

AGE, INTERNAL STRATIGRAPHIC ARCHITECTURE AND STRUCTURAL STYLE OF THE OLIGOCENE–MIOCENE NUMIDIAN FORMATION OF NORTHERN TUNISIA

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Abstract: The stratigraphy of the Numidian Formation of northern Tunisia and its internal organization are updated. Planktonic foraminifera point to a mainly Oligocene–Early Miocene age of this formation in the majority of the sections studied. Some key lithological horizons are recognized within the early Miocene succession, allowing lateral correlation between the outcrops of the Mogod and Kroumirie mountains. These include: (1) a conglomeratic interval, up to 1–2 m thick and rich in reworked glauconitic boulders, limestone fragments of the Telliian (Eocene) and pectinid bivalves; and (2) a relatively continuous glauconitic level. In the new stratigraphic scheme, the Zouza, Ben Metir and Sejnene sections represent the entire Numidian Formation. A lower unit (200–700 m thick), highly pelitic with subordinate sandstone beds was distinguished, overlain by an upper unit which is sandier, especially in its uppermost part (1,000–1,500 m thick). In the present study, these have been stratigraphically dated as Oligocene–Early Miocene p.p. (Rupelian–Chattian; P19–P21 zones) to Aquitanian (N4 Zone) and Miocene (Aquitanian–early Burdigalian; N4–N5 zones), respectively. In the areas studied, the sandy succession assigned to the Kroumirie Member begins with a sandstone unit with an erosional base or a major discontinuity, locally marked by conglomerates made up of various reworked components. It rests generally on a thick shale unit that characterises the upper part of the Zouza Member. The thinner, uppermost succession of the Numidian Formation represents the Babouch Member, dated as Burdigalian (N6–N7 zones).

Within the framework of the new proposal, the total stratigraphic thickness of the Numidian Formation in northern Tunisia does not exceed 2,200–2,600 m.

Internally, the Numidian Formation is transected by the Intra-Numidian Thrust and back-thrust faults, associated with faulted folds that are recognized in outcrop on different scales and in seismic sections. Along these thrust and/or reverse faults, the middle to upper Eocene deposits have undergone uplift and are exposed at the surface (e.g., Dowar Larmel in Meloula-Tabarka, Gaâret Sejnene and Sidi M'chreg sections).

Key words: Numidian Formation, stratigraphy, Oligocene, Miocene, turbidites, structural analyses.

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INTRODUCTION

The well exposed Oligocene–Miocene Numidian Formation of northern Tunisia is an interesting and important example of a deep-water hydrocarbon reservoir and a slope depositional system. This formation provides a limited reservoir for gas in Sicily (e.g., the Galiano Field) and constitutes a current target for petroleum exploration in offshore Tunisia, where it is found below a gently sloping continental shelf at water depths of 200–250 m. It is closely linked with the much more extensive Numidian facies, which extends along the south of the Mediterranean coast, from the Gibraltar Arc in the west to southern Italy in the east (Fig. 1). In northern Tunisia, the Oligocene–Miocene Numidian Formation is an allochthonous unit (Rouvier, 1977; Carr and

Miller, 1979; El Euch *et al.*, 2004; Oued Bagga *et al.*, 2006, Riahi *et al.*, 2010), occupying the highest structural position in the Kroumirie and Mogod mountains over a surface area of 2000 km². It comprises a succession of alternating sandstone, quartz-pebble conglomerates and mudstones, approximately 2200–2600 m thick. They belong to a turbiditic depositional system, the lithosomes of which are stacked above the tectonic Telliian units (Kasseb, Ed Diss, Adissa and Aïn Draham units; Figs 1, 2). These units are built of Maastrichtian to Eocene limestones and marls, which are overlain by a thin, locally-preserved veneer of clastic rocks, deposited in the Early Oligocene (Rouvier, 1977; Boukhalfa *et al.*, 2015).

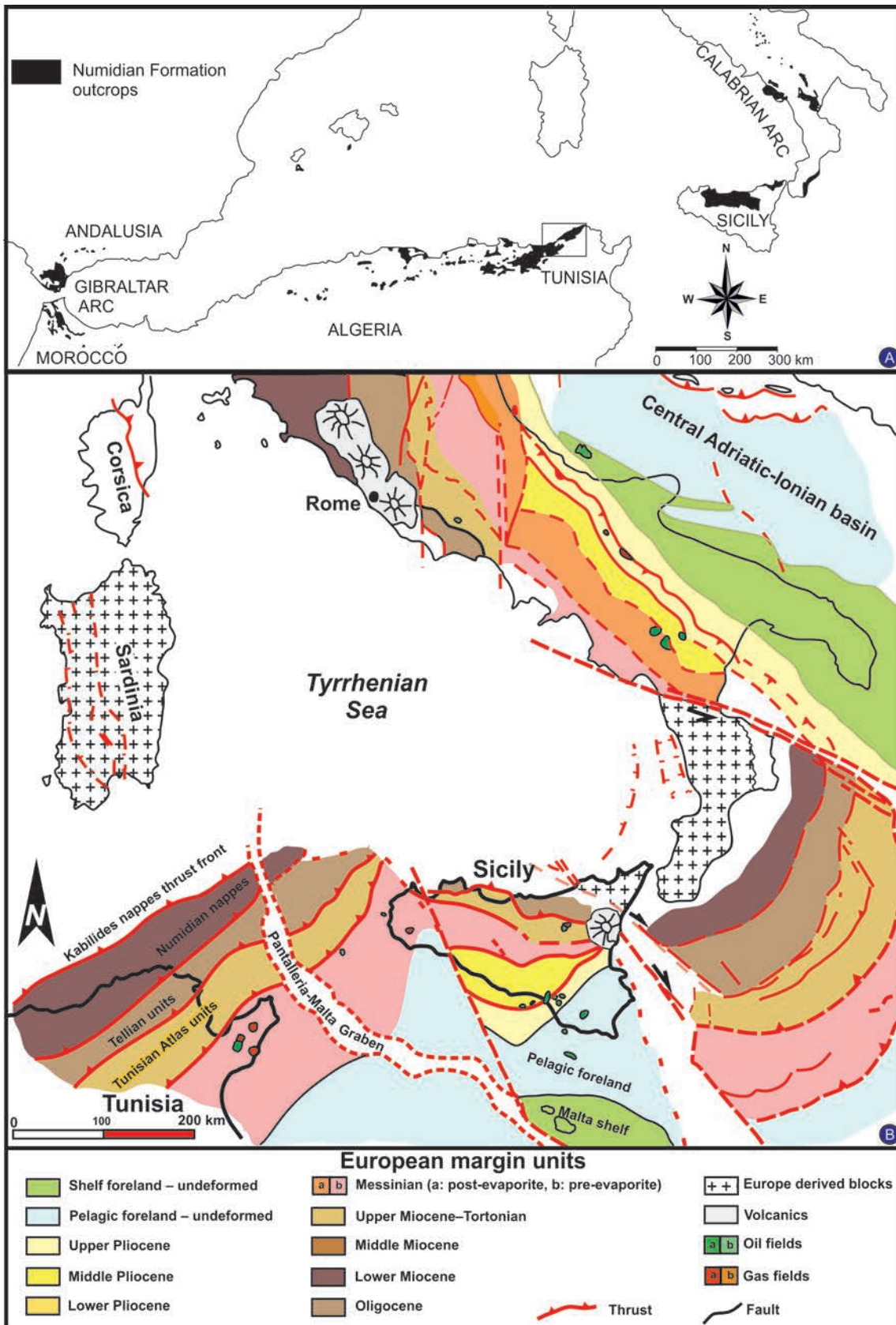


Fig. 1. Distribution and structural position of the Numidian Formation in northern Tunisia and the central Mediterranean area. **A.** Numidian Formation outcrops in the western Mediterranean region (Hoyez, 1989); the boxed area corresponds to northern Tunisia. **B.** Map of the central Mediterranean, including the Sicilian Channel, and extent of the Messinian *versus* Pliocene foredeeps in the Tunisian offshore and Sicily, as well as the Ionian Basin and its surroundings. The colour code of Neogene series defines the age of the onset of the foreland flexure and sedimentary infill of the foredeep with clastics, derived from the uplifted/exhumed inner parts of the belt (Roure *et al.*, 2012).

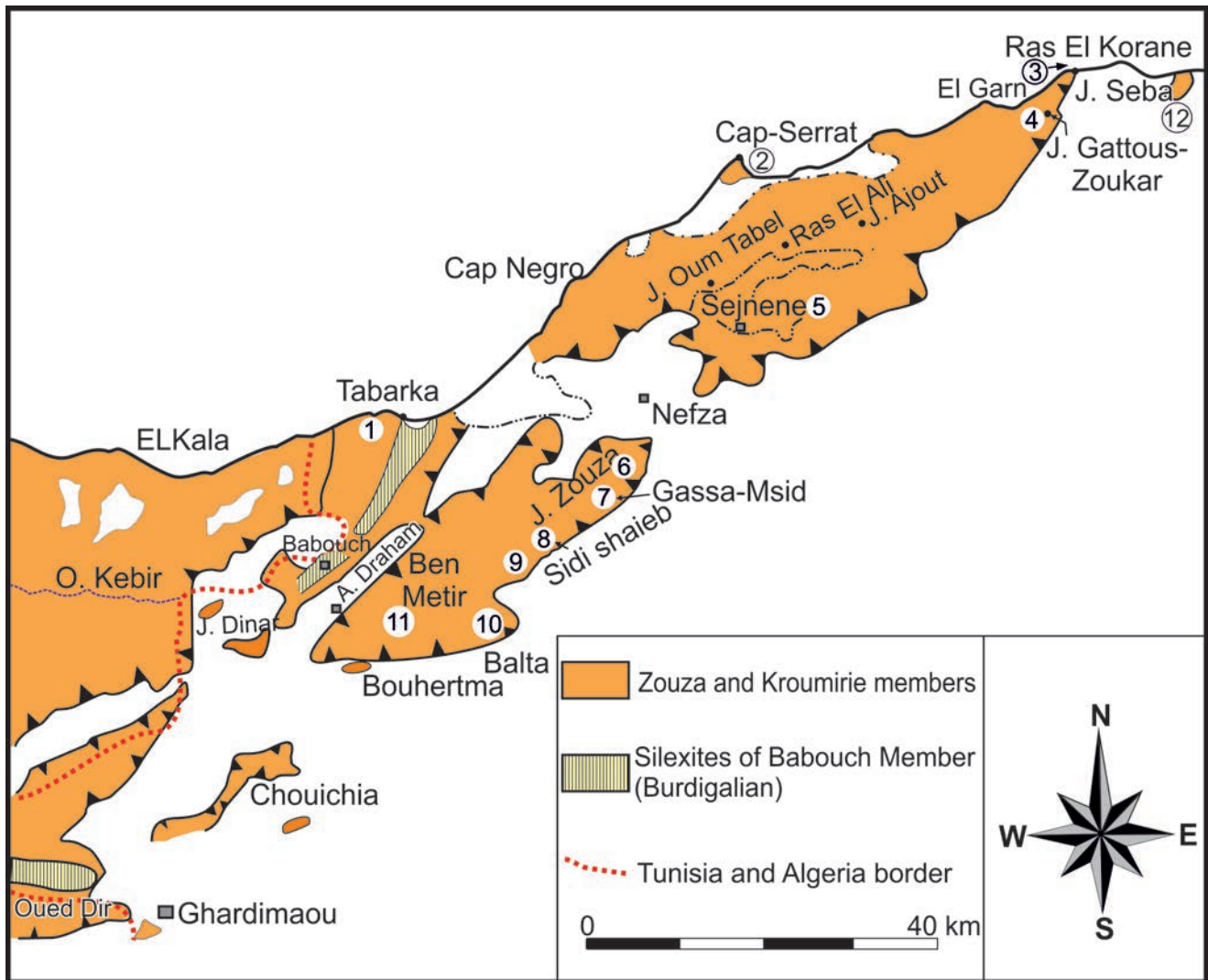


Fig. 2. Map showing the spatial distribution of the Numidian Formation outcrops in northern Tunisia. The numbers indicate the position of the sections studied: 1 – Meloula-Needles; 2 – Cap-Serrat; 3 – Ras El Korane; 4 – Jebel Zoukar; 5 – Sejnene; 6 – Jebel Tebaba; 7 – Gassa-Msid; 8 – Oued Jabeur; 9 – Oued Guastel; 10 – Balta; 11 – Ben Metir, 12 – Jebel Sebaâ.

During the past several decades, the stratigraphy and internal organisation of the Oligocene–Miocene Numidian Formation of northern Tunisia have been widely discussed in the literature and several conceptual schemes have been developed.

1) The original hypothesis is that of Gottis (1962), who distinguished a “lower Numidian Flysch” of Oligocene age and an “upper Numidian Flysch” of Early Miocene age.

2) Galçon and Rouvier (1967) subdivided the Numidian Formation into three members. These are: the Zouza Member at the base, outcropping along the southern margin of the Kroumirie Mountains; the Kroumirie Member in the middle, outcropping along the coast (Tabarka area) and in some inland outcrops (Ben Metir and Jebel Khreroufa areas); and the Babouch Member at the top, comprising mudstones and glauconitic sandstones with associated chert-rich horizons (two distinct pelitic/siliceous-bearing horizons; Fig. 3). These members were only defined in the Kroumirie Mountains (Fig. 3). The chert-rich horizons are called silixites, which in the Numidian Formation are understood as very

fine-grained, massive or someplace layered siliceous sedimentary rocks. Silica is of volcanic, biochemical or chemical origin, but its origin is still a subject of debate. Some silicified bedded marls also are termed silixites.

However, there are several problems with this earlier scheme. Firstly, the Zouza and Kroumirie members were shown by recent stratigraphic dating to be approximately coeval. Moreover, the Kroumirie Member was proposed as a more proximal equivalent of the Zouza Member (Torricelli and Biffi, 2001; Riahi *et al.*, 2007, 2010). According to Rouvier (1977), one of the most distinctive features of the Kroumirie Member is its richness in sandstones in comparison to the Zouza Member. This is not evident when the Numidian Formation of the Ben Metir area and those of the Zouza, Sejnene and Cap-Serrat areas are compared, as in all of these areas the Numidian Formation is mud-rich.

