

A Miocene-restricted platform of the Zibane zone (Saharan Atlas, Algeria), depositional sequences and paleogeographic reconstruction

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Abstract Depositional sequences and paleogeographic evolution of the Miocene deposits have been studied in the Zibane zone (Saharan Atlas, Algeria) located at the north of the African platform. During the Miocene, this region corresponded to a fault-bounded collapse area and filled by diversified deposits, showing important lateral facies and thicknesses variations. The studied deposits are divided into five depositional sequences separated by major unconformities. These depositional sequences are well developed in the whole basin and testify a paleogeographic differentiation from E–W, induced by a set of NW–SE-trending old faults inherited from the Atlasic orogeny. The organization and the development of those sequences make it possible to correlate them better to the basin scale, which is integrated in a model of restricted platform intersected by NW–SE faults where the tectonic-sedimentation duality is predominant. These new data point to a paleogeographic evolution different from the one usually admitted environment for this region during Miocene time and plead in favour of a reconsideration of the depositional environments of the post-Burdigalian formations in the Zibane zone of the Algerian Atlasic domain.

Keywords Algeria · Atlasic domain · Zibane zone · Miocene · Depositional environment · Paleogeography

Introduction

The Neogene Zibane zone, in the northern part of the South Atlasic Fault, is developed at the north of the African platform and forms a hinge zone linking the two major Atlasic ensembles of Algeria, Saharan Atlas in the West and the Aures in the East (Fig. 1), shifted according to a dextral movement (Guiraud 1973, 1990; Chebbah 2007). This region is characterized by a small-scale rhomboidal shape (with axis respectively of 35 and 80 km), bounded by faults (E–W, NW–SE and NE–SW) and by its place in the Atlasic domain (Fig. 1). This is a Neogene subsident area with an orientation which is sensibly E–W superposed to a syncline and located between the two anticlines of Djebel Bou Rhezal (Biskra) in the South and of the Djebel El Melah (El Outaya) in the North (Fig. 2). Its structure is due to the superposition of two major compressive tectonic phases which are identified in the whole region, the Lutetian phase (Atlasic or Alpine phase) and the basal Quaternary phase (Laffitte 1939; Gousskov 1962; Guiraud 1973, 1990; Guiraud and Bellion 1995). The first tectonic phase is responsible for major deformation and the development of large NE–SW-trending folds. The second tectonic phase generates east–west-trending folds and thrusts (Laffitte 1939; Guiraud 1973; Ghandriche 1991; Chebbah and Lamouroux 2012). Between these two compressive tectonic pulses, the Miocene was a period of relative quiescence, characterized by the deposition of a relatively thick flexural sequence deposited in continental or marine environment (Guiraud 1990; Bracène and de Frizon 2002). Normal faulting developed in some places during this period (Bracène and de Frizon 2002; Chebbah and Lamouroux 2012).

During the Miocene, the Zibane zone was filled by siliciclastic and confined (mixed) sediments showing important lateral facies and thicknesses variations and controlled by the

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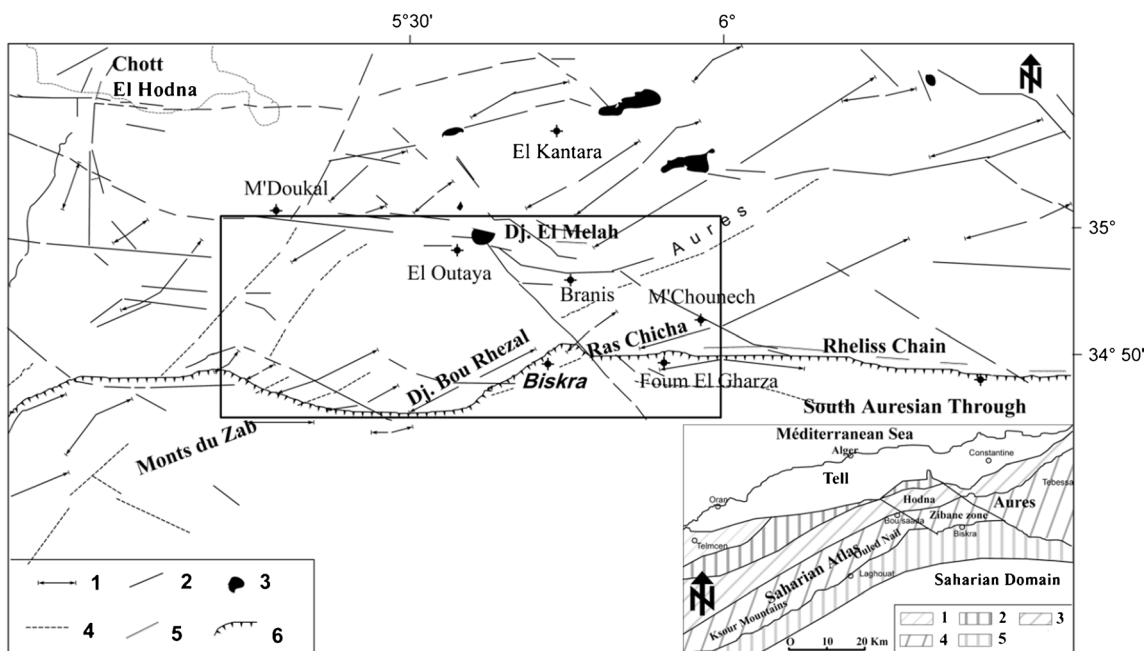


Fig. 1 Structural schema of the study area (Laffitte 1939; Guiraud 1973, modified). 1 Anticlinal, 2 Synclinal, 3 Trias, 4 Shear fault, 5: Reverse fault, 6 South Atlasian fault. The box corresponds to Fig. 2. In cartridge:

Localisation of major geomorphologic units in North of Algeria (Piqué et al. 2002); 1 Pre-tellian belt, 2 Pre-atlasic belt, 3 Pre-atlasic trough, 4 Atlas belt, 5 Pre-African trough

activity of old structures inherited from the Atlasic orogeny (Aissaoui 1984; Guiraud 1990; Herkat 1999; Chebbah 2007). This region is part of a series of intracontinental Neogene basins considered, by different authors, as pull-apart basins (Kazi Tani 1986), piggy-back (transported) basins (Ghandriche 1991) or fault-bounded collapse basins (Herkat 1999).

The evolution of the Zibane zone during the Neogene was linked to a preexisting fragmentation of the post-Triassic sedimentary cover along NW/SE faults (Aissaoui 1984; Guiraud 1973, 1990; Chebbah 2007) and accompanied by a collapsing process of the Atlasic domain during a post-orogenic extension tectonics (Guiraud 1973, 1990; Chebbah 2007).

