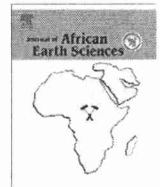




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## Stratigraphy, sedimentology and structure of the Numidian Flysch thrust belt in northern Tunisia

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### ABSTRACT

The Oligo-Miocene Numidian Flysch of northern Tunisia has long been divided into three distinct litho-stratigraphic 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  $514 \pm 19$  Ma from Tunisia and  $550 \pm 28$  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  $1698 \pm 67$  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 allochthonous 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.

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### 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; Guerrero 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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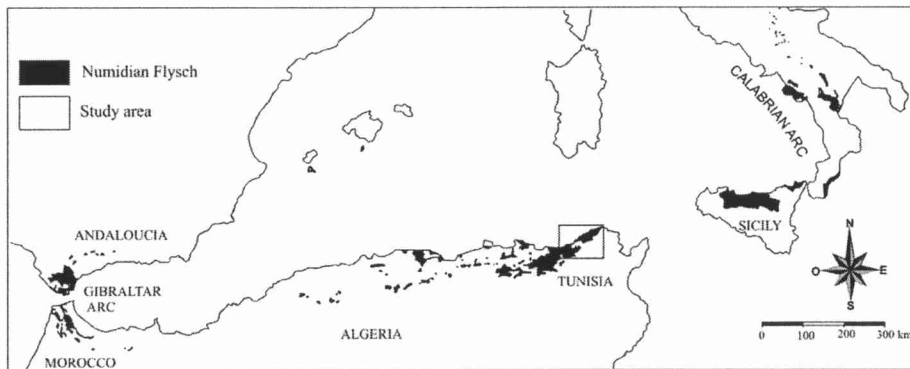


Fig. 1. Location map of Numidian Flysch orogenic belt, Western Mediterranean region (Hoyez, 1989).

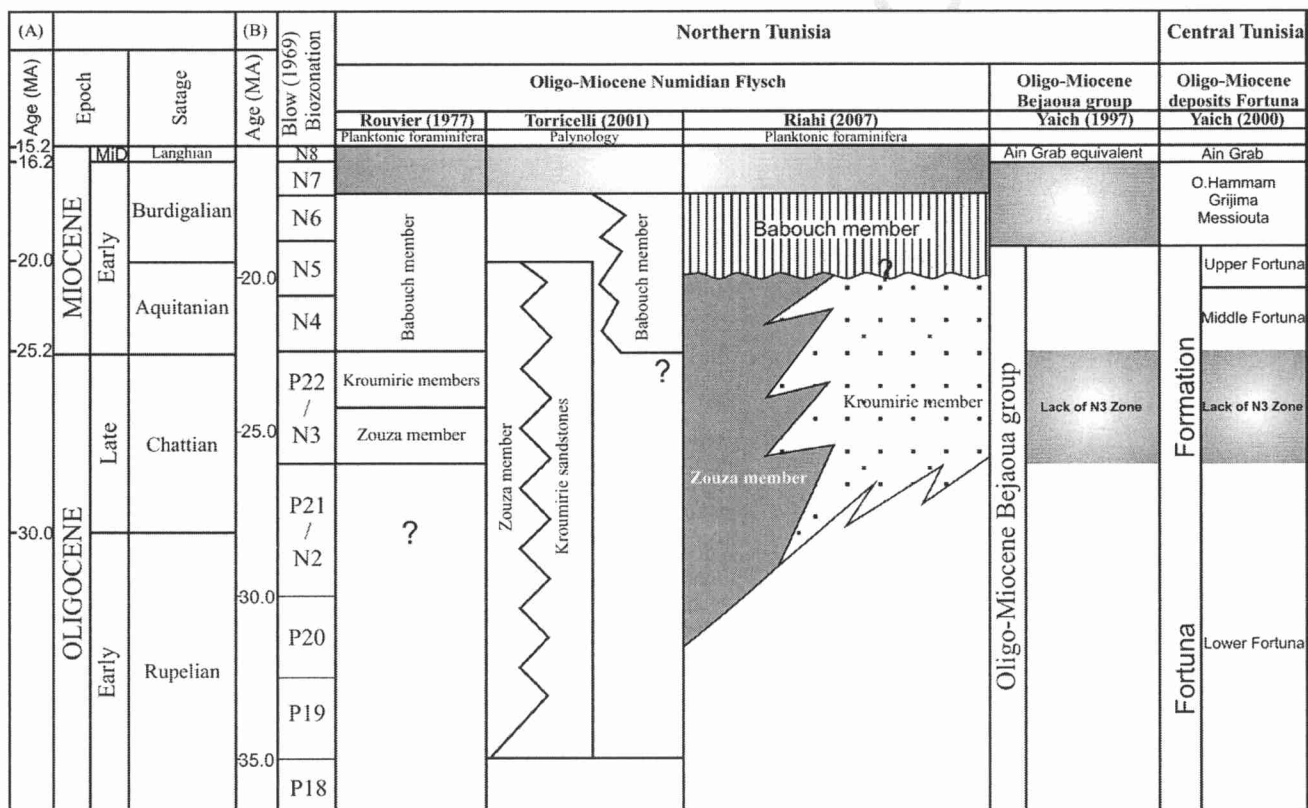


Fig. 2. Stratigraphy of the Oligo-Miocene deposits in northern Tunisia, mainly drawn after Rouvier (1977), on the basis of Torricelli (2000) and Yaich (1997).

76 (1500–2000 m thick) at the base, the Kroumirie sandstones (1000–  
77 1200 m thick) in the middle and the Babouch shales (300 m thick)  
78 at the top. In this stratigraphic scheme the two lower members  
79 were attributed to the Upper Oligocene (N3 zone), whereas a Lower  
80 Miocene age was inferred for the third member (N4–N6 zone).  
81 More recently, on the basis of a detailed palynological investiga-  
82 Q3 tion, Torricelli et al. (2000) and Torricelli and Biffi (2001) have sug-  
83 gested that Zouza and Kroumirie members are age equivalent  
84 rather than stratigraphically superimposed (Fig. 2).

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

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

The alternative view considers the Numidian Flysch as a com-  
100 plex thrust unit displaced from North to South and now resting  
101 in different areas on older rocks, which themselves are allochtho-  
102 103

104 nous or para-autochthonous units with variable detachment levels  
105 Q4 represented either by Triassic evaporites or Tertiary shales (Rou-  
106 vier, 1977; Caire et al., 1971; Carr and Miller, 1979; El Euch  
107 et al., 2004; Ould Bagga et al., 2006).

108 In order to shed further light on these controversies and to bet-  
109 ter understand the internal organization of the Numidian Flysch  
110 Formation as well as its sedimentary characteristics, architecture  
111 and its paleogeographic relationship with the underlying Tellian  
112 rocks and the Bejaoua group, a detailed interdisciplinary study  
113 has been undertaken, integrating biostratigraphy, sedimentology  
114 and structural geology. This study focuses on the Numidian rocks  
115 of the southern part of the orogenic belt in the Kroumirie range  
116 (Fig. 3). It aims to: (1) review the stratigraphy of different sections  
117 within the Zouza and Kroumirie members (sensu Glaçon et al.,  
118 1967; Rouvier, 1977) using planktonic foraminifera, (2) document  
119 the specific sedimentological characteristics, architecture and  
120 depositional setting of these members in their type locality, (3)  
121 to establish a comparison with the coeval Bejaoua group deposits  
122 and (4) to discuss the ultimate provenance of the Numidian Flysch  
123 sandstones.

## 124 2. Methodology

125 The study area is situated in northern Tunisia and represents  
126 the southern part of Kroumirie range (Fig. 3). The Oligo-Miocene

127 deposits outcropping in this area are represented by the Bejaoua  
128 group in the south and the Numidian Flysch in the north. A series  
129 of sections were logged on a detailed bed-by-bed scale within the  
130 Numidian Flysch including, from east to west; Jebel Zouza (Tebaba  
131 and Gassa-Msid sections), Bougoutrane-Balta and Ben Metir sec-  
132 tions. In addition, five sections were logged within the Bejaoua  
133 group, of which one is documented herein – the Jebel Hajra touila  
134 section. These sections form the basis of our sedimentological  
135 interpretations and were further sampled for biostratigraphy and  
136 petrographic analysis.

