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Repetitive Subtidal-to-Coastal Sabkha Cycles from a Lower-Middle Miocene Marine Sequence, Eastern Sivas Basin

FARUK OCAKOĞLU

Osmangazi University, Department of Geological Engineering, TR-26030 Bademlik, Eskişehir-TURKEY (e-mail: focak@ogu.edu.tr)

Abstract: In the study area, southeast of Zara in the Sivas Basin, the Lower-Middle Miocene marine Karacaören Formation consists of a succession of marine sedimentary rocks deposited within two trangressive-regressive cycles. The present study focuses on the facies characteristics, cyclic nature, and significance of the basin-wide distribution of a 100-m-thick gypsiferous sedimentary package overlying an otherwise transgressive segment of the lower sequence, within a marine setting.

The typical lithologic expression of the studied sedimentary interval comprises generally fossiliferous mudstones, rare algal limestones and nodular gypsum. Detailed sedimentological observations, combined with palaeontological evidence, indicate that the mudstone intervals were deposited in a subtidal to lower intertidal setting, while the algal limestones represent intertidal areas. Nodular gypsum and associated rare reddish-greenish clays, which constitute nearly half of the studied sequence, were probably deposited within a coastal sabkha environment.

The internal architecture of the studied interval is characterized by some fifteen shallowing-upwards (i.e., progradational) cycles. Each cycle typically has a basal mudstone interval, locally overlain by an algal carbonaceous mudstone/limestone, and an upper nodular gypsum (with or without reddish-greenish clays) interval. These cycles probably correspond to parasequences which were driven by high-frequency changes in relative sea-level.

The lateral distribution pattern of the studied evaporitic interval implies that conditions giving rise to evaporites prevailed over the entire central and eastern parts of the Sivas Basin, and that the local palaeogeography at that time was characterized by widespread coastal sabkhas to the south, and a reefal-to-muddy shelf to the north.

Key Words: Cycle, Evaporite, Parasequence, Sabkha, Subtidal, Sivas Basin

Zara Yöresi (Sivas Havzası Doğusu) Denizel Alt-Orta Miyosen İstifinde Tekrarlanan Gelgitaltı-Kıyı Sabkası Çevrimleri

Özet: Erken-Orta Miyosen yaşlı denizel Karacaören Formasyonu inceleme alanında (Sivas Havzası doğusunda yeralan Zara'nın GD kesimleri) iki adet transgressif-regressif çevrim sürecinde çökelmiş bir sedimanter istiften oluşur. Bu çalışma sözü edilen denizel sedimanter kaydın genellikle transgressif olan segmenti üzerine oturan yaklaşık 100 m kalınlığındaki jips içeren sedimanların fasiyes özellikleri, gözlenen çevrimselliğin doğası ve havza ölçeğinde yayılımına odaklanmıştır.

İncelenen sedimanter istifin tipik litolojik ögelerini çoğunlukla fosilli olan çamurtaşı, az miktarda algal kireçtaşı ve yumrulu jips oluşturur. Ayrıntılı sedimantolojik gözlemler ile paleontolojik kanıtlar istifteki çamurtaşı segmentinin olasılıkla gelgitaltı-aşağı gelgitarası yerleşimde çökeldiğini, algal kireçtaşının ise gelgitarası alanları temsil ettiğini kanıtlamaktadır. Ayrıntılı olarak ele alınan istifin neredeyse yarısını oluşturan yumrulu jipsler ve bunlara ender olarak eşlik eden kırmızımsı-yeşilimsi ince tanelilerin ise olasılıkla kıyı sabkası ortamlarında çökeldiği ileri sürülmüştür.

İncelenen istifin iç mimarisi onbeş kadar yukarı doğru sığlaşan (yani her biri "ilerleyen" karakterde) çevrimle belirlenmiştir. Her bir çevrim, tipik olarak, çamurtaşından oluşan bir taban seviyesinden, bazen hiç bulunmayabilen algal karbonatlı çamurtaşı-algal kireçtaşı orta seviyesinden ve kırmızımsı-yeşilimsi ince tanelileri yer yer içerebilen bir yumrulu jips üst seviyesinden oluşur. Her bir çevrimin, yüksek frekanslı görece deniz seviyesi değişimleriyle ortaya çıkan parasekanslara karşılık geldiği düşünülmüştür.

Son olarak, incelenen evaporitik istifin dağılım deseni, ona neden olan evaporitik olayın Sivas Havzası'nın bütün orta ve doğu kesimi boyunca etkin olduğunu ve bu evaporit çökelme döneminde, paleocoğrafyanın güney alanlardaki yaygın kıyı sabkaları ve buradan kuzey alanlara doğru giderek derinleşen resifal-çamurlu bir şelfle biçimlendiğini anlatmaktadır.

Anahtar Sözcükler: Çevrim, Evaporit, Gelgitaltı, Parasekans, Sabka, Sivas Havzası

Introduction

Coastal evaporites constitute a range of evaporitic lithofacies, and because of their occurrence in proximity to seawater, they convey valuable palaeoenvironmental information in several respects. They are good climatic indicators, reflecting an arid climate with high net evaporation and very low clastic input (Till 1979). They require specific topographic conditions, which inhibit the free circulation of seawater and cause super-saturation in certain restricted zones, such as lagoons and bays (Kinsman 1969). As they are deposited on wide, flat coastal areas, they are highly sensitive to even small-scale relative sea-level changes. Hence, they provide excellent opportunities to study the dynamics of these high-frequency sea-level fluctuations.

The Sivas Basin, which is probably the largest Tertiary evaporite basin in Anatolia, includes a thin (ca. 100 m) evaporitic succession interbedded with marine mudstones and limestones of Early to Middle Miocene age. These deposits were previously described by several authors (SE of Sivas: Kurtman 1961; Baysal & Ataman 1980); SE of Zara: Çiner *et al.* 1995; Ocakoğlu 1997). Using a multidisciplinary approach, the present study re-evaluates the details of the depositional environments of these deposits, as well as their geographic distribution and cyclic nature.

Geological Setting and Stratigraphy

The Sivas Basin is one of the largest basins in central Anatolia, extending for about 300 km from Gemerek in the SW to Refahiye in the east (Figure 1). The basin-fill comprises a ca. 5000-m-thick sedimentary sequence, ranging from Eocene to Miocene in age (Kurtman 1973). Recent geotectonic interpretations conclude that the basin behaved as a foreland basin during the Tertiary (Yılmaz 1994; Poisson *et al.* 1996; Görür *et al.* 1998).