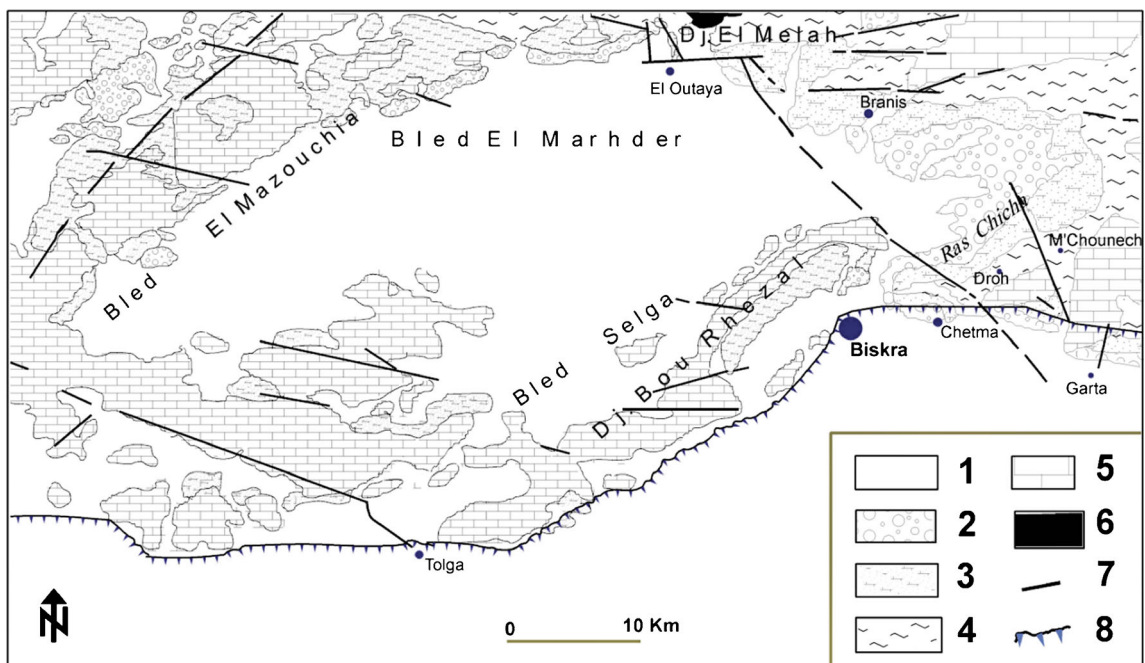


Fig. 2 Simplified geological map of the Zibane zone (after Chebbah 2007). 1 Quaternary, 2 Pliocene, 3 Upper Miocene, 4 Middle and lower Miocene, 5 Bedrock, 6 Trias, 7 Faults, 8 South Atlasian fault

In the Zibane zone and adjacent regions, the Neogene occupies a large area and unconformably overlies formations of different ages (Oligocene, Eocene and Upper Cretaceous). Its main exposures are located in the borders of the basins; by against, in the centres of those basins, the Neogene deposits are hidden under a thick Quaternary formation that unconformably covers them (Laffitte 1939; Guiraud 1973, 1990; Chebbah 2007). Despite various existing subdivisions of Neogene succession in the study area, most authors agree to give this series the following superposition: at the base green or brown clays and limestones of the Aquitano-Burdigalian, brown clays with intercalated gypsum beds of the Langho-Serravalian, red clays with gypsum of the Tortonian, sandstones or brown-red sands of the Messenian and red sands and conglomerates of the Pliocene at the top. In reality, this succession corresponds to a simplified schema of major Neogene units that, in the field, present the important lateral and vertical facies variations.

The Miocene deposits of the Zibane zone, often poorly fossiliferous, do not provide support for precise and reliable dating. Though they have been early described in the middle of the ninetieth century (Fournel 1849), no detailed studies and no correlations have been proposed later Laffitte (1939) and Guiraud (1973, 1990) associated all the post-Burdigalian formations to continental deposits. Their correlation with the Hodna and neighbouring area series, well dated of the Miocene by Guiraud (1973, 1990), permits us to calibrate them stratigraphically.

The purpose of this work is to study the Miocene evolution of the Zibane zone and locate it in global geodynamic framework. The study is based on a detailed description of the lithostratigraphy and sedimentology of the Miocene deposits in this region and provides sequence stratigraphy and paleoenvironmental interpretations of the sedimentary succession. The repartition and enchainment of different lithofacies permit us to propose an evolution of the Miocene deposits in a restricted platform model.

Methods

Detailed lithological and sedimentological study was performed on several sections throughout the study area (Fig. 3a and b). In this study, the sedimentary facies interpretations follow the Kendall's facies model (1988, 1996) for restricted (carbonate and evaporate) lithologies and Mial's facies model (1978, 1988 and 1996) for siliclastic lithologies. Special attention was paid to indicative surfaces (hardgrounds, subaerial exposure surface), sedimentary structures and the lateral and vertical facies distribution.

Litho-stratigraphic units and sequences of deposits

The detailed lithostratigraphic and sedimentological investigation of the studied Miocene deposits has allowed to recognize five third-order sequences (Haq et al. 1988; Vail et al. 1977, 1991), for the Aquitanian-Messinian interval. These sequences are recorded as SD I to V. They are separated by major unconformities, designated as d0 to d5 (Fig. 6b and c) (Chebbah 2007; Chebbah and Lamouroux 2012). The discordances d0, d4 and d5 are angular unconformities of regional extent and are recognized on all the southern slope of the Aures Massif and adjacent areas (Laffitte 1939; Guiraud 1973, 1990; Chebbah 2007; Chebbah and Lamouroux 2012). The discordances d2 and d3, often materialized by erosive or hardened surfaces, lithofacies change with basic conglomerate (or gravel) and polarity inversion of sequences, are eustatic origin (Chebbah 2007; Chebbah and Lamouroux 2012). The various sequences have been grouped into three (3) main units that are described here below.

The mineralogical and granulometric characteristics of the studied samples were determined using a convenient number of robust statistical measures (Pye and Blott 2004), including the percentage of sand (>63 μm), silt (2–63 μm) and clay (<2 μm), the median size (M_d), the primary modal particle size (C_μ), the mean (M_z), inclusive graphic standard deviation or sorting (σ_i), the inclusive graphic skewness (S_{ki}) and the Kurtosis (K_g). Indices that permit a better granulometric characterization of the siliclastic deposits (Folk and Ward 1957; Heiden and Holmes 1998; Trindde et al. 2013). Table 1 (Appendix A) presents the summary of the particle size data of the studied deposits.

Unit I—early Miocene

This unit is a progradational set and unconformably overlies all anti-Miocene formations (Chebbah 2007; Chebbah and Lamouroux 2012). It is mainly argillaceous sulphated and locally shows conglomerate base in the East (Fig. 5a). It is clayey-carbonated in the centre and clayey-conglomeratic on the West (Fig. 5c). It comprises two sequences, the first one, Aquitanian in age (SD1) and the second Burdigalian in age (SD2).

The SD1

In the eastern sector (Branis), this sequence is 50-m thick and contains greenish brown clays with gypsum levels which are rarefied toward its summit. Locally, SE Dj. El Mellah, it begins with a thick conglomerate series (300 m). The reddish brown conglomerates are constituted of heterogeneous, poorly cemented, very poorly sorted and disorganized coarse pebbles and contain a metric block of limestone (olistholiths) at their base. In the central sector (El Outaya), the SD1, 90–160-m thick, is made up of green clays with gypsum occasionally

