of older rocks overlying younger rocks favours the emplacement via a major thrust fault at the base of the Numidian Flysch (Figs. 15 and 16) which is inevitably, an ''Out-of-sequence thrust fault'' as described by Morley (1988).

Additionally, and as well demonstrated in the Mogods Mountains (Carr and Miller, 1979), the Numidian complex and the underlying Tellian rocks shows significant disharmony manifested by the broad open folds (sensu Carr and Miller, 1979) within the Numidian Flysch which are not expressed in the underlying Tellian rocks. These relationships require tectonic detachment between the two units (Fig. 15).

All these fact taken together, allowed us to reconstruct the tectonic style of the southern Kroumirie Mountain (Fig. 15). Some major faults could not be inspected through direct field observations, but appear to be a geometric necessity (e.g. the fault at the base of the Numidian complex (Fig. 15)). The fault separating the Zouza and the Kroumirie members is suggested based on biostratigraphic data carried out the locality type of the both members (Fig. 15).

The style of deformation of the Tellian unit is characterized by folding and reverse faulting of massive limestone units. This geometry is well exposed north of Zahret Madien and along the main thrust contact (Figs. 15 and 16). These rocks extending from upper Cretaceous to Eocene and Oligo-Miocene are involved in a series of northeast-trending, narrow and faulted anticlines that are separated by apparent narrow synclines (e.g. Jebel Sra and Jebel Sabbah) (Figs. 15 and 16).

The question of the amount of displacement of the Numidian complex is still of major concern. The variations in the estimated amount depend on the nature of the basal contact (e.g. whether the Numidian is allochthounous or autchnous unit). Some previous work addressed to this point, have proposed an estimation ranging from 1 km to more than 50 km. Glaçon and Rouvier (1967) have

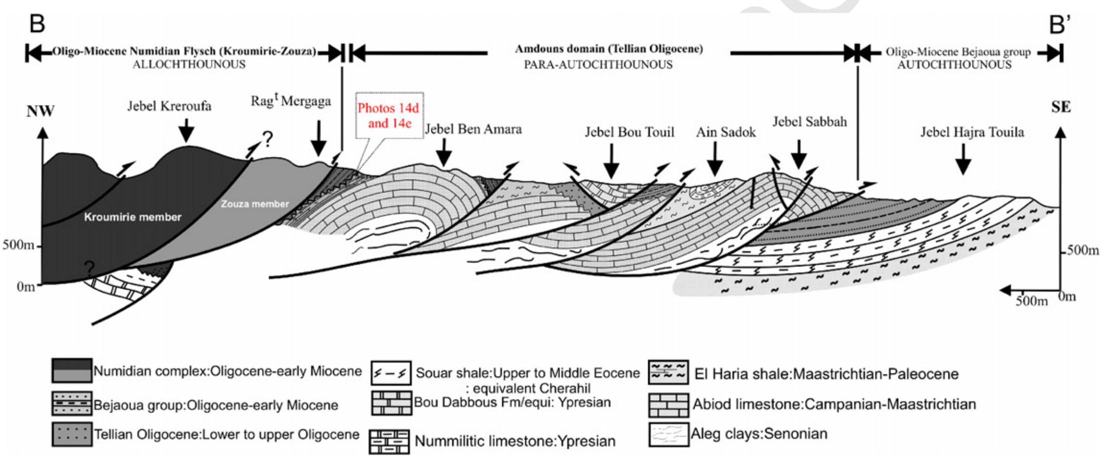

Fig. 15. Synthetic structural cross-section showing tectonic style of southern Kroumirie Mountain. This section has been constructed utilising data from different lithostratigraphic sections carried out on the Numidian Flysch, Tellian and Bejaoua deposits. Sedimentologic and biostratigraphic data are used in the emplacement of some thrust contact. Field observations of the relationship between different series outcropping in the front of the Numidian Flysch as demonstrated in Fig. 14.