The present study is concerned with a small area in the eastern part of the basin where the oldest rocks are represented by the evaporitic Hafik Formation (Figures 1 & 2). An Oligocene age was assigned to this unit on the basis of its stratigraphic position (Poisson *et al.* 1996). The Selimiye Formation, a fluvial unit that is typically the colour of red wine (*şarabi* in Turkish), conformably overlies the Hafik Formation, and is in turn overlain by a 200-m-thick alluvial-to-fluvial sequence, the Karayün Formation. Gökçen & Kelling (1985) described various depositional environments ranging from shelf to river in

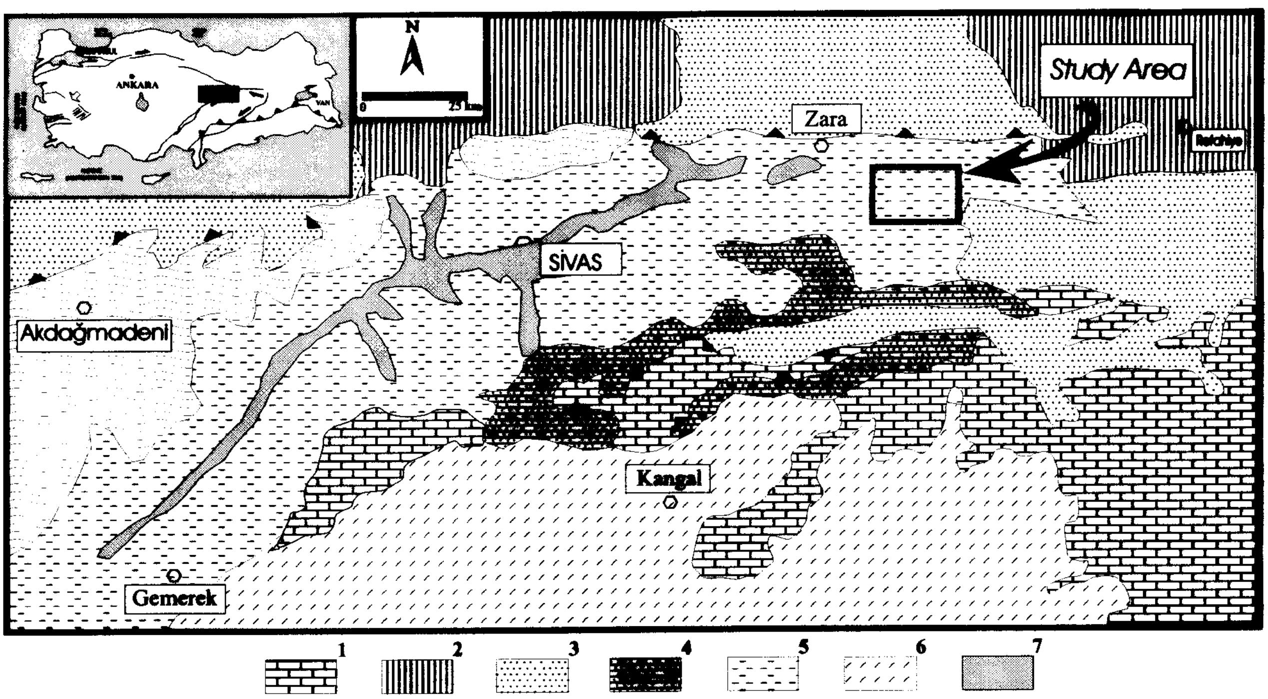

Figure 1. Location and regional geological setting of the study area (simplified after the 1/2.000.000 scale Geological Map of Turkey). 1- Tauride Platform, 2- Pontides, 3- Eocene, 4- Oligocene, 5- Oligo-Miocene, 6- Mio-Pliocene and 7- Quaternary.

the southern part of the basin, and attributed it a Middle-Late Oligocene age. Even though the Karayün Formation conformably overlies the Selimiye Formation, it is much coarser at its base, and has a general fining-upwards signature (see Ocakoğlu 1997 for details). The Karacaören Formation is a marine unit of Aquitanian-Helvetian age (Kurtman 1973) and was previously subdivided into six subunits in the study area (Ocakoğlu 1997; Figure 2). The formation is transgressive onto the Karayün Formation up to unit 2 (comprising the coastal plain-shallow muddy shelf and coastal sabkha-to-subtidal environments), and is interrupted by an unconformity at that level (Figure 3). After a coarse grained sedimentary tongue about 20-m-thick, it is transgressive again up to unit 4 (deeper muddy shelf) and is followed by a stillstand period (shallow carbonate shelf) and a regressive phase (with coal-bearing coastal plain and fluvial deposits). The fluvial Benlikaya Formation occurs on top of these units and is the youngest (probably late Middle Miocene) conformable unit in this area.

Karacaören Formation: Record of an Early-Middle Miocene Marine Inundation

The Karacaören Formation (nomenclature after Kurtman 1973) is a lithostratigraphic unit of marine origin, which extends from the east end of the basin to the area southwest of the city of Sivas (Figure 4). The type locality for the formation is in the vicinity of Karacaören village, where exposure is extensive. Kurtman (1973) suggested that the formation interfingers with the gypsiferous Hafik Formation and envelops the underlying and overlying units (i.e., the Karayün and Benlikaya formations) at the same time. Kurtman (1973) interpreted two transgressive-regressive cycles, one of which Aquitanian-Burdigalian, and the other Burdigalian-Helvetian, in age.

However, the basal relationships of the Karacaören Formation with underlying sediments vary from place to place. Around Karaman and Karayün in the central part of the basin, the unit conformably overlies a fluvial unit (i.e. the Karayün Formation) while farther west around Celalli, Selimiye and Benlikaya, the unconformity on the Selimiye Formation is marked. Cater *et al.* (1991) suggested that these unconformities within the Oligo-Miocene sequence were mainly controlled by activity on N-S trending extensional faults.

Several aspects of the Karacaören Formation remain unclear. First, in the western part of the basin (around Sivas, Karayün, Celalli) were there two separate marine incursions within a continental sequence (as suggested by Çiner & Koşun 1996; Çubuk 1994; Gökçe & Ceyhan 1998) or only one (Poisson *et al.* 1997)? What is the real age of this marine incursion, and did it really inundate the basin from the east? Some convincing data were described for the Sivas area by Poisson *et al.* (1997), but a palaeogeographic picture of basin-wide scale still has not been constructed. Middle and Late Oligocene fossil findings by Poisson *et al.* (1997) stand still anomalous in the basin. They signal either reworking of Oligocene sediments or the existence of an E-W trough in which sedimentation was restricted for a relatively long time (up to Aquitanian-Burdigalian), which is the common age assignment of the marine sediments in the basin.