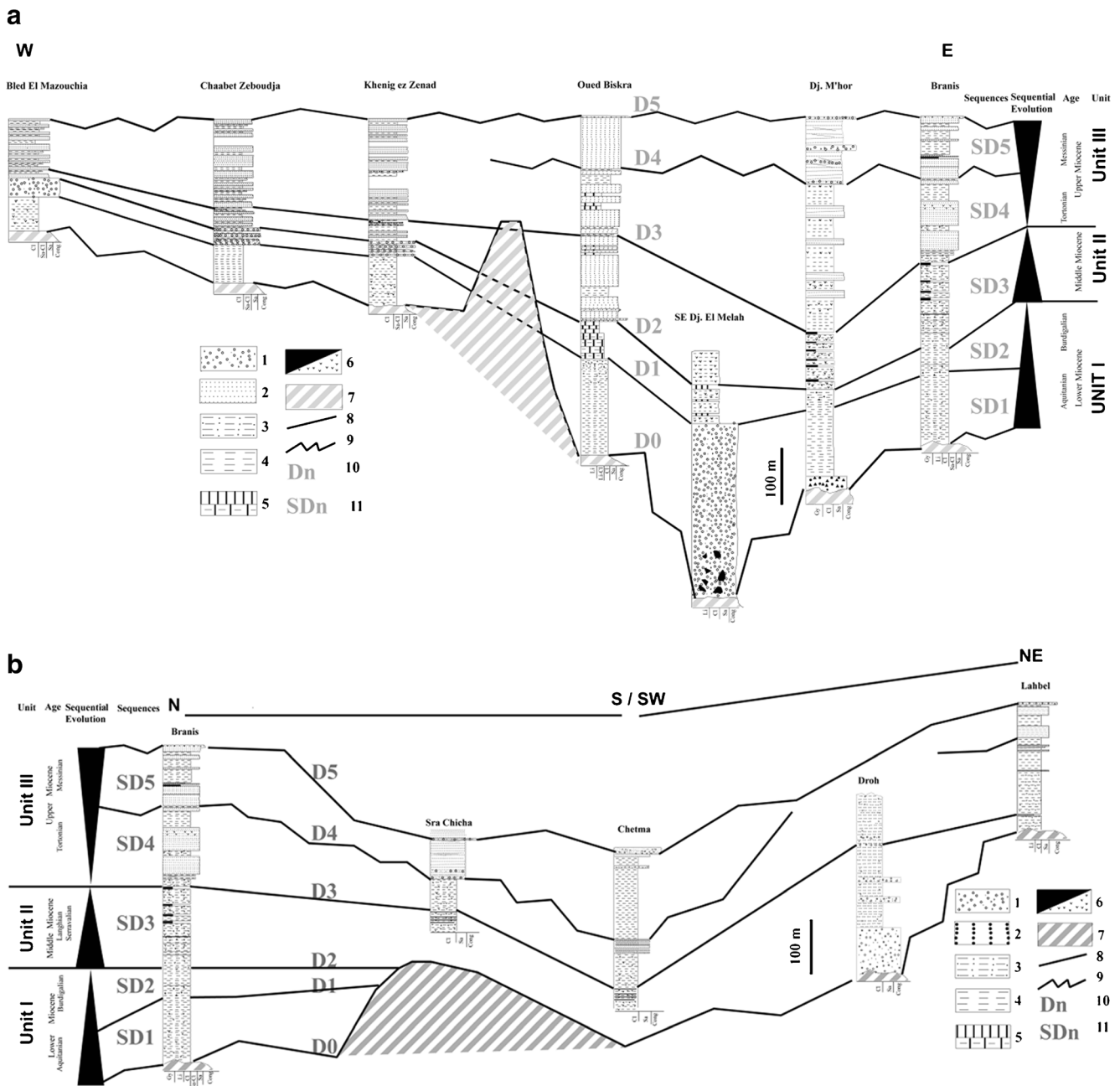


Fig. 3 Correlations and sequential evolution of the third-order sequences of the Miocene deposits in the Zibane zone. 1 Conglomerates, 2 Sandstone, 3 Clayey sandstone to sandy clay, 4 Clay, 5 limestone and marly limestone, 6 Gypsum, 7 Bedrock, 8 Boundaries of the third-order

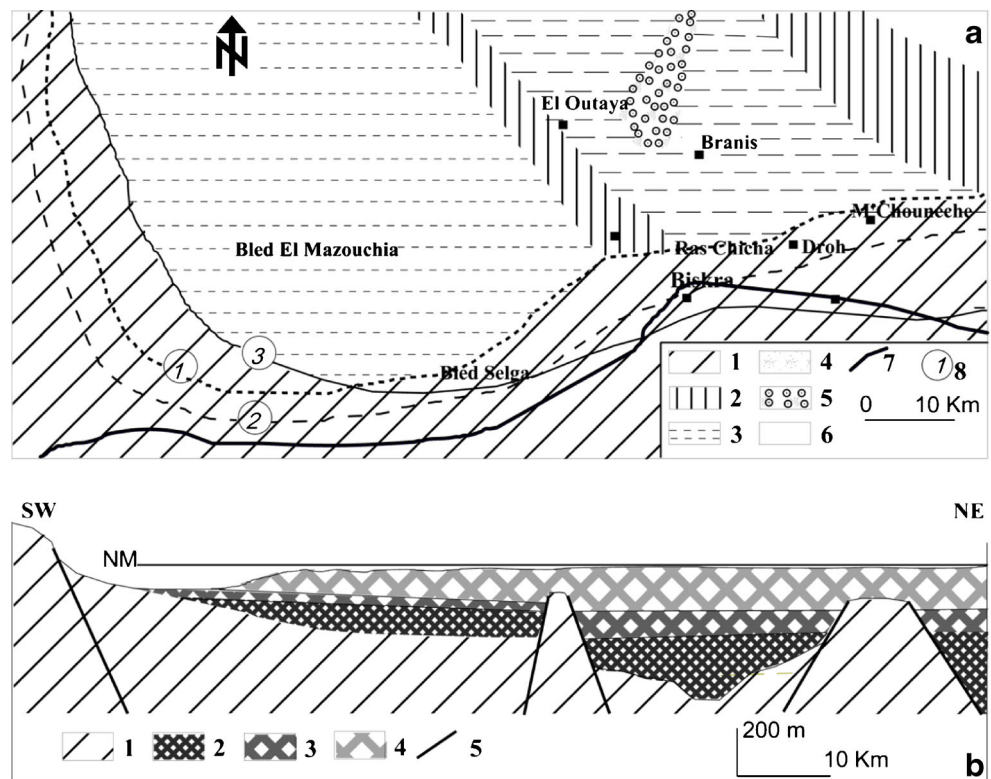
sequences, 9 Tectonic discordance, 10 Discordance, 11 Sequence granulometry. *Gy* gypsum, *Li* limestone, *Li-Cl* clayey limestone, *Cl* clay, *Sa-Cl* sandy clay, *Sa* sand, *Cong* conglomerate

containing quartz grains and small limestone pebbles; gypsum occurs in small crystals in the base or in decimetric beds to the sequence summit. In the western sector (Bled El Marhder and Bled El Mazouchia), this sequence attains a thickness ranges from 60 to 70 m and consists of yellow-green clays with millimetric gypsum crystals.

Two facies associations are defined: the gypseous clay facies and the conglomerate facies.

Facies 1: gypseous clay facies This facies consists mainly of clays enclosing gypsum (Fig. 7a). The gypsum occurs as small crystals and intercalated decimetric benches. It corresponds an evaporitic deposits formed in a restricted (partially closed) environment probably, associated with a relative ascent of the sea level toward its top and occasionally fed by detrital elements, an environment of sabkha type (in the Kendal's sense 1992).

Fig. 4 **a** Paleogeographic sketch during the Miocene in the Zibane zone. 1 Continent, 2 Horsts, 3 Confined sea, 4 External sea (opened), 5 Channel, 6 At sea, 7 South Atlasian fault, 8 Minimal sea area during Miocene (1 Lower, 2 Middle, 3 Upper). **b** Schematic NE-SW cross-section showing the series of deposit sequences in accordance with paleogeography. 1 Bedrock, 2 Lower Miocene, 3 Middle Miocene, 4 Upper Miocene, 5 Faults



Facies 2: conglomerate facies This facies consists of conglomerates with metric blocks of limestone (olistholiths). They present the characters of debris flow and Gms facies (Miall 1978, 1988, 1996) and correspond to proximal depositions showing evidence of the presence of a northern continental border. The abundant clay-sand matrix, absence of sorting and the disorganized fabric of the conglomerate point to a rapid deposition due to a catastrophic event (Walker 1990; Anis and Shahnawaz 2012; Toshifumi et al. 2014). The large blocks indicate an active mostly extensive tectonics, inducing a deepening of the deposition environment.

The SD2

In the eastern sector, this sequence consists of 20 m of greenish brown clays with oysters overlain by 70 m of brown clays with echinoids and pectinids (*Ostrea crassissima Lmk*) that are intercalated by argillaceous limestones with bivalves. In the SE of Dj El Mellah, the deposits of this sequence unconformably overlie the conglomerate series and consist of an alternation of greenish yellow clays and clayey or microconglomeratic limestones with bivalves in which Guiraud (1973, 1990) signals the presence of Burdigalian pectin sp. In the central sector (El Outaya), two subzones can be distinguished: (a) East Oued Biskra, the section, 80-m thick, consists of clayey limestones and fine limestone showing slightly wavy bedding more or less ordered (Fig. 5b.a). They yield the bivalves and the Globigerinoids which are attributed

to the Burdigalian according to Guiraud (1973, 1990). (b) West Oued Biskra (Khenig ez Zenad), the section is 70-m thick and is clayey-conglomeratic organized into decametric parasequences each comprising two terms (conglomerates—red clays). Conglomerates, bars of 2.5–5-m thick, are very heterogeneous with rounded and elongated grains poorly sorted (pebbles 2.5 to 20 cm in diameter). Clays are gypseous in the sequence summit; gypsum is disseminated in small crystals or into intercalated fine parallel laminae. In the western sector (Bled El Mazouchia), the SD2 is 50-m thick; it is also clay-conglomeratic as in Khenig ez Zenad where it presents the same pattern (organization). It is organized into decametric parasequences of conglomerates—red clays. The conglomerates to coarse elements (8–35 cm) are poorly cemented, poorly sorted, in thicker bars (5.4 to 9.5 m) and without clear internal organization.

