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Evolution of and Factors Controlling Eocene Sedimentation in the Darende-Balaban Basin, Malatya (Eastern Turkey)

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Abstract: Collision of the Arabian and Anatolian plates affected evolution of basins located along the southern flank of the Anatolian Plate. The Darende-Balaban foreland basin is one such basin – a basin filled with Upper Cretaceous and Eocene sediments, accumulated unconformably and transgressively above ophiolitic and carbonate basement rocks. This basin is locally surrounded, to the north and south, by Late Jurassic–Early Cretaceous structural highs created by tectonic elements during the collision of Arabia and Anatolia. This paper aims to describe the factors controlling and evolution of the Eocene sedimentation in the Darende-Balaban basin.

The basin fill comprises two distinct sequences separated by an angular unconformity: (1) the Upper Cretaceous continental to shallow-marine sediments that fall into three formations, namely reefal carbonates of the Tohma formation, the continental to shallow-marine Ulupınar formation and shallow-marine calcarenites of the Kırankaya formation. In the southern and northern parts of the basin, there are distinct lateral and vertical lithological variations in each formation; (2) Lutetian shoreline to shallow-marine successions of the Korgantepe formation, shallow-marine to offshore successions of the Yenice formation, and reefal carbonates of the Asartepe formation. The basin fill ends with the Priabonian shallow-marine Darende formation. Several sedimentological sections were measured and rock samples were collected for petrographic and palaeontological studies to examine facies distribution, lithological and sedimentological changes in the Eocene units, and to obtain precise dates for the sedimentary succession.

The results suggest that Eocene sedimentation in the Darende-Balaban foreland basin was highly affected externally by the north–south compressional regime as a consequence of collision between the Anatolian and Arabian plates which commenced just after the Late Cretaceous and continued until the Eocene. The basin fill was also affected internally by the sedimentary factors or processes, such as provenance, basin topography, sedimentary input and climate.

Key Words: Darende-Balaban basin, Malatya, Turkey, Eocene, foreland basin, factors controlling sedimentation

Darende-Balaban Havzasında Eosen Sedimantasyonunun Evrimi ve Sedimantasyonu Kontrol Eden Faktörler, Malatya (Doğu Türkiye)

Özet: Arap ve Anadolu levhalarının sıkışması, Anadolu levhasının güney kısmında yer alan havzaların oluşumunu etkilemiştir. Bu çalışma Darende-Balaban havzasının oluşumunu ve sedimantasyonu etkileyen faktörleri açıklamaktadır. Önülke (foreland) özellikteki Darende-Balaban havzası yersel olarak kuzey ve güneyde Arap ve Anadolu levhalarının çarpışması ile ilgili tektonik unsurlardan oluşan yapısal yükselimlerle sınırlanmıştır. Havza dolgusu genel olarak açısal diskordan ve transgresif olarak ofiyolitik ve karbonat kayaçlardan oluşan temeli üzerleyen Üst Kretase ve Eosen sedimanları ile temsil edilir.

Havza dolgusu Geç Kretase'ye ait ve havzanın güney ve kuzey kısmında yanal ve düşey litolojik farklılıklar sunan karasal-sığ denizel sedimanların ardalanmalarından oluşmaktadır. Bunlar: resifal özellikteki Tohma formasyonu, karasal-sığ denizel Ulupınar formasyonu ve sığ denizel kalkarenitli Kırankaya formasyonudur. Üst Kretase birimleri diskordan olarak kıyı-sığ denizel Korgantepe formasyonu (Lütesiyen), sığ deniz-kıyı ilerisi özellikteki Yenice formasyonu (Lütesiyen), resifal özellikteki Asartepe formasyonu ve son olarak sığ denizel Darende formasyonu (Priaboniyen) tarafından üzerlenmektedir. Eosen birimlerindeki fasiyes değişimleri, litolojik ve sedimantolojik değişiklikleri incelemek üzere sedimantolojik kesitler ölçülmüş ve örnekler derlenmiştir. Sedimanter istifin yaşını ve fosil içeriğini saptamak amacıyla paleontolojik örneklerde alınmıştır.

Bu çalışmadan elde edilen veriler Eosen sedimantasyonunun Geç Kretase sonrasında oluşan ve Eosen'de de oluşumuna devam eden Anadolu-Arap levhalarının kuzey-güney yöndeki sıkışma rejiminden oldukça etkilendiğini göstermiştir. Bu önülke (foreland) havzasının dolgusu içsel olarak kaynak havza, havza topografyası, sedimanter girdi ve iklim gibi sedimantolojik etmenlerden de etkilenmiştir.

Anahtar Sözcükler: Darende-Balaban Havzası, Malatya, Türkiye, Eosen, önülke havzası, sedimantasyonu kontrol eden faktörler

Introduction

The Darende-Balaban basin (Malatya, eastern Turkey) is located in the eastern part of the Taurides and evolved under the effects of the Alpine orogeny (Figure 1). The Taurus Mountains are divided in three main tectonic elements: namely, western, central and eastern (Ketin 1960, 1966; Altınlı 1966; Arpat & Şaroğlu 1972; Özgül 1976; Robertson 2000). Özgül (1976) emphasized that the Ecemiş fault forms the western boundary of the eastern Taurides, while Robertson (2000) implied that the junction of the East Anatolian Fault Zone and Dead Sea Fault Zone near Kahraman Maraş is the western limit. On the other hand, Akay (1989) claimed that the eastern Taurides is the region located to the east of the East Anatolian Fault System and lies to the north of the Southeast Anatolian thrust belt. Neotethys opened after the Late Triassic, following closure of Palaeotethys (Şengör & Yılmaz 1981). The northern branch of Neotethys was situated between the Anatolide-Tauride platform to the south and the Pontides to the north, while the southern branch was situated between the Anatolide-Tauride platform to the north and the African-Arabian plate to the south (Şengör & Yılmaz 1981; Yazgan 1984; Kozlu 1997; Gül 2000). North-dipping subduction zone(s) developed as a consequence of collision between the Eurasian and Arabian-African plates during the late Early Cretaceous (Yazgan 1984) or Late Cretaceous (Şengör & Yılmaz 1981; Kozlu 1997; Gül 2000). Volcanic arcs, and several back-arc and foreland basins developed in connection with subduction during Late Cretaceous–Palaeocene time (e.g., Şengör & Yılmaz 1981; Yazgan 1984; Aktaş & Robertson 1984, 1990; Robertson 2000; Aksoy *et al.* 2005). Yazgan & Chessex (1991) implied that the collision between the arc and continent began in Late Campanian–Early Maastrichtian time and continued until the Early Eocene. The geologic units that belong to this time interval occur as para-allochthonous and/or autochthonous units that overlie either the allochthonous Malatya metamorphics or sedimentary successions deposited in continental, shallow-marine, fan and deep-sea environments (Önal & Gözübol 1992). The nappes evolved and were emplaced towards the south during Late Cretaceous, Early–Late Eocene and Early–Middle Miocene times. Subsequent to complete consumption of the Neotethyan ocean, neotectonic deformation in Turkey began.

The neotectonic architecture of Turkey is controlled by three major structural elements: (1) the Aegean-Cyprean Arc; (2) the North Anatolian Fault System; and (3) the East Anatolian Fault System (EAFS) (e.g., Bozkurt 2001 and references therein). The EAFS is the major structural element closest to the Darende-Balaban basin. The age and evolution of this structure is under debate and proposals range between Late Miocene and 3 Ma (e.g., Bozkurt 2001 and references therein). Conversely, others claim that sinistral motion along the EAFS commenced sometime between 5–3 Ma following cessation of motion along the Malatya-Ovacık fault zone (Westaway & Arger 1996, 2001; Westaway 2003).

Several researchers have indicated that a compressional regime prevailed in the area between Malatya and Elazığ causing foreland-basin(s) development during the Late Cretaceous–Early Palaeocene (Yazgan 1984; Cronin *et al.* 2000; Aksoy *et al.* 2005). A continuum of Anatolia-Arabia collision during the Eocene resulted in formation of rather narrow, elongate sedimentary basins at the margins of these plates, particularly in the foreland and on the southern flank of the Anatolian plate. Some of these are described as elongate strike-slip/thrust-bounded basins (e.g., Van and Muş basins; Dewey *et al.* 1986). During this time, arcs and back-arc basins developed in the Elazığ and Hazar areas (Aksoy *et al.* 2005), while initially foreland basins also developed over the Arabian plate and consuming oceanic plate situated between the Arabian plate and the Maden Complex (Yazgan 1984). The continuum of this compression resulted in closure of Neotethys and caused large tectonic- slab emplacements and development of several intramontane basins with irregular basin surfaces upon these slabs (Yazgan 1984).

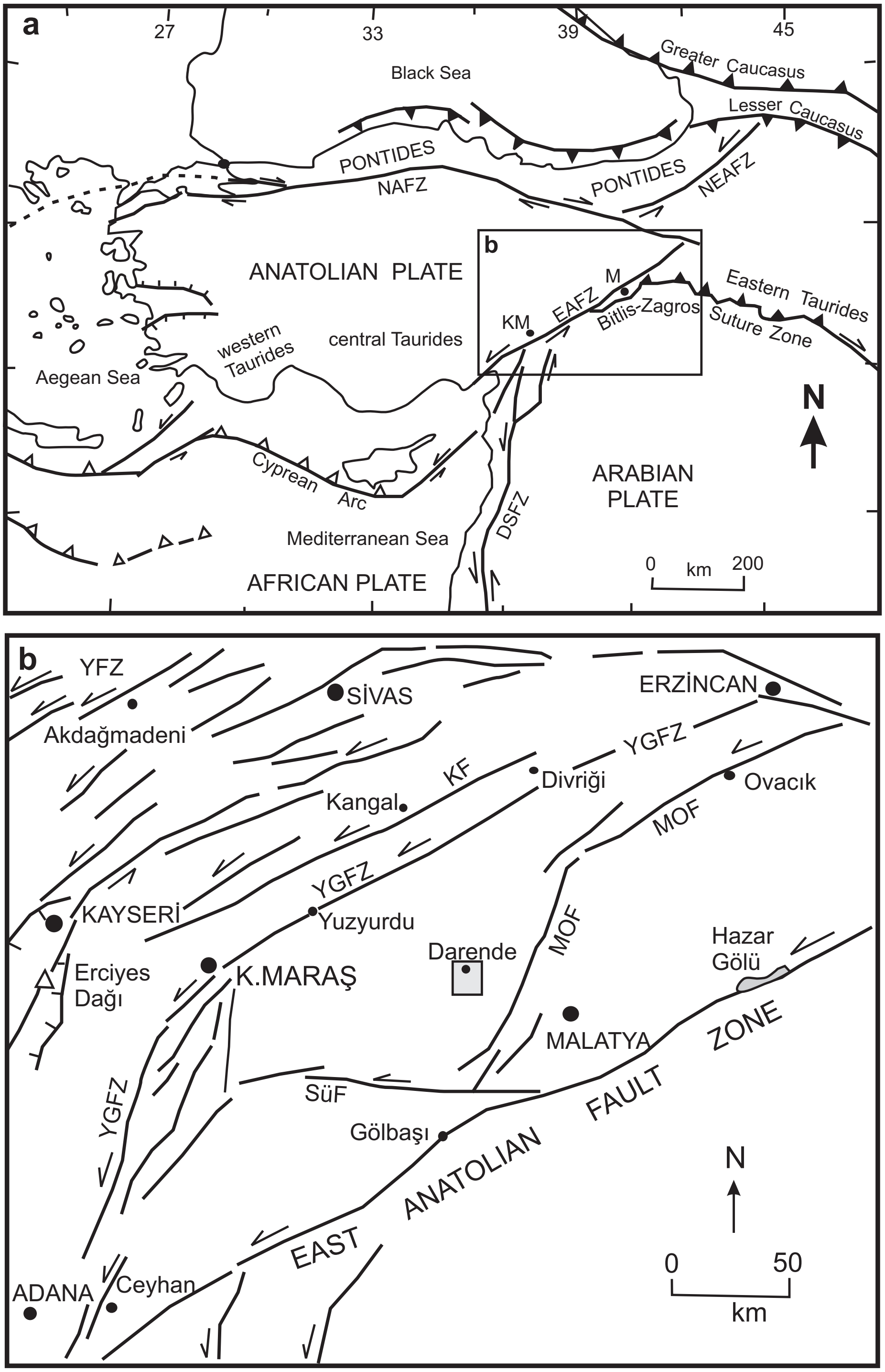

Figure 1. Simplified tectonic map of Turkey showing major neotectonic structures and plates (a) and location map (b) of the study area (simplified and modified from Bozkurt 2001). M – Malatya, KF – Kangal Fault, KM– Kahramanmaraş, MOF – Malatya-Ovacık Fault, SüF – Sürgü Fault, YFZ – Yıldızeli Fault Zone, DSFZ – Dead-Sea Fault Zone, EAFZ– East Anatolian Fault Zone, NAFZ– North Anatolian Fault Zone, YGFZ – Yakapınar-Göksun Fault Zone, and NEAFZ – Northeast Anatolian Fault Zone.