Lithologically, the Karacaören Formation is composed mainly of mudstone and limestone, with subordinate amounts of gypsum and locally conglomerates. In the very east, around Boğazviran (Figure 4) mudstone constitutes the bulk of the unit while reefal limestones at the base and at the top constitute the crest of the formation (Çubuk 1994). In this area, a Lower Burdigalian age has been assigned from benthic foraminifera in the lower limestone (Dizer 1962). On the other hand, some small outcrops scattered between Zara and İmranlı, are totally composed of massive reefal limestone. Farther west, to the NE of Hafik (around Günyamaç), coastal clastic sediments unconformably overlie the gypsiferous Hafik Formation, and pass upward into reefal limestones (Gökten & Kelling 1991). In the two last areas, it should be stressed that only a limited part of the marine formation has been preserved. In the area around the city of Sivas, the marine unit is again composed mainly of marine mudstones and to a lesser degree, of re-sedimented gypsum and reefal limestone (Poisson *et al.* 1997). This seems anomalous, since the same sediments have been previously described and interpreted as lagoonal by Kurtman (1961).

In order to establish a sequence-stratigraphic framework on which the cyclicity of the gypsiferous sediments overlay, vertical palaeoenvironmental changes (i.e., deepening/shallowing of the sea-bottom) in the Karacaören Formation are re-evaluated in the Zara area. Data that was previously presented in Ocakoğlu (1997) is re-interpreted here to produce relative sea-level rises and

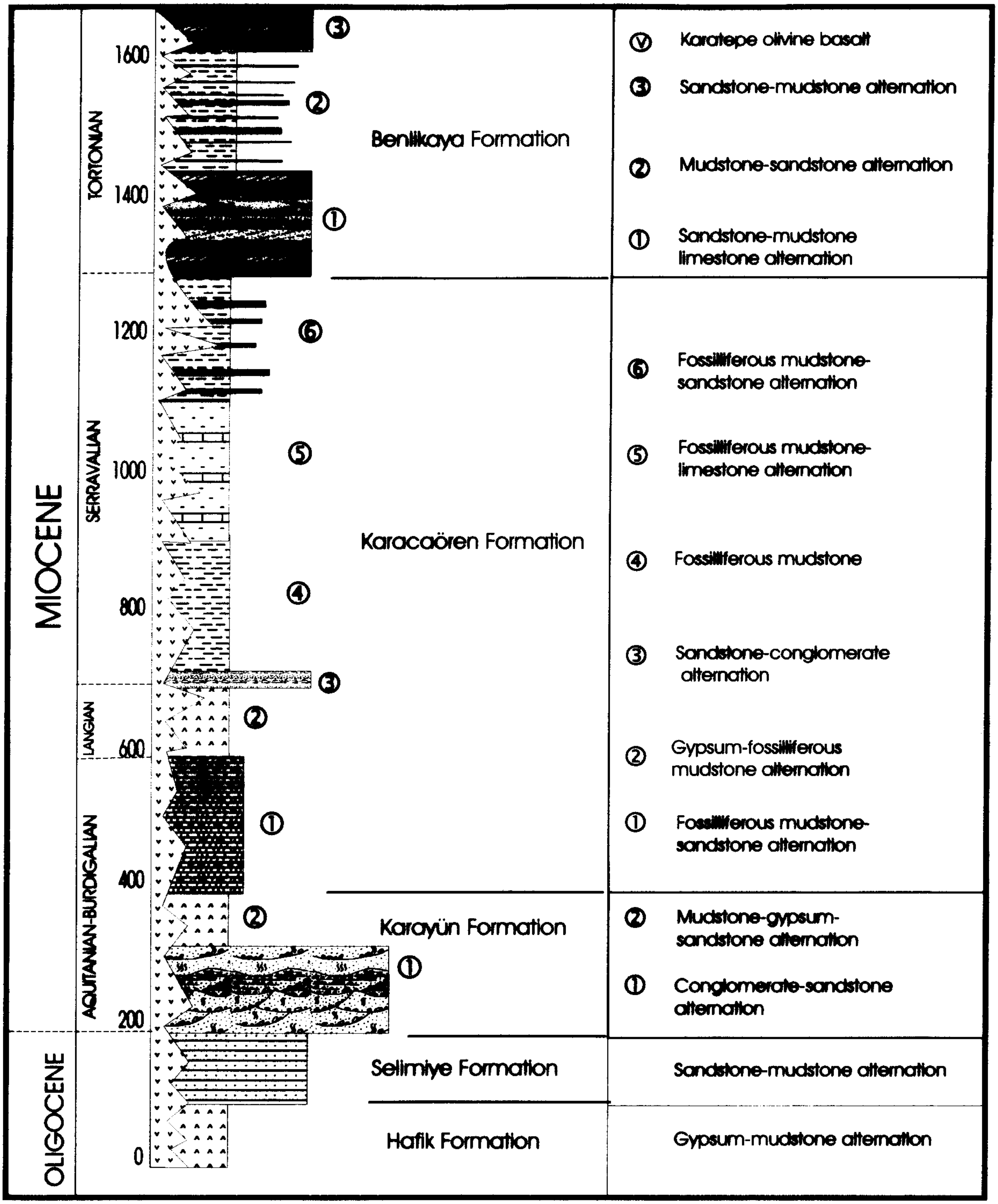

Figure 2. Generalized stratigraphic column for the Zara area.