Similar formations are found on the northern slope of DJ. Magraoua on the West of the study area and in the southern Hodna and are dated by Guiraud (1973, 1990) from Aquitano-Burdigalian.

Three facies are found in this sequence: the clay facies in the East, limestone facies in the Centre and the clay-conglomerate facies in the West.

Facies 1: clay facies This facies consists of green clay-rich oysters and is overlain by brown clays with echinoids and pectinids that are intercalated by argillaceous limestones with bivalves. Such facies is clearly deposited in a marine

environment. The fairly diverse fossil content indicates normal marine water conditions. Despite its shallow character indicated by the fossiliferous association, this succession shows a relative increase of sea level during the deposition with probably a maximum flood. The depositional environment can be an external platform type (Moissette et al. 2010).

Facies 2: limestone facies This facies consists of argillaceous limestones with bivalves and fine grained limestone with globigerinoids showing slightly wavy beddings. This carbonate sequence is deposited in external platform.

Facies 3: clay-conglomerate facies This facies consists of conglomerates and red clays with small crystals or fine lamellae of gypsum. The section records an increase of coarser layers (microconglomeratic or conglomeratic) upwards. Such facies evolution indicates an increase of energy or shallowing upwards during deposition, similar to the one observed in the coastal zone of a continental shelf supplied by an episodic tectonic activity. The depositional environment can be an internal platform (Xiaowei et al. 2011; Amirshahkarami 2013).

Unit II—middle Miocene

This unit shows a progradational set; it is clayey-sulfated in the East, sandy-clayey-carbonated in the centre and sandy-clayey in the West. It is represented by one sequence (SD3).

The SD3

In the NE sector (Branis), this sequence is 140-m thick and consists of clay-gypsum complex organized in several decametric parasequences composed of metric gypsum beds (3 to 1.5 m) intercalated with gypseous clays (Fig. 6a). The parasequence terminates with a sandy limestone bed. The gypsum beds occur into centimetric at the lower part of the sequence and in decimetric laminae in its uppermost part drawing a clear parallel stratification in this unit. The sequence is richer in gypsum toward the top confirming a shallowing upward trend. In the SE of Dj El Mellah, this sequence is formed by gypseous brown red clay beds. In the SE sector, (a) Douar Chetma, the SD3, ±50-m thick, is made of gypseous brown or red clays; the gypsum is present either in decimetric benches intercalated in brown clays or in centimetric crystals well developed in the red clays; (b) Droh, the SD3, ± 60-m thick, is composed of an alternation of decametric parasequences of gypseous red clays and gypsum benches (0.3 to 0.70 m) in decimetric to centimetric laminae; locally, it is almost entirely composed of conglomerate; and (c) Lahbel, the SD3, 36-m thick, is composed of brown-red clays with millimetric gypsum crystals passing upward to green-brown marls and at the top a metric bank marly limestone landmark which one can follow Droh until M'Chounech. In the central sector (El Outaya), (a) East Oued Biskra, the SD3, consists of

siliciclastic decametric parasequences of Delfaud's G-M-C type (sandstone-marl or clay-limestone) often incomplete and similar to those encountered in the Neogene of Chelef (Neurdin-Trescartes 1992). In its lower part, the sandstones are brown medium-grained with conglomeratic basis in variable thickness beds (0.30 and 2.5 m) surmounted by polygenic and heterometric conglomerates which terminate by fine whitish limestones. In the median part, in slight unconformity, the layer is made of coarse-grained sandstones with basal gravels or limestone fragments, red clays containing small gypsum crystals and sandstones in decimetric beds. Sandstones are composed of coarse and fine-grained alternating laminae showing oblique stratifications. They contain, locally, nodules of green or brown clays and at their summit, lenses of multicolored sands. In the uppermost part of the sequence, the sands are massive medium-grained sometimes brecciated in small benches (0.2 to 0.7 m) containing argillaceous nodules and with algae having oblique laminations. (b) West Oued Biskra (Khenig Ez Zenad), the SD3, 35-m thick, is composed of stratified inverse grading parasequences, decametric at the base and metric to the top, formed by sandstones and gypseous red clays. Sandstones in beds (0.3 to 1 m) are medium to fine grained with parallel (Fig. 8i) and cross-bedded stratifications and show clay increase toward the top; the sequence SD3 is capped by a metric bank of sandstone which gradually passes to a sandy limestone. In the western sector, the SD3, 30-m thick, is also formed of decametric strato and grano-decreasing (stratified inverse grading) parasequences of sands and gypseous red clays. The sands, in metric banks, are medium to coarse grained showing parallel or low-angle inclined stratifications at the base and fine-grained with cross-bedded or oblique stratifications at the top. Clays contain gypsum of centimetric crystals, or some fine intercalated centimetric laminae are present containing, locally, green clay balls.

According to Guiraud (1990), its fossiliferous contents indicate to Langhian-Serravallian; in fact, the marls of Bled Salaouine, in the North of El Outaya, contain Serravallian species (*Globigerinoides trilobus*, *Globigerinoides quadrilobatus* and *Uvigerina gr. Papapi*).

Four facies associations are present in this sequence: the clay-gypsum and gypseous clay facies associations in the East, sandstone-marl-limestone facies association in the Centre and the sandstone-clay facies association in the West.

Facies 1: clay-gypsum facies This facies association consists of gypseous clays with intercalated gypsum beds. Those deposits were developed in an episodically or partially closed marine environment in restricted platform isolated from the open marine area by shoals where evaporation induced salt precipitation (Kendall and Harwood 1996).

Facies 2: gypseous clay facies This facies association consists of gypseous red or brown clays (Fig. 8d) with local presence of some banks of gypsum, marls or marly limestone. This

facies was deposited in coastal mudflats with minor detrital contributions corresponding to a coastal sabkha (Kendall 1988; Kendall and Harwood 1996).

Facies 3: sandstone-marl-limestone facies association This facies association consists of an alternation of sandstones, marls, clays and limestones corresponded of Delfaud's G-M-C type sequences (1974) often incomplete. The sandstones are overlain by clays or argillaceous sandstones with a coarser layer at the base (conglomerates or pebbly sandstone) could indicate a decrease of the environment hydrodynamics induced by an increase of the bathymetry. The presence of oblique to crossed stratifications, hard grounds, with algae organisms and polyps at the summit of the sequence is the evidence for shore instability during deposition.

Facies 4: sandstone-clay facies association This facies association consists of sandstones, red clays and sandy limestones in decametric to metric fining up sequences showing normal-graded bedding with large parallel laminations (Figs. 7f and 8c). By its characters, this facies corresponds to coastal depositions.

Unit III—late Miocene

This unit is retrogradational set essentially clay-sandy. Two sequences are identified, the lower of the Tortonian (SD4) and the upper of the Messinian (SD5) (Fig. 6b). However, it is worth noting that in the western sector (west Oued Biskra), we have not been able to draw the boundary between the two sequences because of the lack of identifiable landmarks. The following description is about central and eastern sectors.

The SD4

In the NE sector, the SD4 is 65 m thick and composed of metric to decametric parasequences made of sandy or gypseous red clays, crystalline reddish limestones and red clayey sandstones containing millimetric gypsum crystals and showing large parallel stratifications locally lenticular or oblique.