The Darende–Balaban basin is one of these foreland basins, and is connected with a back-arc basin (Yazgan 1984; Aktaş & Robertson 1984, 1990; Özkul 1988; Cronin *et al.* 2000) located to the ESE, namely the Kırkgeçit (Turan 1993; Aksoy 1988) or Elazığ basin (Cronin *et al.* 2000; Aksoy *et al.* 2005). Jurassic–Cretaceous limestones and Upper Cretaceous ophiolites comprise basement to this basin. Upper Cretaceous and Tertiary sediments successively and unconformably overlie the basement rocks (Akkuş 1970, 1971).

Many general geological and petroleum exploration-related studies have been done in and around the Darende-Balaban basin since 1938 (Blumenthal 1938; Baykal 1944; Demirtaşlı & Ayan 1963; Ürgün 1963; Ayan & Bulut 1964; Wirtz 1965; Akkuş 1970, 1971; Kurtman & Akkuş 1974; Kurtman 1978; Örçen 1985-1986; Metin *et al.* 1987; Tarhan 1987; Yazgan & Chessex 1991; Dilek *et al.* 1996; Dumanlılar *et al.* 1999). Despite this enormous amount of work, studies of the sedimentological aspects and evolution of the basin are scarce. Studying the evolution of this basin is therefore important and would contribute to a better understanding of the regional processes related to collision of the Anatolian and Arabian plates and consequent closure of Neotethys. The depositional characteristics of the basin have been examined in order to assess the external and internal factors that controlled basin evolution.

Stratigraphy and Sedimentology of the Basin

The basement to the Darende-Balaban basin is represented by Upper Jurassic–Lower Cretaceous carbonate and ophiolitic rocks that are exposed on tectonically uplifted structural highs north and south of the basin (Figure 2). The oldest basement unit is the Geniz limestone, comprising limestone, chert, chalk and some dolomite horizons of Jurassic–Early Cretaceous age (Figures 2 & 3). The limestones are interpreted as having formed on a shallow-marine carbonate platform during the opening of the southern branch of Neotethys (Akkuş 1970, 1971). These shallow-marine carbonates are tectonically overlain by tectonically transported ophiolitic rocks of the İspendere ophiolites – remnants of Neotethys (Metin *et al.* 1987; Dumanlılar *et al.* 1999). These ophiolites consist of serpentinite, gabbro, spilite and Jurassic limestone olistoliths (Akkuş 1970, 1971; Robertson 2000).

The sedimentary fill of the Darende-Balaban basin (Figures 2 & 3) is composed mainly of shallow-marine to offshore sediments and can be divided – based on age and contact relationhips – into three parts: pre-Eocene, Eocene and post-Eocene units.

Pre-Eocene Basin Fill

As a result of the collision between the Taurides and the Arabian Plate during the Late Cretaceous, the İspendere ophiolite was thrust over Jurassic–Cretaceous platform carbonates (Akkuş 1970, 1971; Yazgan 1984). Thus, several narrow and elongate basins, such as the Darende-Balaban basin, formed and evolved in and around this thrust zone (Yazgan 1984; Dewey *et al.* 1986). The basal part of the basin fill is represented by Upper Cretaceous siliciclastics (Ulupınar formation), reefal limestones (Tohma reefs) and limestones (Kırankaya formation); these rocks unconformably and transgressively overlie the basement limestones (Jurassic) and ophiolites (Cretaceous). Reddish conglomerates and sandstones of the Ulupınar formation (Figure 4) are composed of pebbles derived and transported from the nearby basement highs. As the transgression continued, reddish to beige, medium- to fine-grained sandstones together with beige siltstone and marl alternations developed in the upper parts of the Ulupınar formation. The overlying reefal limestones (Tohma reef) were deposited on palaeotopographic highs as patch reefs where the water was clean, warm and nutrient-rich (Akkuş 1970). These carbonate build-ups contain abundant microfossils and have transitional contacts with underlying fine-grained clastics of the Ulupınar formation. Reactivation of the basin-bounding extensional faults restricted the basin and caused deposition of first coarse-grained then fine-grained sediments in a shallow-marine environment. These are conformably overlain first by clayey limestones and later by limestones of the Kırankaya formation, forming the uppermost levels of the Cretaceous sedimentation in the basin (Figure 4). This was followed by regression and uplift and consequent erosion in the Late Cretaceous (Akkuş 1970).

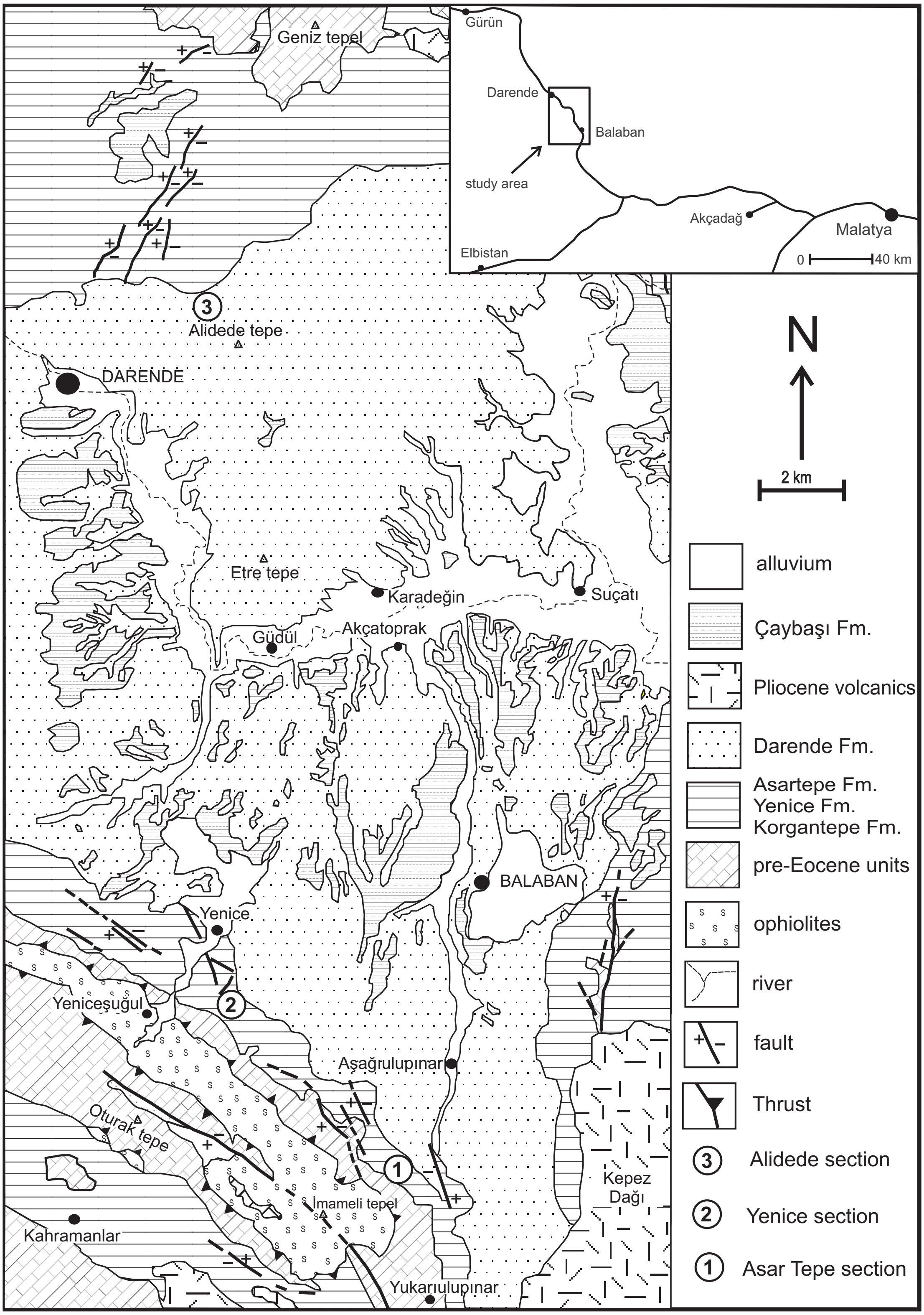

Figure 2. Simplified geological map of the Darende-Balaban basin and locations of measured sections (modified after Akkuş 1971).