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

148 Taking account of the stratigraphic variation in occurrence of  
149 some planktonic species as a result of geographical influence, we  
150 have mainly compared our results with the principal studies car-  
151 ried out in the Mediterranean basin by Bizon and Bizon (1972), Q5

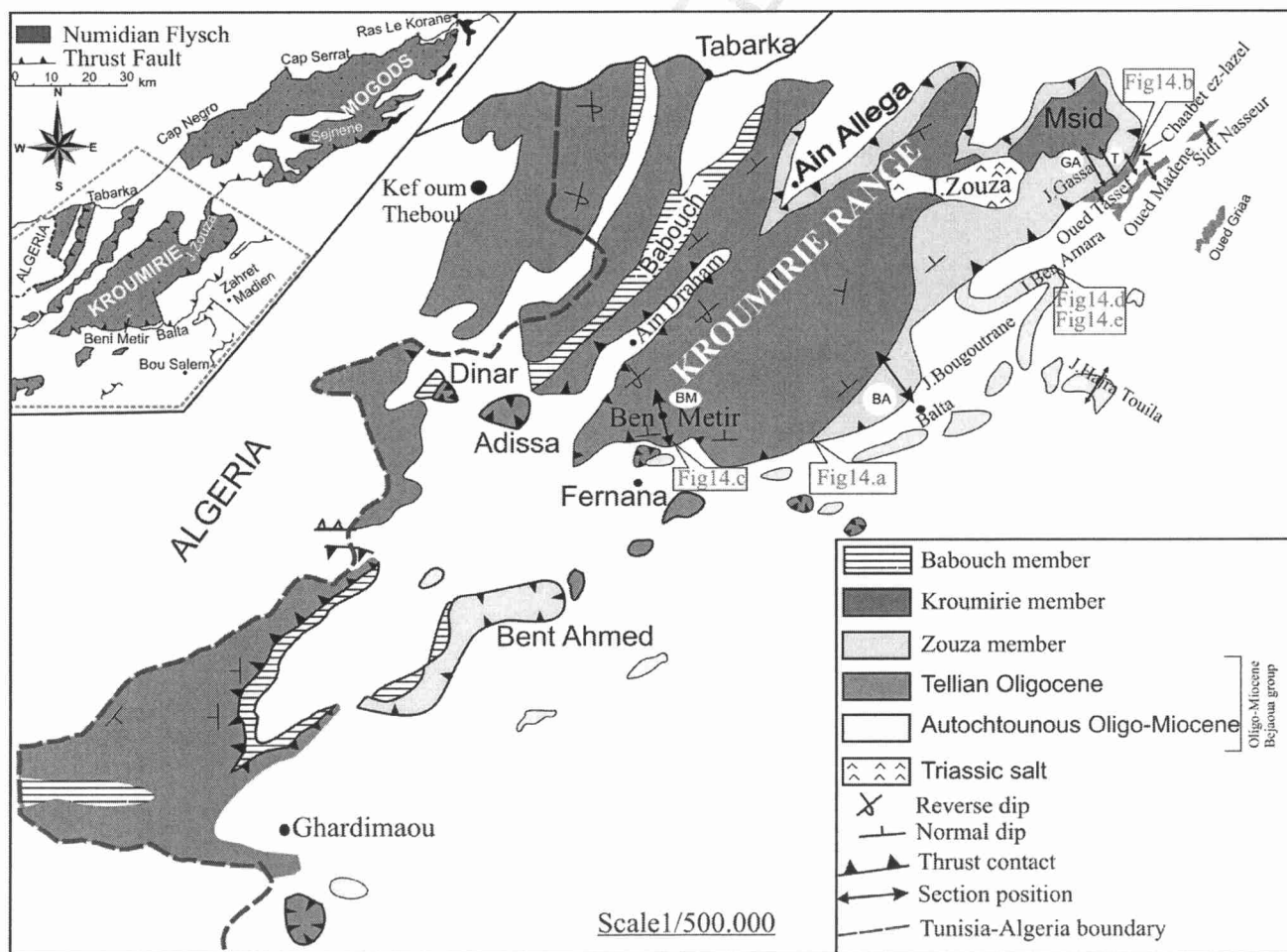


Fig. 3. Schematic map of the Kroumirie range showing the distribution of different members of the Numidian Flysch and the Oligo-Miocene Bejaoua group, near the main thrust front (Glaçon et al., 1967). T: Tebaba, GM: Gassa-Msid section, BA: Balta-Bougoutrane section, BM: Ben Metir section.

152 Ben Ismail-lattrache and Bobier (1984), Bolli et al. (1985) and Berg-  
153 gren et al. (1995).

154 **3. Biostratigraphic results**

155 **3.1. Tebaba section (T)**

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

163 Biostratigraphic investigations (Fig. 5) indicate that samples T1,  
164 T2, T3 and T5 are rich in a diverse planktonic foraminiferal assem-  
165 blage including; *Globorotalia opima nana*, *Globigerina ampliapertura*,  
166 *Catapsydrax dissimilis* and *Globigerina sellii*. These species  
167 correspond to the *G. ampliapertura* zone (P20 zone) of early Oligo-  
168 cene (Upper Rupelian) age. Samples T11, T13, T16, T17, T18 and  
169 T19 include the same species, but *G. sellii* becomes rare and *G. opi-*  
170 *ma-opima* becomes very abundant. These levels are attributed to  
171 the *G. opima opima* zone (P21 zone) characterising the late Oligo-  
172 cene (early Chattian). The samples T24 and T26 display a plank-  
173 tonic foraminifera association comprising *Globorotalia kugleri*,  
174 *Globigerina preabuloides*, *G. dissimilis* and *Globigerina ciproensis*  
175 *angustiumbilitata*. This association dates as early Miocene (Aquit-

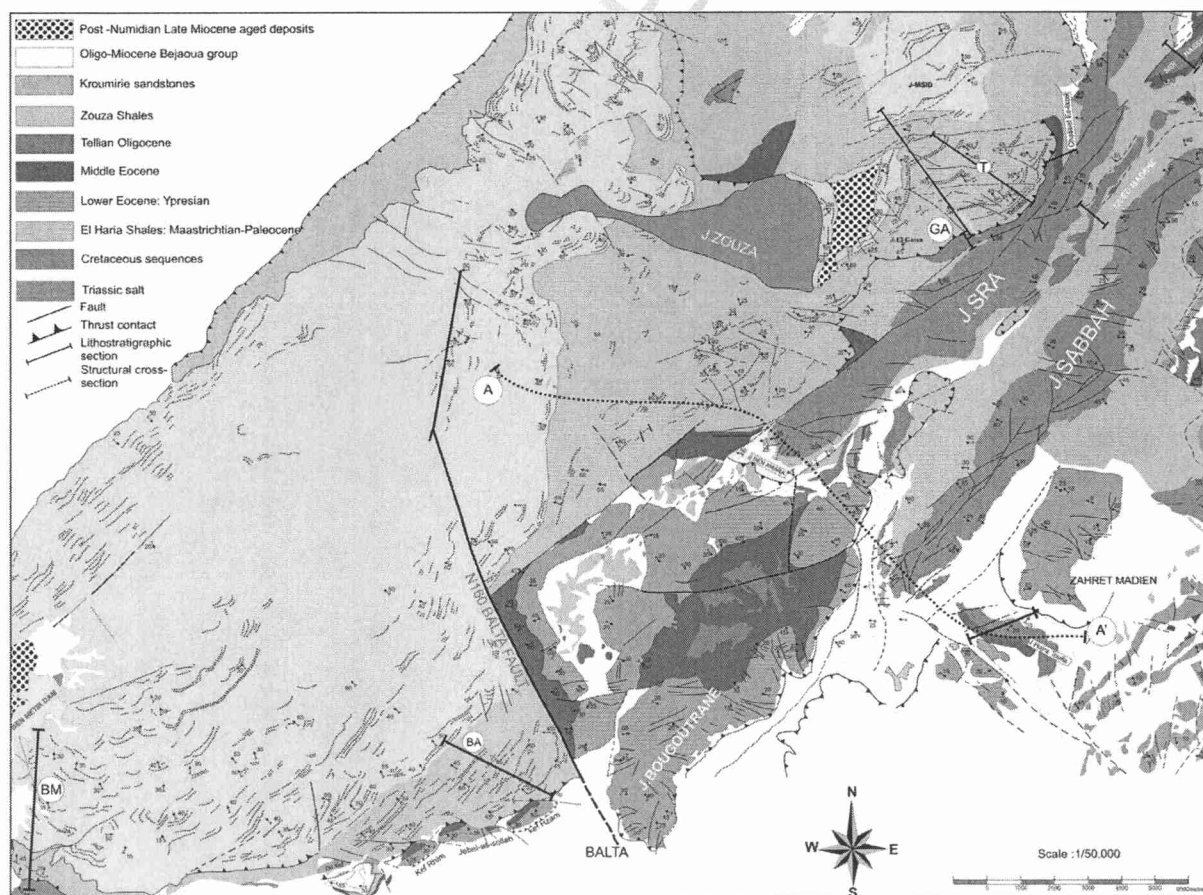
176 nian: N4 zone). The species identified within the uppermost mud-  
177 stone interval (MI5, samples T30 and T31) also indicate a Lower  
178 Miocene age.