In the SE sector, (a) Ras Chicha, the SD4, +100-m thick, is composed of parasequences comprising two or three sandy terms at increasing granulometry. Sands, brown reddish, are fine to medium grained with pebbles at the base. They are badly sorted at the base and moderately well sorted at the top in metric to decimetric beds. They show a conglomerate bar to the sequence top with intercalation of clayey sandstone (3.5 m) and greenish marl beds (0.25 m). These deposits are organized into sandy transversal bars widely distributed that are traceable along a distance on the southern flank of Ras Chicha. Sedimentary structures are cross-bedding stratifications that alternate in some places with oblique or low-angle inclined stratifications. (b) Chetma, the sequence SD4, 20-m thick, consists of sandy clays,

brown or green clays and fine or medium grained sandstones, brown-yellow, appearing in decimetric to metric benches showing parallel or oblique stratifications and containing the elongate burrow (suspensivore type). (c) Droh, the large variation in the facies is observed in this sequence which is characterized by many internal discordances. The SD4, 10–20-m thick, consists of brown and green clays and fine or medium grained sandstones in decimetric benches presenting wavy and convolute lamination. (d) Lahbel, the SD4, 100-m thick, consists of 70 m of gypseous red clays starting with a very gypsum level surmounted by the alternation of gypseous red clays, clayey sandstones and yellow sandstones in decimetric beds showing parallel laminations. In the central sector (El Outaya—East Oued Biskra), the SD4, 45-m thick, is made of several metric to decametric stratified inverse grading parasequences type G-M-C (sandstone-limestone-marl). It is formed, at the base, by clayey sandstones and fine-grained sandstones in metric benches showing horizontal laminations and calcareous marls, brown-beige, with parallel or slightly wavy laminations; At the top, it is made up of fine to medium-grained sandstones, brown reddish, showing parallel or slightly inclined locally cross-stratification (Fig. 7g)-containing globules of siderite and few clayey or calcareous nodules and brown carbonate, occurring in metric beds with traces of symsedimentary slip and globular structures.

Five facies are present in this sequence: gypseous clay facies association, sandstone facies association, clay-sandstone facies association, limestone-clay-clayey sandstone facies association and sandstone-marl-limestone facies association.

Facies 1: gypseous clay facies This facies consists of gypseous red clays formed in a confined environment with episodic arrival of remobilized material (globules or nodules of carbonates). They correspond to evaporite flat facies type passing to mudflat facies type of Kendall (1988). The facies was probably deposited in a very shallow protected environment with a lateral gradient in the degree of restriction. The environment of deposit can be a coastal sabkha.

Facies 2: sandstone facies This facies is composed of two or three sandy units with coarsening upward trends organized into sandy longitudinal bars showing cross-bedding stratifications that alternate in some places with oblique or low-angle inclined stratifications (Fig. 7c). This facies corresponds to fluvial deposits in coastal environment with transition to the tidal zone.

Facies 3: clay-sandstone facies This facies consists of clays, sandy clays and fine or medium-grained sandstones showing parallel, locally slightly wavy, or oblique stratifications (Figs. 7i and 8j). The presence of elongated burrow may indicate a nearshore marine environment. This facies can be interpreted as beach deposit.

Facies 4: limestone-clay-clayey sandstone facies This facies consists of sandy or gypseous clays, crystalline limestones and clayey sandstones showing mostly thick parallel stratifications locally lenticular or oblique. This unit corresponds probably to filling deposit in coastal mudflats with episodes of a confined sedimentation (gypsum). The environment can be defined as a coastal sabkha (Kendall 1988).

Facies 5: sandstone-marl-limestone facies This facies consists of an alternation of sandstone-marl-limestone corresponding to G-M-C sequence type often incomplete of Delfaut (Ksour sequences: G: sandstones-M: marls-C: limestones). The presence of parallel or slightly wavy or inclined laminations with locally trough stratifications indicates that these facies are deposited in a shallow water tranche, in shallow platform with episodic input of remobilized material (Delfaut 1974; Neurdin-Trescartes 1992).

The SD5

In the NE sector (+100 m), the SD5 unconformably overlies the SD4. It is composed of metric to decametric parasequences constituted of coarse-grained yellow sands without visible sedimentary structures, gypseous red clays and fine yellow sands. Above, the massive sands are present. They are brown or red, in metric banks with parallel laminations; locally, lenticular stratifications are shown. The SD5 top is made of alternations of medium-grained sands, clayey sands and clays with persistence of sulphated or carbonated levels (gypsum or calcareous marls in metric banks). In the SE sector, (a) Ras Chicha, the SD5, 20-m thick, unconformably overlies the SD4; it is sandy-conglomeratic, formed of massive brown sands in decimetric beds with a conglomerate base and heterogeneous conglomerates with unjoined grains (Fig. 7j). Sedimentary structures are mostly parallel and cross-bedding or metric trough-cross stratifications. This is a sequence characterized by deposits of crossbars alternating with channel deposition with vertical and lateral aggradations in its top. (b) Chetma, the SD5, 160-m thick, is made up of gypseous brown clays with intercalations of metric sandstone benches showing parallel laminations. (c) Droh, the SD5, 30-m thick, unconformably overlies the SD4 and is composed of fine or medium-grained sandstones in metric to decimetric beds with oblique or parallel stratifications intercalated with cross-bedded stratifications. (d) Lahbel, the SD5, 70-m thick, unconformably overlies the SD4 (Fig. 7h) and is formed of massive yellow sandstone in metric beds showing cross-bedded or parallel to low-angle inclined stratifications; locally, conglomerates, clay balls, clayey sandstones, gypseous clays and marls with marly limestones are present at the top. In the central sector (El Outaya—East Oued Biskra), the SD5, 130-m thick, is formed of decimetric to metric sandstone benches with parallel laminations, clayey sands, fine-grained sands with intercalations of

clayey-limestones or sandy beds presenting globular structures and red clays with gypsum intercalations at the layer top.

Given the shortage fossils, by parallelism between formations in this area and in the neighbouring regions, this unit is related to Tortonian-Messinian; moreover, the presence in the upper terms of the SD5 of many species of *Helix Helix (leucochroa) Tissoti Bayan* recognized at the upper Messinian in the Aures and southern Tunisia (Laffitte 1939) allows us to place the SD4 in the Tortonian and the SD5 in the Messinian.

Three facies are present in this sequence: sandstone facies association, clay-sand facies association and sandy-conglomeratic facies association.

Facies 1: sandstone facies This facies consists of fine or medium-grained sandstones containing, by places, conglomerates and clay balls. The sedimentary structures are oblique or parallel to low-angle inclined stratifications intercalated with cross-bedded stratifications (Fig. 8e). The sandstone is deposited in coastal shoreface environment (Walker 1990).

Facies 2: clay-sand facies This facies consists of gypseous clays, clayey sands and fine to coarse-grained sands with the presence of sulphated or carbonated levels toward the top of the sequence (Fig. 8b). The sedimentary structures are principally parallel stratifications, locally, lenticular or oblique. This facies is deposited in coastal environment (coastal mudflats) with episodes of confined conditions (gypsum, limestone) in an overall internal platform or a coastal sabkha (Kendall and Harwood 1996; Walker 1990).

Facies 3: sandy-conglomeratic facies This facies consists of massive sands and heterogeneous conglomerates. Sedimentary structures are mostly parallel and cross-bedding or metric trough-cross stratifications (Figs. 7k and 8f). It is characterized by deposits of crossbars alternating with channel deposition with vertical and lateral aggradations at its top. This facies corresponds to filling deposits in very coastal environment; it is typical of beach face deposition (Miall 1988).

In the western sector, unit III, 70–180-m thick, is composed of decametric strato-grano increasing parasequences with two (clay-sandstone) or three terms (clay-sandy clay-sand). Clays are sometimes sandy or with small crystals of gypsum; locally, they contain small green clay balls and some millimetric to centimetric laminae of gypsum. Sands, brown-red or yellowish-white, are fine to medium grained; at the base of the unit, they are in metric beds showing oblique or cross-bedded then parallel stratification showing coarsening up sequence and containing centimetric nodules of green or red clays passing at sandstones in decimetric benches with parallel laminations. Next come gypseous brown red clays and white sandstones containing millimetric to centimetric gypsum crystals.