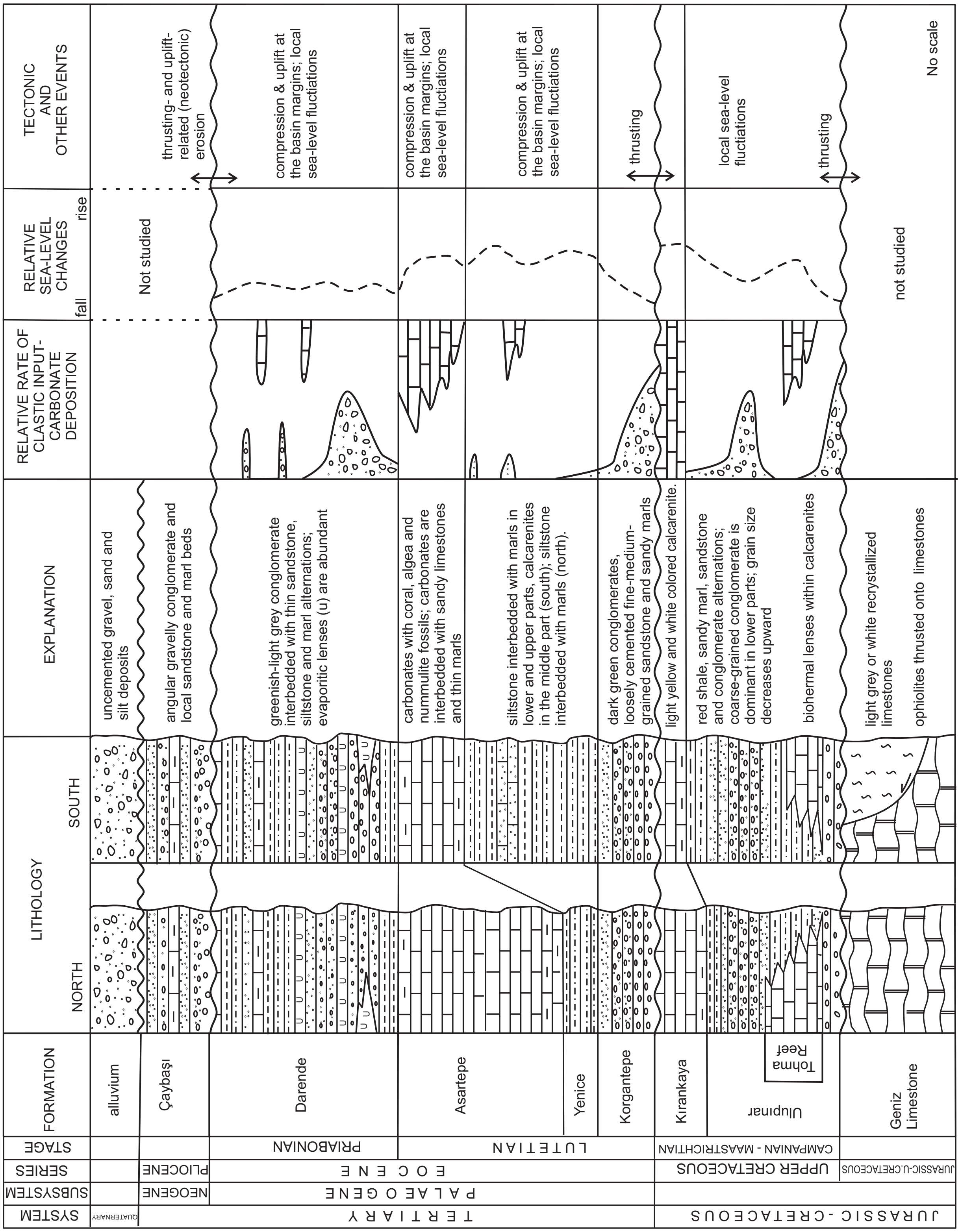

Figure 3. Generalized stratigraphy of the Darende-Balaban basin (modified and redrawn after Akkuş 1971).

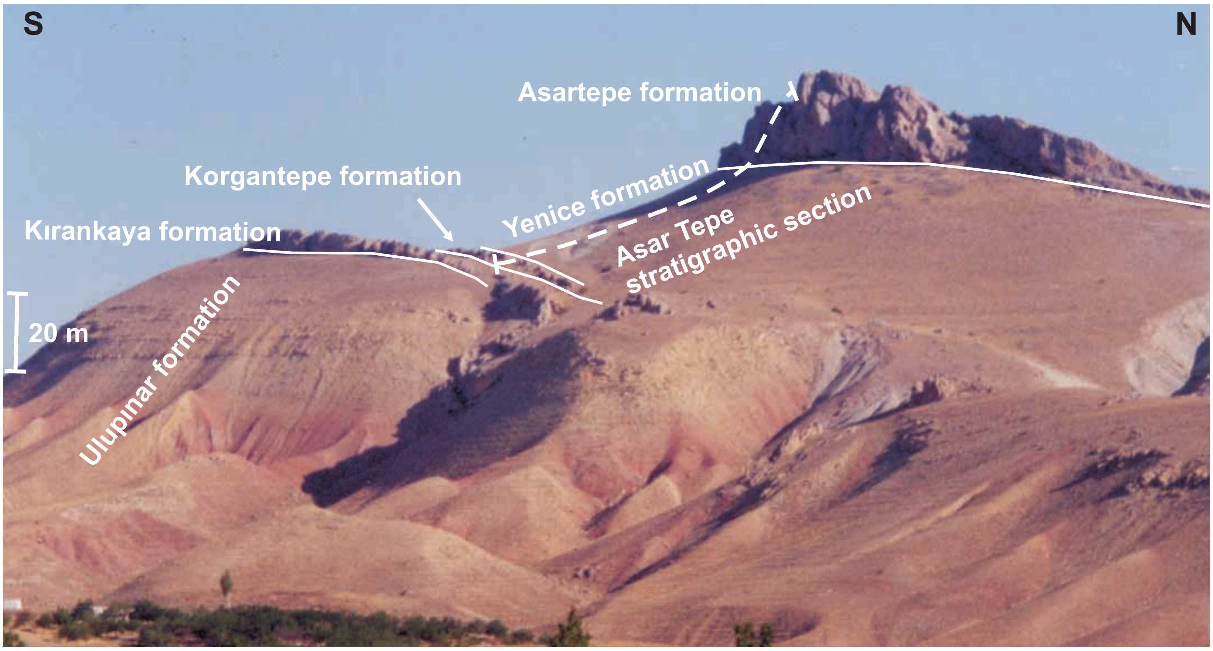

Figure 4. General view of the geologic units in the Darende-Balaban basin. The Lutetian includes conglomerates of the Korgantepe formation, calcarenites of the Yenice formation and reefal limestones of the Asar Tepe formation, and unconformably overlies pre-Lutetian clastics of the Ulupınar formation and limestones of the Kırankaya formation. White dashed line represents the Asar Tepe stratigraphic section.

Eocene Basin Fill

Eocene basin fill unconformably overlies the pre-Eocene rocks and is represented by very shallow- to deep (offshore)-marine sedimentary successions with some biohermal build-ups and evaporitic occurrences. The succession comprises the Lutetian Korgantepe, Yenice and Asartepe formations, and the Priabonian Darende formation. The lower parts of the succession (Lutetian) are aligned parallel to the Upper Cretaceous basement rocks and display thickness- and facies-change variations over short distances in both N–S and E–W directions. The Priabonian rocks are relatively widespread and exhibit low-angle dips (10–20°) compared to the Lutetian sediments (15–45°) in the marginal parts of the basin. Three sections (two from the southern part and one from the northern part of the study area) were measured to examine possible lateral and vertical differences in the sedimentary succession, particularly between the northern and southern parts of the basin (Figure 2). Those differences will be discussed in the following sections.

The Korgantepe Formation. The Korgantepe formation overlies carbonates of the Kırankaya formation and siliciclastics of the Ulupınar formation along an angular unconformity and is overlain gradationally by the Yenice formation (Figures 3 & 5). The maximum measured thickness is about 100 m in the northeastern part of the Darende-Balaban basin (Akkuş 1971) and only 4–25 m in the south. These rocks have also been named the Korgantepe conglomerates because of their coarse-grained character (Akkuş 1971).

Two sections were measured to identify and analyze the lithological character of the Korgantepe formation at Asar Tepe and Yenice. This formation commences with conglomerates unconformably overlying fine-grained sediments of the Ulupınar formation; the contact is sharp and erosional in the two measured sections. The conglomerates display thinning- and fining-upward character, and typically pinch-out over short distances and grade into pebbly sandstones and sandstones.

Five conglomeratic packages with various thicknesses are observed in the Asar Tepe section (Figures 4 & 6). On

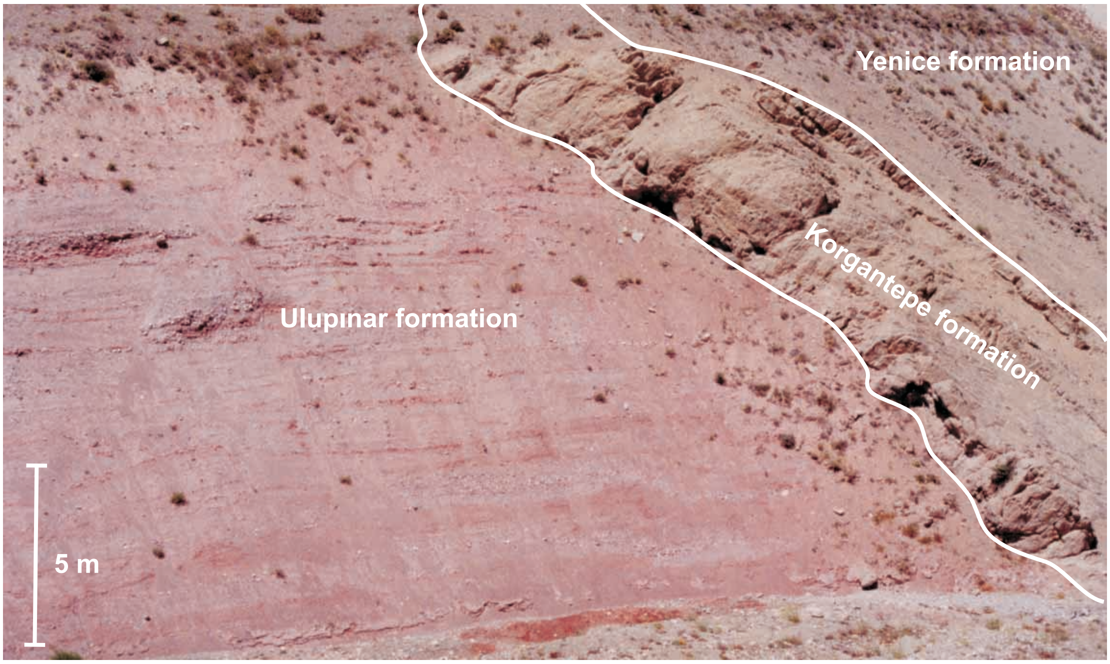

Figure 5. Field view showing conglomerates of the Korgantepe formation that overlie the fine-grained clastics of the Ulupınar formation with an angular unconformity. Marl and siltstone alternations of the Yenice formation concordantly overlie sandy conglomerates of the Korgantepe formation.

the other hand, there is only one conglomeratic package at the base of the Yenice section in the SW part of the basin (Figure 7). The thickness of individual conglomerate beds ranges from 2 m to 4 m. Conglomerates are polygenic, grain-supported and well-imbricated. They first grade upward into pebbly sandstones (1–1.2 m thick), then into 20–30-cm-thick medium-grained sandstones, and finally thin-bedded, fine-grained sandstones intercalated with marls.

The conglomerates and sandstones are composed dominantly of subrounded-rounded grains of crystallized limestone, ophiolitic material and Cretaceous siliciclastic material that crop out at the southern margin of the basin. The Korgantepe formation is characteristically fossiliferous and contains large benthic foraminifers of Lutetian age, such as *Assilina exponens* (Sowerby), *Nummulites beaumonti* d'Archiac & Haime, *Nummulites millecaput* Boubee, *Nummulites praeaturicus* Schaub (*Nummulites, Assilina*) that are abundant (up to 80 %) in some levels (Figure 8a). There is also a sandstone horizon in the upper part of the conglomerate which is classified as lithic arenite (Pettijohn *et al.* 1987; Figure 8b).

Similar coarse-grained sediments deposited in terrestrial (alluvial fan) or shallow-marine environments, with asymmetric distributions along basin margins, have been reported from different localities (in the vicinity of Karaman: Şafak 1999; in the Sivas basin: Ocakoğlu 1999; in the Çankırı basin: Akgün *et al.* 2002; and in Igualada, NE Spain: Taberner *et al.* 2002). Levin (2003) indicated that compression and uplift along basin margins cause release of coarse-grained particles and formation of clastic wedges. Leeder (1982) emphasized that shoreline changes with subsidence at basin margins cause lateral and vertical facies changes in shallow-marine environment.