Secondly, the so-called “Zouza Member”, classically considered as being equivalent to the “Infra-Numidian Clay with *Tubotomaculum*”, displays a much greater thickness (1,500–2,000 m) in northern Tunisia than its apparent equi-

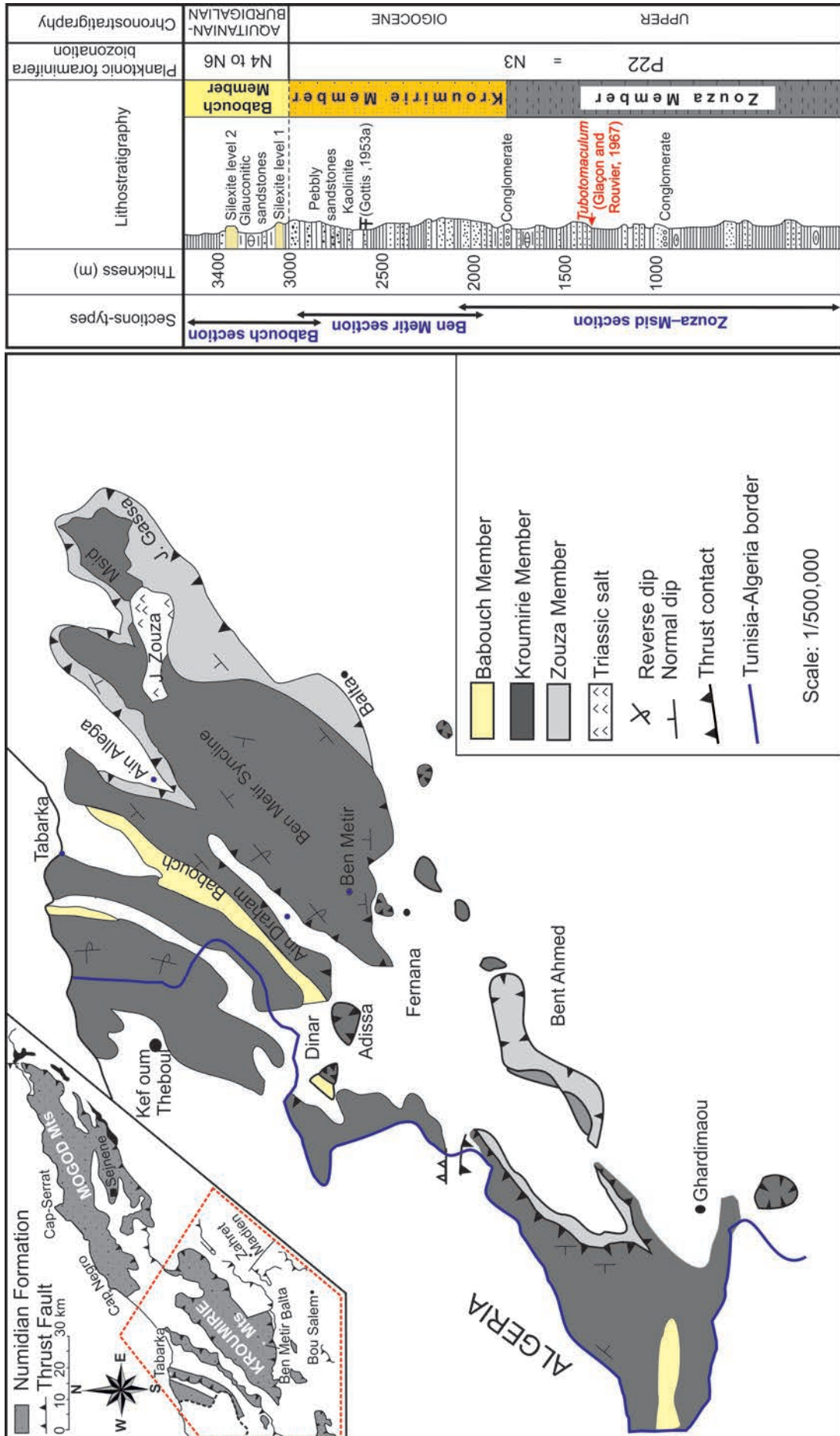


Fig. 3. Lithostratigraphic succession and spatial distribution of members of the Numidian Formation, according to Glaçon and Rouvier (1967).

Table 1

Location of sections studied, stratigraphic divisions, their age and thickness

Locality	GPS coordinates	Members according to Rouvier (1977)	Age according to Rouvier (1977)	Thickness
Tebaba	N36°53'7.43"; E9°5'30.62" N36°53'29.23"; E9°2'54.51"	Zouza	Upper Oligocene	1800 m
Oued Jabeur	N36°48'48.30"; E8°56'53.88" N36°49'1.85"; E8°56'39.00"	Zouza	Upper Oligocene	700 m
Oued Guastel	N36°47'38.14"; E8°55'32.10" N36°47'45.10"; E8°54'24.33"	Zouza	Upper Oligocene	1500 m
Meloula-Needles	N36°57'43.51"; E8°42'52.29" N36°57'33.96"; E8°45'15.99"	Kroumirie	Upper Oligocene	2100 m
Sejnene	N37°5'29.77"; E9°25'25.80" N37°5'26.13"; E 9°20'1.14"	Not defined		2300 m
Cap-Serrat	N37°14'20.28"; E9°12'53.22" N37°13'14.11"; E9°13'24.29"	Not defined		1450 m
Jebel Gattous-Zoukar	N37°17'19.21"; E9°39'9.95" N37°18'2.71"; E9°37'36.91"	Not defined		1400 m

valent in Algeria (e.g., 200 m thick in the Douar Khorfan section; Raoult, 1974). In order to explain the cause of the additional thickness of the Zouza Member at its type locality, Hoyez (1989) suggested that this resulted from deposition as a separate mud-rich fan, situated to the west of the main deep-sea fan system, inferred for the remaining part of the Numidian Formation succession. According to the same author, interference between the two fans explains the accumulation of such additional thickness of mudstones as well as the generation of the more sand-rich upper part of the Zouza Member.

Thirdly, there is no section in northern Tunisia, where the three members *sensu* Rouvier (1977) are actually superimposed along the same vertical section. Instead, a tectonic contact was generally interpreted by Rouvier (1977) to explain the absence of one of the members (e.g., in the Tabarka area and on the northern side of Ben Metir). This latter fact is evident on the geologic map of the Tabarka area (Rouvier, 1992), where only a few metres of the Zouza Member were mapped along the length of the N–S-oriented Meloula morphological corridor, while the remaining part of the succession is considered to be the Kroumirie Member (1: 50,000 geological map of Tabarka). However, a closer inspection of the nature of the contact between the Numidian Formation and the underlying strata in the field (in Tabarka) does not give any evidence of such truncation.

Belayouni *et al.* (2012, 2013) reviewed the stratigraphy of the Numidian Formation on the basis of 9 sections, of which only two yielded a diagnostic microfauna (Cap-Serrat and Zahret Madien). An earlier age (late Aquitanian p.p. – early Burdigalian p.p.) was proposed for this formation. In their scheme, the Zouza and Kroumirie members were considered to be late Aquitanian–early Burdigalian. Furthermore, these authors stressed the transitional character of the underlying Late Eocene Souar Formation and the overlying Numidian Formation in the Zahret Madien area and distinguished a “pre-Numidian Intermediate Interval” of Oligocene–Early Miocene age, terminating upwards with a glau-

conitic interval of Aquitanian age, on which rests the Numidian Formation (Belayouni *et al.*, 2013, fig. 6).

All these stratigraphic schemes of the Numidian Formation have a direct impact on the assessment of its exact thickness. This in turn has a direct impact on related seismic interpretations and petroleum exploration in northern Tunisia. The extremely variable thickness of the Zouza Member (in Rouvier, (1977) scheme) did not permit easy evaluation. A rough estimate advanced by Rouvier (1977) and Carr and Miller (1979) envisages a thickness of 3,500–4,000 m.

The present study was conducted in the Kroumirie and Mogod mountains in northern Tunisia and represents a complete overview of the stratigraphy of the Numidian Formation. It responds to some unresolved questions through new data collected from different areas (seven sections), integrated with previous biostratigraphic data already presented in detail by Riahi *et al.* (2010, 2014) and Riahi (2011). A comparison between the coastal Numidian Formation succession (e.g., Meloula-Needles, Cap-Serrat and Ras El Korane sections) and that of the main thrust front (e.g., Zouza, Sejnene, Jebel Sebaâ and Jebel Gattous-Zoukar areas) is now well established. The identification of new stratigraphic markers was useful for clarifying the internal organisation of the Numidian Formation.

Additionally, on the basis of this work, a stratigraphic update is proposed for the Numidian Formation in northern Tunisia that refines the earlier one presented in Riahi *et al.*, 2010 and a new assessment of its thickness. The mapping of part of the Oued Sejnene area and its calibration with seismic re-interpretation allowed the characterisation of the main structural features of the Numidian structural unit. The seismic line traverses the entire exposed Numidian Formation in the Mogod Mountains, from Cap-Serrat to the Bazina Triassic outcrops. In the absence of deep wells, seismic interpretation is based on outcrops and a regional structural cross-section, in which the structural elements and the general dip are accurately characterised.

Table 2

Facies of the Numidian Formation

Facies class	Facies associations
A: conglomerates	F1. Disorganised pebbly sandstone and shale clast conglomerate F2. Stratified pebbly sandstone F3. Normally graded pebbly sandstone F4. Inversely graded pebbly sandstone F5. Graded-stratified pebbly sandstone F6. Stratified conglomerate
B: massive sandstones	F7. Structureless thick to very thick-bedded sandstone F8. Thick- to very thick-bedded sandstone with water-escape structures F9. Thick to very thick-bedded sandstone with minor structures/grading
C: structured sandstones	F10. Very thick-bedded graded sandstone F11. Thick-bedded graded sandstone F12. Medium to thin-bedded graded sandstone F13. Stratified sandstone/pebbly sandstone
D: mudstone-siltstone (20–90% of mudstone)	F14. Thin-bedded mudstone-siltstone (silt>mud) F15. Thin-bedded mudstone-siltstone (mud>silt)
E: mudstone (> 90% of mudstone)	F16. Mudstone with graded silt-laminated layers F17. Bioturbated mudstone/calcareous mudstone
F: chaotica	F18. Slide-slump deposits F19. Sandy debrites F20. Muddy debrites F21. Injectite sandstone

METHODS

The study area is situated in northern Tunisia. It comprises different outcrops of the Numidian Formation in the Kroumirie and Mogod mountains (Table 1; Fig. 2). A series of sections of this formation were logged on a bed-by-bed scale, including, from west to east the Ben Metir, Bougoutrane-Balta, Oued Guastel, Oued Jabeur, Gassa-Msid, Tebaba, Sejnene, Jebel Sebaâ, Jebel Gattous-Zoukar and Ras El Korane sections (Fig. 2). In addition, three sections were logged along the coast and these include the Meloula-Needles; Cap-Serrat and Ras El Korane sections (Fig. 2). These sections form the basis of the present stratigraphic interpretations and were further used for studying the structural position of the Numidian Formation. Over 123 samples were collected systematically from both the mudstone-rich units and isolated mudstone beds, associated with sandstone units of the Numidian Formation. All of the samples were processed for biostratigraphic study. Parts of the mudstone-rich succession contain abundant planktonic foraminifera, but the mudstones that are more closely associated with sandstone facies typically contain none or very few. Care was taken to look for older, reworked species, eroded and re-deposited in the turbidites. In many samples, there were significant numbers of benthic foraminifera, and in particular deep-sea agglutinated forms. Taking into account the stratigraphic variation in the occurrence of some planktonic species as a result of palaeogeographical distribution, the authors have compared their results with the studies carried out in the Mediterranean region by Bizon and Bizon (1972),

Ben Ismail-Latrache and Bobier (1984), Bolli *et al.* (1985) and Berggren and Person (2005). Detailed mapping and new sampling was undertaken in the Mogod Mountains for palynological investigations and structural geology interpretation.

RESULTS**Facies****Classic Numidian Formation facies**

The vertical succession of the Numidian Formation in different sections (e.g., Meloula-Needles, Cap-Serrat, Ras El Korane, Tebaba, Sejnene, Jebel Sebaâ and Jebel Gattous-Zoukar sections) is made up of sandstone units, separated by mudstone intervals with thinner-bedded sandstones and slump-slide packages. Some sandstone units (e.g., the base of the Meloula-Tabarka, Cap-Serrat and Jebel Gattous-Zoukar sections) form a belt of lens-shaped sandstone bodies, up to 4 km wide and 4–30 m thick. The sandstone bodies are formed by composite sequences of thick and very thick sandstone beds (on average 1–9 m) that have amalgamated with little evidence of intervening mudstone horizons. These facies have been described in several works (Parize and Beaudoin, 1988; El Maherssi, 1992; Yaïch, 1997; Fildes *et al.*, 2010; Riahi, 2011).

On the basis of grain size, sedimentary structures, bed thickness and depositional features, twenty-one distinct sediment facies were recognised in the Numidian Formation (Table 2). The facies and facies associations identified can be grouped into six major facies classes including: conglomerates, massive sandstones and/or “ungraded sandstones”, structured sandstones, mudstone and sandstone-siltstone couplets, mudstones, and chaotic facies.

Quantification of the various sediment facies observed in the Meloula-Needles section allowed classifying this succession as a “mud-to-sand-rich system” *sensu* Richards and Bowman (1998), as the overall sand content is less than 30% and the associated sand/shale ratio is approximately 1:2 to 1:3, whereas the Numidian Formation succession of the Cap-Serrat, Sejnene and Zouza areas represent a “mud-rich system”. In terms of architectural elements, the Numidian Formation of northern Tunisia constitutes an excellent record of submarine-channel complexes and locally unchannelized bodies (Riahi *et al.*, 2014). Internally, the main sandstone bodies are more conglomeratic in the NE part of the Mogod Mountains (Ras El Korane and Jebel Zoukar sections; Fig. 2), while ungraded, fine- and fine- to medium-grained massive sands tend to be prominent in the Tabarka and Cap-Serrat sections and to a lesser extent in the Zouza and Sejnene areas.

Numidian Formation facies markers

Facies mapping undertaken in the Mogod domain allowed identification and characterisation of the key sedimentary features and distinctive facies markers which are easily recognizable from the Sejnene area to the Bizerte area (Soussi *et al.*, 2012). These facies are considered to be good markers and were used for better definition of the internal organisation of the Numidian succession as well as for re-

gional correlation. They are described and presented in detail for the first time in the present work.

Conglomerates with reworked glauconite and shelf macrofauna

It is dominated by high proportion of pebbles (pebbles 50%) and varying amounts of mud in the matrix, commonly made up of finer quartzose pebbles and coarse sand. It contains also silexites of variable colour (white, black, grey) and limestone fragments of Ypresian age with redeposited shells that are in some cases undeterminable (Fig. 4).

This facies was encountered in Tabarka, Sejnene (Jebel Ajout, Ras El Ali and Jebel Margued Essid) and Bizerte (Jebel Sebaâ, Ras El Korane and Jebel Gran). In some cases, pectinid bivalves co-occur with glauconite and clays that form the background sediment of shale clasts (Ras El Ali). This attests to their erosion from an uplifted domain and their reworking and resedimentation in the sedimentary basin.