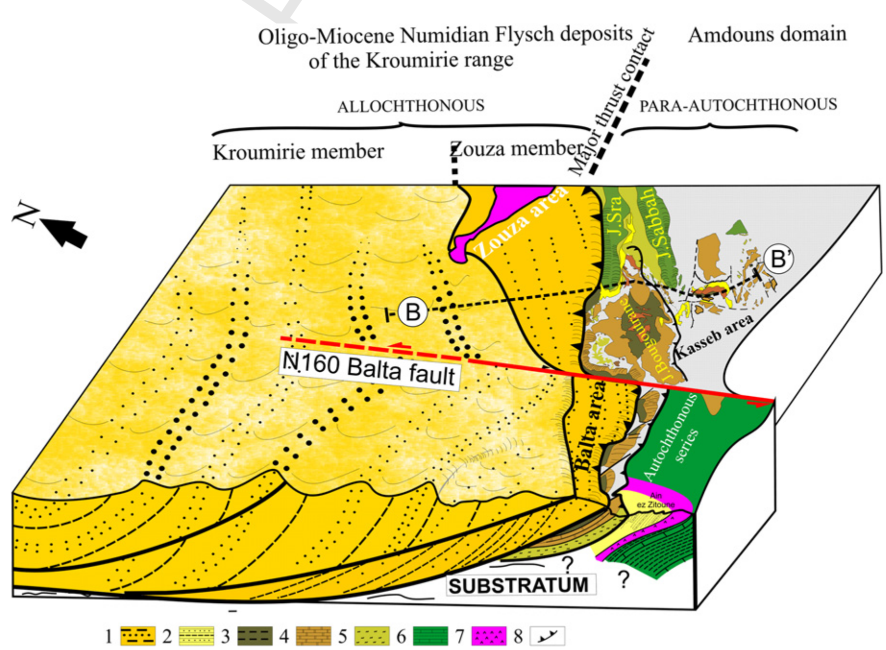

Fig. 16. Simplified bloc diagram showing the different series along the thrust belt front after displacement of the Numidian Flysch. Note strike slip post-thrusting. (1) Sands and clays (Numidian Flysch). (2) Glauconitic sands and clays (Bejaoua group). (3) Clays (early to middle Eocene). (4) Limestones (Ypresian). (5) Clays (El Haria formation). (6) Limestones (Abiod formation). (7) Triassic salt. (8) Major thrust fault.

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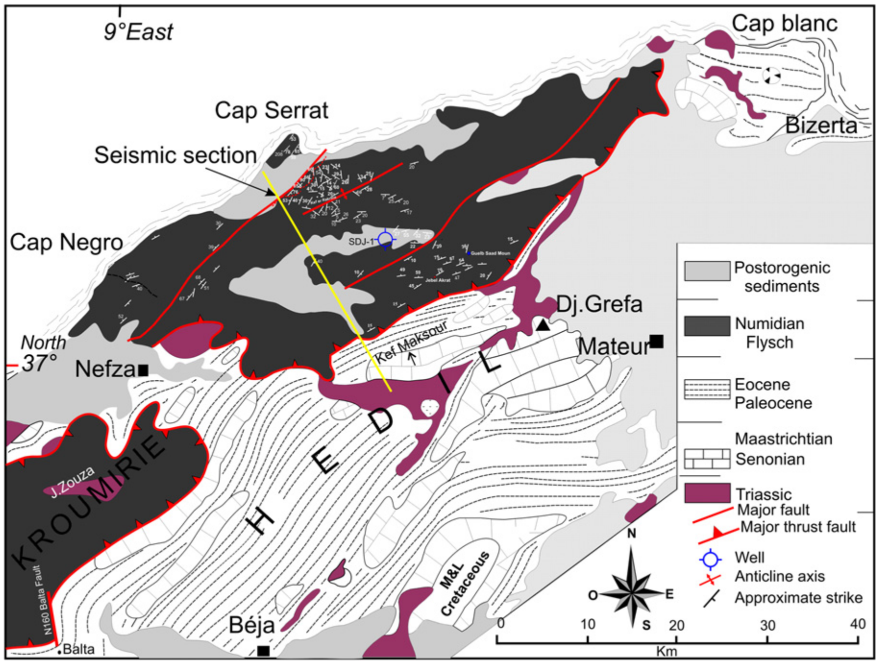

Fig. 17. Schematic geologic map of the Mogods–Hedil area, and the eastern part of Kroumirie, (modified from De Jong, 1975). Black line (S1) shows the position of the seismic line interpreted below. The corresponding strike and dip are on the basis of field observation and map of Carr and Miller (1979).