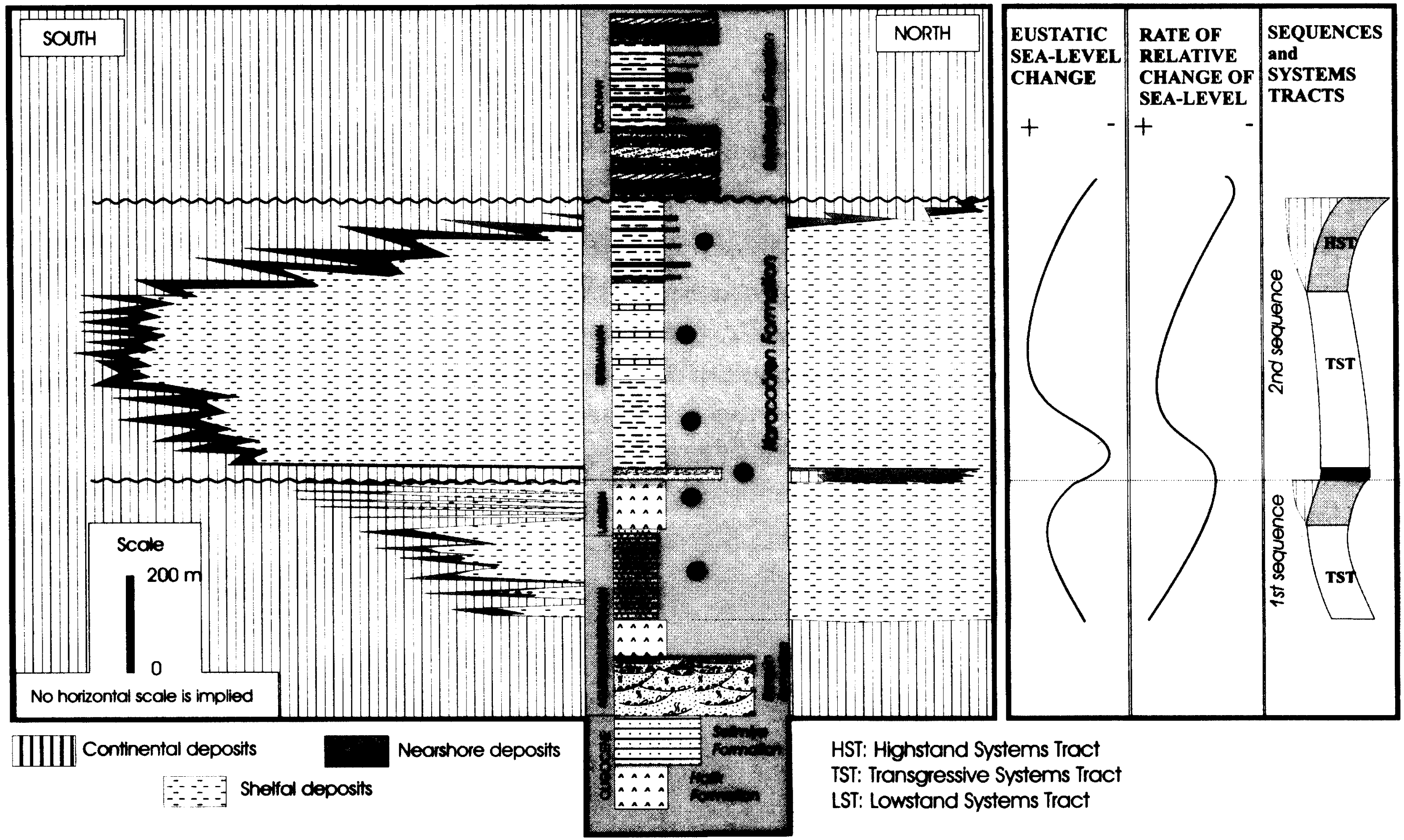

Figure 3. Sequence-stratigraphic framework of the marine Karacaören Formation in the Zara area (eastern Sivas Basin). Refer to section 2 for description of the central lithostratigraphic column.

falls (Figure 3, first column). The second column is the inferred rate of this change, which theoretically corresponds to a derivative of the former (Posamentier *et al.* 1988). The third column shows interpreted systems tracts on the base of the former two as proposed by Posamentier & Vail (1988).

In the study area, the Karacaören Formation contains six mappable subunits (Figures 2 & 4). The basal unit (subunit 1) comprises fossiliferous mudstones interbedded with frequently wave-rippled sandstones, and conformably overlies the fluvial Karayün Formation. Two-m-thick, red mudstone intercalations, bituminous-smelling thin (10-15 cm) carbonates and coal-bearing fine-grained clastic sediments are also found within this lowest subunit. During the deposition of these sediments, relative sea-level generally rose, keeping pace with the overall sediment supply since the area of deposition always remained in littoral domain.

Subunit 2 overlies a relatively thick (40 m) mud-dominated macrofossiliferous interval and is characterized by alternations of mudstone and gypsum (detailed description and interpretation found in the following sections). It seems that this subunit comprises numerous cycles, subtidal-to-supratidal in nature, and is characterized by a rapid relative sea-level rise and subsequently, the progradation of a subaerial evaporitic system. Dizer (1962) collected seven samples (five of them belonging to subunit 2, while the remaining two fall within subunit 3) in the area southwest of Ballıkbala (Figure 5) and, based on benthic foraminifera determinations, suggested a probable Burdigalian age for the section. However, the nannofossil findings (from sample N4) in the present study, suggest that the gypsiferous sequence is Langhian (zone NN5).

The following subunit (subunit 3) begins with subtidal mudstones interbedded with fossiliferous coarse-grained beach sediments (coarse sand to fine gravel), passing upward into grey lenticular, non-fossiliferous fluvial sandstones. This packet represents a major shift of the clastic system basinward, probably due to a drop in relative sea-level (Figure 3). Subunit 4 is a 210-m-thick marine sequence, which is predominantly composed of fossiliferous grey-green mudstones over subunit 3. In its uppermost levels a 20-cm-thick coaly horizon and a well-sorted mega-rippled sandstone bed are present. The subunit is interpreted to correspond to a rapid sea-level rise, turning the area of deposition into an outer shelf, then shoaling. Just afterward, the cyclic reefal limestone-mudstone couplets (of 3- to 7-m-scale) appear (subunit 5). In this case, the relative sea-level seems to have been quite stable, but was interrupted by small, sudden deepening events (punctuations) similar to the evaporitic cycles in subunit 2. The uppermost subunit (the subunit 6) of the Karacaören Formation is characterized by coal seams and coquina (fossil-rich) levels as well as channelized sands, and is interpreted as a deltaic system. This subunit again probably represents a still-stand of relative sea-level and simultaneous basinward progradation of a deltaic system (Figure 3).

To summarize the overall relative sea-level history, two rapid rises and subsequent still-stand periods interrupted by two unconformities characterize the Karacaören succession. In sequence-stratigraphic terms, one can speak about two depositional sequences (sensu Vail *et al.* 1977) as shown in Figure 3. The studied evaporitic succession falls within the highstand segment of the lower sequence.

The correlation of this local relative sea-level record with the global relative sea-level change (by Vail *et al.* 1977) reveals a close match (Figure 6). First, a general trend of sea-level change with time (a relative rise from Early Miocene to Late Middle Miocene) is common. Second, a minor sequence boundary in the Langhian is seen on the global chart as well (although three minor boundaries occur). These two pieces of evidence may show that the eustatic change of sea-level exerted a significant effect in the local stratigraphic record.