Conglomerates with reworked Telliian material

Within these conglomerates, the clasts are commonly poorly sorted and with sub-rounded to rounded forms dominant, and the pebbles are centimetres in size, in some places exceeding 7 cm in diameter. This facies also contains various resedimented white, black and grey silexite fragments (Fig. 5) and blocks to boulders of Ypresian limestones (Fig. 5). This marker facies is encountered in Jebel Gattous-Zoukar, Ras El Korane, Jebel Sebaâ, Jebel Ajout and in the Zouza areas.

It is noteworthy that the stratigraphic relationship between these two distinct facies is not yet well established, although both are of Early Miocene age (see below).

Glauconitic fine grained sandstones

Fine- to medium-grained glauconitic sandstone deposits were encountered in the Sejnene area and appear to be *in-situ* deposits. They extend from Jebel Hamra to Kef Ghlem more eastward (Fig. 8). In some cases, the entire level contains more than 90% of glauconite, e.g., in the Zahret Madien area (Oued Jabeur section) and at Zouza and Jebel Sebaâ (Fig. 5).

Biostratigraphy

Kroumirie Mountains

A series of sections was logged on a bed-by-bed scale in the Kroumirie Mountains, including the outcrops at Ben Metir, Bougoutrane-Balta, Oued Guastel, Oued Jabeur, Gassa-Msid, Tebaba and in the Meloula-Tabarka area. The main biostratigraphic results of these sections were published in Riahi *et al.* (2010) and were used for stratigraphic correlations. Only the biostratigraphic investigation of the Meloula-Needles section is presented here.

Tabarka: Meloula-Needles section

The Numidian Formation outcropping in the Meloula-Tabarka area is well exposed on both sides of the Meloula Tectonic Window (Fig. 2) and comprises a more than 2,000-m-thick succession of alternating turbiditic sandstones and mudstones. The section strikes approximately N–S, and the beds are overturned to highly dipping throughout.

Clays of the lowermost part of the section represent the typical characteristics of the so-called “infra-Numidian Member and/or argile à *Tubotomaculum*”.

Twenty-eight samples labelled TBK were collected from Meloula-Needles section at muddy intervals. Nine samples were collected from the lowermost part and eleven samples from the upper part of the section (Fig. 6). The middle part (interval: 800–1,000 m) of the section did not allow easy sampling, owing to rock falls and disturbance by tectonic (faulting and small scale folding) and only eight samples were collected.

The Numidian Formation at Meloula rests on the Upper Eocene, which was readily identified on the basis of the common occurrence of planktonic foraminifera in sample TBK1 (Fig. 7), including *Globigerina praebulloides praebulloides*, *G. praebulloides leroy*, *G. yaguaensis*, *G. venezuelana*, *G. cryptomphala*, *G. eocena*, *Turborotalia cerroazulensis-cerroazulensis*, *Catapsydrax dissimilis*, *Turborotalia cocaensis*, *Turborotalia cunialensis* and *Pseudohastigerina micra* (P19 Zone of Blow, 1969).

Samples TBK3 and TBK4, collected from the brownish to grey mudstones, yielded abundant planktonic foraminifera (Fig. 7), represented by *Globigerina ampliapertura* with frequent to abundant species of *G. venezuelana*, *G. tripartita*, *G. euapertura*, *G. praebulloides praebulloides*, *G. tapuriensis*, *G. sellii*, *Turborotalia increbescens*, *Paragloborotalia opima nana* and *Catapsydrax dissimilis*. These species and subspecies correspond to the *Globigerina ampliapertura* Zone (P20 Zone of Blow, 1969) of the Early Oligocene (upper Rupelian). Therefore, the first zone of the Oligocene is missing at the base of the Meloula-Needles section, indicating an unconformity or stratigraphic hiatus across the Eocene–Oligocene boundary and/or a detachment level that is situated below the Ypresian limestone, belonging to the Ain Draham Unit.

Sample TBK5 yielded the same microfauna already identified in samples TBK3 and TBK4. Samples TBK6 and TBK7 were rich in deep-water agglutinated foraminifera (DWAF) and no planktonic foraminifera were recorded.

Samples TBK8 and TBK9 were characterised by the presence of *Paragloborotalia opima opima* and the absence of *Globigerina ampliapertura*, a species that became extinct at the top of the *Globigerina ampliapertura* Zone; both these were useful for the identification of this zone. Other species such as *Paragloborotalia opima nana*, *Globigerina praebulloides*, *G. tripartita*, *G. euapertura*, *Catapsydrax dissimilis*, *Catapsydrax unicavus* and *Globigerina ciperoensis angustumbilicata* were also present. Their occurrence may be correlated with the *Paragloborotalia opima-opima* Zone (N2 Zone of Blow, 1969).

Sample 10 contained only DWAF, whereas TBK11 yielded abundant planktonic foraminifera, including *Globigerina ampliapertura*, *G. tripartita*, *G. tapuriensis*, *G. venezuelana*, *G. praebulloides*, *Catapsydrax dissimilis*, *Catapsydrax unicavus* and *Paragloborotalia opima nana*. This assemblage was assigned to an Early Oligocene age (Rupelian; P19/P20 Zone of Blow, 1969). Samples TBK12 and TBK13 contained the same foraminifers encountered in samples TBK10 and TBK11 and consequently they are of the same age.



Fig. 4. Facies markers of the Numidian Formation. **A** Numidian Formation conglomeratic facies containing glauconitic shale clasts (the arrows indicate their position within sandstones beds). The shale clasts encompass a pectinid, which indicates that the eroded strata were originally glauconitic with pectens. **B.** Coarse-grained Numidian sandstones encompassing reworked benthic shells at Jebel Sebaâ. **C.** Close view of benthic shells recorded in the Numidian strata. **D.** Cast of a shell encountered at El Harka dam (Sejnene area). **E.** Glauconitic conglomerates including pectinid bivalve (just to the south of Jebel el Garn) showed in F. **G.** Cast of pectinid bivalve encountered in Jebel Ajout (in Sejnene area).

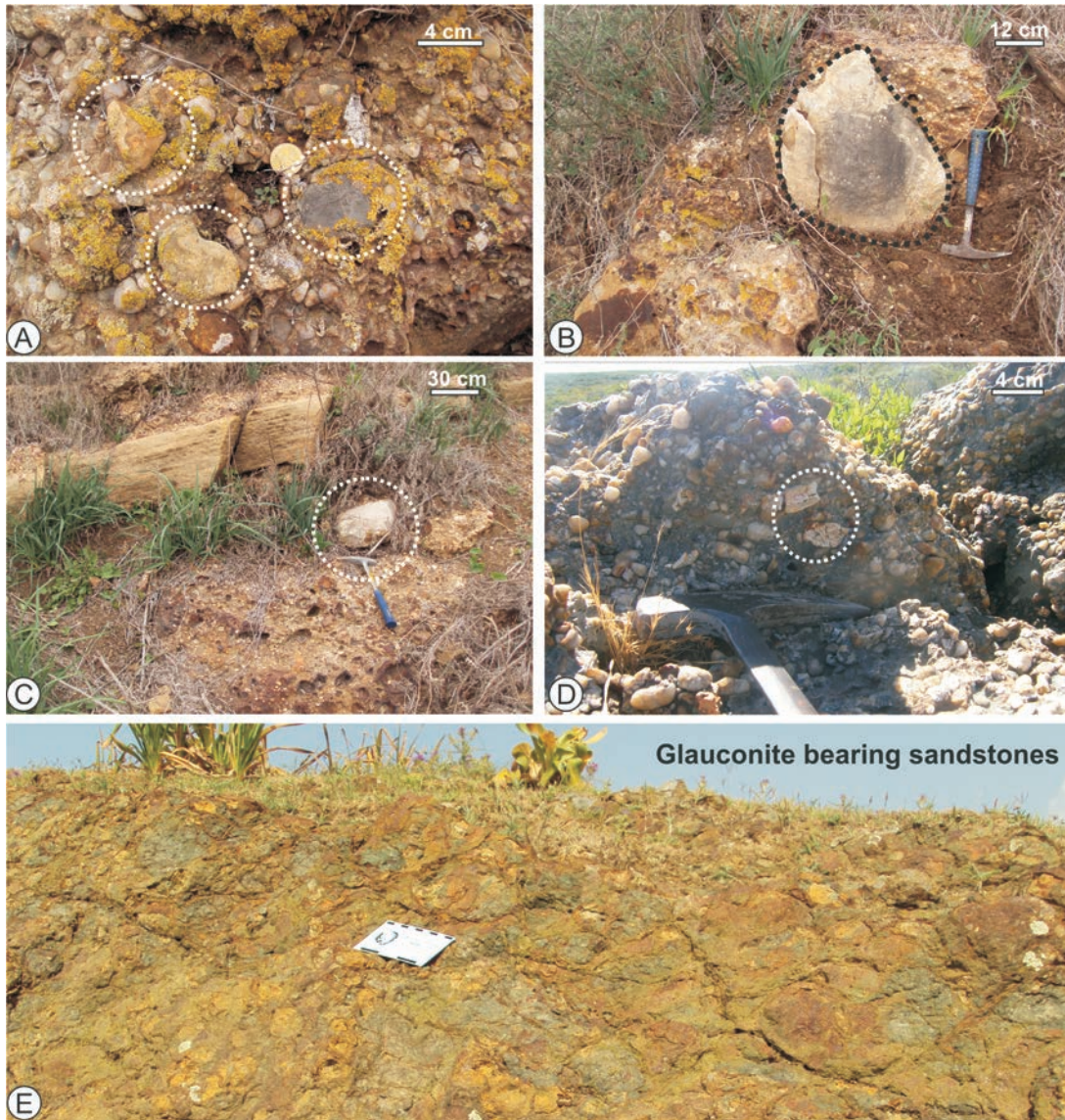


Fig. 5. Examples of resedimented Tellian facies within the conglomeratic facies of the Numidian sandstones. **A.** Grey blocks of early Eocene (Ypresian) resedimented within the Numidian pebbly facies (Jebel Sebaâ locality). **B, C,** and **D** illustrate resedimented boulders of Lower Eocene age within the Numidian sequence. **E.** Glauconitic interval within the Numidian Formation in Oued Jabeur locality (Kroumirie Mountains).

Samples TBK15 and TBK16 contained an assemblage characteristic of the Upper Eocene, including *Globigerina praebulloides praebulloides*, *G. venezuelana*, *Turborotalia cerroazulensis-cerroazulensis*, *Catapsydrax dissimilis*, *Turborotalia cocaensis*, *Turborotalia cunialensis* and *Pseudohastigerina micra*. This assemblage allowed envisaging a thrust fault along Oued Larmel (Figs 7–10) and the emer-

gence of the Upper Eocene, which has the same lithological characteristics as those at the base of the succession near Meloula area.

Samples TBK17 and TBK18 showed a fauna characteristic of the Lower Oligocene represented by *Globigerina ampliapertura*, *Catapsydrax unicavus*, *Catapsydrax dissimilis* (P20 Zone of Blow, 1969).

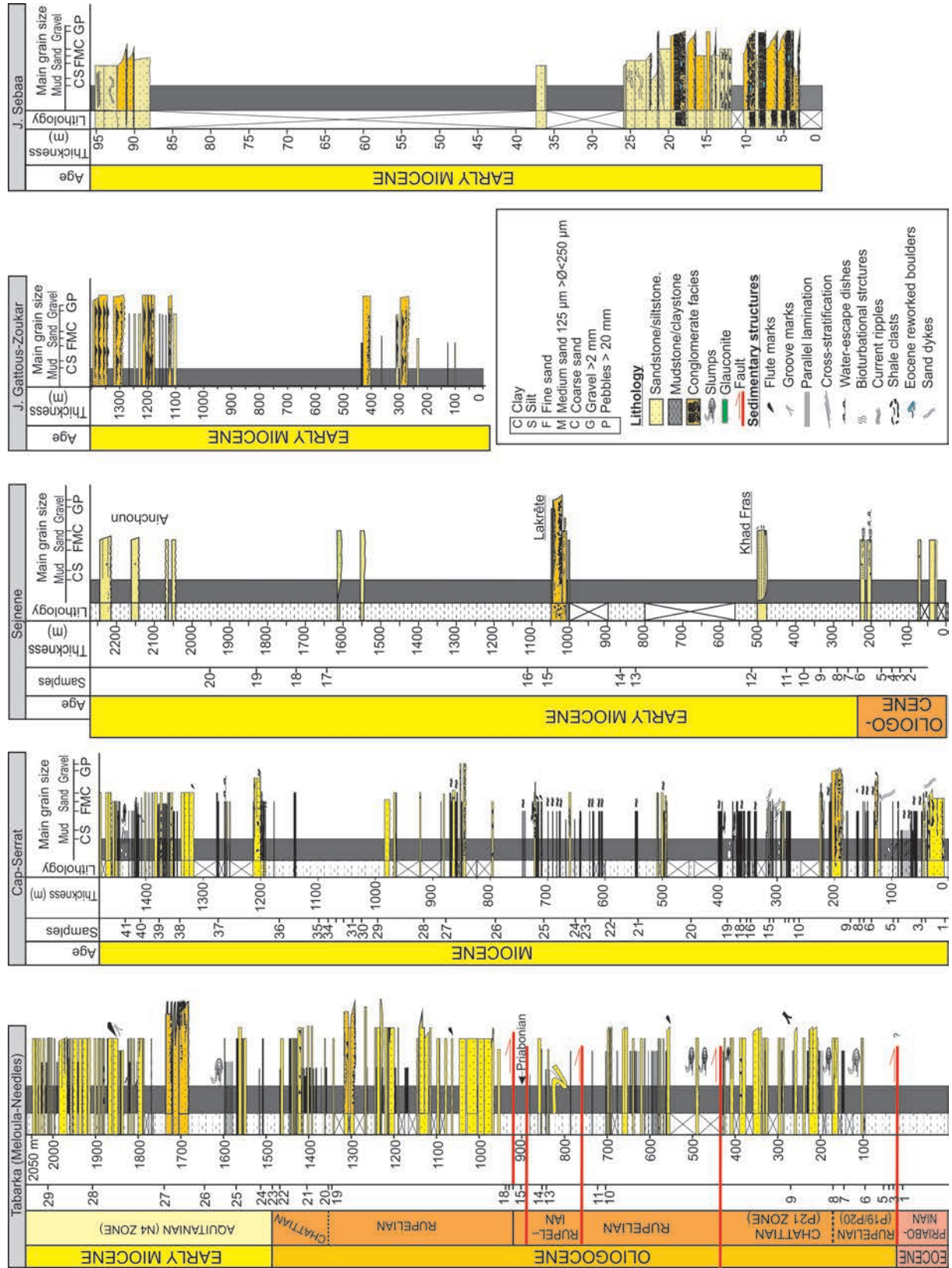


Fig. 6. Sedimentary logs through the Numidian Formation of the Meloula-Needles, Cap-Serrat, Sejnene, Jebel Zoukar and Jebel Sebaa sections. The sample locations are shown on the logs.