The erosional base of the conglomeratic beds, the lenticular geometry of whole strata, sequence characteristics and palaeontological evidence from the Korgantepe formation are consistent with deposition in a shoreline- to shallow-marine (shoreline-shore face) environment (Nazik 1993; Erdoğan 2003). A sharp erosional base and imbricated conglomerates in the first part of the section, along with abundant large benthic foraminifers, may reflect the initial flooding of the

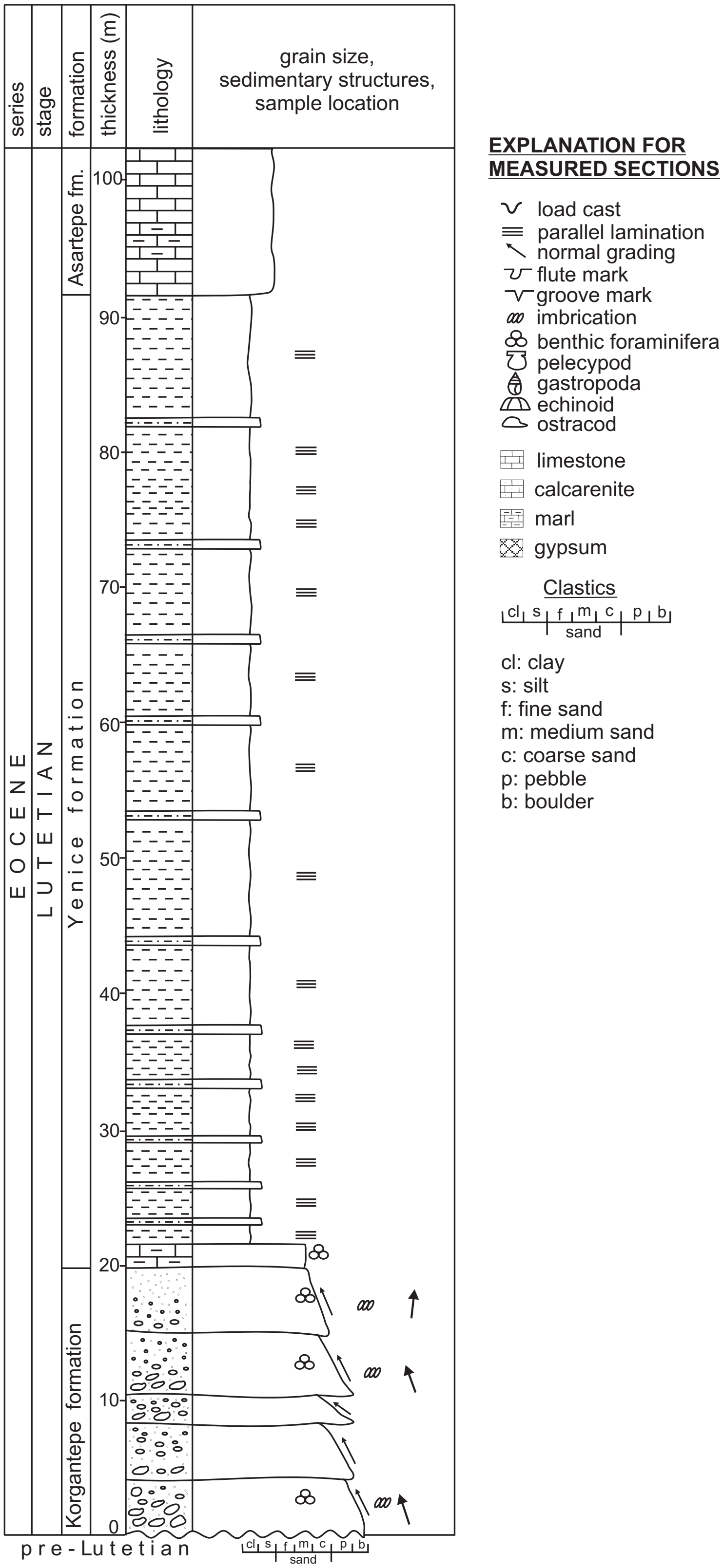

Figure 6. Asartepe measured stratigraphic section of the Asar Tepe formation.

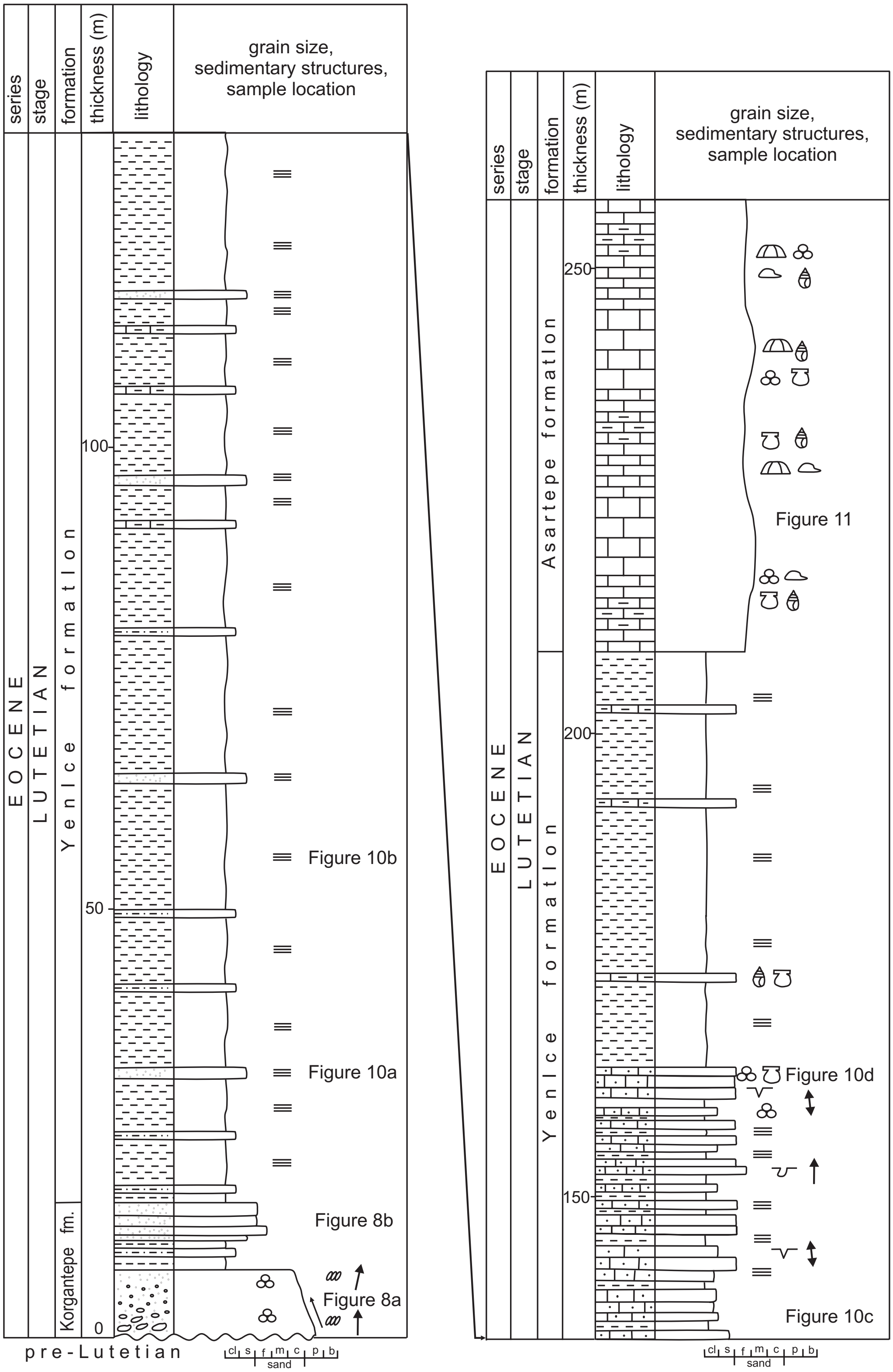

Figure 7. Yenice measured stratigraphic section of the Yenice formation.

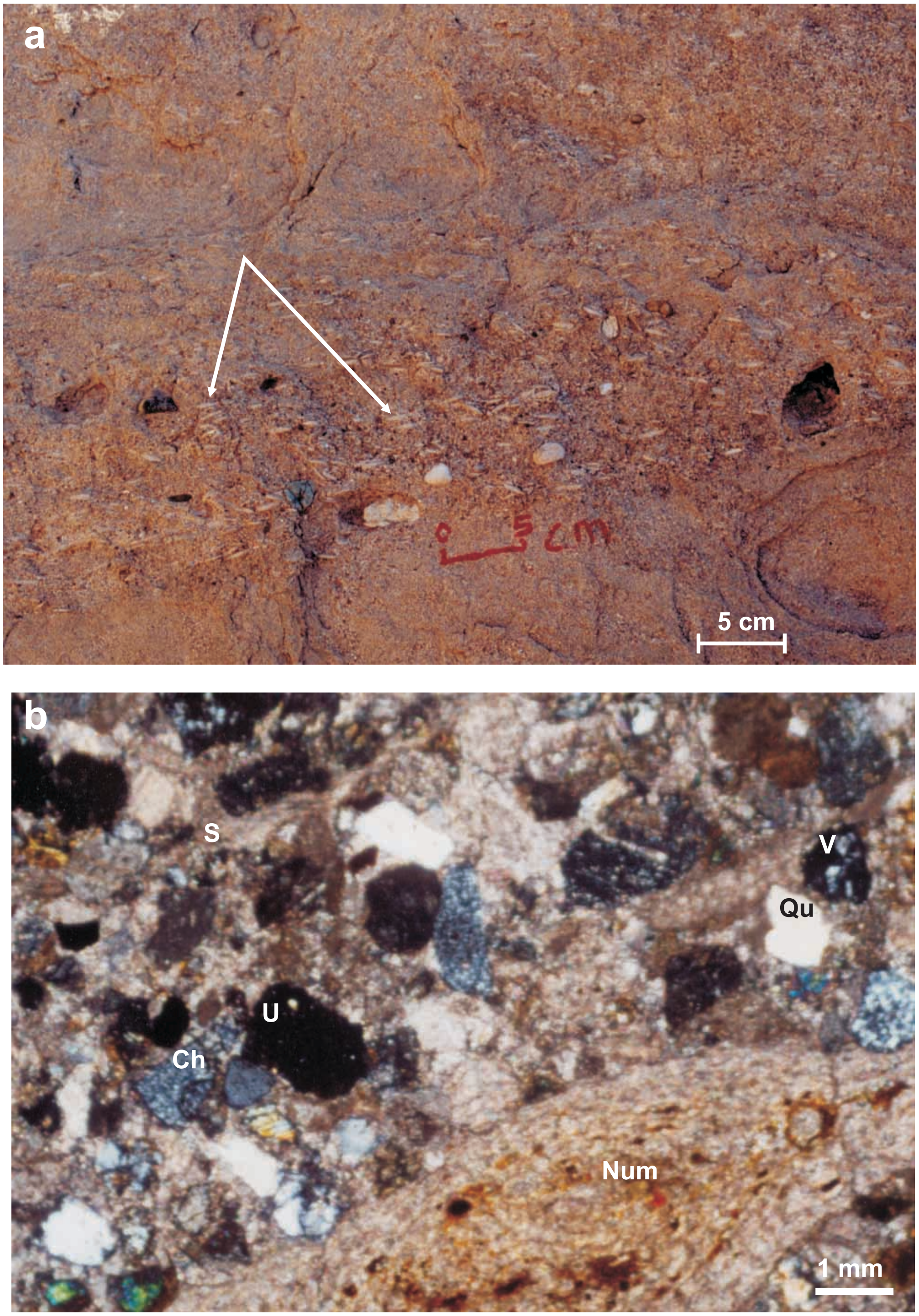

Figure 8. (a) Close up view fossilliferous conglomerates of the Korgantepe formation (5 m of the Yenice section). Platy white grains are *Nummulites* (arrows). Large, elongated or circular white grains are limestone pebbles; (b) photomicrograph of the sandy level from the upper part of the Korgantepe formation (12 m of the Yenice section; **Num** – *Nummulites*, **Qu** – quartz, **Ch** – chert; **U** – ultrabasic rocks, **V** – volcanic rocks, and **S** – sparite).