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

183 **3.2. El Gassa–Msid section (GA)**

184 This section forms the western prolongation of the Tebaba (T)  
185 section. It was partly studied by Torricelli (2000) and Riahi et al.  
186 (2007) and comprises the Zouza member and part of what is con-  
187 sidered by Glaçon et al. (1967) and Rouvier (1977) to be the Kro-  
188 umirie member (Figs. 3 and 4). Detailed mapping of the study  
189 area indicates that the lowermost sandstone unit encountered in  
190 the Tebaba section (SLT1) pinches out in the El Gassa area and is  
191 progressively replaced, to the west by a thick mudrock unit.

192 Samples GAS1, GAS2 and GAS3 collected from the lowermost  
193 exposed mudrock intervals contain an association of planktonic  
194 foraminifera characteristic of the *G. ampliapertura* zone of early Oli-  
195 gocene age (Rupelian: P20 zone) (Fig. 6). The presence of *G. opima*  
196 *opima* and the absence of *G. sellii* in GAS7 and GAS8 samples, sug-  
197 gest the Late Oligocene P21/N2 zone (Rupelian to late Chattian).  
198 The assemblage identified in the GAS14–GAS20 samples is charac-  
199 terized by the presence of *Cassigerinella chipolensis*, *Globigerina*  
200 *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 lazal, AA': Structural cross-section location.

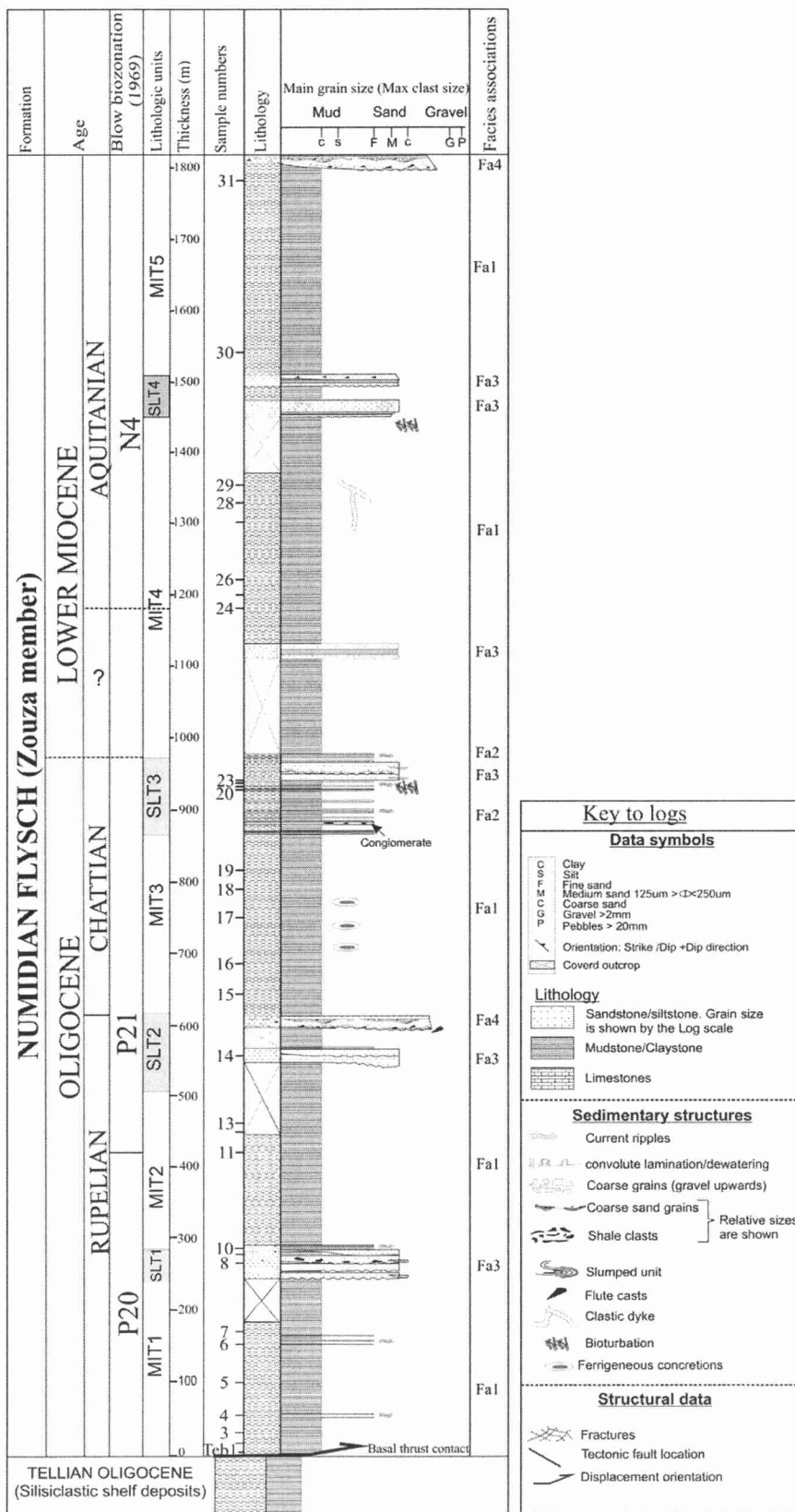


Fig. 5. Lithological succession, biostratigraphy and facies association of the Oligo-Miocene Numidian Flysch in Jebel Zouza (Tebaba section). MIT: Mudstone interval Tebaba; SLT: Sandy lens Tebaba.