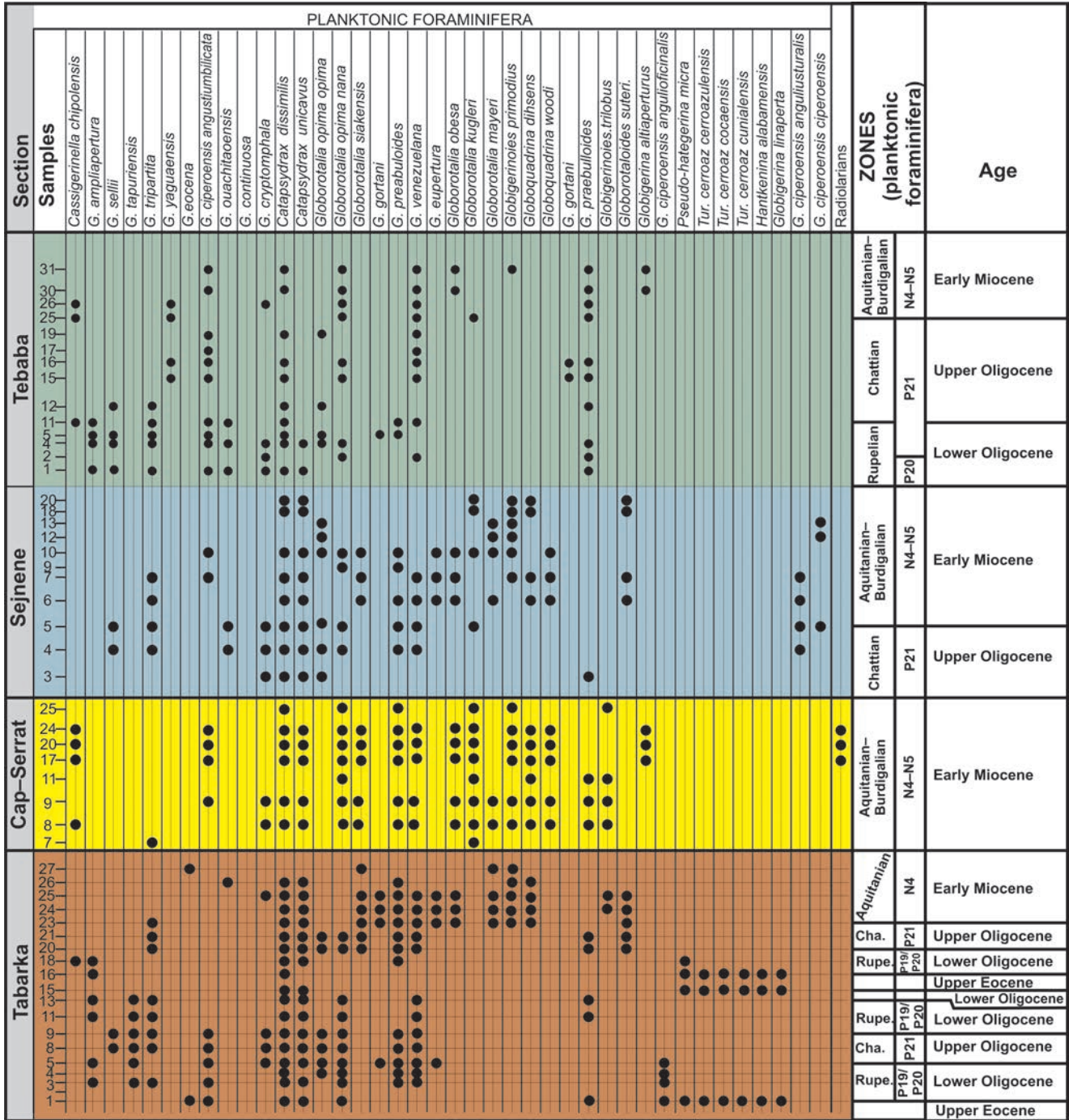


Fig. 7. Planktonic foraminifera identified in different sections studied and age assignment of each section

The planktonic foraminifera encountered in samples TBK20 and TBK21 were dominated by *Paragloborotalia opima opima*, *Paragloborotalia mayeri-Paragloborotalia siakensis*, *Paragloborotalia opima nana*, *Globorotaloides suteri*, *Globigerina praebulloides*, *G. venezuelana*, *G. tripartita*, *Catapsydrax dissimilis* and *Catapsydrax unicavus*. The occurrence of *Paragloborotalia opima opima* and *Paragloborotalia mayeri-Paragloborotalia siakensis* is characteristic of the Upper Oligocene.

Samples TBK23–26 were dominated by *Paragloborotalia mayeri-Paragloborotalia siakensis*, *Paragloborotalia kugleri*, *Globigerinoides primordius*, *Globigerinoides trilobus*, *Globoquadrina dehiscens*, *Globigerina praebulloides*, *G. venezuelana*, *G. tripartita* *Globorotaloides suteri*, *Globigerinoides primordius* is characteristic of an Early Miocene age (N4 Zone of Blow, 1969). Higher in the suc-

cession, sample TBK27 was dominated by *Paragloborotalia mayeri*, *Globigerinoides primordius*, *Catapsydrax dissimilis*, *Catapsydrax unicavus*, *Globigerina venezuelana* and *G. opima nana*. The occurrence of *Globigerinoides primordius* indicates an age no older than Early Miocene (N4 Zone of Blow, 1969). Sample TBK29, gathered from the top of the section, was barren.

Mogod Mountains

Numidian Formation of the Cap-Serrat area

The Cap-Serrat section is well exposed along the coast, on a peninsula located W-NW of the Sejnene area (Mogod Mountain). There the Numidian Formation is included in an apparently monoclinical structure with a general SE dip (50° to 75°) and forms a succession as much as 1,400 m thick, with its lowermost part covered by the sea and its upper part affected by a branch of the Ghardimou–Cap-Serrat Fault (Figs 2–6). In its uppermost part, some distinct pelitic/siliceous-bearing deposits outcrop locally north of Jebel Rhiran, close to Oued Ziatine (Fig. 14). The vertical succession has led to the recognition of three main lithologic units (Fig. 6), including from base to top: (1) a lower sandy unit (0–220 m); (2) a middle hemipelagic shale and thin-bedded turbidites with subordinate sand intervals (220–1180 m); and (3) upper thick-to amalgamated bedded sandstone units (1180–1400 m).

Historically, the Numidian succession in the Cap-Serrat area was the subject of several studies (El Maherssi, 1992; Yaïch, 1997; Torricelli and Biffi, 2001). El Maherssi (1992) assigned the lowermost part of the section to the Upper Oligocene and the upper part to the Oligocene–Lower Miocene, and outlined the impossibility of identifying the Oligocene – Early Miocene boundary. On the basis of palynological investigations, Torricelli and Biffi (2001) assigned the whole Numidian Formation outcropping at Cap-Serrat to the Lower Miocene (Aquitanian).

In the present work, 41 samples were collected at the Cap-Serrat section and examined for planktonic and benthic foraminifera. Most samples were barren and contained only benthic foraminifera. A few samples yielded various species and subspecies. Their occurrences at different levels of the logged section allowed dating of the entire Numidian succession in the Cap-Serrat area.

A biostratigraphic analysis of the lowermost part of the section was impossible, as this stretch of the section is completely submerged by the sea. Hence, samples CPS1–6 collected from the mudstone intervals ranging from 0–130 m, dominated by green to grey shales and thin-bedded turbidite packages, contained only DWF (Figs 6, 7).

Sample CPS7 (at 150 m) yielded few, but significant planktonic foraminifera, including *Globigerina tripartita* and *Paragloborotalia kugleri*. The occurrence of this latter species enabled the assignment of this part to the Lower Miocene (Aquitanian: N4 Zone of Blow, 1969).

Samples CPS8–9, collected from green to grey mudstone, were very rich in both planktonic and benthic foraminifera. The assemblage included *Paragloborotalia kugleri* (very frequent), *Globoquadrina dehiscens* (very frequent), *Globigerinoides primordius* (frequent), *Zeaglobigerina woodi*, *Paragloborotalia mayeri*, *Globigerinoides trilobus*,

Globigerinella obesa, *Paragloborotalia siakensis*, *Globigerina continuosa*, *G. venezuelana*, *Catapsydrax dissimilis* and *Catapsydrax unicavus*. The common occurrence of *Paragloborotalia kugleri*, *Globoquadrina dehiscens* and *Globigerinoides primordius* is characteristic of an Early Miocene age (Aquitanian; N4 Zone of Blow, 1969). It is important to note that all these samples were rich in radiolarian fauna.

Samples CPS10–19 were rich in silt and contain rare planktonic foraminifera (samples CPS10 and CPS17), but they also yielded abundant agglutinated and calcareous benthic foraminifera, which have little stratigraphic significance. The planktonic foraminifera encountered in sample CPS11 included *Globigerina continuosa* and *Globigerina praebulloides*.

Samples CPS17 and CPS20 yielded diversified and well preserved species and subspecies of planktonic microfauna, represented by *Paragloborotalia kugleri* (very frequent), *Globoquadrina dehiscens* (very frequent), *Globigerinoides primordius* (frequent), *Zeaglobigerina woodi*, *Paragloborotalia mayeri*, *Globigerinoides trilobus*, *Globigerinella obesa*, *Paragloborotalia siakensis*, *Globigerina continuosa*, *G. venezuelana*, *Catapsydrax dissimilis* and *Catapsydrax unicavus*.

The common occurrence of *Paragloborotalia kugleri*, *Globoquadrina dehiscens* and *Globigerinoides primordius* is characteristic of an Early Miocene age (Aquitanian: N4 Zone of Blow, 1969). Seven samples were collected from the very thick mudstone interval in the upper part of the section. Most of them were barren and only sample CPS31 contained a few planktonic foraminifera, including *Catapsydrax dissimilis*, *Paragloborotalia kugleri*, *Globigerina venezuelana*, *Paragloborotalia continuosa* and *Globigerinoides primordius*. This assemblage was associated with ostracods and indicates an Early Miocene age (Aquitanian to Burdigalian: N4 to N5 zones of Blow, 1969). This dating, proposed in Riahi (2011), was confirmed by Belayouni *et al.* (2013).

The samples collected from the upper part of the section (CPS37–41) were barren of planktonic foraminifera and contained only benthic foraminifera, indicative of an upper-bathyal depositional setting.

On the basis of the present study, the authors noted the absence of the Oligocene; nevertheless, it is important to outline that the submerged part of the section may correspond to the Oligocene. Along the Cap-Serrat to Sejnene road and close to Oued Ziatine, the Babouchite facies outcrops and is made up of alternating, well laminated, white limestones, particularly rich in radiolarian and whitish mudstones.

Numidian Formation of the Sejnene area:

Boujrir-Ainchouna section

The Sejnene area forms the southern margin of the Mogod Mountains and represents the lateral extension of the Numidian Formation outcropping in the Zouza area (i.e., Tebaba and Gassa-Msid sections in Riahi *et al.*, 2010) and belonging to the southern margin of the Kroumirie Mountains (Fig. 2). In this area, the Numidian Formation consists of approximately 2200 m of alternating sandstone

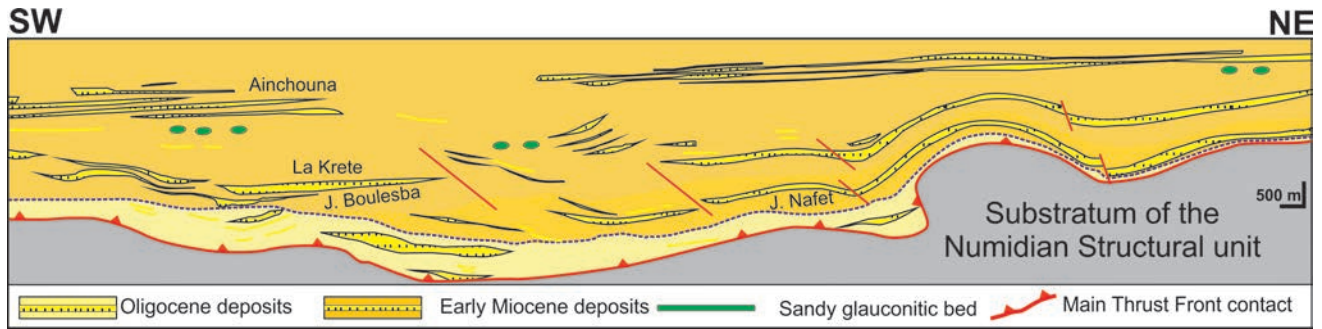


Fig. 8. Stratigraphic architecture of the Numidian Formation in the Sejnene area. The glauconitic interval is continuous from Jebel Ainchouna to Kef Ghlem eastward (modified after El Maherssi, 1992).

units (20–30 m) that protrude from the hillside and shale units (100–400 m). These are only exposed locally along wadis, owing to the vegetation cover (Fig. 6). Thick massive sandstone units show variable dip directions and the north-to-northwest-dipping strata are included in a NE–SW perched syncline at Ainchoun. The Numidian Formation outcropping in the Sejnene area can be considered as a well studied and the well dated representative section of the unit in northern Tunisia, because of detailed stratigraphic investigations (Maherssi, 1992; Yaïch, 1997), which succeeded in the differentiation of the Oligocene and Lower Miocene deposits as well as the recognition of major discontinuities. Field mapping and analysis of the geometry of the sandstone units allowed Yaïch (1997) to characterize them into two broad sedimentary units, with the first corresponding to the Oligocene (U1) and the second to the Early Miocene (U2: Aquitanian to Aquitanian–Burdigalian). In this scheme, the Oligocene unit was subdivided into two sub-units (U1.1 and U1.2), based on the geometrical relationship between the sandstone units of Dir Gsir and Jebel Boulesba (Fig. 8). Also, three distinctive sub-units were proposed (U2.1; U2.2 and U2.3) for the Lower Miocene of the Sejnene area. Sub-unit U2.3 was inferred to be Aquitanian and Aquitanian–Burdigalian, equivalent to the “Babouch Silexites”. The present study, confirms the assignment of the Numidian Formation of the Sejnene area to the Oligocene–Lower Miocene (Figs 5–8), as previously proposed by El Maherssi (1992) and Yaïch (1997). Nevertheless, unit U2.1 of Yaïch (1997) begins with the mudstone interval, just below the sand-rich unit of Jebel Lakrète (Fig. 8).

A glauconitic bed marker outcrops discontinuously and can be traced from Jebel Hamra to Kef Ghlem (Fig. 8). As well, it was noted that in the perched Jebel Msid Syncline (Zouza area) there is a total absence of the Babouch Member, which also is the case in the Sejnene area.

As a whole, the Numidian Formation outcrops in the Sejnene area show (Fig. 9) close similarities in age, organization, and lithological characteristics to that outcropping in the Zouza area.