Lutetian sea. As transgression continued, sandstones and finally sandstones with marl alternations were deposited. Conglomerate packages with finer-grained sediment alternations may indicate either sea-level fluctuations or increase in erosion of the source area due to local tectonics, such as reactivation of faults and uplift in marginal areas (Figure 3). The fact that these conglomerates do not occur in all parts of the basin may be attributed: (i) to lesser amounts of detritus accumulated on the coast or (ii) to the sudden deepening of the basin.

The Yenice Formation. Conglomerates of the Korgantepe formation grade upward into the fine-grained sediments of the Yenice formation (Figure 3). This formation also unconformably overlies the Ulupınar formation (Figure 9a), and comprises two distinct facies which were previously described as two members (Akkuş 1971): the Yenice marls in the lower and upper parts of the formation, and the Yenice calcarenites in the middle (Figure 9b). This calcarenite interval pinches-out laterally into the marls and displays some lenticular geometry in the middle parts of the Yenice formation. Exposures of the Yenice formation in the northern and southern parts of the basin display characteristic lithological and sedimentological differences. For example, the marls do not have great thicknesses in the northern part of the study area, while the lower and upper parts of the marls – with calcarenites in the middle parts – occur only in the southern part (Figure 3). The geometry of the calcarenite interval also shows distinct variations in the southeastern and southwestern parts of the study area. It is not present in the Asar Tepe section in the southeastern part of the study area (Figure 6) but is about 32-m thick in the Yenice section. On the other hand, in its type section the unit contains sandstones of variable thickness (between 125 m and 250 m) interbedded with marls at different levels: thin-bedded (5–10 cm), medium- to coarse-grained sandstones, 125-m-thick medium-bedded (10–30 cm) sandy limestones (calcarenites) and 250-m-thick, thin-bedded (5–10 cm) fine- to medium-grained sandstone (Akkuş 1971). At the top, the marls grades into limestones of the Asartepe formation.

The Yenice marls are represented by alternating white to beige marl and siltstone that typically occupy the lower and upper parts of the Yenice formation. The Yenice calcarenite interval is composed mainly of carbonates with extrabasinal (derived from the ophiolite suite and older rocks situated south of the study area) and intrabasinal (derived from the lower part of the Yenice marls) fragments and some body fossils (coral, algae and nummulites). 71.1 m of uninterrupted claystone-siltstone alternations was measured in the Yenice formation at the Asar Tepe section (Figure 6).

The lower part of the Yenice formation in the Yenice section consists of 123.7-m-thick, claystone-siltstone alternations followed upward by claystone and marl alternations (Figure 7). Abundant rock fragments and less abundant planktonic foraminifera occur in the transitional zone with the Korgantepe formation; the sandstone sample from this horizon can be classified as a lithic graywacke (Pettijohn *et al.* 1987; Figure 10a). The marls are rich in planktonic foraminifers and can be classified as biomicrite (Folk 1962) or packstone (Dunham 1962) (Figure 10b). The measured sedimentary section continues upward with a 31.3-m-thick calcarenite – defined as extrabiomicrite in Folk's classification (1962) or as packstone in Dunham's classification (1962) (Figure 10c) – then by 47.5-m-thick claystone-marl alternation. The calcarenites in this transition, which are classified as biointrasparite (Folk 1962) or grainstone (Dunham 1962), include intraclasts from the lower part of the succession and red algae (Figure 10d). Ostracods *Acarinina bulbrooki* (Bolli), *Turborotalia cerroazulensis frontosa* (Subbotina), *Turborotalia cerroazulensis possagnoensis* (Toumarkine & Bolli), *Bairdia cymbula* (Deltel), *Cytherella triestina* (Kollmann), *Cytherella ihsaniyensis* (Sönmez-Gökçen), and *Krite rutoti* (Keij), and foraminifers *Globigerina cryptomphala* (Glaessner), *Globigerina venezuelana* Hedberg, "*Globigerinoides*" *higginsi* Bolli, *Globigerinatheka subconglobota subconglobota* (Stutskaya), *Globigerinatheka subconglobota lutherbaheri* (Bolli), *Truncorotaloides topilensis* (Cushman), *Truncorotaloides rohri* Brönnimann & Bermüdez, and *Globigerina eocaena* Guembel, were identified by Erdoğan (2003). This fossil content is consistent with a Lutetian age and indicates a rise in sea level during deposition of the Yenice formation marls.

We interpret the Yenice calcarenites as having been deposited in a shallow-marine environment, while the marls were deposited in relatively deeper environment. Our model is supported by the following arguments, set forth in a number of previous studies: (i) claystone-

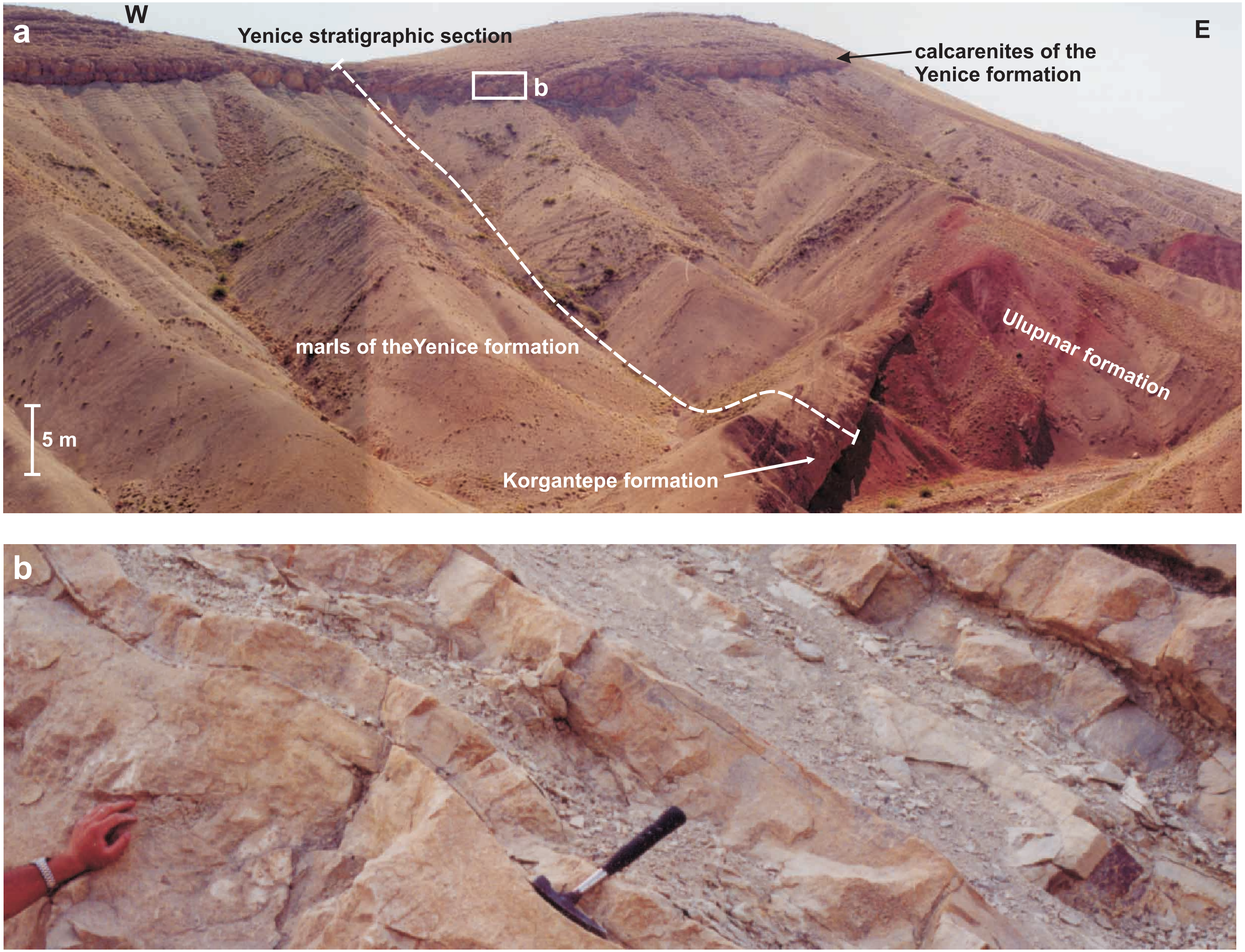

Figure 9. (a) A field view of the Yenice stratigraphic section. The Yenice and Korgantepe formations unconformably overlie the Ulupınar formation; (b) close-up view of laminated claystone and medium-bedded calcarenite alternations of the Yenice formation (rectangular area in a). Hammer is 33-cm long.

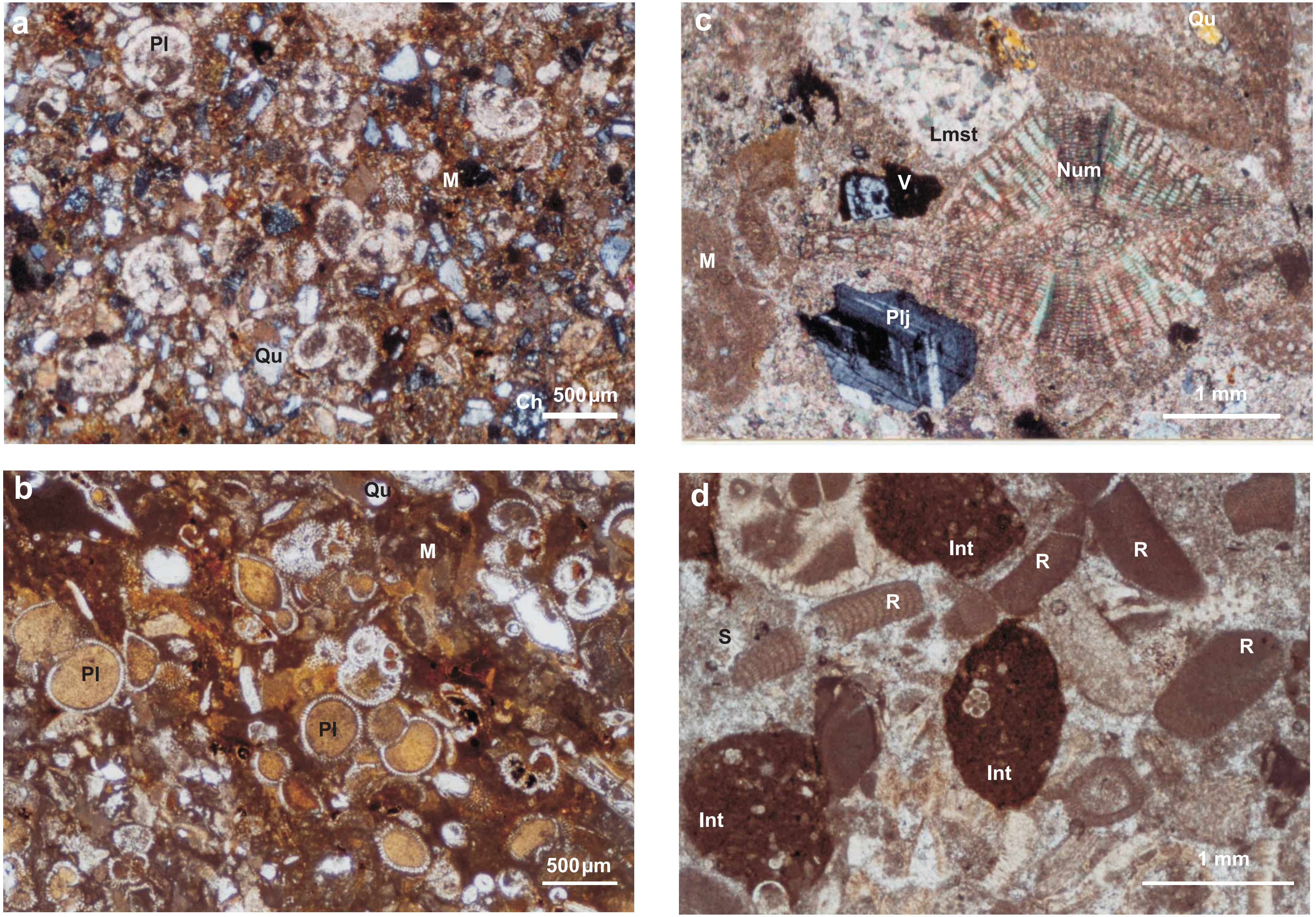

Figure 10. Photomicrographs of the Yenice formation. (a) Lower part, transition of the Korgantepe formation (30 m of the Yenice section; **Pl** – planktic foraminifera, **Qu** – quartz, **Ch** – chert and **M** – micrite); (b) planktic foraminifera (**Pl**) rich marl (60 m of the Yenice section; **Qu** – quartz; **M** – micrite); (c) lower part of the calcarenites (138 m of the Yenice section; **Num** – *Nummulites*, **Plj** – plagioclase, **V** – volcanic rock, **Lmst** – limestone, and **M** – micrite); (d) upper part of the calcarenites (165 m of the Yenice section; **Int** – intraclast, **R** – red algae, and **S** – sparite).