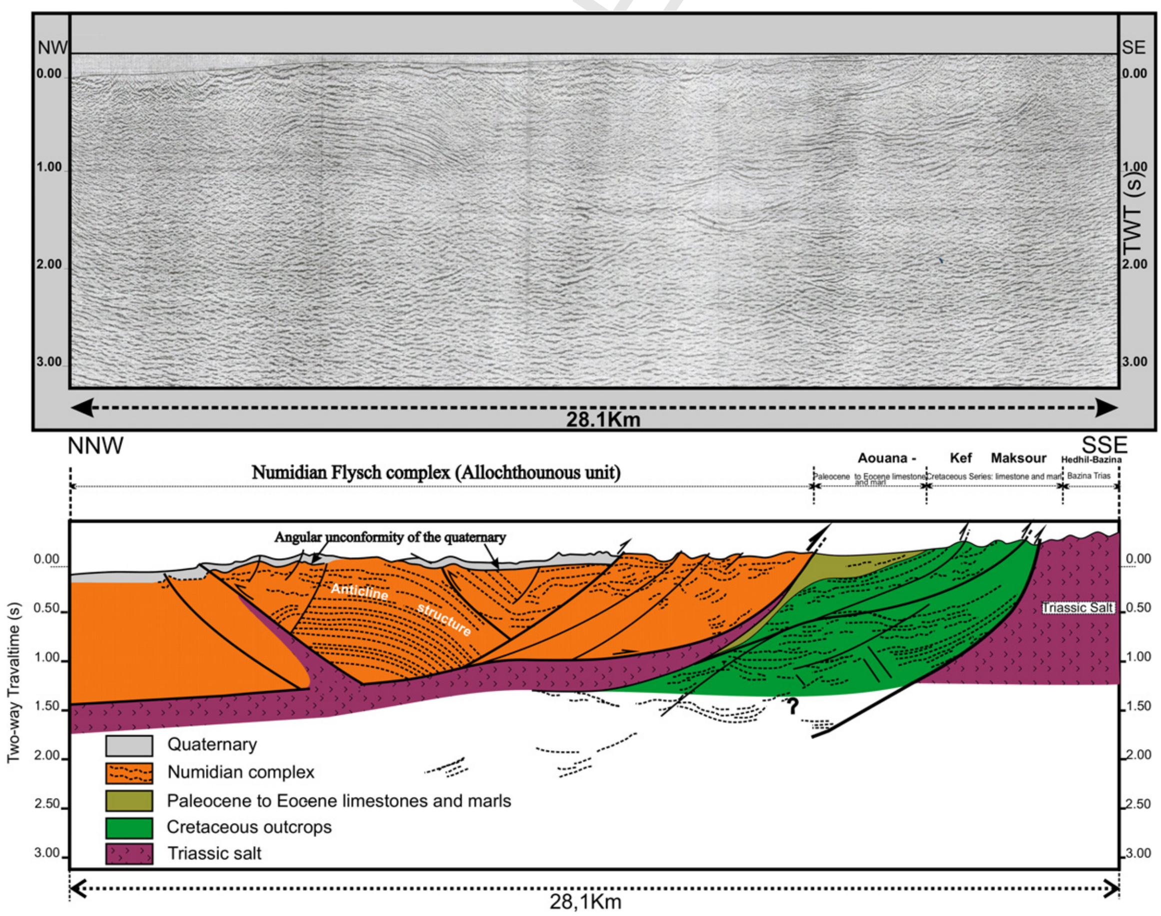

Fig. 18. Interpretation of seismic section S1 cutting the Numidian front. (a) Non interpreted NNW–SSE seismic line (S1) lying between Cap-Serrat and kef Maksour to the south. (b) Interpretation of the seismic line showing the basal thrust of the Numidian and imbrications on its front. This seismic line demonstrates well that the Triassic of Bazina was emplaced diapircally and not injected as tectonic slices or injected along the sole of major thrust plates as previously interpreted (Biely and Rouvier, 1970; Caire et al., 1971; Rouvier, 1977).

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proposed 30 km, and 20–30 km displacement in northeastern Tunisia by Caire (1971). On the basis of a work on the "out-of sequence thrusts", Morley (1988) proposed 45–50 km of total minimum displacement. This estimate is close to an estimate of 15–26 km displacement proposed by Carr and Miller (1979) in the Mogods Mountains.