Subtidal To Coastal Sabkha Deposits Within The Karacaören Formation

As mentioned in the previous section, the succession described here forms the lower part of the Karacaören Formation (Subunit 2, Figure 2). This subunit grades upward from mud-dominated upper part of subunit 1 to a one-metre-thick, white nodular gypsum (Figure 7). Throughout the 100-m-thick evaporite-bearing section, one can observe the cyclic stacking of mudstone and gypsum. Subunit 2, in turn, is sharply overlain by two-m-thick, well-sorted coarse sandstone with rare trough-crossbedded pebble lenses. Both well-preserved and broken shells are present within the clastics. Upward, generally non-fossiliferous, lenticular sand bodies displaying a variety of cross-bedding types occur.

In order to study the depositional conditions which prevailed during the formation of the evaporitic section (subunit 2), a detailed log of the unit was constructed near Karaman, and sampling from the muddy intervals was also undertaken (Figures 5 & 7). The samples were collected for both palaeontological (nannoplankton and pelagic foraminifera) and mineralogical (both whole-rock and clay-fraction) analysis.

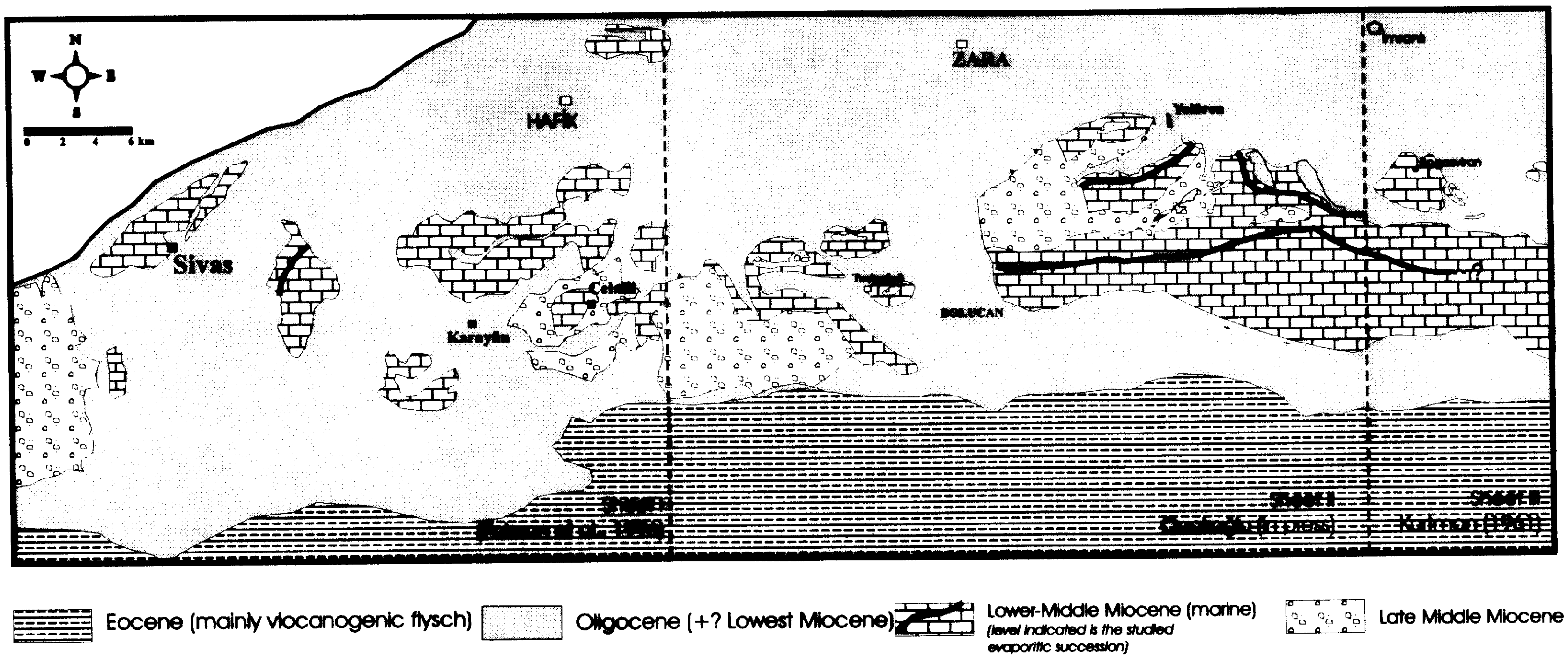

Figure 4. Lateral distribution of the marine Karacaören Formation and the studied evaporitic sequence in the central and eastern Sivas Basin.