sandstone-nummulite-bearing limestone-claystone alternations are lithological associations typical of shallow marine–lagoon environments (Şafak 1999); (ii) carbonate deposition in shallow-marine environments depends on siliciclastic input: carbonate-poor period develops during lowstands and high siliciclastic input (Dunbar & Dickens 2003); (iii) calcarenites in Caravaca, Spain were products of bottom currents and deposited with hemipelagic marl during high siliciclastic input (Chacon & Martin-Chivelet 2005); (iv) fine-grained sediments such as shale and micrite were deposited in a low-energy environment beneath the wave base or mud line (Selley 1998; Esteves & Finkl 1999); and (v) Late Cenomanian–Satonian sandstone-siltstone-bioclastic calcareous sandstone alternations in Sinai (Egypt) were deposited in a shallow shore-face siliciclastic environment (Bauer *et al.* 2003).

After deposition of the Korgantepe formation, the Lutetian sea continued to deepen and to deposit the Yenice marls under deeper-water conditions with abundant planktic foraminifers, as listed above. Following sea-level drop due to local tectonic activity, the calcarenites were deposited in relatively shallow waters (Figure 3). Palaeocurrents and petrographic evidence (especially reworked grains from the lower part of the Yenice marls and reef occurrences) indicate shallowing of the sea and increasing energy level. These calcarenites have lateral and vertical transitional contacts with marl-claystone alternations in the southern part of the basin but are not present in the northern part of the basin. The occurrence of second-level marls above the calcarenites together with their sedimentological and paleontological characteristics reflect a second phase of sea-level rise.

The Asartepe Formation. The Yenice marls grade upward into the Asartepe formation with increase of sandy material and decrease of lime mud, followed by coral- and algal-rich carbonates in the southern part of the basin (Figures 6 & 7). On the other hand, in the north the Asartepe formation was contemporaneously deposited with marls and calcarenites of the Yenice formation and conformably overlies conglomerates of the Korgantepe formation (Figure 3). Reefal carbonates are much thicker and laterally extensive in the northern part, but are less thick, not extensive and display lenticular geometries in the southern part (Figure 4). Based on pronounced lithological differences and fossil content (Erdoğan 2003), overlying fine-grained sandstones and marls are classified as post-Lutetian units in this study, although they were described as the second part of the Asartepe formation by previous researchers (Akkuş 1970, 1971; Nazik 1993).

The Asartepe formation comprises white-yellow, finely crystallized limestone with marl intercalations in its lower part; this part has extrabasinal and intrabasinal grains with some coral and algae fossils. Intrabasinal grains were derived from underlying units (mostly from the Yenice marls). Extraclasts were derived from basement rocks located in the marginal areas of the basin. Petrographically, this part of the sequence has characteristics similar to the Yenice calcarenites (intraclasts of underlying marls, extraclasts, corals and algae). Towards its upper parts, the unit gradationally passes into pale grey-green, uniform, medium- to thick-bedded limestones; moreover, this part is characterized by corals, algae, and other macro- and micro-fossils with fewer extrabasinal fragments. Petrographically, these limestones can be classified as biointrasparite (Folk 1962) or grainstone (Dunham 1962) (Figure 11).

The thickness of the formation is variable and ranges from 10.7 m (Asartepe section) to 52.0 m (Yenice section). However, the occurrence of a roughly 120-m-thick limestone has been reported by Akkuş (1971), but it gradually decreases laterally down to 5 m because of the lenticular geometry of the unit. Ostracods *Bairdia (Bairdiopplata) gliberti* Keij, *Echinocythereis isabenana* Oertli, *Echinocythereis scabra* (Munster), *Krite rutoti* (Keij), *Xestoleberis subglobosa* (Bosquet), *Pokornyella ventricosa* (Bosquet), *Uroleberis striatapunctata* (Ducasse), *Bairdia subdeltoidea* (Muenster), *Echinocythereis lutfullahi* Sönmez-Gokcen, and *Leguminocythereis* sp., and benthic foraminifers Nummulites perforatus (Monfort), *Nummulites beaumonti* d'Archiac & Haime, *Nummulites aturicus* Joly & Leymerie, *Fabiania cassis* (Oppenheim), *Assilina exponens* Sowerby, and *Dentalina communis* d'Orbigny (Lutetian age) are documented from the marly limestone levels of the Asartepe formation (Nazik 1993; Erdoğan 2003).

The initial (basal) part of the unit is comprised of marl and sandy limestone intercalations reflecting a shallowing phase of the sea. The second phase is dominated by coral and algae with shallow-marine fossils (listed above) but with less or no extrabasinal fragments. Coral colonies generally prefer a clear, well-oxygenated, warm environment (Hayward *et al.* 1996; Calvet & Tucker 1995; Gül & Eren 2003). The diversity of organisms in

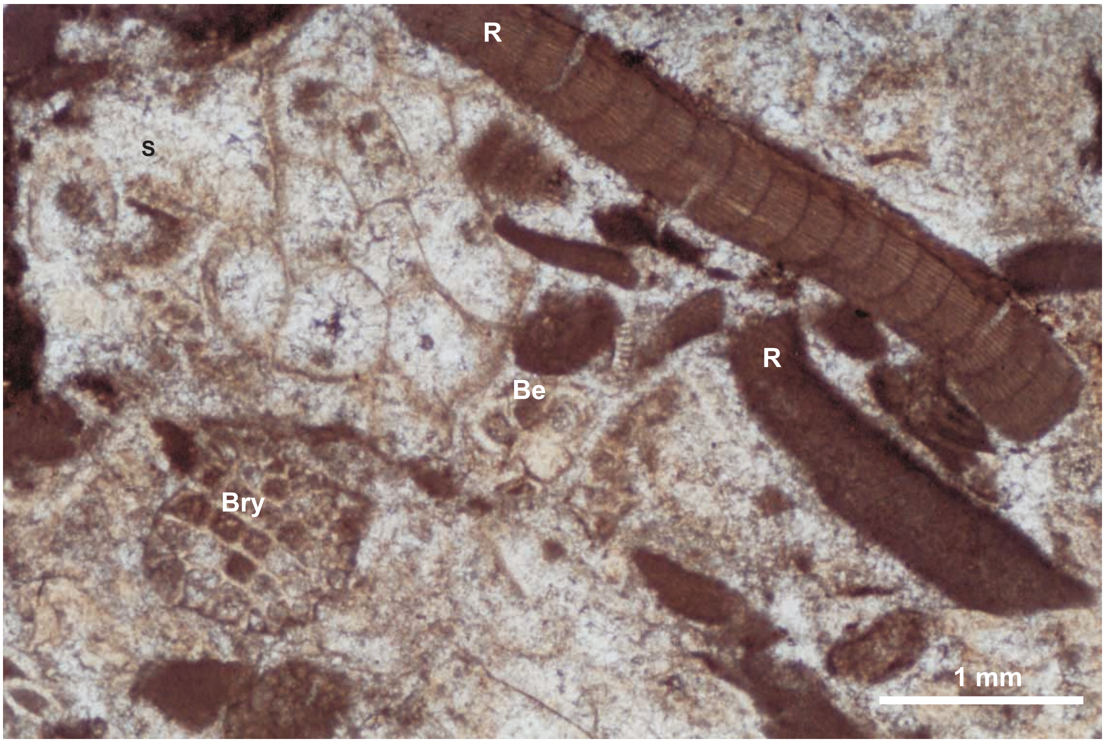

Figure 11. Photomicrograph from the reefal limestone of the Asartepe formation. (220 m of the Yenice section; R – red algae, Bry– bryozoa, Be – benthic foraminifera, and S – sparite).

carbonates may relate to changes in the amounts of nutrients (Calvet & Tucker 1995). Encrusting algae stabilize the coral framework (Strasser & Strohmenger 1997). Beavington-Penney *et al.* (2005) summarized the evolution of large benthic-foraminifera-bearing Eocene facies in three different areas: large benthic-foraminifera-bearing build-ups deposited at the boundary of an inner ramp-mid ramp in the El Garia formation (Spain); over the shelf margin in the Sirte Basin (Libya); and one interpreted as a bank (Croatia). Massive or thick-bedded limestone and marl alternations of the formation in the Yenice section indicate that sea-level fluctuations may have been created by local tectonics or differential subsidence. These fossil contents and the geometry of the formation indicate that this part of the Asartepe formation developed as patch reefs in a shallow-marine sea, while marls of the Yenice formation were deposited in a relatively deeper, quiescent environment.

Priabonian Basin Fill

According to Akkuş (1970, 1971), the Priabonian is represented by two formations: the Darende and Balaban formations. The Balaban formation consists mainly of coarse-grained clastics (conglomerates and sandstones) alternating with finer-grained clastics (fine-grained sandstone-siltstone-claystone alternations) and some evaporite occurrences. This unit crops out only around the town of Balaban in the southeastern part of the basin and is located stratigraphically in the lower part of the Priabonian sequence. It has a lateral transitional contact with the Darende formation in the southern part of the basin. In the northern part of the study area, the Balaban formation is absent, but the same levels correspond to exposures of the Darende formation. The rest of the sequence (the middle and upper parts of the Priabonian fill), is represented by the Darende formation throughout the basin and comprises pebbly sandstone, sandstone and marl intercalations with some gypsum beds. Thus, there are distinct lithological differences – particularly with respect to the grain size of the clastic rocks – between the exposures of basin fill in the northern and southern parts of the basin; this was the main reason why the Priabonian sediments were mapped as two different formations (Akkuş 1970, 1971). On the other hand, because of the only local occurrence of the Balaban formation – with only grain-size differences and its internal transitional contact with Darende formation – we have chosen to combine these two units in the Darende formation.