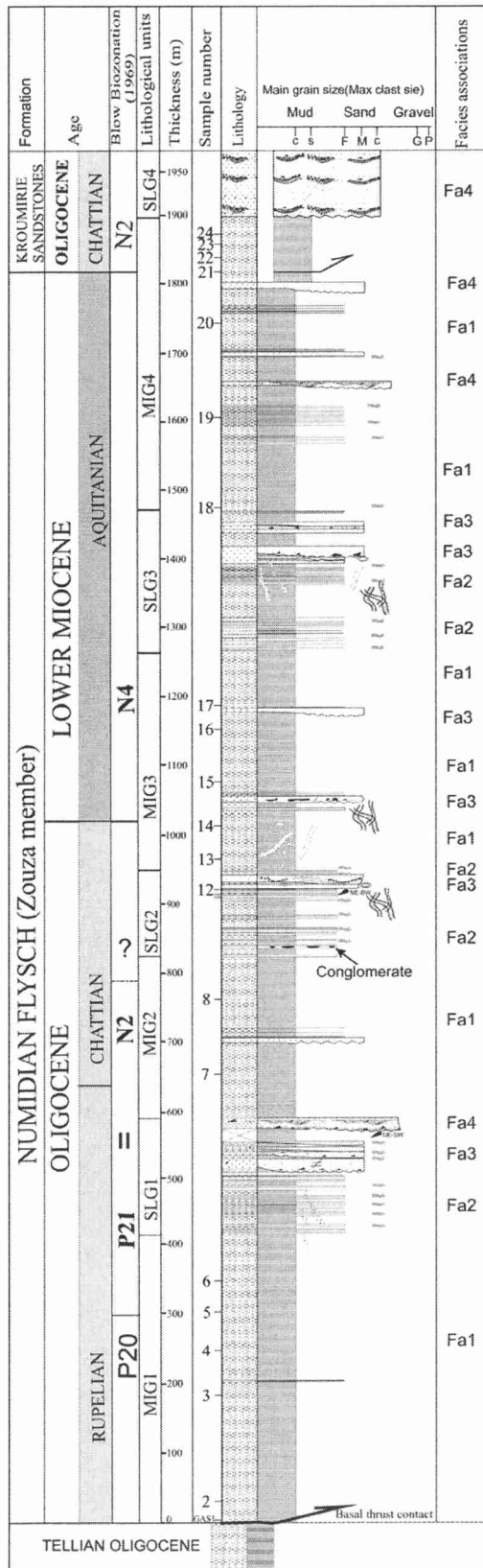


Fig. 6. Lithological succession, biostratigraphy and facies association of Oligo-Miocene Numidian Flysch in Jebel Zouza (Gassa-Msid section). MIG: mudstone interval Gassa, SLG: Sandstone interval Gassa.

cf., the appearance of *G. kugleri*, *Globigerinoides 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. ciproensis*, *G. preabulloides*, *G. opima opima*, *G. dissimilis*, *G. 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*, *G. dissimilis*, *G. ciproensis angustumbricata*, *Globigerina binaiensis*, *G. primordius* and *Globobotalia 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.

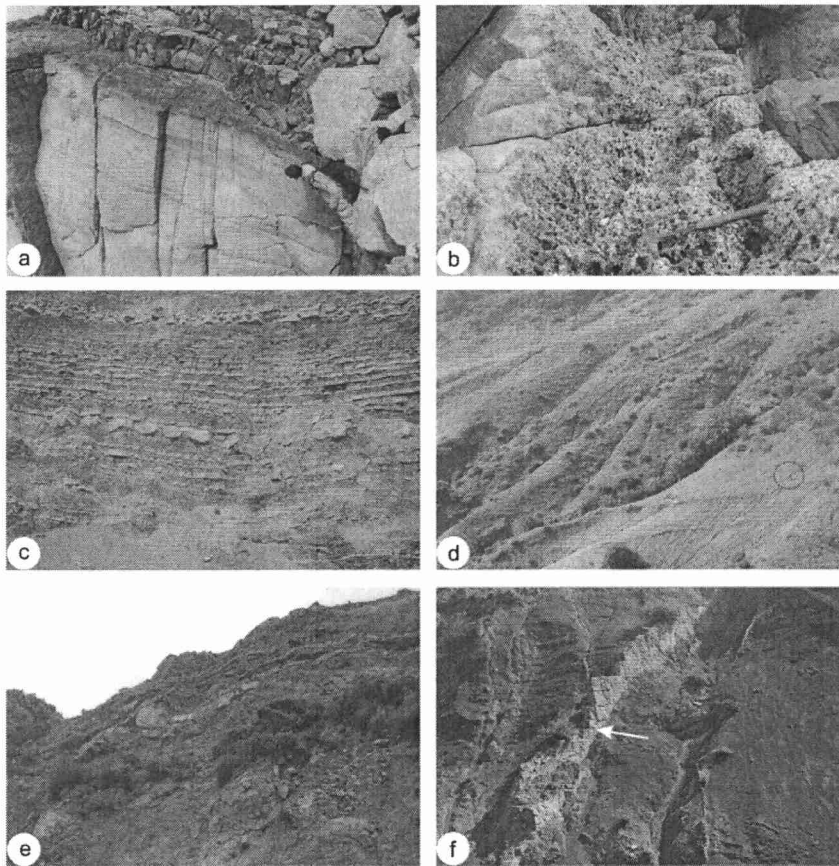
Biostratigraphic analysis (Fig. 8) reveals that samples collected from the lower part of the section (BM1, BM2, BM3, BM4 and BM5) contain *Globigerina angulisuturalis*, *G. ciproensis*, *G. preabulloides*, *G. opima opima*, *G. dissimilis*, *G. opima nana*, *G. primordius* and *Globigerina Tapuriensis* 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. 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 (Aquitainian: 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 pre-

vious 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<sup>1</sup> (Fig. 9d and f). They generally display indistinct to massive bedding and some ellipsoidal yellow to brownish ferruginous concretions

<sup>1</sup> For interpretation of colour in Fig. 9, the reader is referred to the web version of this article.

(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<sub>3</sub> (generally <10–20%). Geochemical evaluation by El Maherssi 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 cretaceus*, *Ammodiscus* cf. *pennyi*, *Ammobaculites* sp., *Bathysiphon latissimus*, *Glomospira charoides*, *Glomospira diffundens*, *Haplophragmoides impensus*, *Haplophragmoides walteri*, *Hyperammina* gp. *Subnodosiformis*, *Paratrochamminoides acervulatus*, *Paratrochamminoides heteromorphus*, *Reticulophragmium amplexens*, *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-

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 combination 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 Maherssi, 1992; Yaich, 1997; Fildes et al., in press). Additional paleocurrents data collected from sole marking in Ben Metir, Balta

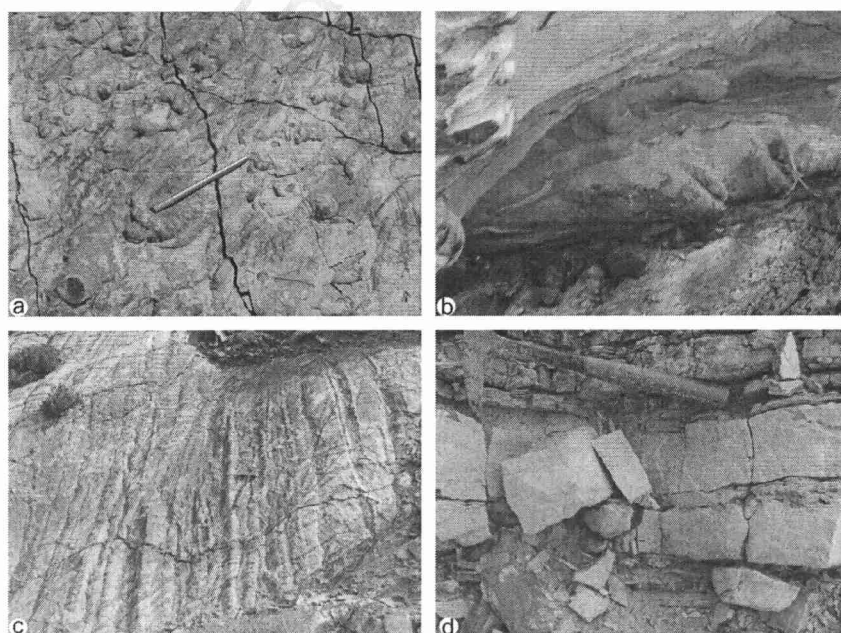


Fig. 10. Sole marking recorded at the base of thick massive sandstone units constituting the Numidian Flysch complex. Photos (a) and (b) show flute casts with a NW–SE (N12°–140°) direction which indicate a NW current direction (Tabarka area); (c) groove marks recorded at the base of massive sandstone 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).