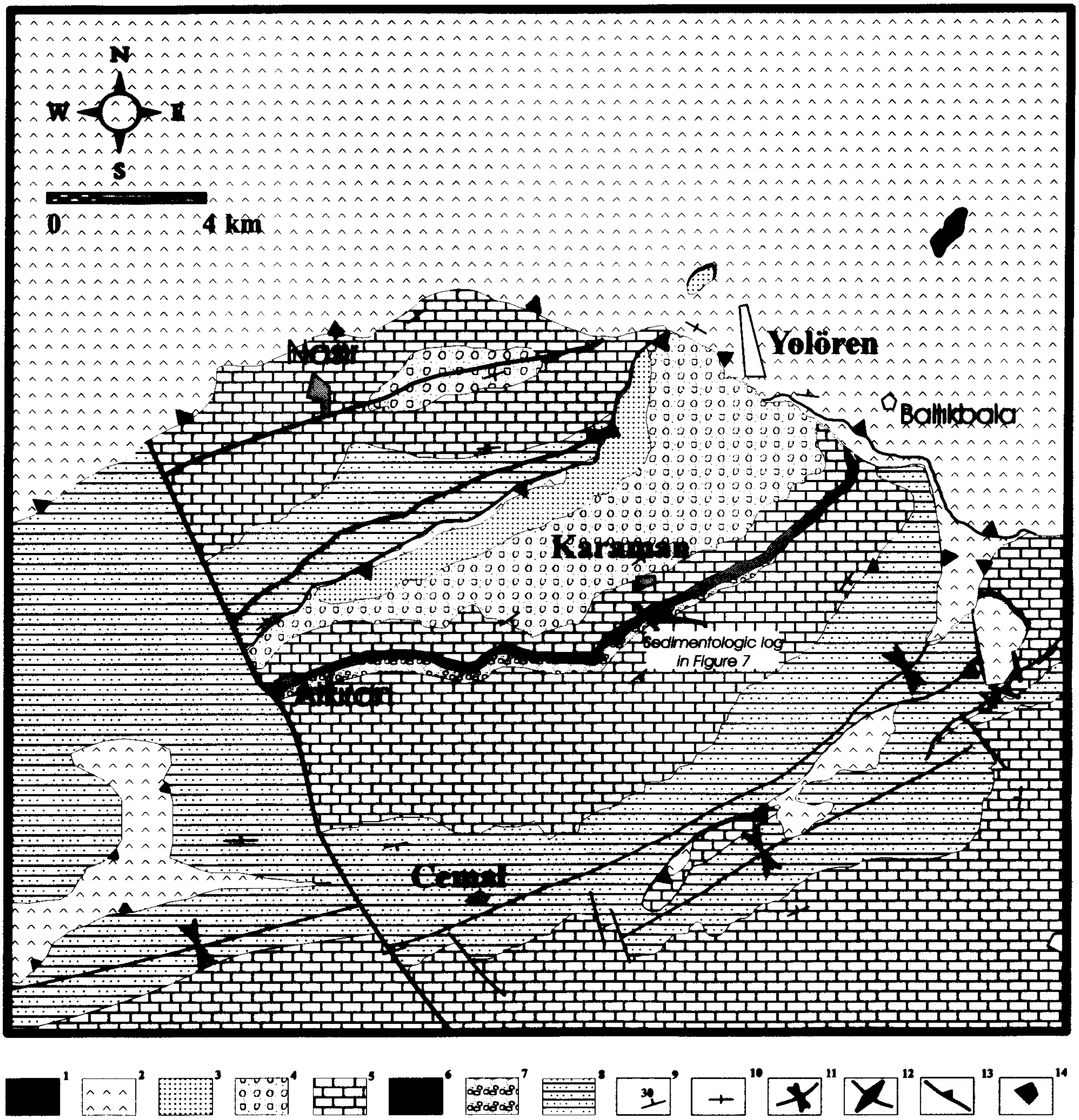

Figure 5. Geological map of the study area. 1- Serpentinite block, 2- Hafik Formation, 3- Selimiye Formation, 4- Karayün Formation, 5- Karacaören Formation, 6- gypsum member, 7- sandstone member, 8- Benlikaya Formation, 9- strike and dip of bedding, 10- vertical bed, 11- syncline axis, 12- anticline axis, 13- thrust fault, 14- village.

Description and Environmental Interpretation

Facies A: Massive to Finely Laminated Mudstone

This facies makes up almost half of the thickness of subunit 2, and is represented by grey to green mudstones (Figure 8a). Some mm-thick silt-size intervals (sometimes with ripple lamination) are also common. This facies occurs as two- to 11.5-m-thick packets separated mainly by evaporitic levels. Where the appearance is massive,

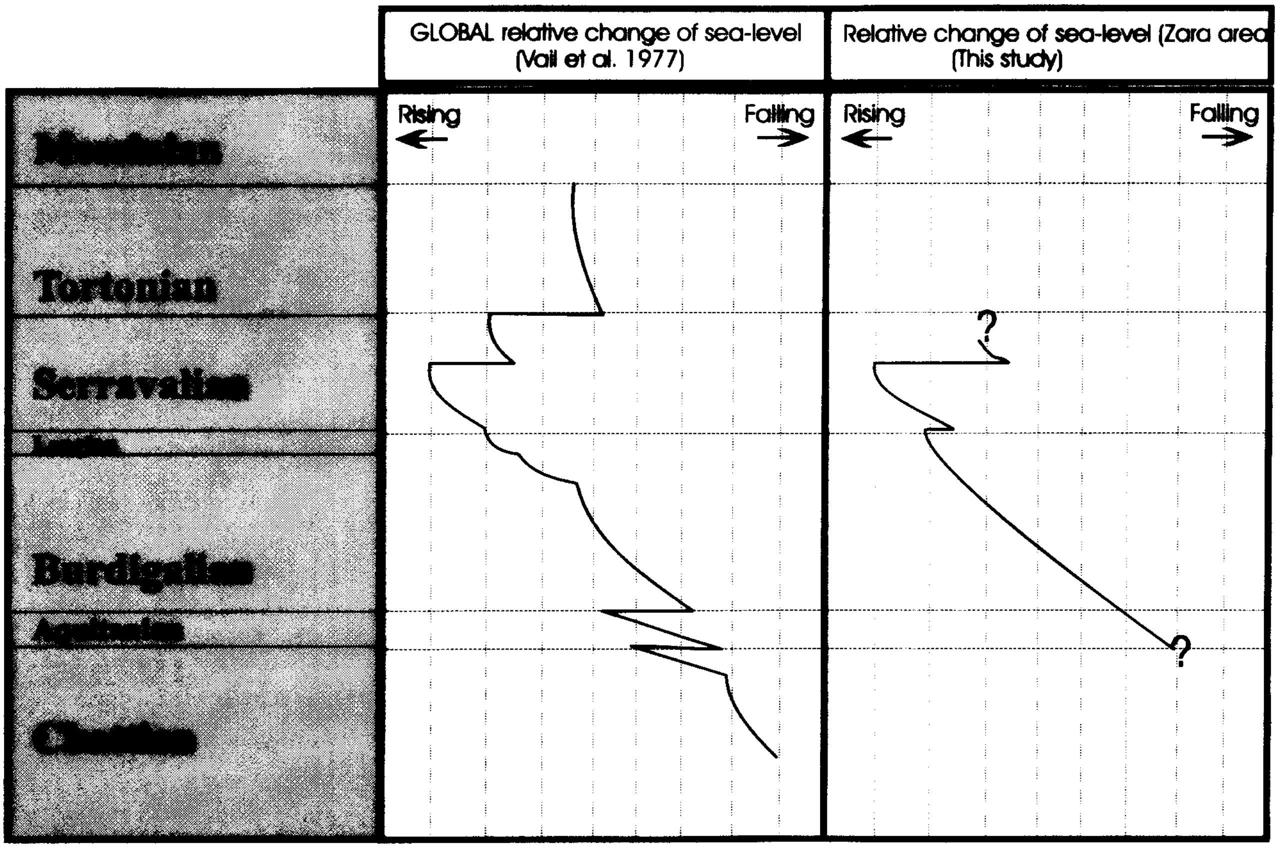

Figure 6. Global (Vail *et al.* 1977) and local (Zara area, this study) relative sea-level changes.

which is most common, and apparently carbonaceous, it weathers with conchoidal fracture. Finely laminated sediments are generally darker in colour, and thinner (commonly several tens of cm). These mudstones also host mm-thick gypsum beds. Certain levels of the facies contain a variety of fossils, both reworked and intact. For example, in N-2, there are some reworked Eocene and Late Oligocene nannoplankton, and gastropods *Trutella terebralis Lamarck*, which suggests a shelfal area of probable Aquitanian-Burdigalian age (Bernasconi & Robba 1993). In sample N-3, the abundant nannoplankton assemblage (*Sphenolithus heteromorphus Deflandre, Helicosphaera intermedia Martini, Helicosphaera kamptneri Hay and Mohler, Braarudosphaera bigelowi Gran and Braarud*) represents a Langhian age (i.e. 15-16 Ma) and is accompanied by pelagic foraminifera. The pelagic foraminifera assemblage is unusual as it is entirely made up of small *Globigerina Cyproensis*. Samples N-2, N-3, N-5, N-6 and N-8 include a number of ostracod species (i.e. *Beirdia* sp, *Rugeria* sp, *Cytherella* sp) indicating relatively deeper shelf conditions (Morkhoven 1963).