Numidian Formation of Jebel Zoukar

The Numidian Formation tends to be well exposed in the easternmost part of the Mogod Mountains, where the succession is exceptionally well exposed at Jebel Zoukar (Fig. 2). Nevertheless, the succession is affected by wrench

faults with small offsets. The succession comprises thick shaly units at the base, followed vertically by a distinct unit forming a cliff and composed of a thick conglomeratic facies (Fig. 6). In this area the stratigraphy of the Numidian Formation has never been assessed. On the basis of a new palynologic investigation (Soussi *et al.*, 2012), the outcropping Numidian Formation can be assigned to the Lower Miocene (Aquitanian). Detailed mapping of the area indicates that the absence of the Oligocene portion, well identified in Sejnene area, is most likely related to the E–W fault separating the Kef Nsour series from those of Jebel Saidene.

Numidian Formation of Jebel Sebaâ

The Jebel Sebaâ section is located to the north of Bizerte town and south of the Numidian thrust front (Fig. 2). In this area, The Numidian deposits overlie the Souar Shales and are included in a synclinal structure with a gentle dip to the NW (Crampon, 1973; Melki, 1993). The succession has been considered to be fluvial in origin and accordingly representing the Fortuna Formation (Melki, 1997; Fildes *et al.*, 2010; Fig. 6). It begins with a clayey unit that passes upwards into two relatively thick sandstone units forming a cliff. The first unit is represented by fine to medium sandstones with extensive water-escape features. The second unit is composed of five conglomeratic beds passing upward into a metres-thick, cross-stratified sandstone bed. The uppermost part of the succession is made up of a medium to coarse sandstone bed showing subtle grading.

In this section, abundant reworked limestone boulders (Eocene of the Bou Dabbous Formation) associated with a shallow-marine macrofauna (well preserved shells), have been identified at several stratigraphic levels within the first unit (Fig. 5).

It is difficult to ascertain the age of this succession, owing to difficulty in sampling. Nevertheless, all the lithological characteristics are similar to the Early Miocene deposits of the Numidian Formation outcropping no so far away in Ras El Korane and Jebel Gattous-Zoukar. In addition, the presence of well preserved flute casts indicates the turbidite affinity of these deposits. Cross-stratification and flute casts indicate NE–SW-directed palaeocurrents.

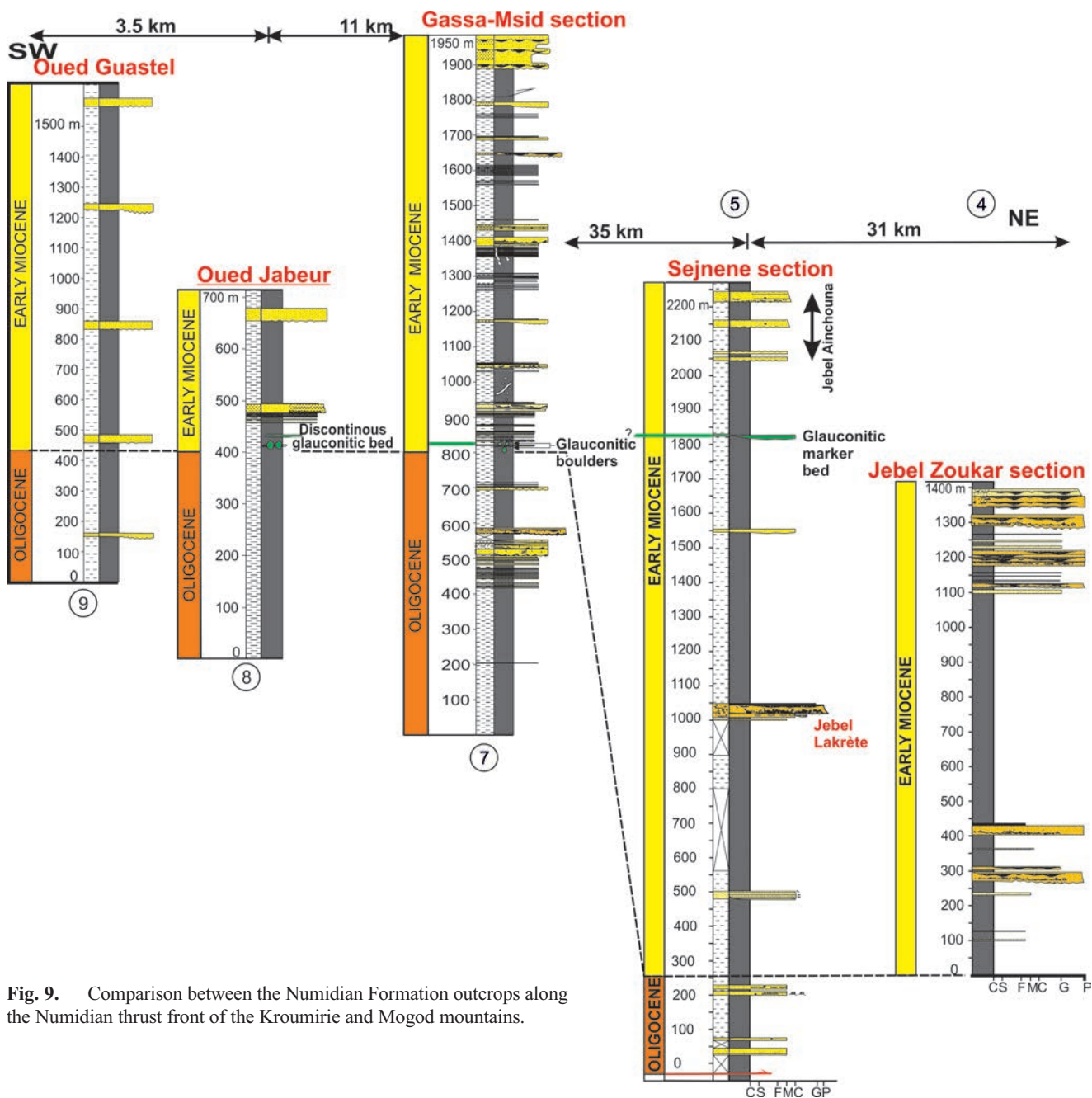


Fig. 9. Comparison between the Numidian Formation outcrops along the Numidian thrust front of the Kroumirie and Mogod mountains.

Lithostratigraphic Correlation between the Numidian Formation of the front of the Kroumirie and the Mogod mountains

Comparison and lithostratigraphic correlation of the Numidian Formation of the southern margins of the Kroumirie (Tebaba, Oued Jabeur and Gassa-Msid sections) and the Mogod mountains (Sejnene, Jebel Gattous-Zoukar and Jebel Sebaâ sections) in the present account show two sedimentary bed markers, which can be very useful in assessing the stratigraphic architecture, the lateral facies changes, and the regional lithostratigraphic correlation between the sections (Fig. 7). They include:

(1) a glauconitic sandy layer (Early Miocene age; Figs 8, 9). This layer was identified within the third shale unit in the Sejnene section (Figs 6–8), which could be interpreted

as a condensed section, developed during a major flooding event (Yaïch, 2000). In terms of age, this glauconitic interval is Early Miocene and can be regarded as *in-situ* deposits. Nevertheless, the glauconite interval recognised by Riahi (2004) and Belayouni *et al.* (2013) in the Oued Jabeur (Zahret Madien area) may be considered as reworked material, rather than *in-situ* deposits, marking the onset of Numidian Formation deposition, as interpreted by Belayouni *et al.* (2013). This interpretation is supported by the fact that the glauconitic interval of Zahret Madien (Oued Jabeur section) shows strong similarity to the glauconite of the autochthonous Oligocene–Miocene Bejaoua Group outcropping no so far away (e.g., Jebel Ben Amara and Jebel Hajra Touila; Boukhalfa *et al.*, 2015) and even to the north and south of Bizerte area, close to the “la baie des carrieres” section (Soussi *et al.*, 2012). The limited lateral extent (approx-

imately 500 m) and the intense deformation of this interval may indicate resedimentation within the Numidian Formation from an uplifted and eroded, shallow shelf, which is thought to have been situated southward of the Numidian basin during Miocene time. The presence of common reworked glauconitic boulders throughout the Miocene Numidian Formation deposits in Oued Jabeur and in the Oued Zouza, and also in the northeastern portion of the Numidian Formation in the Mogod domain (El Garn, Ras El Korane and Jebel Sebaâ sections) support this interpretation. The analysis of the evolution and maturity of glauconite between the two areas may bring accurate answers to this question. In addition, Belayouni *et al.* (2013) assigned the shaley unit situated just below the glauconitic horizon to the Pre-Numidian “Intermediate Interval” that has characteristics intermediate between those of the Souar Formation and the Numidian Formation. The detailed logging of this section clearly demonstrated that this interval encompasses laterally a sandstone interval, displaying ichnofacies and sedimentary features typical of a deep-marine setting (Riahi *et al.*, 2014). The trace fossils include *Chondrites*, *Planolites montanus*, *Selenichnites* sp., ?*Cochlichnus* sp., ?*Gyrochorte* sp., *Scolicia vertebralis* and, *Diplocraterion* cf. *habichi*. In addition, the grayish-greenish clays of this interval exhibit common *Chondrites* and *Planolites montanus* ichnofacies, which are very common in the Numidian clays (e.g., Cap-Serrat and Tabarka; in Riahi *et al.*, 2014, fig. 5G) rather than the Souar Formation. These observations strongly indicate that what is considered as an “intermediate interval” between the Souar and the Numidian formations in fact most likely corresponds to a sedimentary package belonging to the Numidian Formation.

(2) a thick conglomeratic horizon, delimiting the Ras El Ali sandstone unit and containing pebbly sandstones with frequent reworked carbonate material, derived from the Telliian facies, reworked macrofossils (pectinid bivalves), and glauconitic sandstone boulders, probably derived from a Miocene shallow-shelf setting (Fig. 5) that can be correlated with the Lakrète Sandy Unit, belonging to the Ainchoun Syncline. This conglomeratic facies marks a major change in the composition of the Numidian Formation, constituting strong evidence of intense erosion that can be correlated with a major intra-Miocene fall in sea level. This event is clearly evident in the northeastern part of the Mogod Mountains (Jebel Gattous-Jebel Zoukar, Ras El Korane and El Garn) and extends to Ras El Ali, Tabarka and Zouza areas.

In the Kroumirie and Mogod mountains, the Oligocene (upper Rupelian: P20 Zone of Blow, 1969; Fig. 9) was recognised in Meloula-Needles, Balta, Oued Jabeur, Zouza, Sejnene (Boujrir-Ainchouna section) and in Ras El Korane. This disagrees with the proposal of a late Aquitanian age for the Zouza Member by Belayouni *et al.* (2013).

Eastward of the Mogod Mountains (Jebel Gattous-Zoukar), the age of the Numidian Formation is Early Miocene. This age variation is interpreted by some authors as evidence of diachrony, which could be the result of an eastward younging of the beginning of Numidian Formation deposition, reported between Algeria and Sicily by Wezel (1973) and Belayouni *et al.* (2013). The structural organiza-

tion of northern Tunisia, based on detailed mapping (Rouvier, 1977; Carr and Miller, 1979; Riahi *et al.*, 2010), allowed interpreting the absence of the Oligocene part of the succession at some localities as being the result of a local phenomenon, produced by ramping of the decollement surface at the base of the Numidian Nappe to higher stratigraphic horizons in the more external portions of the thrust belt system (see below).

Numidian Formation of Meloula-Needles section versus Numidian Formation of the front of nappes

A comparison of the Numidian Formation outcrops of the Meloula-Needles section with those located along the main thrust front (e.g., Zouza, Sejnene and Jebel Gattous-Zoukar sections) has revealed interesting results that have direct implications for the understanding of the internal organisation of the Numidian Formation. The stratigraphy and the sedimentological characteristics of the Numidian succession of the thrust front (Ben Metir, Balta and Gassa-Msid sections) previously were studied in detail (see Riahi *et al.*, 2007, 2010) and here the authors use only the main results for comparison with the Numidian Formation of the Meloula-Needles section and the Cap-Serrat area. The main results are:

- the Numidian Formation of the Meloula-Needles section shows a close similarity in organisation to that of the Tebaba and Sejnene sections. Each of those sections is characterised by a basal Oligocene part of late Rupelian–early Chattian age, rich in mudstones and thin-bedded, fine-grained turbidites, and by a distinctive sandier succession, corresponding to the Early Miocene (Aquitanian; N4 Zone of Blow, 1969). Nevertheless, such enrichment in sandstones is clearly documented in the Tabarka section;

- the “*Tubotomaculum* level” was only recognised in the Meloula-Needles section and never observed it in the Sejnene and Zouza areas. Accordingly, the Numidian Formation outcrops confined to the Meloula Tectonic Window show the typical characteristics of what is referred to as the “infra-Numidian member”, recognised in Algeria;

- the upper part of the Numidian Formation (Early Miocene) shows an ichnoassemblage that includes *Diplocraterion* cf. *habichi*, *Scolicia vertebralis* and *Ophiomorpha* spp. and is interpreted as the shallower part of the *Ophiomorpha rudis* ichnosubfacies of the *Nereites* ichnofacies (Riahi *et al.*, 2014) This ichnofacies presumably indicates a higher energy level, environmental disturbance, and a shallowing upward through the Numidian sequence (Riahi *et al.*, 2014);

- the occurrence of the “*Tubotomaculum* level” near the basal part (approximately at the 200-m level) of the Meloula-Needles section was regarded as a correlation horizon in explaining the absence of the greater part of the Zouza Member in the Tabarka section by thrusting and tectonic deformation (Rouvier, 1977). Nevertheless, the same author mentioned that the *Tubotomaculum* level occurs at 1,500 m in the Tebaba section (Fig. 3). This difference in the occurrence of this level led Rouvier (1977) to suppose that all parts below 1,500 m in the Zouza area (Fig. 3) has been ablated by tangential tectonics.