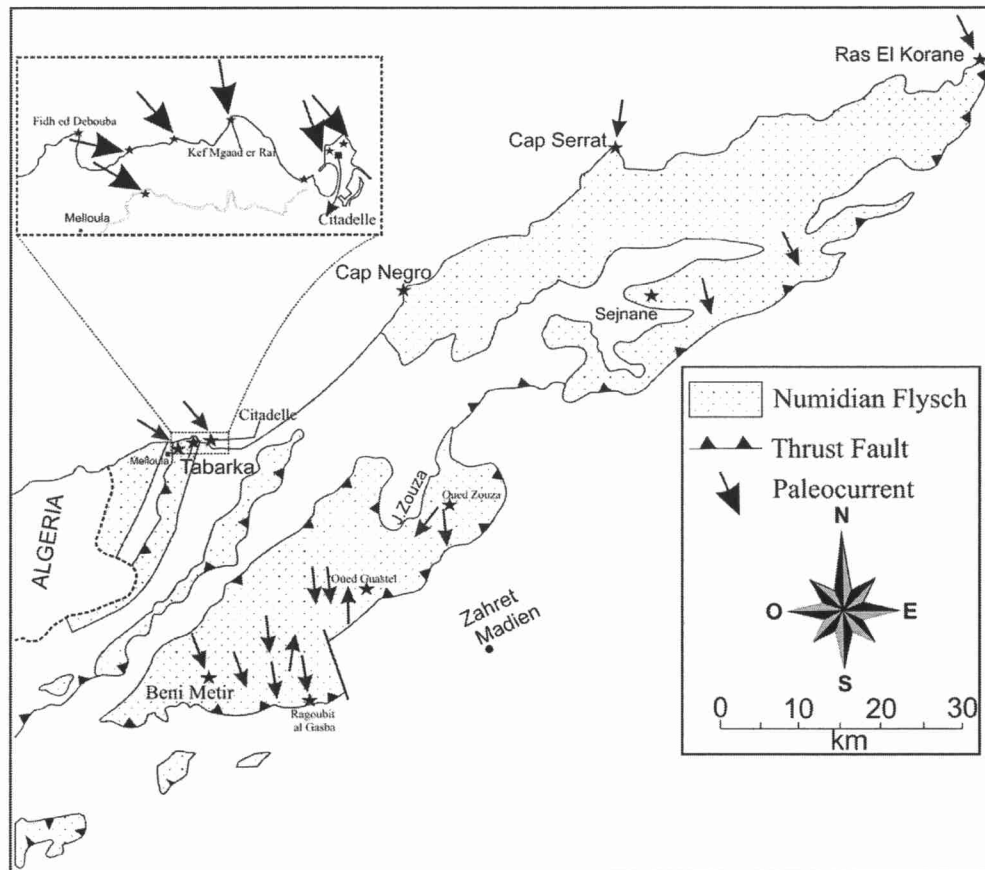


Fig. 11. Map showing pleocurrent directions based on flutes and ripples recorded from different outcrops of the Numidian Flysch in northern Tunisia.

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

515 **4.5. Petrography and modal analysis**

516 Modal analysis of the Numidian sandstones has revealed that all  
517 samples have a quartz arenite composition (Fig. 12a) with slightly  
518 different amounts of quartz and feldspar ( $Q_{34-99}, F_{0-4.5}, L_{0.34-2.5}$ ).  
519 Most of the quartz grains are dominantly monocrystalline (90%  
520 of total quartz grains) showing non-undulose extinction (63% of  
521 the total monocrystalline quartz grains), whilst approximately  
522 37% display undulose extinction. Polycrystalline quartz forms more  
523 than 6% and is present in different amounts depending on grain  
524 size. Feldspars occur in low amounts (average 1.25%), together  
525 with an even greater paucity of rock fragments and heavy  
526 minerals.

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

4.6. Zircon data

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

542 Zircon ages of  $514 \pm 19$  Ma from Tunisia and  $550 \pm 28$  Ma from  
543 Sicily can only have derived from rocks of European affinity. The  
544 original European provenance is most likely now represented by  
545 predominantly metamorphic rocks of the Kabylia belt in northern  
546 Algeria, whereas the Fortuna formation has a southern provenance  
547 from the African craton, confirmed by new zircon ages of  
548  $1698 \pm 67$  Ma (Fildes et al., in press).

5. Oligo-Miocene Bejaoua group

5.1. Para-autochthonous Tellian facies

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

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

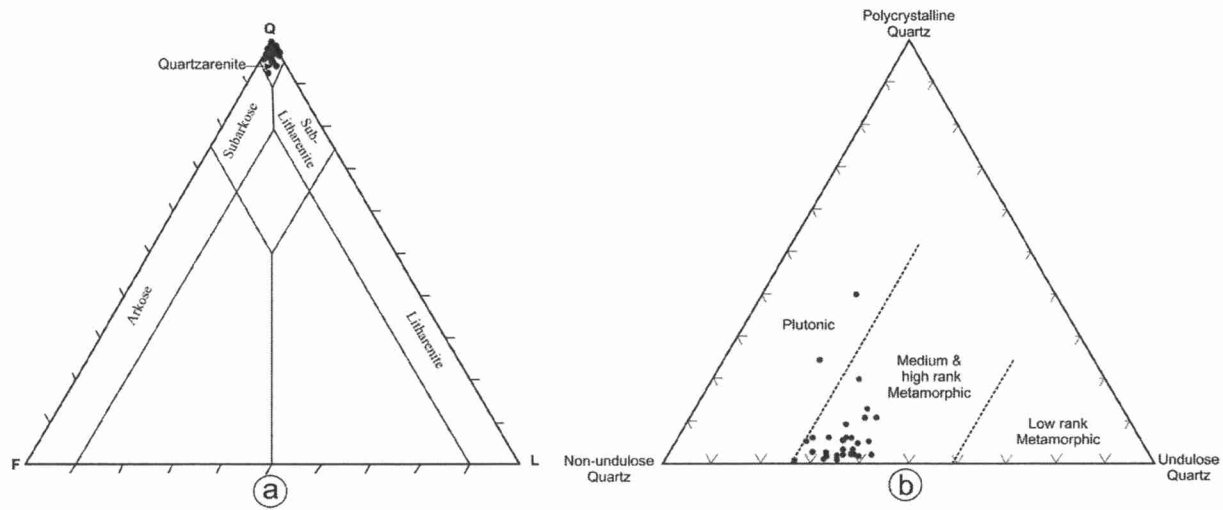


Fig. 12. QFL plots. (a) Classification of the Numidian sandstones: QFL plot (after Pettijohn et al., 1987). (b) Ternary plot of detrital quartz types of the Oligo-Miocene Numidian Flysch sandstones (after Basu et al., 1975). Filled circles represent the sandstone samples.

562 *ampliapertura*, *Globigerina tripartita*, *Globigrina venezuelana*, *Globi-*  
 563 *gerina yagaouensis*, *C. preabulloides* and *C. dissimilis*. At the top of  
 564 the all four sections, the mudstones are of late Oligocene age (Chat-  
 565 tian: P21 zone), as evidenced by the co-occurrence of *C. opima opi-*  
 566 *ma* and *Globigerina angulusituralis*. The faunal assemblage is  
 567 indicative of an outer shelf depositional setting.

568 **5.2. Oligo-Miocene autochthonous facies**

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

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

588 **5.3. Palaeogeographic relationships between Numidian Flysch and**  
 589 **Bejaoua group**

590 Sediment facies and biofacies characteristics of the Numidian  
 591 Flysch sections studied in this work indicate a deep-water depo-  
 592 sitional setting with abundant input from turbidity currents and  
 593 related downslope depositional process. These show an appar-  
 594 ently more proximal facies aspect along the northernmost part  
 595 of Tunisia (Tabarka area) and correspondingly more distal aspect  
 596 southwards towards the thrust front (The Zouza, Balta and Sejn-  
 597 ene areas).

598 Nevertheless, the sedimentological and biostratigraphic charac-  
 599 teristics of the Tellian Oligocene succession, which outcrops in the  
 600 Oued el Madene syncline and on which rests the Numidian Flysch,

are generally indicative of an offshore, shallow-marine deposi-  
 tional 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 sedi-  
 mentary 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 north-  
 ern Tunisia, where they occur in submarine channel facies of high  
 density turbidites since the Oligocene time (Tebaba and Gassa sec-  
 tions). Paleocurrent data recorded in both coastal and interior out-  
 crops 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 juxtapo-  
 sition has resulted from the thrusting of the Numidian Flysch  
 southwards during the inversion phase that accompanied the con-  
 vergence 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 sys-  
 tem 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 win-  
 dow (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 af-  
 fected later on by strike slip faults of NW-SE orientation (the N160  
 Balta fault). Structural observations made in the study area support  
 this interpretation.