Interpretation. Reworked Eocene and Oligocene nannoplankton (as the age of the studied marine sequence is Langhian in age) presumably reflect an unconformity between the Oligocene and Miocene elsewhere, even though the passage from the probable Oligocene (Selimiye Formation) to the Miocene is conformable in the study area. The predominantly northward supply of sediments (Ocakoğlu 1997) is confirmed since marine Eocene and Oligocene outcrops are mostly situated in the south.

As indicated by non-reworked marine fossils (nannoplankton, rare pelagic foraminifera and ostracoda) and monotonous fine sediments (without major input of coarse clastics), the environment of deposition is marine and below wave base, corresponding to a relatively calm subtidal environment. Very fine-scale lamination in some levels probably indicates marked anoxic periods when the

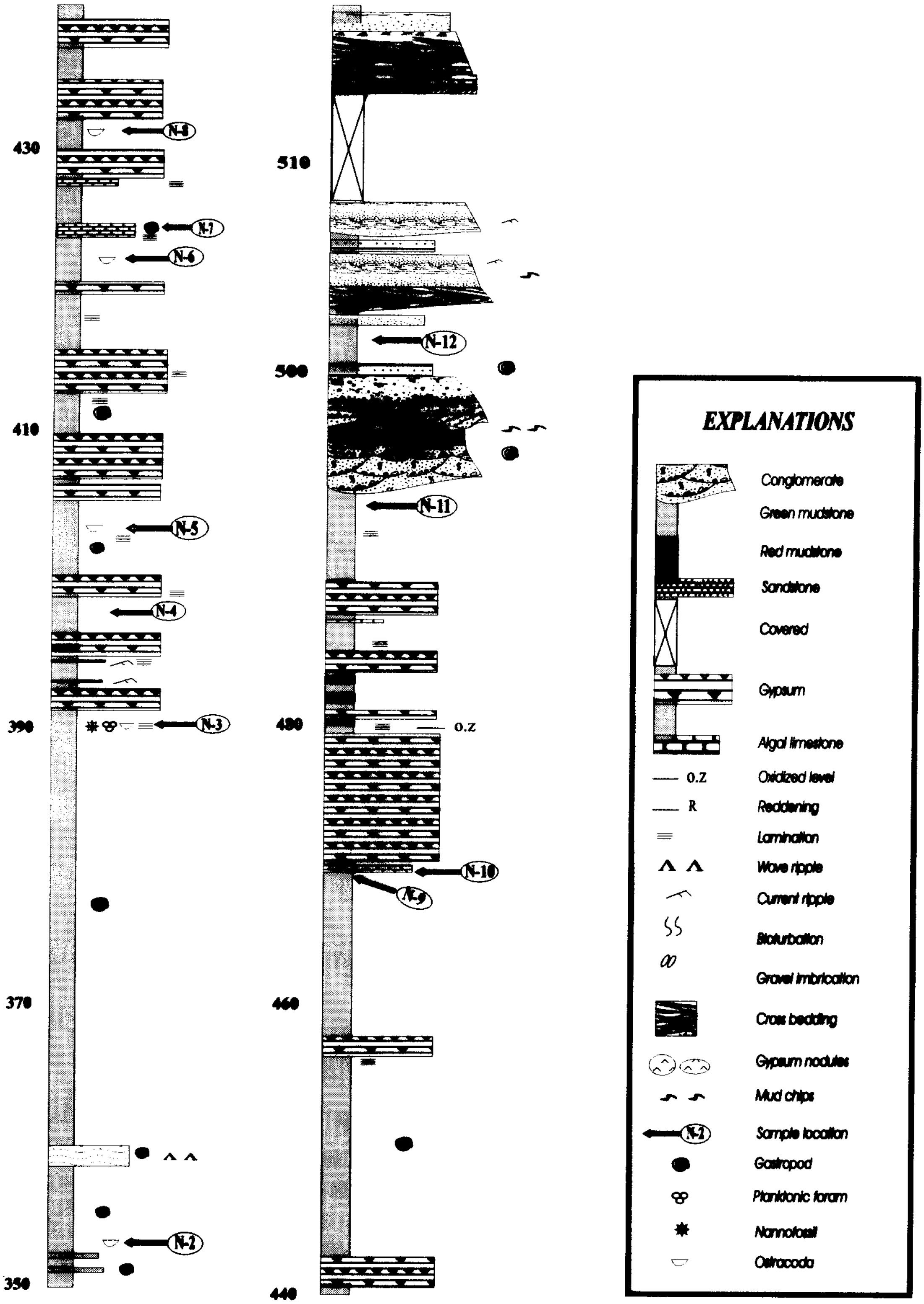

Figure 7. Detailed log of the studied evaporitic succession.

bottom benthic activity was appreciably reduced. On the other hand, the monospecific and dwarf pelagic foraminiferal fauna probably reflects a stressed environment during deposition of the facies, possibly highly saline, since evaporite beds overlie the facies each time.

Very similar facies have been described in the literature. Purser & Evans (1973) described cerithid gastropod-bearing coastal muds toward the back of lagoons along the Abu Dhabi coast where the tidal effect is weak. This facies passes upward into algal mats. Garrison *et al.* (1978) observed numerous examples of this mudstone facies from the cores of Leg 42A of the Deep Sea Drilling Project (DSDP) in the Mediterranean Sea. Scattered within these mudstones are sparse and poorly preserved shells of small pelecypods, ostracods and possibly gastropods. The present writer interpreted this facies as largely the product of shallow subaqueous deposition.