Two facies are present in this unit: the clay-sandstone or clay-sandy clays-sand facies and gypseous clay-sandstone facies.

Those facies correspond to fluvial deposits. They represent the evolution from brackish to continental environment.

Paleogeographic evolution model and discussion

After the orogenic Lutetian phase, responsible for the formation of the Atlasic chain (Saharan Atlas and Aures), the whole Aures and Zibans areas emerged and experienced a peneplanation during the Oligocene (Laffitte 1939; Guiraud 1973, 1990). The sea then, at the start of the Miocene, covered the region which corresponds presently to the Aures massif in the NE of the study zone (Guiraud 1990; Chebbah 2007).

In the early Miocene, the active extensional tectonics caused the formation of NW-SE normal faults which allowed the sea transgression through the channels belonging to preexisting fluvial network (Guiraud 1973, 1990; Chebbah 2007). The sea coming from the North invaded the Zibane zone, what was site of the onset of shallow water sectors to the NE while to the west and central part of the study area, the open sea conditions were established. Thus, paleogeography was characterized by the juxtaposition of several depositional environments (shoreline 1, Fig. 4a). In the W and S, the erosion of emerged area supplied a coastal basin with a detrital environment and internal platform; this basin is a true stocking zone for the coarse detrital elements. It was separated from the open sea by a sandy barrier which reduced detrital contributions to the more external zones formed by a horst and graben system.

During the middle Miocene, following the collapse toward the NW of Biskra-Droh sector, which formed a highest area in the lower Miocene, a hemi-graben was created and immediately invaded by the sea coming from the Nord. The graben was separated from the NE sector by horst lying in the present location of Ras Chicha—Dj. Bou Rhezal. The paleogeography corresponded to a small trench as a coastal basin type filled with coarse silicoclastic deposits (debris flows). Thereafter, tectonic readjustments favoured the confinement of the environment, then evaporite facies similar to those equivalents of the NE sector were deposited; the area was shed from coarse contributions (small graben bordering a shallow platform). The paleogeography was a graben bordering a shallow platform, limited by a horst inducing an environment confinement subject to marine incursions under warm and arid climate. In parallel, the marine transgression continued toward the S (shoreline 2, Fig. 4a), but the sea become shallower due to the filling of different sub-basins. In spite of marine transgression, the sea level decreased due to the high sedimentation rate that filled the basin, during a decrease of the tectonic subsidence. The confinement is becoming more pronounced in the NE area with the installation of a thick gypsum formation (clay-gypsum facies).

During the upper Miocene, the sea tended to cover the southern area; the tectonic readjustments promote the contributions of materials especially in the western zones and confinement in the

eastern zones (shoreline 3, Fig. 4a). Therefore, after a confinement period, there is a recovery of erosion on the continental margin; the environment without strong subsidence without significant contributions was filling slowly (fluvial spreading deposits of shallow environment more or less protected) during the Tortonian.

During the Messinian, the uprising of the Aures massif produced a regional angular unconformity above, which mixed environment sediments laid on the Tortonian; the sediments vary from evaporite or restricted environment to the coastal environment or beach deposits.

This depositional reconstruction based on the distribution and facies associations and the filling modalities of various sectors of the study area shows a paleogeographic evolution different from the one commonly accepted by all authors for this area and for most of the eastern Atlasic basins of Algeria during the Miocene, where all post-Burdigalian deposits were attributed to continental environments (fluvial or lagoonal). At the regional scale, these new data imply a reconsideration of the environments of the Miocene depositions in some Neogene atlasic basins mainly those of the eastern Atlasic domain.

Conclusions

A new interpretation of the Miocene deposits in the Zibane zone has been developed based on field data and facies analysis. The collected data provides a new conceptual model for the paleogeographic evolution of the Miocene deposits of this Atlasic zone.

The stacking patterns and the distribution of the various facies associations in each part of the Zibane zone allow to consider its filling during the Miocene within the framework of a restricted platform model where three sub-basins are bounded by NW-SE faults with different filling modalities. After a post-Lutetian generalized sub-aerial emersion, the lower Miocene sea covered progressively the region, which was a shallow shelf compartmented by high-fund subsiding lagoon zones which were confined and supersaturated in brine.

The transgression is generalized during the Burdigalian resulted in the progressive flooding of the platform. During the middle Miocene, the paleogeography was made of sub-basins limited by horsts which induced an environment confinement subjected to marine intrusions under a hot and arid climate. During the upper Miocene, the sea progressively retreated from the west sector while coastal mud flats and tidal system developed to the East.

This paleogeographic evolution differs from the one commonly accepted in the region during the Neogene where all post-Burdigalian formations were considered by all authors as continental deposits; this implies a reconsideration of the environments of Miocene depositions in some Neogene basins of the eastern Atlasic domain in Algeria.

Appendix A

Table 1 Relative abundance of sand, silt and clay percentages and granulometric indices of studied samples collected from Miocene deposits in the Zibane zone

Units	Sequences	Sectors	Sand (%)	Silt (%)		Clay (%)	2–0.063-mm fraction				Standard deviation σ (ϕ)	Skewness S _{ki} (ϕ)	Kurtosis K _g (ϕ)
				Carbonate + Gypsum	Gypsum		Mean Md (μ m)	Prim. mod particle Cu (μ m)	Median Mz (ϕ)				
Unit III	SD5	SE	91.8–97.8	1.2–7.66	0.6–2.13	0.71–1.90	110–670	320–1180	0.65–2.98	0.73–1.13	–0.05–0.47	0.70	1.89
		NE	95.4–98.3	1.2–1.6	0–0.8	0.40–1.98	150–420	530–3450	1.26–2.86	0.63–0.88	–0.06–0.27	0.93	1.66
		Centre	4.3–96.91	1.4–36.9	0–18	1.93–58.68	87–270	450–800	1.75–3.23	0.69–1.61	–0.43–0.42	0.74	–0.83
	SD4	W	46.3–95.35	2.1–17.1	1.–7.1	1.78–30.83	120–330	430–790	1.69–3.15	0.58–0.95	–0.03–0.95	0.60	1.68
		SE	0.3–96.4	0.6–11.9	0.6–7.2	1.3–92.36	90–600	470–1580	0.47–2.46	0.62–1.31	–0.01–0.48	0.95	1.65
		NE	99.82–82.44	0.1–8.05	0.1–1.3	0.52–9.51	84–240	260–840	2.07–3.47	0.44–1.89	–0.01–0.12	0.75	1.77
Unit II	SD3	Centre	2.2–98.55	0.5–39.5	0.5–5.6	0.95–58.30	105–280	430–820	1.92–3.06	0.69–1.23	–0.07–0.30	0.78	–1.44
		W	0.5–94.21	3.1–5.2	3.1–4.8	3.14–92.7	110–670	320–1180	0.65–2.98	0.73–1.13	–0.05–0.46	0.70	1.89
		SE	0–95.75	2.4–27.2	2.4–25.2	1.62–69.76	86–240	390–580	2.09–3.59	0.65–1.09	–0.04–0.32	0.83	1.60
	SD2	NE	2.80–71.35	0–93.5	12.8–87.5	3.6–94.25	345–330	820–780	1.79–4.81	1.06–1.08	0.38–0.32	0.94	0.89
		Centre	82.05–98.37	0.7–42.1	0.7–22.3	0.8–57.93	190–220	570–750	2.16–2.,31	0.86–1.01	–0.16–0.12	0.70	–1.43
		W	38.61–82.0	3.2–15.3	2.1–5.6	1.78–90.3	210–280	450–520	1.96–2.31	0.66–0.82	0.215–0.45	0.77	–1.1
Unit I	SD2	NE	1.34–11.6	12.7–18.5	12.7–18.5	75.87–82.7	234–290	710–730	1.5–3.7	0.6–0.8	0.3–0.34	0.94	0.03
		Centre	0	63.4–79.8	0–2.8	20.2–36.6	–	–	–	–	–	–	–
		W	4.80–71.35	5–10.5	0.8–5.6	3.6–94.25	190–340	460–980	–0.06–0.59	1.08–1.81	1.17–2.17	0.59	–1.05
	SD1	NE	0–12.3	21.4–46.7	20.7–42.3	51.2–76.5	–	–	–	–	–	–	–
		Centre	0–0.3	26–32	26–32	68.00–74.00	–	–	–	–	–	–	–
		W	0.3–1.3	24–30	24–27.9	58.00–71.00	–	–	–	–	–	–	–