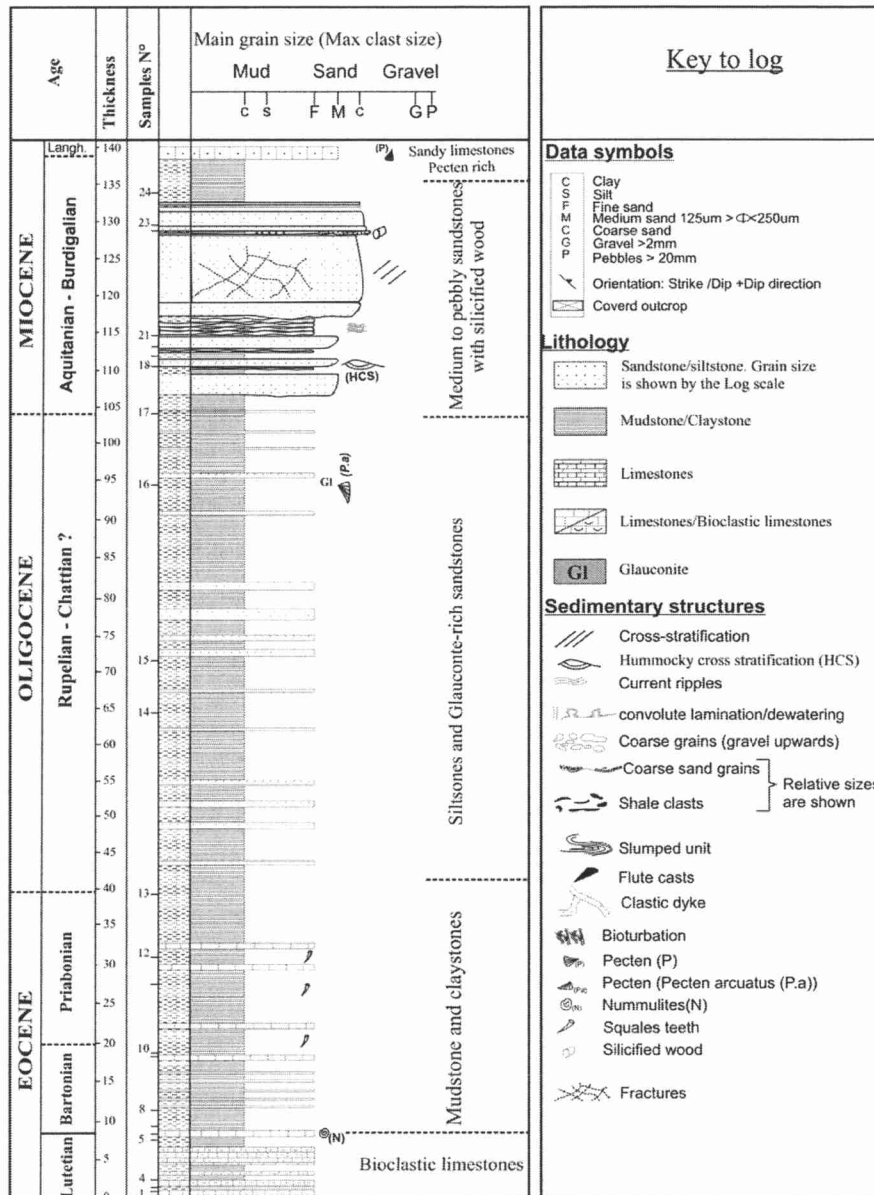


Fig. 13. Lithological succession, biostratigraphy and corresponding facies association of the Oligo-Miocene Bejaoua group in Jebel Hajra Touila.

644 **6. Structural position of the Numidian Flysch**

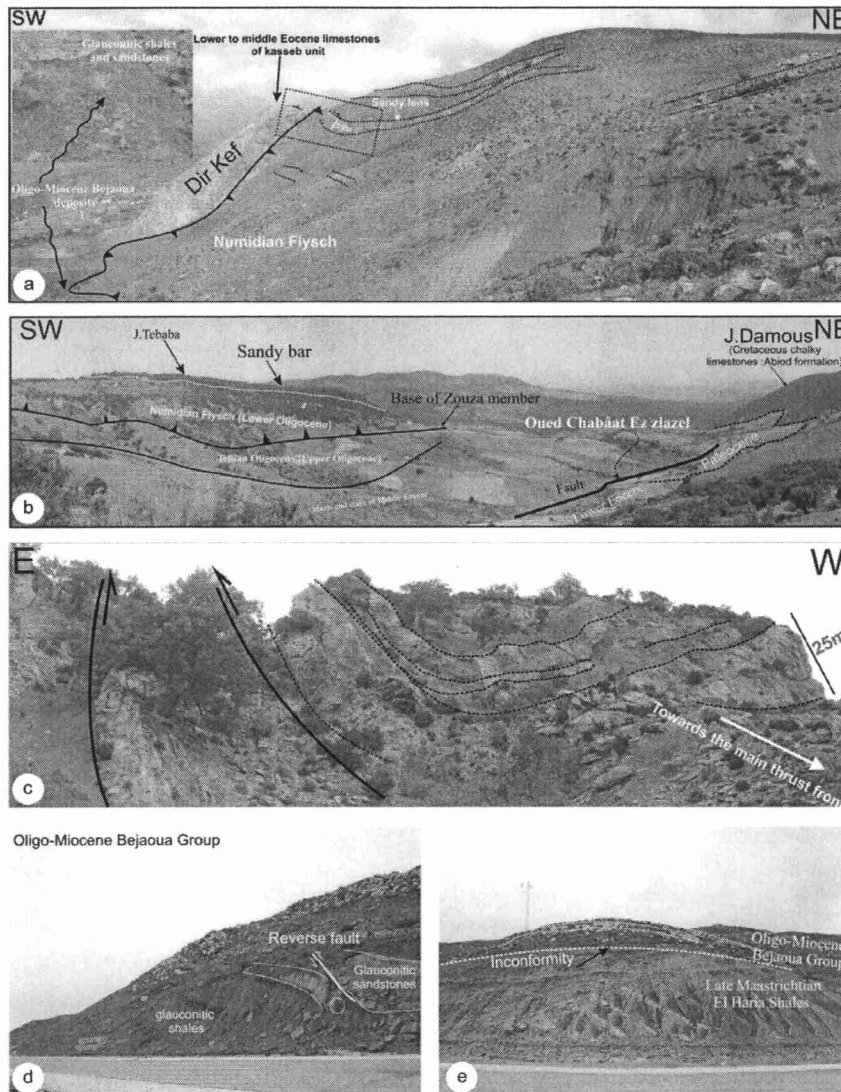
645 **6.1. Surface data**

646 The Numidian Flysch complex of the southern Kroumirie range  
 647 overlies several different older series ranging in age from the late-  
 648 Cretaceous to Paleocene-Eocene that are intensively deformed and  
 649 folded. According to several authors, the contact between the  
 650 Numidian Flysch and the underlying Tellian series is transgressive  
 651 and the lack of the late Eocene (Priabonian time) deposits between  
 652 the two units corresponds to a depositional hiatus (Gottis, 1962;  
 653 Kujawski, 1964, 1969; Wezel, 1968; Crampon, 1973; Alouani  
 654 et al., 1996). However, the presence of Triassic rocks along the basal  
 655 contact of the Numidian Flysch, such as in the Hedil and Sejnene  
 656 area, are considered in other works (Rouvier, 1973, 1977;  
 657 Caire et al., 1971; Carr and Miller, 1979) as a strong argument in  
 658 favour of a thrust displacement of the Numidian complex. In the

659 Mogod domain Carr and Miller (1979) concluded, on the basis of  
 660 a detailed mapping and structural analysis of both the Numidian  
 661 Flysch complex and the Tellian rocks, that these two units are separated  
 662 by a major thrust system.

663 Our detailed study of the area indicates that the contact between  
 664 the Numidian Flysch and the underlying Tellian rocks is not outlined by  
 665 Triassic rocks. Nevertheless, the abrupt truncation of the sandstone  
 666 units of the Numidian Flysch is clearly evident in many localities. Such  
 667 truncation is especially well documented in the Western Balta area  
 668 where Eocene limestones (Kef Hzam, Kef Sollah and Kef Abiod) cut  
 669 abruptly the Numidian Flysch deposits (Fig. 14a).  
 670

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



**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 Bejaoua 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 Telliian shales (Chattian: P21 zone). The contact is marked by a major sub-horizontal fault. Other faults can be traced in the depression separating the Telliian 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.