The Darende Formation. The Darende formation conformably overlies the Asartepe formation (Figure 12a) and is unconformably overlain by Plio–Quaternary deposits. In places, the lower part of this unit has lateral and vertical gradational contacts with the Asartepe formation. The formation begins with roughly 20–25 m of beige marls, possibly deposited on/in front of the Asartepe reef bodies in the southern and northern parts of the basin (Figure 12a). These marls were previously included in the Asartepe formation by Akkuş (1971). However, a recent palaeontological study (Erdoğan 2003) shows that the Priabonian begins chronologically with this level. Thus, we prefer to include this level in the Darende formation. The succession continues with an alternation of coarse-grained polygenic rounded-subrounded conglomerates and medium- to thin-bedded sandstones (much coarser in the southern part of the basin) that pass laterally into evaporites (Figure 12a & b). The upper part of the sequence is represented by an alternation of medium- to thin-bedded pebbly sandstones, thin-bedded sandstones, marls and thin evaporite layers. In the Darende sequence, there are distinct dip changes from the marginal parts (15–45°) into the central part (10–20°) of the basin; this is attributed to the continuation of differential uplift at the marginal parts of the basin. It also reflects the filling-up of the basin during the Eocene time interval.

This formation is composed mainly of conglomerate, pebbly sandstone, and sandstone-siltstone-marl alternations interbedded with gypsum in the Alidede section (Figure 13). The lower part consists mainly of coarser-grained sediments on both sides (north and south) of the basin, but much coarser in the south. The middle part is characterised by coarse- to fine-grained, medium- to thin-bedded sandstone – classified as a lithic graywacke (cf. Pettijohn *et al.* 1987; Figure 12c) – and marl intercalations. The sequence fines upward into fine- to medium-grained, thin-bedded sandstones and ends up with marls toward the central part of the basin. Thin gypsum beds are also observed at different levels of the upper parts of the unit. Ostracods *Quadracythere orbignyana* (Bosquet), *Nucleolina multicostata* (Deltel), *Pokornyella osnabrungensis* (Lienenklaus), and *Neocyprideis apostolescui* (Keij) and benthic foraminifers *Nodosaria, Sphaerogypsina globulus* (Reuss), *Halkyardia minima* Liebus, *Quinqueloculina, Rotalia trochidiformis* Lamarck, *Cibicides* sp., *Nonion* sp., *Uvigerina* sp., and *Eponides* sp. have been identified and described from fine-grained levels as shallow-marine fossils by Nazik (1993) and Erdoğan (2003). A Priabonian age was assigned to the Darende formation because of this fossil content.

The origin of gypsum has been the subject of much recent research and many different views have been set forth. Ocakoğlu (1999) implied that similar-aged gypsum deposition in the Sivas Basin developed as a result of regional regression, while Tekin (2001) emphasized that laminated gypsum was deposited in depressions during the Late Eocene regression or in a shallow inner-lagoon environment, and that Oligocene sandstone-nodular gypsum alternations developed in coastal sabkhas and abandonment channels of meandering river in the Ulukışla-Sivas basin. Taberner *et al.* (2002) reported that restrictions, isolation and hydrochemical changes during the Eocene caused evaporite deposition in the Iguala basin of NE Spain. In a very similar way, we propose that uplift at the margins and rapid shallowing of the basin led to development of some evaporitic occurrences in local restricted areas, while very coarse materials derived from local sources along the northern and southern margins were deposited in the lower parts of the basin. Grain-size differences between the northern and southern parts of the basin may have resulted from differences in rates of uplift in the marginal parts of these areas. Uplift created more clastic input into the basin (Figure 3) during very shallow-marine conditions and led to infilling of the basin with conglomerates, sandstones and marl intercalations with thin evaporate layers. This type of alternations in the sequence may reflect local sea-level fluctuations, possibly created by local tectonic activity at the margins of the basin.

Post-Eocene Basin Fill

Post-Eocene basin fill comprises the Plio–Quaternary Çaybaşı formation and Quaternary alluvium – mainly conglomerates – that were deposited in a continental environment; this material unconformably overlies most of the older sediments (Akkuş 1970, 1971).

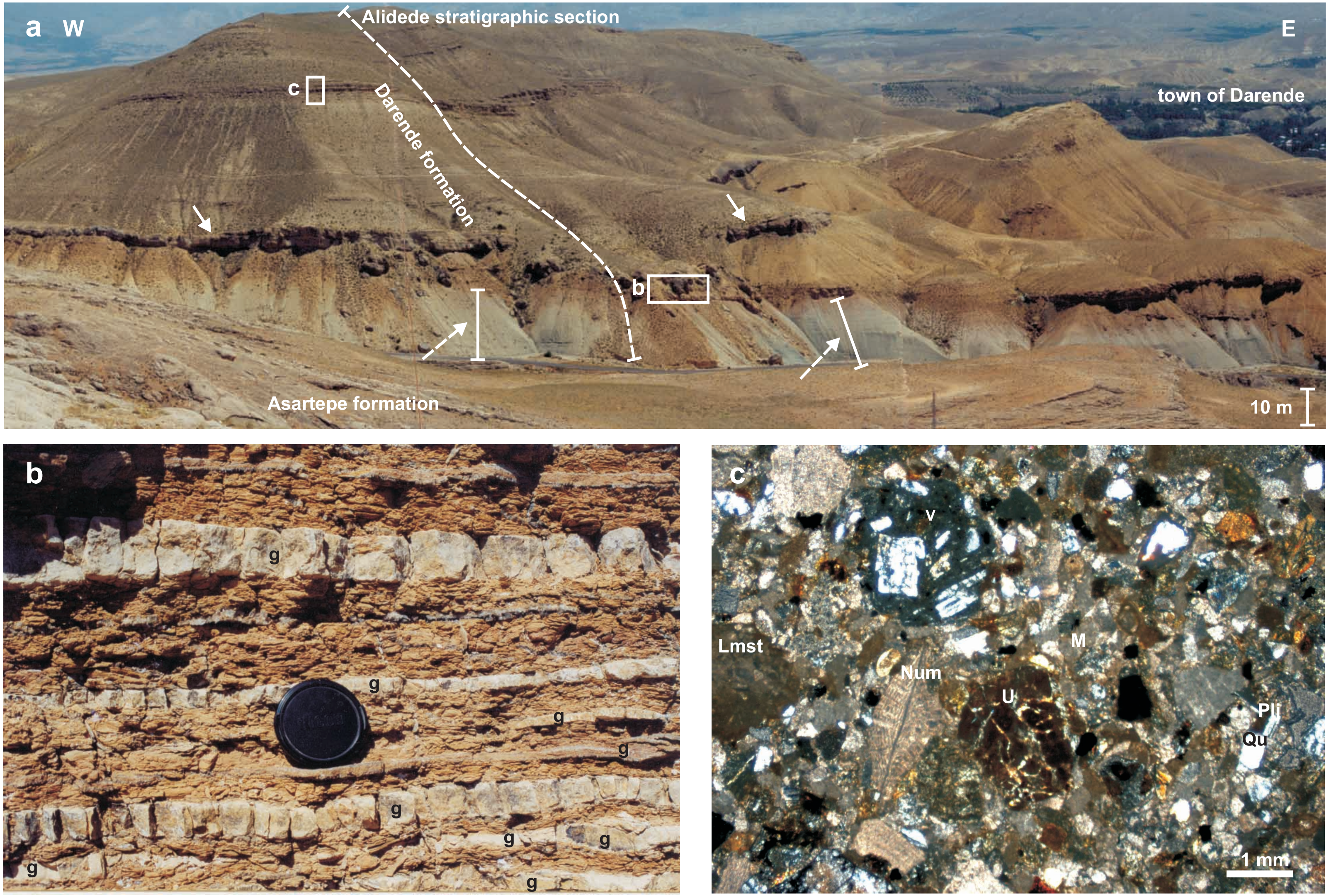

Figure 12. (a) A field view of the Alidede stratigraphic section. The Darende formation conformably overlies reefal carbonates of the Asartepe formation. Arrows with continuous line indicate gypsum horizons in the claystone and calcarenite alternations. The arrow with dashed line shows marls previously described as the uppermost parts of the Asartepe formation; (b) close-up view of the gypsum (g) and marl alternations (rectangular area in a); (c) thin-section photomicrograph from the Darende formation (140 m of the Alidede section; **Num** – *Nummulites*, **Qu** – quartz, **Plj** – plagioclase, **V** – volcanic rock, **Lmst** – limestone, **U** – ultrabasic rocks, and **M** – micrite).

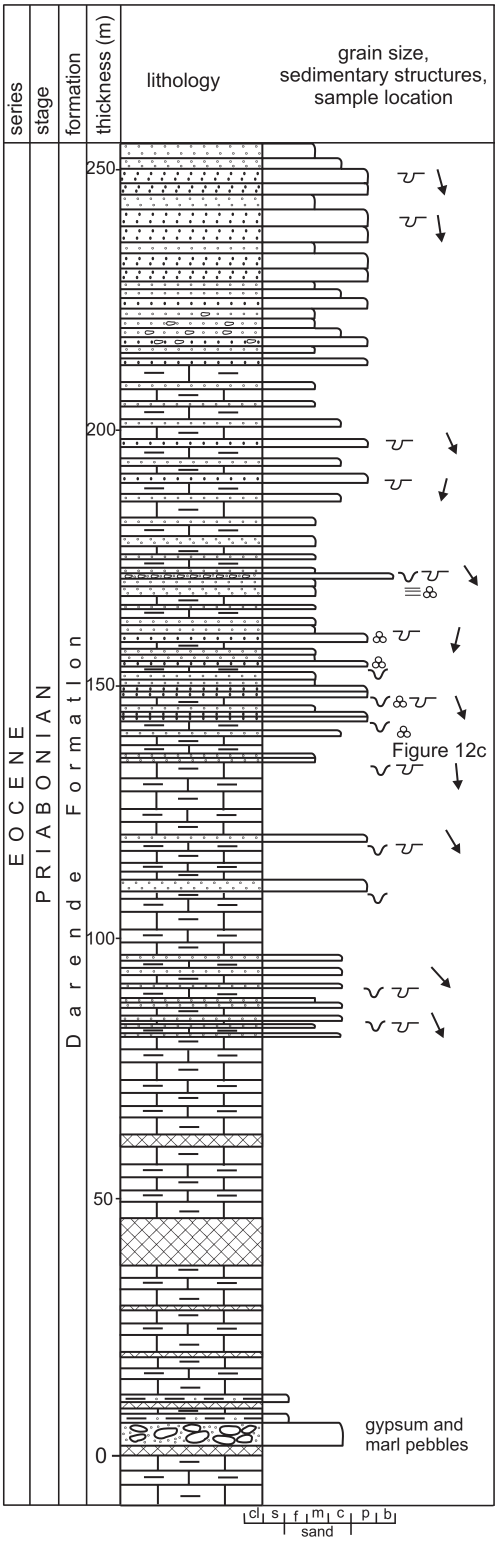

Figure 13. Alidede measured stratigraphic section.

Basin Evolution and Controlling Factors of Eocene Sedimentation

Dorsey & Kidwell (1999) pointed out that descriptions of controlling factors and similar facies distributions in different basins are important for understanding ancient carbonate production, oceanography, climate and tectonic activity. The controlling factors for sedimentation are varied: nature of the source area, elevation of the source, types of transportation agents, physical-chemical-biological processes, climate, diagenesis, tectonics, sea-level fluctuations (eustatic or global), distance from the shore, presence of carbonate-secreting organisms, sunlight, water depth, platform topography, etc. (Bauer *et al.* 2003; Levin 2003). Tectonically active areas are affected by compression and uplift that caused release of coarse sediments. These coarse sediments form clastic wedges in various environments; they show thinning and fining towards the basin centre (Levin 2003). If the environment is marine, the larger particles are deposited closer to the shore. Finer materials are carried by shallow-water currents and wave action to deeper parts of the sea (Levin 2003). The amounts of transgression and regression of sea level in coastal areas are related to both tectonic events and global sea-level changes (Levin 2003). Shorelines are modified by sea-level change, which causes vertical and lateral facies changes in shallow-marine environments (Leeder 1982). Wave base (or, the mudline) reflects the energy of the environment, and below this, laminated shales and micrites are deposited under low-energy conditions (Selley 1998). Sea-level changes at the coast and siliciclastic input effect the sedimentation in shallow-marine environments (Bauer *et al.* 2003). Development of carbonate-poor and carbonate-rich levels depends on siliciclastic input. For example, high siliciclastic input during lowstands prevents carbonate deposition (Dunbar & Dickens 2003).