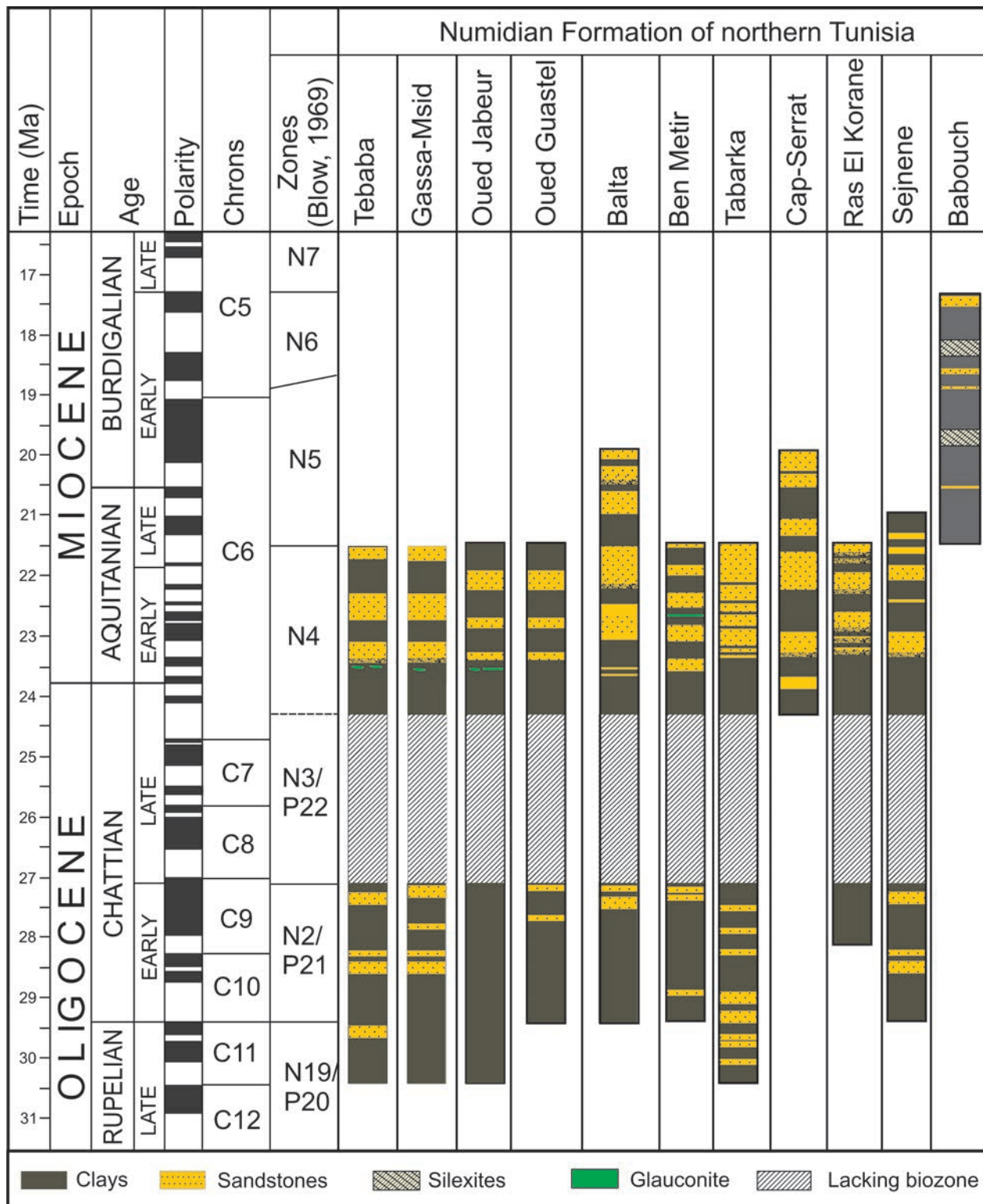


Fig. 10. Main biostratigraphic subdivisions of different sections investigated in the Numidian Formation of northern Tunisia.

On the basis of detailed logging of the sedimentary sequence and a special focus on ichnofacies types and their occurrence in the Meloula-Needles section, the “*Tubotomaculum* level” was recorded in the Lower Oligocene succession. The trace fossil considered to be “*Tubotomaculum*” in the Zouza member in Tebaba (Fig. 3) corresponds to

Diplocraterion habichi, and no *Tubotomaculum* was recognised at the thrust front. Therefore, it cannot be used as the correlation horizon between the coastal outcrops and those of the thrust front. Some additional features are as follows:

- the Numidian succession, forming the base of Meloula-Needles section, shows the typical characteristics of

what is defined as the “infra-Numidian Member” (Fig. 10), and this section is proposed as the type locality for the characteristics of the basal Member of the Numidian Formation;

- the glauconite occurs in different forms (resedimented boulders, disseminated within clays and a “continuous lateral level over some kilometres”). Hence, a continuous sandy, glauconitic level was mapped along the length of the Sejnene area (from Jebel Hamra to Kef Ghlem eastward). Also, it was recorded in the Oued Zouza and Zahret Madien areas (Figs 8, 9). In both areas, this level is dated as Early Miocene (Aquitanian). Nevertheless, the limited lateral extent and its occurrence as boulders in the Numidian Formation clays in the Zahret Madien and Zouza areas lead supposing the possibility of its resedimentation from the Oligocene–Miocene Bejaoua Group.

All these data taken together indicate that the Numidian Formation of the Tabarka area (representing the coastal outcrops) and the Numidian Formation of the thrust front have the same age and these results led to propose an alternative internal organization of the Numidian Formation, which is easily recognizable in different sections.

INTERNAL STRATIGRAPHIC ARCHITECTURE AND SUBDIVISION OF THE NUMIDIAN FORMATION

This paper is primarily a biostratigraphic review of the Numidian Formation outcrops fringing the coastline, i.e. the Tabarka and Cap-Serrat sections, and the nature of their relationship with the Numidian Formation outcrops of the thrust front, which had a great impact on the understanding of the relationships between its constituent members. The new biostratigraphic data show that each section (i.e., the Tebaba and Gassa-Msid sections (Zouza area), Sejnene, Meloula-Needles, Cap-Serrat and Jebel Gattous-Zoukar sections) embraces the complete Numidian Formation and all of them proved to be mostly Oligocene–Early Miocene in age (Fig. 10). In addition, according to the present biostratigraphic review of the members of the Numidian Formation at their type localities (Riahi *et al.*, 2010), it was demonstrated that the so-called Zouza Member and the Kroumirie Member have the same age, and each of these members in reality represents the complete Numidian Formation (Torricelli and Biffi, 2001; Riahi *et al.*, 2011). Therefore, the pinching-out of the called Zouza Member in the Meloula-Needles area and at other localities, such as Jebel Khroufa, cannot be attributed to only tectonic truncation as previously was proposed, but was mostly related to a lack of stratigraphic knowledge. Indeed, in the earlier works (Glaçon and Rouvier, 1967), the correlation between the Numidian Formation outcrops of the Meloula-Needles section (Tabarka area) and those of the thrust front was based on the presence of the *Tubotomaculum* level, rather than on solid biostratigraphic data and this was the basis for the inaccuracy. In the present study, the validity of such a correlation is clearly doubtful, because of the new age assessment. Moreover, as shown in Figures 7–10, all the Numidian Formation outcrops of these different localities are of Oligocene–Early Miocene age.

In the light of the age assessment and in order to facilitate further work on the Numidian Formation of northern Tunisia, a new subdivision appears to be required. This is a refinement of the work of Glaçon and Rouvier (1967) and the earlier scheme of Riahi *et al.* (2010) (Fig. 11). To avoid further complications in the literature with a new nomenclature, we prefer to keep the older names (i.e., Zouza and Kroumirie members), but their use in the new scheme is as follows (Fig. 11).

The Zouza Member is mainly Oligocene–Early Miocene p.p. (Rupelian– Chattian; P19–P21 zones) to Aquitanian (N4 Zone) and characterised by pelitic with subordinate sandstone bodies, whereas the Kroumirie Member is Aquitanian–early Burdigalian (N4–N5 zones) and is a sandy succession especially in the uppermost part. The Zouza Member terminates in the majority of the sections studied (e.g., Meloula-Needles, Sejnene, Jebel Zoukar and Cap-Serrat) with a thick shaly unit reaching the Early Miocene (N4 Zone).

In the new stratigraphic scheme, the Kroumirie Member starts both in the Kroumirie and the Mogod mountains with a sandstone unit forming a distinctive cliff. The latter is delimited at its lowermost part by an erosional base, considered in this work to be a major discontinuity, probably related to an important drop in sea level. This major discontinuity is marked locally by conglomerates with various reworked elements, consisting of glauconitic boulders and limestone fragments, derived from the Tellian domain (Figs 4, 5). The conglomeratic facies, with glauconitic boulders, shallow-shelf macrofauna or with reworked Tellian units, is present only in the Miocene part of the Numidian Formation.

Such a subdivision is applicable to the Numidian Formation in the Zouza, Meloula-Tabarka and Sejnene areas. The existence of the Oligocene in the Numidian Formation is evident at many localities, as in the Zouza (Glaçon and Rouvier, 1967; Torricelli and Biffi 2001; Riahi, 2011), Meloula-Needles (Riahi, 2011), Sejnene (Carr and Miller, 1979; Maherssi, 1992; Yaïch, 1997; Riahi, 2011) and Ras El Korane areas (Maherssi, 1992; Yaïch, 1997), which disagrees with the statement of Belayouni *et al.* (2013) about the absence of the Oligocene.

In the Babouch and Cap-Serrat areas, the Numidian Formation is capped by a siliceous, silicite-bearing horizon of Burdigalian age (N6–N7 zones) (Glaçon and Rouvier, 1967; Belayouni *et al.*, 2013). This subdivision is readily identifiable in all sections of the southern margin of the Kroumirie and Mogod mountains and those fringing the coastline.

In addition, there was a notable facies variation during the Early Miocene. Hence, the NE part of the Mogod Mountains (Ras El Korane, Jebel Sebaâ and Jebel Gattous-Zoukar section) is characterised by a highly conglomeratic facies, mostly related to its location near the source area (Fig. 6).

In the newly presented scheme, each part of the Numidian Formation displays an ichnoassemblage and sedimentological characteristics that are distinctive. The Oligocene Numidian Formation is characterized by diverse deep-water trace fossils of the *Nereites* ichnofacies (e.g., *Chondrites*, *Paleodictyon*, *Spirorhappe* and *Scolicia*); whereas the Lower Miocene Numidian Formation is characterized by common, obliquely inclined U-shaped dwelling tubes of

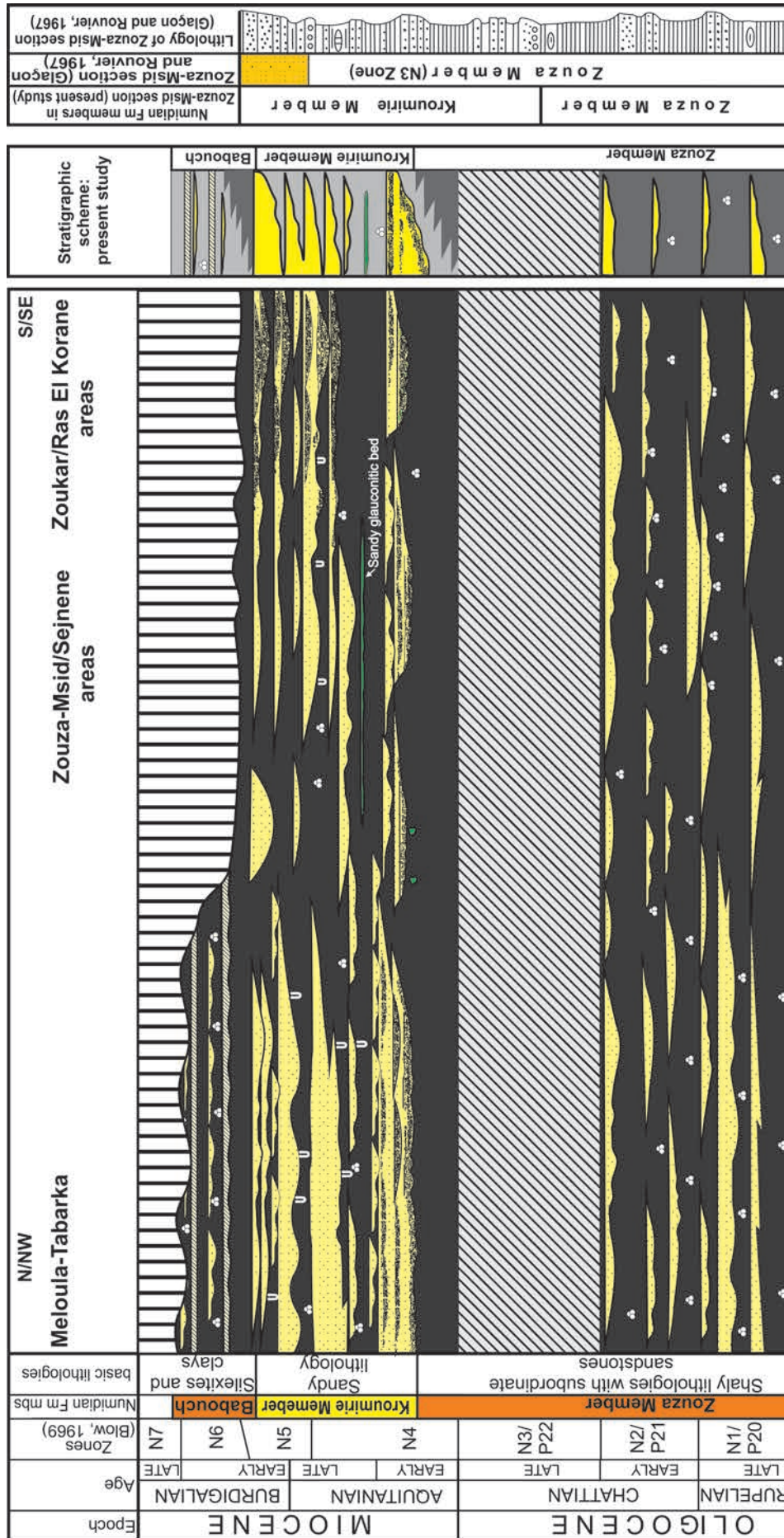


Fig. 11. Stratigraphic subdivision of the Numidian Formation, northern Tunisia. A shaly lower part of the Numidian Formation (Zouza Member; Oligocene–Early Miocene p.p. (Rupelian–Chattian; P19–P21 zones) to Aquitanian (N4–N5 zones) and a sandy upper part of the Numidian Formation (Kroumirie Member; early Miocene) for all the Numidian Formation outcrops. The stratigraphic attribution of the Babouch Member is based on Glagon and Rouvier (1967) and Belayouni *et al.* (2013).