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

685 Further to the south, the Telliian Oligocene shales facies (Chaâ-  
686 bet ez lazal, Oued Tassef, Sidi Nasseur and Oued Madene) are sand-  
687 wiced between the Numidian Flysch and the Maastrichtian series  
688 of Amdouns folds and include locally several metric blocks of black  
689 limestones of Eocene age (Bou Dabbous Formation). Moreover, the  
690 structural organization of the Cretaceous rocks of Amdouns area

691 shows detachment folds with ramping to duplex features locally  
692 marked by shear foliation in the Paleocene to Eocene shales.

693 Immediately to the South of the main thrust front (Jebel Ben  
694 Amara), the Oligocene Numidian Flysch overhangs the Oligo-Mio-  
695 cene terrigenous sediments locally containing glauconite-rich  
696 sandstones horizons. The latter overlie, by means of an angular  
697 unconformity, the folded Cretaceous strata (Fig. 14d and e) that  
698 had been deformed during the major inversion phase of the late  
699 Eocene (Pyrenean phase of the authors (Rouvier, 1977; El Euch  
700 et al., 2004). This major tectonic phase is well documented in sev-  
701 eral regions in surface as well as in subsurface in the Sahel and in  
702 offshore Tunisia (Rabhi et al., 2002; El Euch et al., 2004; Khomsi  
703 et al., 2006). Similar glauconitic beds have also been recorded  
704 westward, to the north of Oued Bou Hartma (Sidi Bou Dali loca-  
705 tion), in front of the Numidian Flysch in Ben Metir (Fig. 14b). This

706 juxtaposition of older rocks overlying younger rocks favours the  
707 emplacement via a major thrust fault at the base of the Numidian  
708 Flysch (Figs. 15 and 16) which is inevitably, an “Out-of-sequence  
709 thrust fault” as described by Morley (1988).

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

717 All these fact taken together, allowed us to reconstruct the tec-  
718 tonic style of the southern Kroumirie Mountain (Fig. 15). Some ma-  
719 jor faults could not be inspected through direct field observations,  
720 but appear to be a geometric necessity (e.g. the fault at the base of  
721 the Numidian complex (Fig. 15)). The fault separating the Zouza

722 and the Kroumirie members is suggested based on biostratigraphic  
723 data carried out the locality type of the both members (Fig. 15).

724 The style of deformation of the Tellian unit is characterized by  
725 folding and reverse faulting of massive limestone units. This geom-  
726 etry is well exposed north of Zahret Madien and along the main  
727 thrust contact (Figs. 15 and 16). These rocks extending from upper  
728 Cretaceous to Eocene and Oligo-Miocene are involved in a series of  
729 northeast-trending, narrow and faulted anticlines that are sepa-  
730 rated by apparent narrow synclines (e.g. Jebel Sra and Jebel Sab-  
731 bah) (Figs. 15 and 16).

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

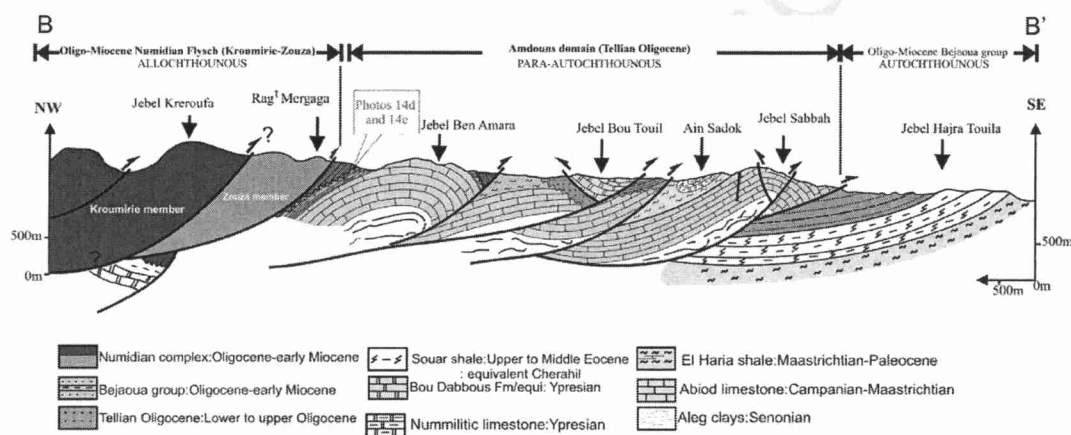


Fig. 15. Synthetic structural cross-section showing tectonic style of southern Kroumirie Mountain. This section has been constructed utilizing data from different lithostratigraphic sections carried out on the Numidian Flysch, Tellian and Bejaoua deposits. Sedimentologic and biostratigraphic data are 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.