Litho-stratigraphic units: Unit I: Early Miocene, Unit II: Middle Miocene, Unit III: Late Miocene
 3rd order sequences: SD1: Aquitanian, SD2: Burdigalian, SD3: Langhian Serravallian, SD4: Tortonian, SD5: Messinian

Appendix B

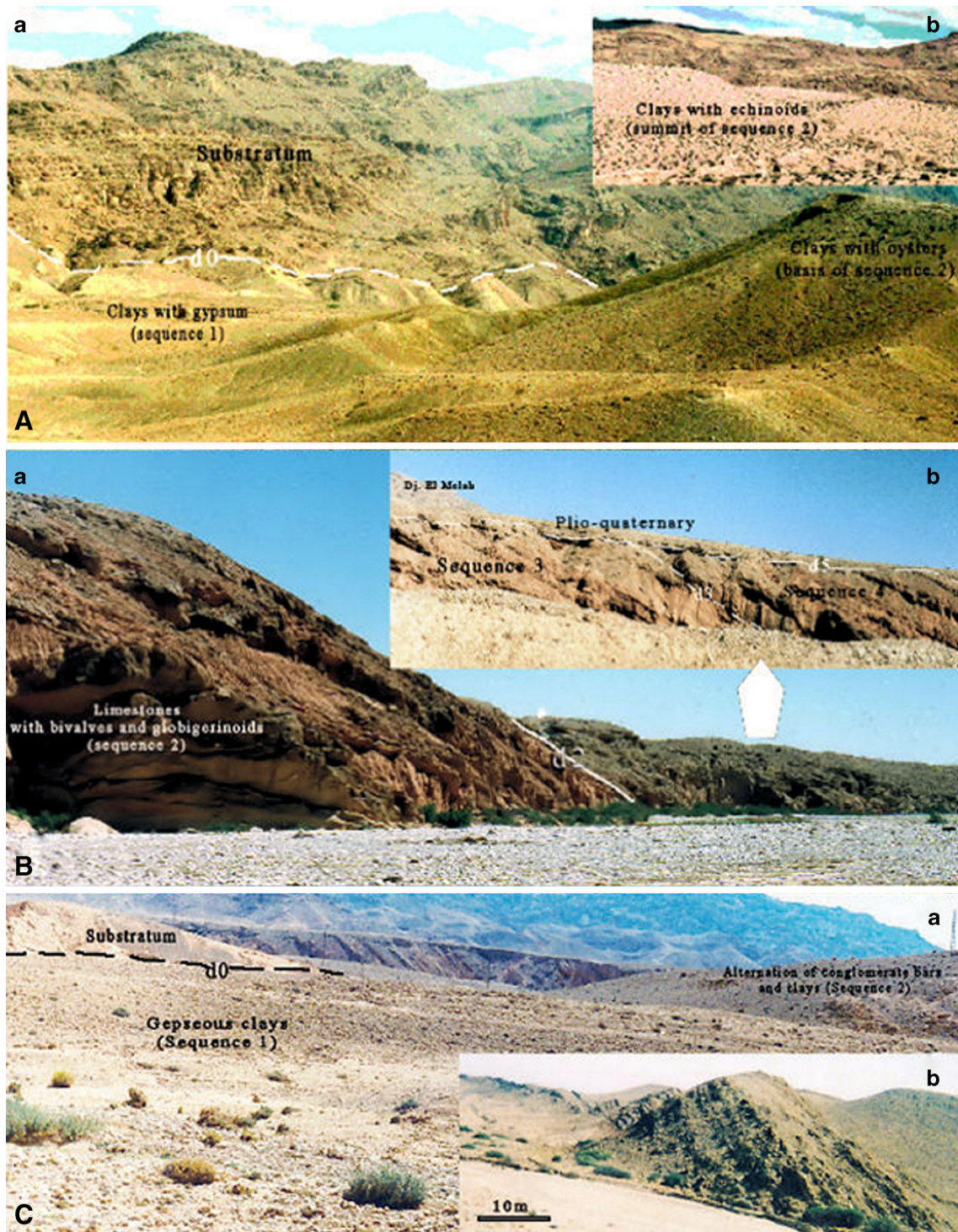


Fig. 5 *a* The early Miocene clays (sequence 1 and sequence 2) in the SE sector (Branis) *a* Greenish brown clays with gypsum (sequence 1) unconformably overlies the anti-Miocene formations (substratum) and overlain by greenish brown clays with oysters (the basis of sequence 2), *b* Brown clays with echinoids (the summit of sequence 2). *b a*. The Burdigalian limestones (sequence 2) in the central sector (El Outaya, East

Oued Biskra) overlain by the sequence 3 (Middle Miocene), *b* Close-up of the sequences 3 and 4 in the central sector (El Outaya, East Oued Biskra) *c a* Yellow-green gypseous clays (sequence 1) unconformably overlies the anti-Miocene formations (substratum) and overlain by alternation of conglomerate bars and clays (sequence 2), *b* Close-up of the sequence 2 where conglomerate bars showing a clear stratification