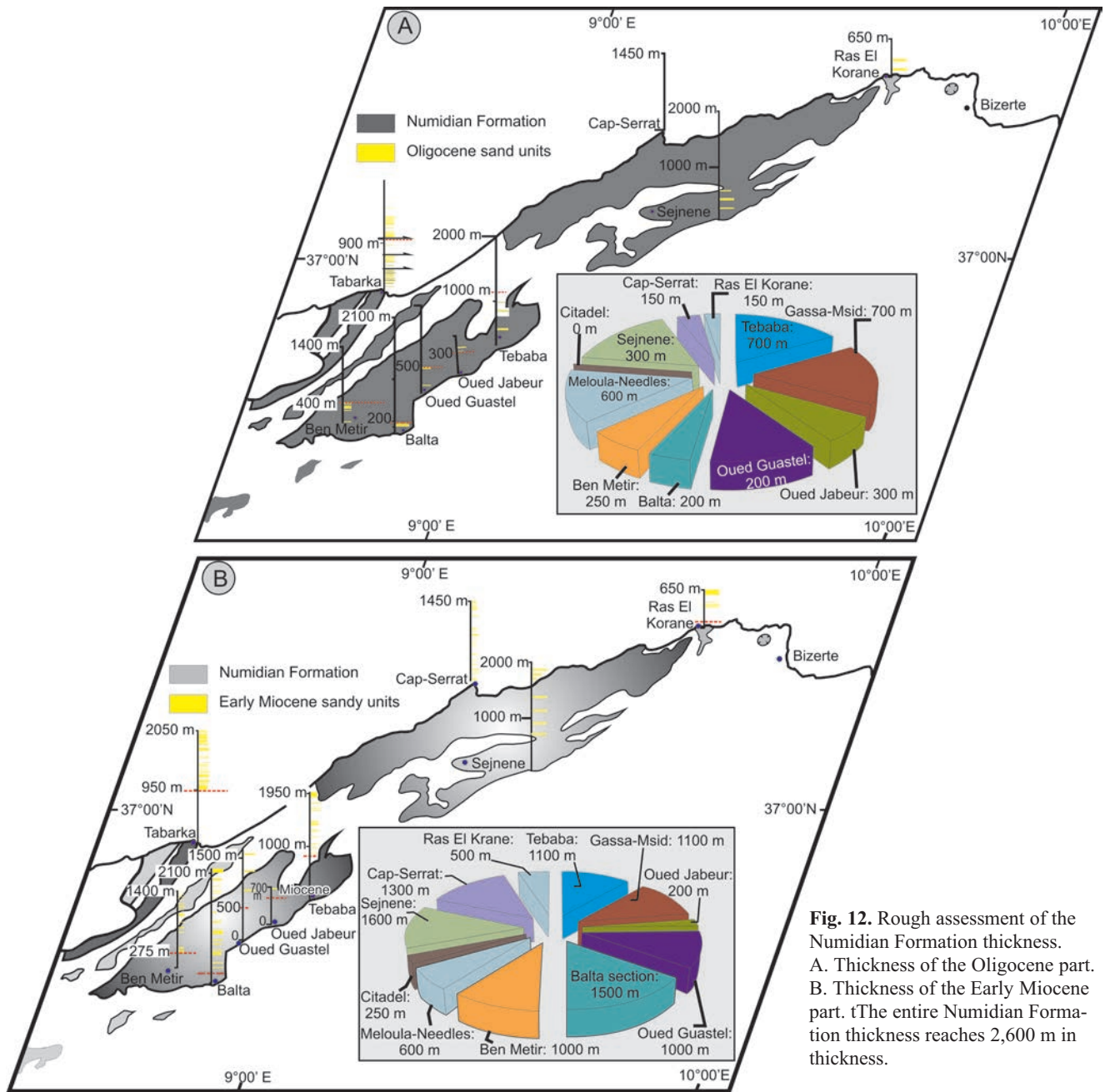


Fig. 12. Rough assessment of the Numidian Formation thickness. A. Thickness of the Oligocene part. B. Thickness of the Early Miocene part. The entire Numidian Formation thickness reaches 2,600 m in thickness.

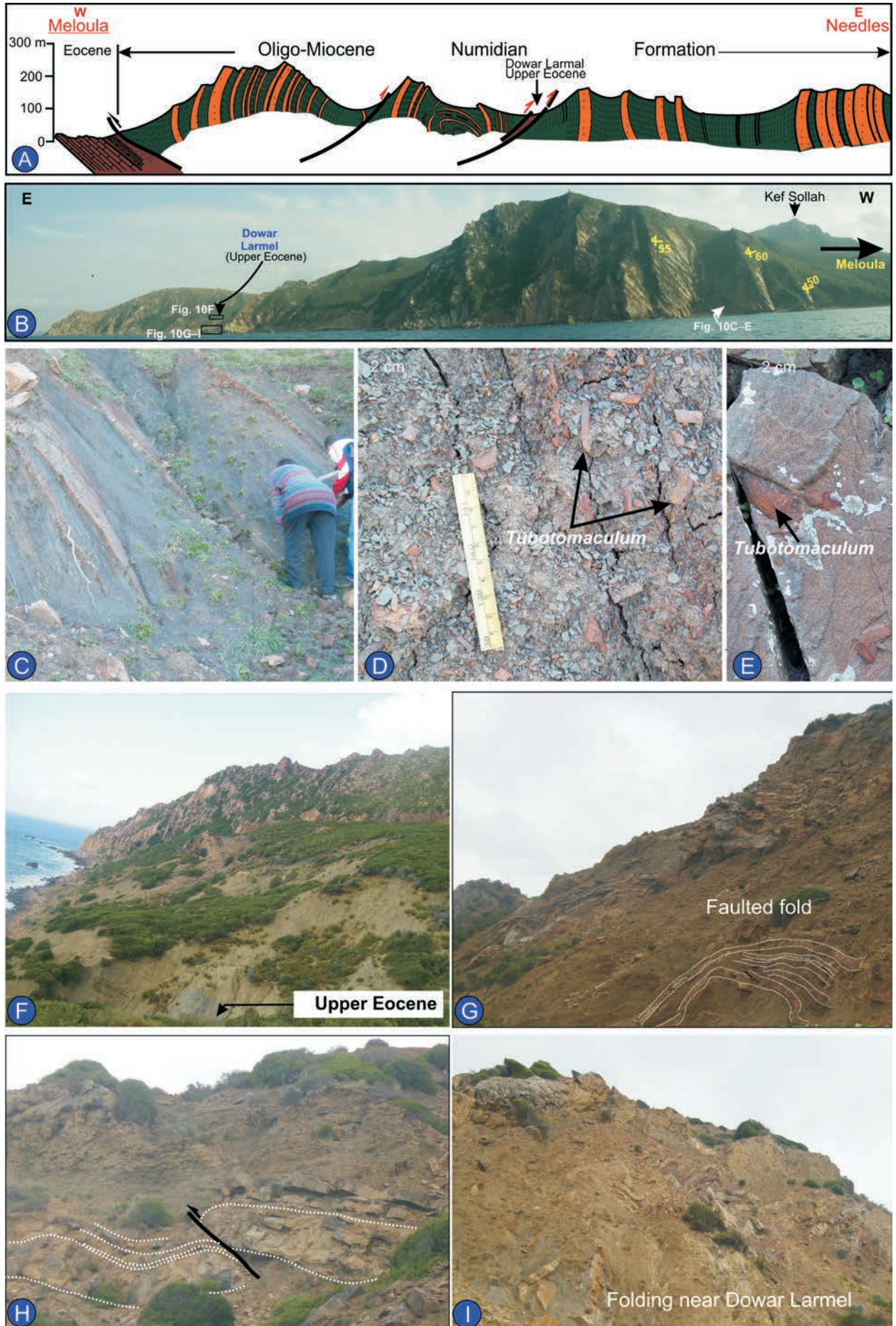
Diplocraterion cf. habichi, indicating a shallowing upward that coincides with the increased sand content (see Riahi *et al.*, 2014).

Finally and to avoid any confusion with the lithostratigraphic scheme of Glaçon and Rouvier (1967), it has to be stressed that the Zouza Member is considered in this work as a shaly unit, while the overlying sandier facies is present in the Kroumirie Member. Accordingly, the Zouza Member (defined at Jebel Zouza) *sensu* Glaçon and Rouvier (1967) makes up the entire Numidian Formation.

NUMIDIAN FORMATION THICKNESS

An estimate of the total stratigraphic thickness of the Numidian Formation in northern Tunisia must take into

consideration the observations presented above. The best sections that can be used to assess the thickness of the Numidian Formation appear to be the Tebaba, Sejnene, Cap-Serrat and the Tabarka sections. The Oligocene part of the Numidian Formation is well developed in the Zouza area and shows a thickness of close to 700 m (Fig. 12A). The Miocene part is in excess of 1,400 m, which is evident from the Numidian succession of the Cap-Serrat and Balta sections (Fig. 12B). Therefore, a rough estimate of the maximum thickness of the Oligocene part of the Numidian Formation is between 500 m and 800 m. The section that is nearly 1,500 m thick in the Cap-Serrat and Balta areas ought to document the maximum thickness of the Miocene portion of the Numidian Formation, even though it does not account for the entire basin fill since the stratigraphically highest horizons have been eroded away (Fig. 12B). Hence, the com-



posite Numidian Formation, reconstructed in this study without considering the Babouch Member and shale, displays a total maximum thickness exceeding 250 m. This is based on the new assumption that takes into account the thickness of the Oligocene and the early Miocene strata within the same section and through different geographic areas. Therefore, the thickness of the Numidian formation does not exceed 2,200–2,600 m without duplication. It is anticipated that the Numidian Formation thickness will have an impact on petroleum-exploration strategy in onshore and offshore Tunisia with the emphasis of the underlying Telliian fractured carbonate reservoirs.

STRUCTURAL POSITION

For studying the style of deformation of the Numidian structural unit we have based our conclusions on field observations in Tabarka (Fig. 13) and Sejnene (Figs 14–16) areas and coupled it with the re-interpretation of one seismic line, extending from Cap-Serrat to the front of the Numidian structural unit in the Sejnene area (Figs 2–15). The new mapping study indicates that the Numidian structural unit is folded and dissected by common NE-SW thrust and back-thrust faults (Figs 14–16). Folds are represented by broad synclines with narrow anticlines, which were commonly reverse-faulted or thrust along their hinges (Figs 14–16).

Tabarka area

The Numidian succession of the Meloula-Needles section is a good example to illustrate the intervening structural deformation. In this area, the basal part of the Numidian Formation is mainly represented by the typical “argile à *Tubotomaculum*” (Fig. 13C–E). In this area, the Numidian Formation exhibits strata that range from dipping at a high angle to overturned (Fig. 13A, B). The direction is mostly N–S and is obviously anomalous, compared to the larger NE–SW structures that resulted from the NW–SE compression of Serravalian–Tortonian age. Common, small-scale “faulted thrust folds” were recorded in the middle part of the Numidian Formation of the Meloula-Needles section (Fig. 13G–I). Such disruption induced the emergence of the Upper Eocene along these faults at Dowar Larmel (Fig. 13F). This structural organisation evidences strong compressional forces and as a consequence the folding and the stacking of thrust/reverse faults along the Tabarka section have caused a thickening of the stratigraphic section (Figs 6–13).

On the geologic map of the Tabarka (Rouvier, 1992), the common N–S direction of the Meloula morphological

corridor and the Numidian Formation strata in general ranging from dipping at a high angle to overturned is the consequence of tectonics that induced rotation of the whole block (Fig. 13). It seems that this area has undergone a levorotatory rotation (Rouvier, 1977) during nappe emplacement or later. According to the geological map (Rouvier, 1992), it appears that the rotation is not related to the Meloula corridor, but to another area located east of Tabarka in the Babouch Syncline and now covered by Quaternary deposits. According to Rouvier (1977), dextral strike-slip faults are visible in the Babouch Northern Syncline and indicate a dextral movement to the north. Taking into account the possibility of rotation of the Numidian Formation blocks, a palaeomagnetic study is recommended to test this assumption and offer a solution to the heated debate on the provenance of the Numidian Formation.

Also, such folding and thrusting has been clearly identified at many other localities in the Mogod Mountains (i.e., on the right bank of Oued El Harka and in Kef El Hamar in the Mogod Mountains (Fig. 15B), where common small-scale disharmonic folding is developed within thin turbiditic sandstones of the Numidian Formation. Such structures are generally developed against a major thrust and/or reverse faults. According to the biostratigraphic dating, the major tectonic episode affecting the Numidian and Telliian units followed the deposition of the youngest exposed Numidian horizons in the Burdigalian. According to the mapping (Fig. 14), during this deformation both the Numidian structural unit and the Cretaceous–Eocene carbonate sequence were folded into broad synclines with narrow intervening anticlines, which were commonly reverse-faulted or thrust along their hinges (Figs 14–16).

Sejnene area

Although there is no available subsurface data from below the Meloula-Needles area, therefore a correlative seismic profile from further to the east, oriented NNW–SSE and extending from west Cap-Serrat to the front of the nappes in the Sejnene area is interpreted (Fig. 5A). The poor quality of the seismic sections in northern Tunisia does not allow interpretation below 2s (TWT). It is supposed that the poor quality of major seismic lines in northern Tunisia is due to the lithology of the Numidian Formation which is generally shaly. Also, the high-angle dips of strata have altered the quality of the seismic survey. The seismic section shows that the structural style in the Oued Sejnene area is folding and thrusting over a decollement surface (Fig. 12A). In the study area, a decollement surface is well defined in the shales at the base of the Numidian Formation (Figs 14–16).

Fig. 13. Deformation style of the Numidian Formation strata in Tabarka area. **A.** Cross-section through the Numidian Formation from Meloula to the Needles (Tabarka town) section. Note the common thrusting and the overturned to steeply dipping strata. **B.** Panoramic view, showing the steeply dipping to overturned Numidian Formation strata from Meloula to Dowar Larmel. **C–E.** Photographs showing features of the “argile à *Tubotomaculum*”, that represent the basal member of the Numidian Formation. **F.** Upper Eocene clays in Dowar Larmel that emerged as a result of the thrust fault of Dowar Larmel. **G–I.** Photographs showing the folding and thrust/reverse faults affecting the Numidian Formation strata north of Dowar Larmel.