6.2. Subsurface data

Although we have no subsurface data from below the study area, we show a correlative seismic profile from further to the east, oriented NNW–SSE and extending from West Cap-Serrat to Bazina Trias in the Hedil area (Fig. 17). This shows between 1 and 2.5s (TWT), at least three superimposed distinct structural units (Fig. 18). From the top, we can distinguish the Quaternary series forming horizontal horizon overlying at a regional scale the underlying deformed unit. The latter is very thick and represents the Numidian Flysch complex involved in an anticline–syncline structure affected by several reverse faults. North of the Oued Sejnene Valley (Figs. 17 and 18), and between Jebel Blida and Kef er Rakina, the Numidian Flysch is involved in a large overturned anticline. This structure has been previously described on surface (Carr and Miller, 1979) and appears evident in the current seismic line. The Numidian unit overlies probable Paleogene rocks intensively deformed and detached from the substratum. These rocks outcrop southward in Aouana–kef Maksour locality.

Significant discordance between the Numidian complex and the underlying Tellian rocks can be observed. The two units are separated by a high angle contact outlined by Triassic evaporites acting as a detachment level. The Triassic rocks outcrop towards the NE (Fig. 18) along a major NE–SW trending fault. The geometry of the seismic horizons which possibly represent the Paleogene and Cretaceous succession suggest that these latter were probably folded before the displacement of the overlying Numidian complex. In addition, the profile shows that the Palaeogene and Cretaceous rocks (Tellian series) are composed of several stacked structural units also bounded by incompetent detachment levels most likely corresponding to the Cretaceous and late Paleocene–Eocene shales. The main features shown by the seismic line is the absence of any lateral continuity between the different horizons of the two structural units. This image outlines the strong similarity of the organization of the structural units described in the Kroumirie range (Figs. 15 and 16) and those existing in subsurface (Fig. 18).

This seismic line (Fig. 18) demonstrates well that the Triassic outcrops of Bazina were emplaced diapircally and not injected as tectonic slices or injected along the sole of major thrust plates as previously interpreted (Biely and Rouvier, 1970; Caire et al., 1971; Rouvier, 1977).

7. Conclusions

New biostratigraphic data presented here, from the inland Kroumirie region of the Numidian Flysch in northern Tunisia, suggest that the Zouza as well as the Kroumirie members are both Oligocene to lower Miocene in age, and so were deposited coevally. This new stratigraphic interpretation modifies the classic model proposed since Rouvier (1977) where the Kroumirie and Zouza members were considered as vertically superposed. The facies and associated sedimentary features of the Numidian Flysch in this area indicate a deep-marine muddy slope–apron depositional setting. The Zouza member is generally represented by mud-rich facies associations, whereas the Kroumirie member is richer in sandstones and conglomerates. These latter may have been supplied by slope channels to terminal lobes. The apparent vertical superposition of these two members is in part, due to tectonic activities that accompanied their transportation from north to south. Thick mudstone intervals have played an important part as local detachment levels. The structural analysis demonstrates that the contact between the Numidian complex and the underlying Tellian rocks, in the Kroumirie range, corresponds to sub-horizontal fault suggesting a major thrust regime.

Although the Bejaoua group deposits and the Numidian Flysch have approximately the same age they cannot be associated to the same sedimentary system as the first corresponds to a shelf setting (shallow water deposits) associated to fluvio-deltaic system sourced from the south while the second corresponds to a deep-marine clastic system mainly sourced from the north. Modal analysis, Paleocurrent measurements and zircon geochronology support strongly this interpretation. Therefore current juxtaposition of these two distinct sedimentary systems resulted from the thrusting of the Numidian Flysch southwards.

The compilation of surface and subsurface data confirms this view of the structural style of Northern Tunisia which is dominated by the juxtaposition of several overthrust units having different detachment levels that can be represented either by Triassic evaporites and/or Cretaceous and Tertiary shales.

In agreement with Caire et al. (1971), Rouvier (1977), Carr and Miller (1979) and Morley (1988), we interpret the Numidian complex as a major allochthounous unit. The material of this allochthounous unit has a northern provenance most likely now represented by the Kabylie belt of northern Algeria.

8. Uncited references

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