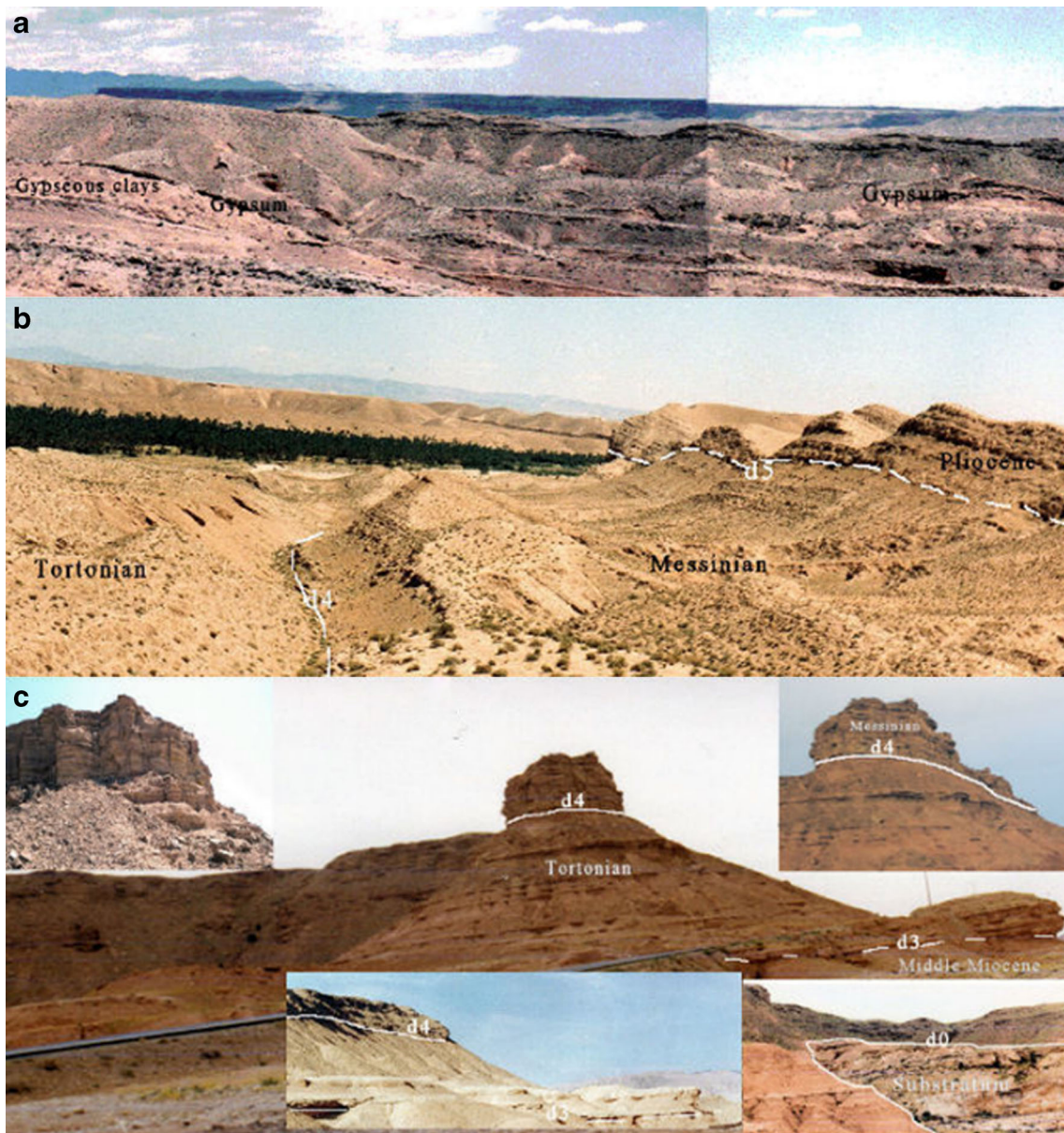


Fig. 6 **a** General view of sequence 3, clays-gypsum alternation; beds of gypsum draw a clear parallel stratification in this sequence, NE sector. **b** The Messinian unconformity overlies the Tortonian which in turn unconformably overlain by the Pliocene in the NE sector. **c** General view of the Miocene showing various unconformities registered in the SE sector

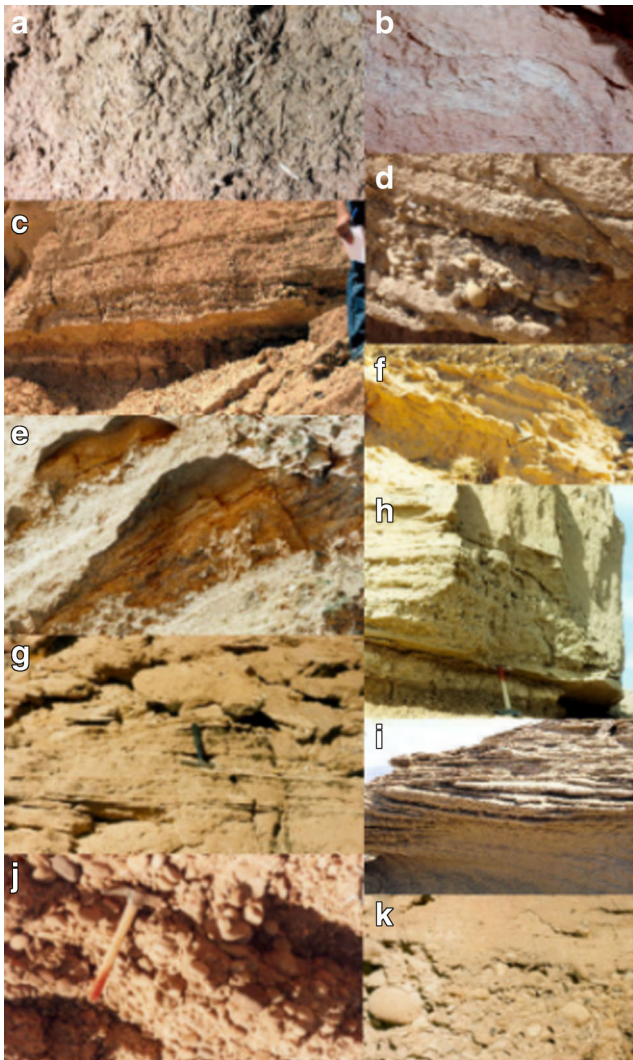


Fig. 7 Some sedimentological features of the Miocene deposits in the Zibane zone. **a** Clay facies containing gypsum crystals (*arrows*), sequence 1, NE sector (Branis). **b** Clay facies showing a synsedimentary deformation, sequence 3, SE sector (Droh). **c** Sandstone facies with erosive contact (*arrows*) showing large parallel stratifications, sequence 4, West Oued Biskra, El Outaya. **d** Close-up of sandstones with conglomerate base, sequence 4, SE sector, Chetma. **e** Sandstones with parallel to slightly wavy stratifications, NE sector, Branis. **f** Sandstone facies showing large parallel stratifications, central sector. **g** Parallel then cross-bedded stratification of the sandstones, sequence 4, East Oued Biskra, El Outaya. **h** Erosive contact between clay facies-SD4 (*below*) and sand facies with conglomerate base SD5 (*above*) in the SE sector (Lahbel). **i** Parallel then oblique stratification in the sandstones, sequence 4, SE sector, Lahbel. **j** General view of conglomerate facies in the NE sector. **k** Sandy-conglomeratic facies association showing trough cross-bedded stratifications, SE sector (Chetma)

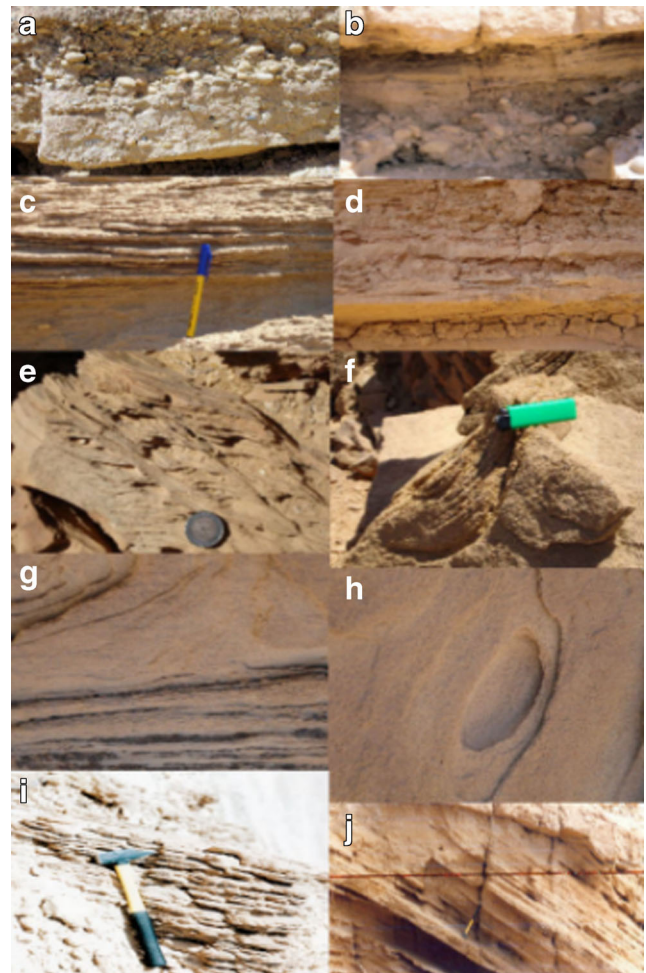


Fig. 8 Some sedimentological features of the Miocene deposits in the Zibane zone (following). **a** Sandstones with conglomeratic crossings, sequence 4, West Oued Biskra, El Outaya. **b** Alternation of clays and sandstones, sequence 4, SE sector, Lahbel. **c** Large parallel stratifications in the sandstones, sequence 3, East Oued Biskra, El outaya. **d** Clay facies, sequence 3, SE sector, Droh. **e** Cross-bedded sandstone facies, sequence 5, SE sector, Chetma. **f** Trough-cross stratifications in the sandstones, sequence 5, Lahbel. **h** and **g** Current figures in the sandstones, sequence 5, SE sector, Droh. **i** sandstones with parallel laminations, sequence 3, El Outaya, West Oued Biskra. **j** Oblique stratifications in the sandstones, sequence 4, SE sector, Chetma

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