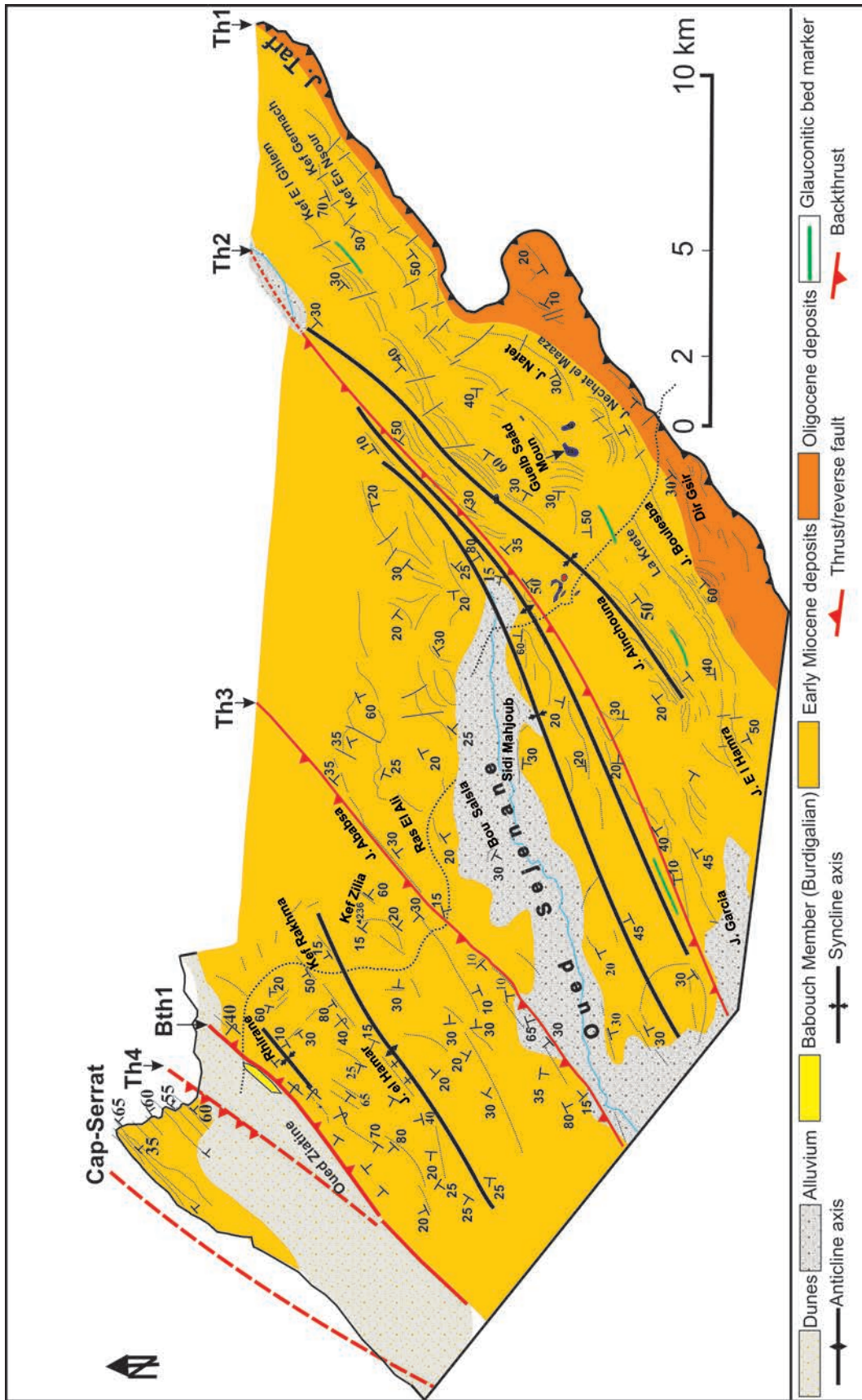


Fig. 14. Spatial distribution of the Oligocene and the early Miocene deposits in the Mogod Mountains as well as the associated main structures (anticlines, synclines, thrust and backthrust faults). The map also shows the members of the Numidian Formation in the Mogod Mountains and the main structural features.

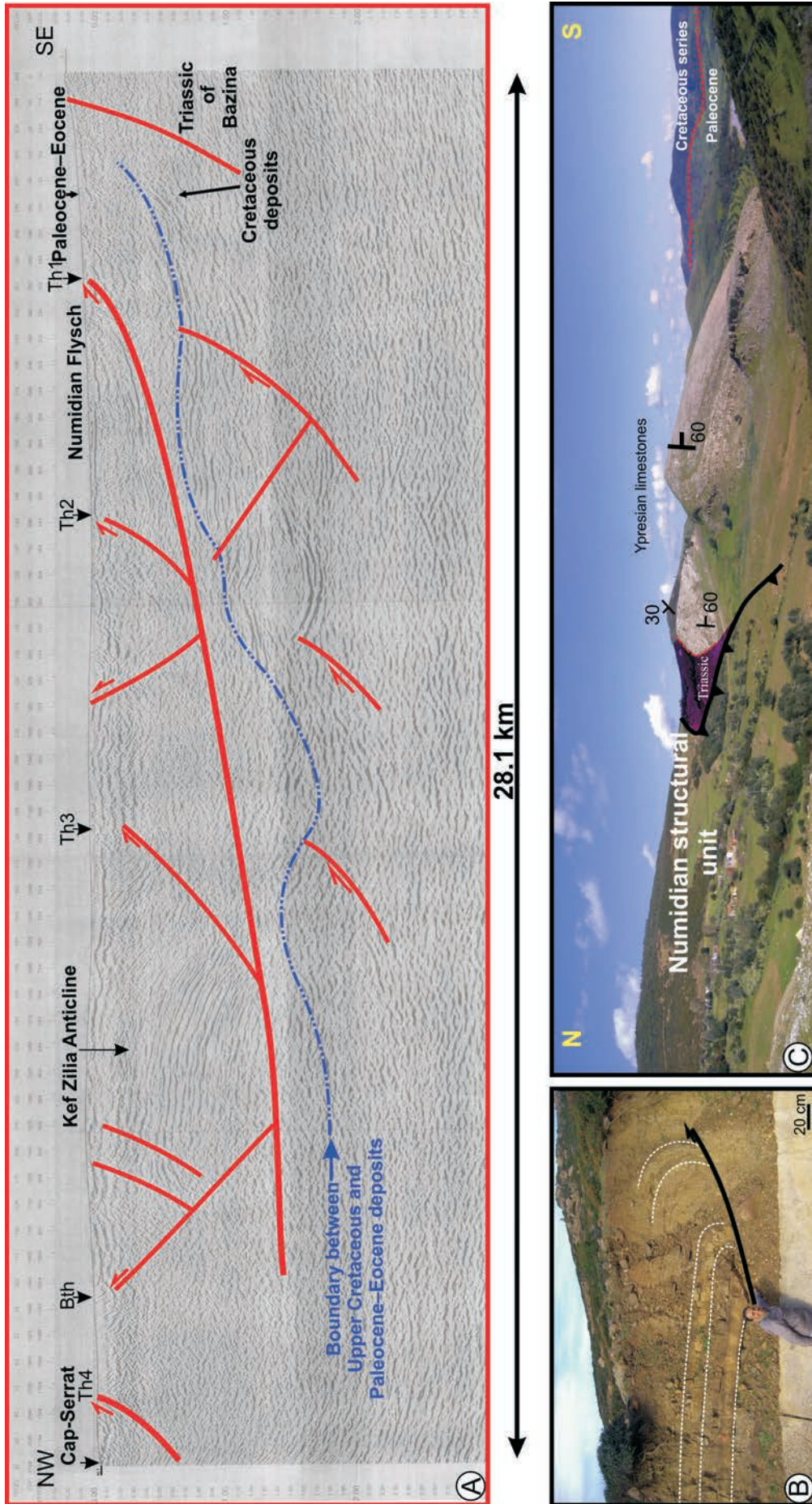


Fig. 15. Style of deformation in the Numidian and marginally sub-Numidian structural units. **A.** Seismic re-interpretation of the structural deformation of the Numidian structural unit in the Mogod Mountains. Note the correlative occurrence of the main structural elements between the surface and subsurface. Seismic line, shown in Fig. 2. **B.** Small-scale deformation in outcrops similar to anticline of Kef Zilia seen on the seismic line. **C.** Panoramic view illustrating the relationship between the Numidian structural unit and the Cretaceous-Eocene series. Note the position of Triassic over Ypresian limestone and just below the Numidian structural unit.

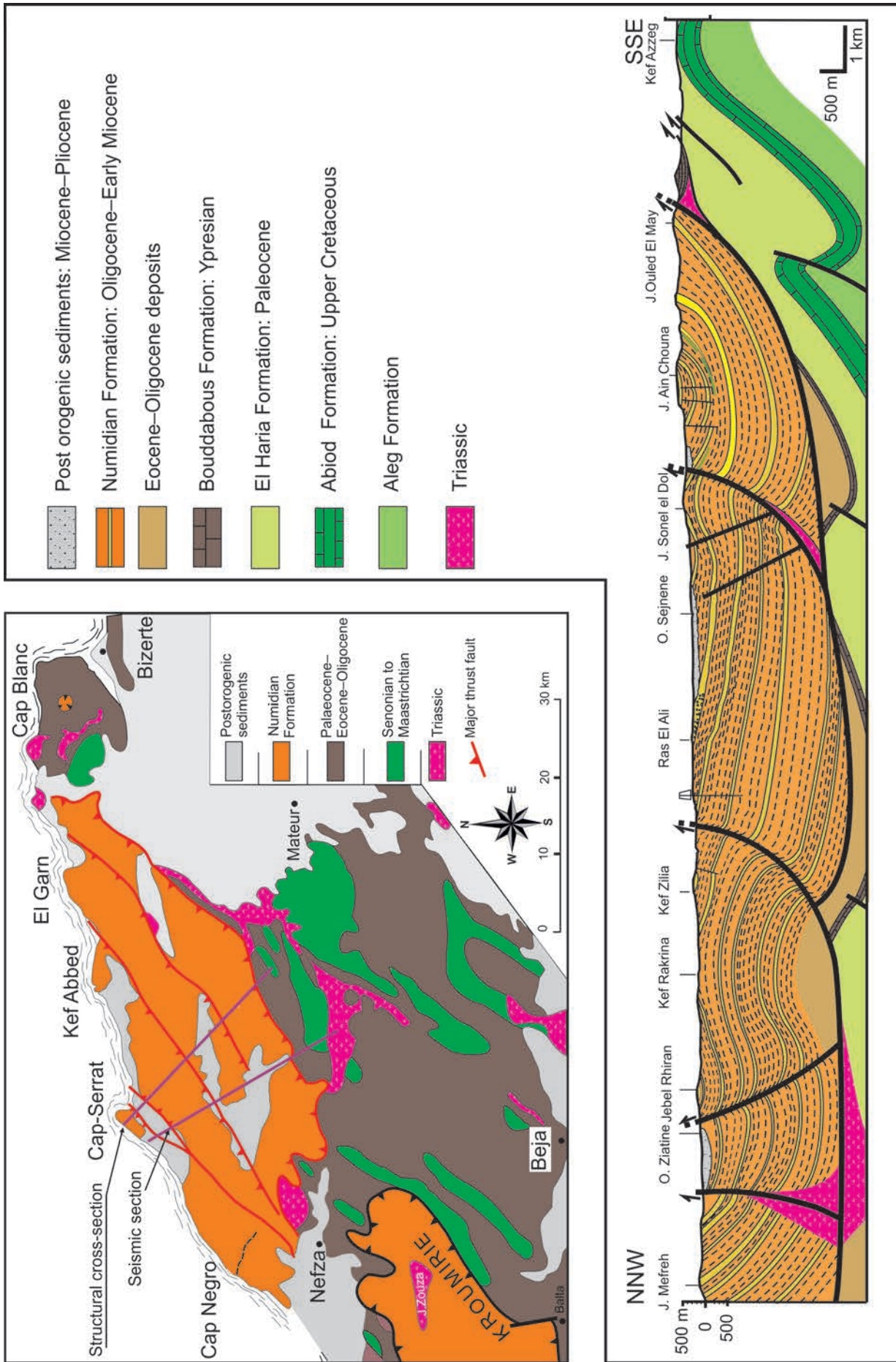


Fig. 16. Numidian–Tellian domain onshore northern. Note the analogy between seismic and outcrop. The structural section is from Cap-Serrat to Jebel Azzeg.

The structural style within the Numidian structural unit is represented by folds and faulted anticlines above a detachment surface (Figs 15, 16). On the basis of field work, we distinguish consecutively from the Numidian nappes front to Cap-Serrat the following structural elements (Figs 14–16):

- (1) the perched Ainchoun Syncline;
- (2) Sonel Dhol Anticline (faulted anticline);
- (3) Oued Sejnene Syncline, already defined by Carr and Miller (1979) and Riahi *et al.* (2010);
- (4) To the north, an anticline structure is developed and underlies the area north of the Sejnene valley, but south of Jebel Ghiran (Figs 14, 15). This will be referred to as the Kef Zilia Anticline (already defined by Carr and Miller, 1979 and Riahi *et al.*, 2010). The style of folding is represented by open and upright folds with sub-horizontal, plunging axes. The axes plunge to both the northeast and southwest. The folds are flat-hinged with the maximum dip of limbs not exceeding 35°. Steeper dips were measured in beds that have been collapsed along the front of the Cap-Serrat Fault (Fig. 14).

Additionally, the occurrences of sandy glauconitic horizons in the Ainchoun Syncline and on the north flank of the Sonel Dhol Anticline (Fig. 14) show that only the lower Miocene part of the Numidian structural unit was involved in the anticline and syncline structures. The Oligocene deposits appear only at the front or along some deep faults and therefore the Oligocene will be in the subsurface. In some cases, the Triassic cross-cuts through the Numidian sequence (e.g., Jebel Ouled Mejri) and elsewhere acts as a decollement level (e.g., Ouled el May). Also and as demonstrated through geological mapping, structural cross-section and the interpreted seismic line, these structures are limited by major thrust/reverse faults and backthrusts. The main structural elements distinguished are as follow:

- (1) Th1, the Numidian major thrust fault;
- (2) Th2, a NE-SW directed thrust fault affecting the Sonel Dhol Anticline;
- (3) Th3, the fault north of the Sejnene trough and very visible on aerial photographs and in satellite images;
- (4) Bth1, a backthrust north of Jebel Ghiran;
- (5) Th4, a reverse fault affecting the top of the Numidian succession of Cap-Serrat.

CONCLUSIONS

The new biostratigraphic data presented here on the Numidian Formation of northern Tunisia refines the stratigraphy of this formation and enables a new thickness assessment for the unit. Also, with the definition of some facies markers, it now is possible to correlate the Numidian Formation outcrops of the Kroumirie Mountains with those of the Mogod Mountains.

The integrated data allowed the refinement of the age and the internal architecture of the Numidian Formation in northern Tunisia. Therefore, in the new proposed stratigraphic chart, each of the considered Zouza and Kroumirie members represents the entire Numidian Formation, with lateral facies variation between the top of the Zouza Mem-

ber and the base of Kroumirie Member. In the new scheme, the authors considered that the Zouza and Ben Metir areas, where the Numidian Formation members were defined, enclose a highly pelitic lower unit with *Tubotomaculum* and subsidiary sandstones and an upper member that is sandier, especially in its uppermost part, and can be assigned to the Kroumirie Member. In the present study, these have been stratigraphically dated as Oligocene–Early Miocene p.p. (Rupelian–Chattian; P19–P21 zones) to Aquitanian (N4 Zone) and Miocene (Aquitanian–early Burdigalian; N4–N5 zones), respectively. The sandy succession assigned to the Kroumirie Member starts with a sandstone unit delimited at its lowermost part by an erosional base or major discontinuity, marked locally by conglomerates with various reworked elements. It rests generally on a thick shale unit that characterises the upper part of Zouza Member. The thinner, uppermost member (Babouch Member), is characterised by two distinct silicified horizons (silexites), and quartzarenites of Burdigalian age (N6–N7 zones). This subdivision is easy to apply and is easily identifiable in all sections of the southern margin of the Kroumirie and Mogod mountains and those fringing the coastline. Even more, this biostratigraphic review demonstrates that the pinching-out of the so-called Zouza Member *sensu* Glaçon and Rouvier (1967) in different areas (e.g., Tabarka, north of Jebel Khreroufa; Ben Metir and Ad'n Allega areas) is mostly related to inaccuracy in correlation between the Numidian Formation outcrops of the Meloula-Needles section and those on the thrust front, rather than to tectonic deformation, as already was proposed (Rouvier, 1977).

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