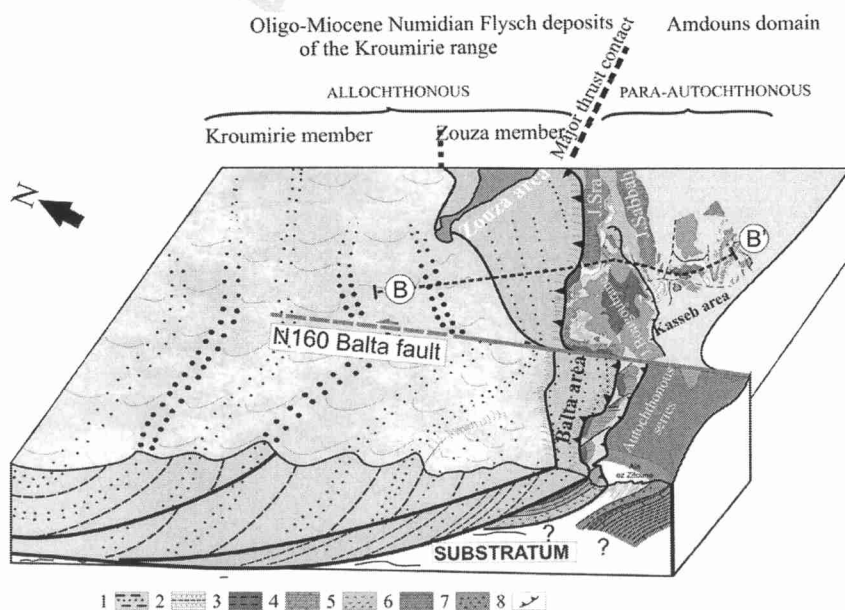
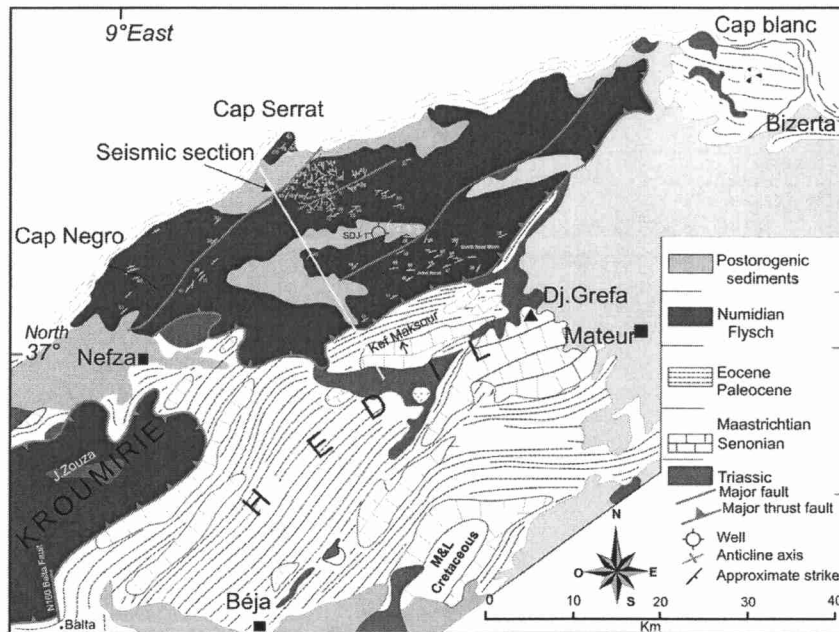
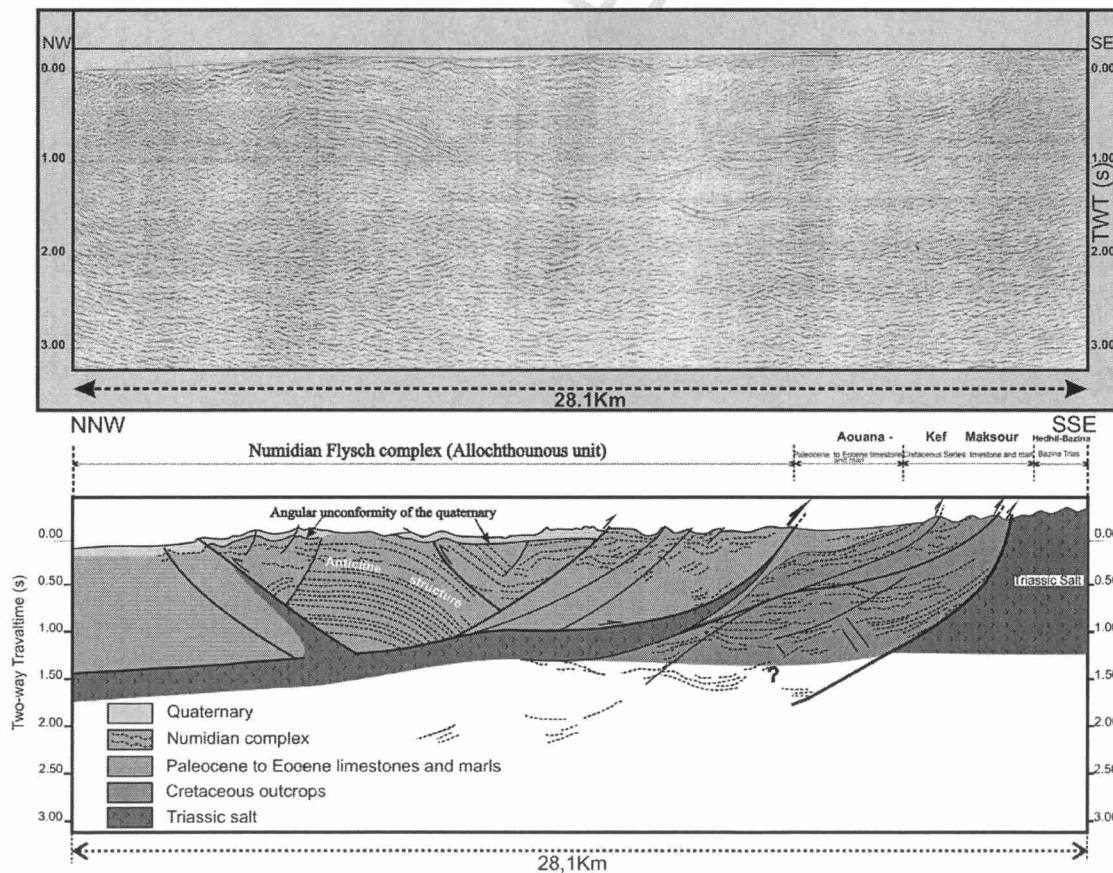


Fig. 16. Simplified bloc diagram showing the different series along the thrust belt front after displacement of the Numidian Flysch. Note strike slip post-thrusting. (1) Sands and clays (Numidian Flysch). (2) Glauconitic sands and clays (Bejaoua group). (3) Clays (early to middle Eocene). (4) Limestones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



**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 diapirically 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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738 proposed 30 km, and 20–30 km displacement in northeastern  
739 Tunisia by Caire (1971). On the basis of a work on the “out-of-se-  
740 quence thrusts”, Morley (1988) proposed 45–50 km of total mini-  
741 mum displacement. This estimate is close to an estimate of 15–  
742 26 km displacement proposed by Carr and Miller (1979) in the Mo-  
743 gods Mountains.

## 744 6.2. Subsurface data

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

762 Significant discordance between the Numidian complex and the  
763 underlying Tellian rocks can be observed. The two units are sepa-  
764 rated by a high angle contact outlined by Triassic evaporites acting  
765 as a detachment level. The Triassic rocks outcrop towards the NE  
766 (Fig. 18) along a major NE–SW trending fault. The geometry of  
767 the seismic horizons which possibly represent the Paleogene and  
768 Cretaceous succession suggest that these latter were probably  
769 folded before the displacement of the overlying Numidian com-  
770 plex. In addition, the profile shows that the Palaeogene and Creta-  
771 ceous rocks (Tellian series) are composed of several stacked  
772 structural units also bounded by incompetent detachment levels  
773 most likely corresponding to the Cretaceous and late Paleocene–  
774 Eocene shales. The main features shown by the seismic line is  
775 the absence of any lateral continuity between the different hori-  
776 zons of the two structural units. This image outlines the strong  
777 similarity of the organization of the structural units described in  
778 the Kroumirie range (Figs. 15 and 16) and those existing in subsur-  
779 face (Fig. 18).

780 This seismic line (Fig. 18) demonstrates well that the Triassic  
781 outcrops of Bazina were emplaced diapirically and not injected as  
782 tectonic slices or injected along the sole of major thrust plates as  
783 previously interpreted (Biely and Rouvier, 1970; Caire et al.,  
784 1971; Rouvier, 1977).

## 785 7. Conclusions

786 New biostratigraphic data presented here, from the inland Krou-  
787 mirie region of the Numidian Flysch in northern Tunisia, suggest  
788 that the Zouza as well as the Kroumirie members are both Oligo-  
789 cene to lower Miocene in age, and so were deposited coevally. This  
790 new stratigraphic interpretation modifies the classic model pro-  
791 posed since Rouvier (1977) where the Kroumirie and Zouza mem-  
792 bers were considered as vertically superposed. The facies and  
793 associated sedimentary features of the Numidian Flysch in this  
794 area indicate a deep-marine muddy slope–apron depositional set-  
795 ting. The Zouza member is generally represented by mud-rich fa-  
796 cies associations, whereas the Kroumirie member is richer in  
797 sandstones and conglomerates. These latter may have been sup-  
798 plied by slope channels to terminal lobes. The apparent vertical

799 superposition of these two members is in part, due to tectonic  
800 activities that accompanied their transportation from north to  
801 south. Thick mudstone intervals have played an important part  
802 as local detachment levels. The structural analysis demonstrates  
803 that the contact between the Numidian complex and the underly-  
804 ing Tellian rocks, in the Kroumirie range, corresponds to sub-hori-  
805 zontal fault suggesting a major thrust regime.

806 Although the Bejaoua group deposits and the Numidian Flysch  
807 have approximately the same age they cannot be associated to  
808 the same sedimentary system as the first corresponds to a shelf  
809 setting (shallow water deposits) associated to fluvio-deltaic system  
810 sourced from the south while the second corresponds to a deep-  
811 marine clastic system mainly sourced from the north. Modal anal-  
812 ysis, Paleocurrent measurements and zircon geochronology sup-  
813 port strongly this interpretation. Therefore current juxtaposition  
814 of these two distinct sedimentary systems resulted from the  
815 thrusting of the Numidian Flysch southwards.

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

821 In agreement with Caire et al. (1971), Rouvier (1977), Carr and  
822 Miller (1979) and Morley (1988), we interpret the Numidian com-  
823 plex as a major allochthonous unit. The material of this alloch-  
824 thonous unit has a northern provenance most likely now  
825 represented by the Kabylie belt of northern Algeria.

## 826 8. Uncited references

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828 et al. (1991), Mutti and Ricci-Lucchi (1972, 1975), Mutti (1977);  
829 Mutti et al. (2003), Solignac (1927), Stow (1985), Stow et al. (1999),  
830 Stow and Mayall (2000), Stow and Johansson (2000) and Stow et al.  
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