Relative sea-level change, controlling factors and their results, rate of clastic input and carbonate deposition for the Darende-Balaban basin, previously explained in parts of this paper, are summarized in Figure 3. Based on our environmental interpretations, the palaeoenvironmental evolution of the study area can be summarized with a schematic diagram (Figures 14 & 15). Pre-Late Cretaceous time in the study area was characterised by several tectonic slices of the Geniz limestones and ophiolitic rocks (Figure 14a). The first marine transgression commenced during the Late Cretaceous.

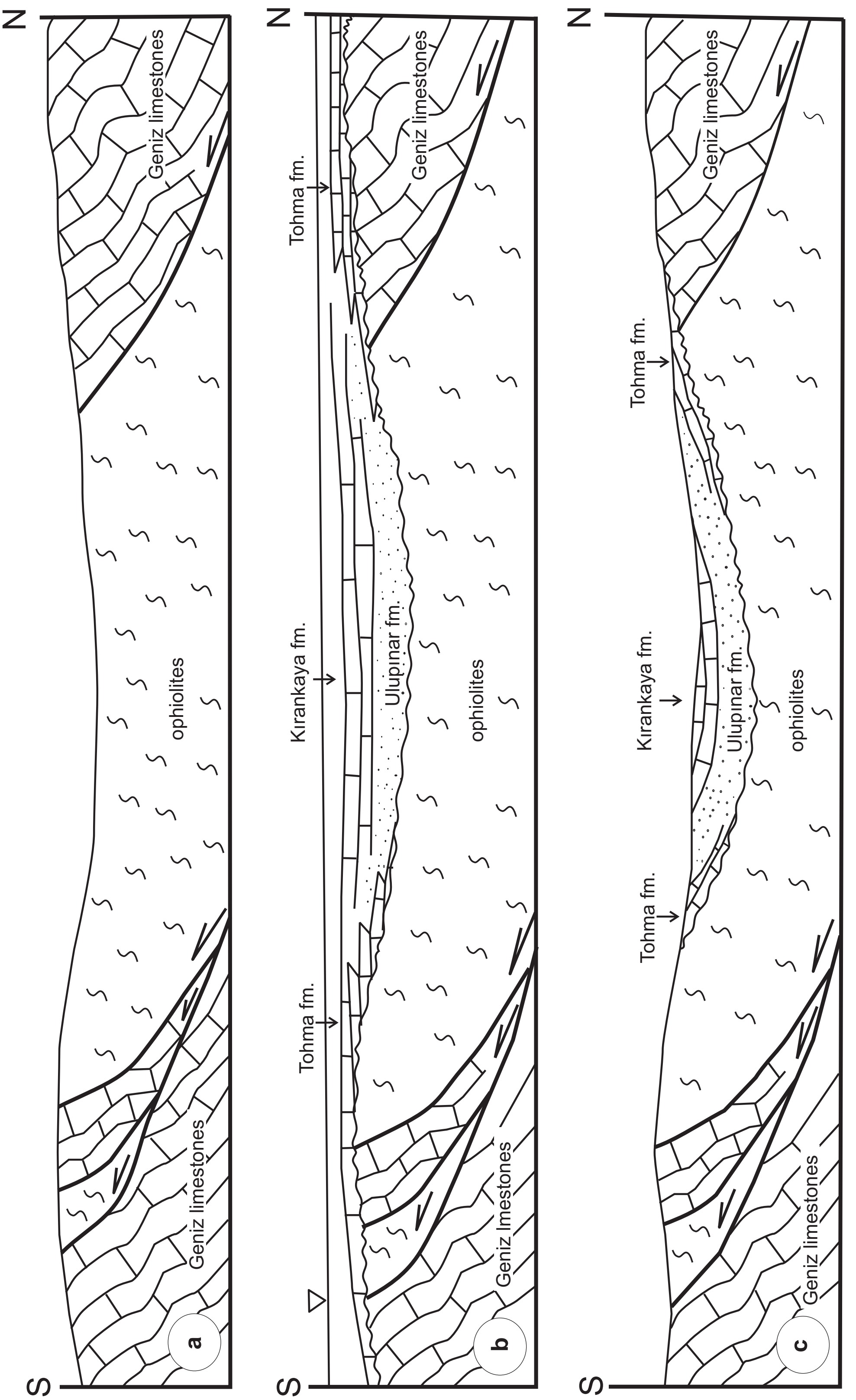

Figure 14. Schematic diagram of the pre-Late Cretaceous–Lutetian evolution of the Darende-Balaban basin: **(a)** Pre-Late Cretaceous: tectonic slabs of the ophiolite and the Geniz limestone; **(b)** Late Cretaceous: transgression and deposition of the Ulupınar, Kirankaya formations and Tohma reef; **(c)** Late Cretaceous–Lutetian: regional uplift and erosion in the basin;

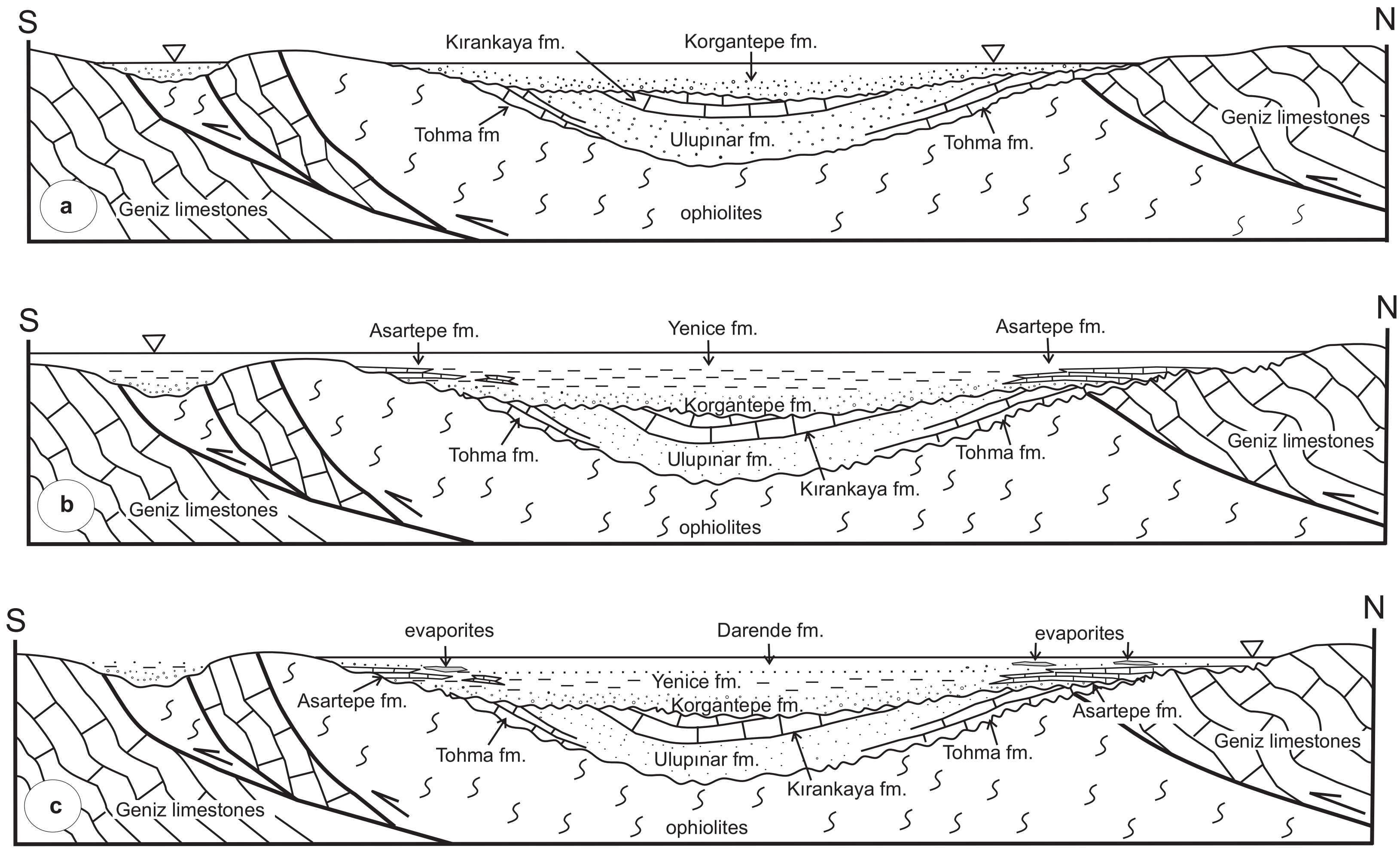

Figure 15. Schematic diagram of the Early Lutetian–Priabonian evolution of the Darende-Balaban basin: (**a**) Early Lutetian: onset of the Lutetian transgression – local uplift and deposition of the Korgantepe formation; (**b**) Late Lutetian: maximum flooding and deposition of the Yenice and Asartepe formations; (**c**) Priabonian: local uplift and regressive deposition of clastics and evaporates of the Darende formation.

Initially, clastics of the Ulupınar formation were deposited onto older rocks. This sedimentation was followed by deposition of calcarenites and marls of the Kırankaya formation in deeper parts, while the Tohma reefs evolved in the shallow-marine environment (Figure 14b). Regional uplift occurred when pre-Late Cretaceous tectonic slices were reactivated between the Upper Cretaceous and Lutetian. This uplift caused erosion, tilting of the Upper Cretaceous units and, consequently, formation of irregular basin topography (Figure 14c). A second marine transgression began in the Early Lutetian; during this period, conglomerates of the Korgantepe formation were deposited unconformably above pre-Eocene rocks. Shoreline-shoreface sediments of the Korgantepe formation were deposited mainly in palaeotopographic depressions (Figure 15a). A continuum of marine transgression was first marked by shallow-marine clastics (sandstone-marl alternations), then by deeper marine sediments (marls) of the Yenice formation, with minor siliciclastic input from the marginal areas. A sea-level drop or local tectonism at that time led to the formation of calcarenites under shallower conditions in the middle parts of the Yenice formation. Subsequently, deposition continued with deeper marine marls in the upper parts of the Yenice formation. The sediments in the uppermost parts of the Yenice formation and lower parts of the Asartepe formation represent another sea-level drop or uplift at the shoulders of the basin; this led to reefal build-ups (reefal limestones of the Asartepe formation; Figure 15b). Finally, in the Priabonian, shallow-marine conditions prevailed during which the Darende formation (conglomerates, pebbly sandstones, sandstones, siltstones, evaporites and marl intercalations with some thin layers of evaporites) was deposited (Figure 15c).

Conclusions

The Eocene in the Darende-Balaban basin is represented by a range of sedimentary environments, from very shallow to deeper marine. Data from the present study show that sedimentation in the basin was first affected by tectonism due to the collision of the Arabian and Anatolian plates; this event was responsible for rapid facies changes, local sea-level fluctuations and major transgressive and regressive cycles within the basin. Internal conditions within the basin, such as basement topography, sedimentary environment, palaeoclimate, and type and amount of clastic input affected the basin evolution and were responsible for the occurrence of various lithologies. Petrographic data from the siliciclastic sediments demonstrates that the main sediment supply throughout this time interval was from ophiolitic and older carbonate sources, presently exposed to the north and south of this basin.

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