Facies B: Nodular to Crudely Stratified Gypsum

These units are 0.5- to 9-m-thick evaporitic bodies with nodular appearance (Figure 8a & d). The colour is generally milky white with patchy grey tones. The nodules are frequently several cm's in diameter (rarely reaching 5 cm) and are coated with grey mud. In some places, lensoidal shapes (chicken-wire structure; Till 1979) dominate. Macroscopic euhedral gypsum crystals are not visible within the nodules; instead, a general chalky appearance predominates. Lamination is rare and where present, crude. The lower contact is gradational either with the underlying laminated gypsum facies or, laminated mudstone facies. Within the facies thick, laminated grey mudstone layers, up to 20 cm, occur,

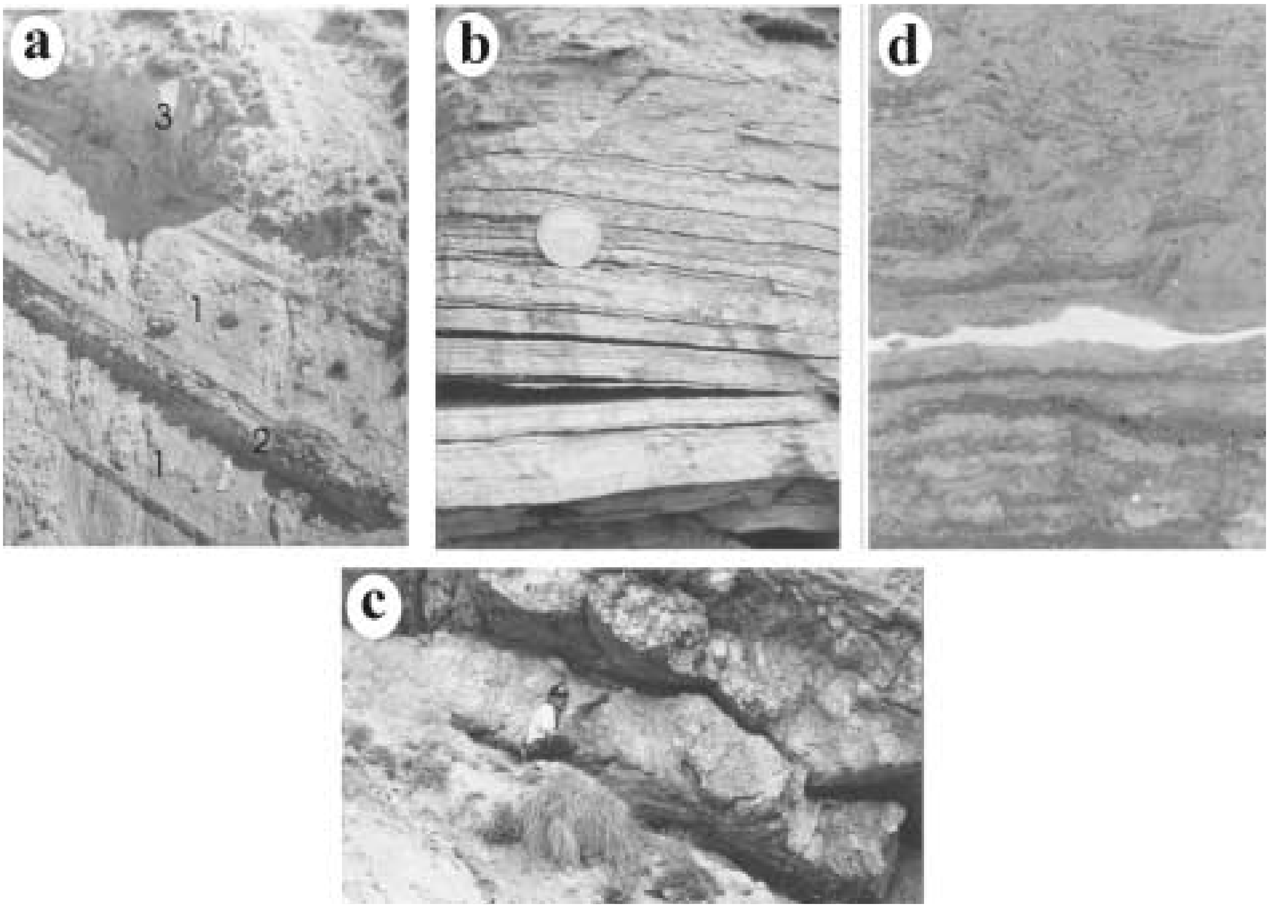

Figure 8. **(a)** Typical appearance of a subtidal mud-to-coastal sabkha evaporite cycle. 1- fossiliferous mudstone, 2- algal mat with tepee structure, 3- nodular massive gypsum. Note sitting man at the top for scale. **(b)** Close-up view of the algal mat on photo 1. Note cryptalgal laminations. Coin (2 cm) for scale. **(c)** Nodular gypsum facies and intercalated finely laminated mudstone and gypsum (field view measures about 0.5 cm wide). **(d)** Alternation of algae-rich (dark) and silt-rich layers of microscopic scale. Note distorted and broken laminae due to dessication (note person for scale).

accompanied by thin gypsum streaks (< 1 cm) (Figure 8d). At one horizon (the thickest gypsum bed in the sequence, between 470-479 m), the facies loses its nodular appearance and is brownish-reddish with a chalky texture. There, brownish mud inclusions occur in a poorly crystallized evaporitic matrix.

Interpretation. Similar facies have been widely attributed to sabkha (i.e. salt flat) environments in the literature (Till 1979; Schreiber *et al.* 1976; Warren & Kendall 1985). It has been thought that such facies form within highly concentrated pore waters of fine-grained sediments in an arid to semi-arid climates (Till 1979). Although the nodular appearance of the facies has been attributed to subsequent diagenetic events such as recrystallization and compaction, the Karacaören example matches all the features observed in the modern evaporite facies deposited along the Abu Dhabi coast.

Facies C: Laminated Gypsum

This facies was encountered at several distinct levels always at the base of the nodular gypsum facies. Lamination is generally fine (<1 cm) and the total thickness of individual beds does not exceed 50 cm. Thin interlayers of green mud occur locally.

Interpretation. Schreiber *et al.* (1976) suggested that this facies can be deposited within shallow (photic) subaqueous environments. Aref *et al.* (1997) on the other hand, observed the cogenetic occurrence of algal and gypsum levels and attributed Holocene facies of this type from the Ras Shukeir area (Gulf of Suez, Egypt) to a subtidal lagoonal environment. Schreiber & Kinsman (1975) observed that laminated gypsum deposits are presently forming by direct subaqueous precipitation in a solar salt pond in North America.

Facies D: Finely Laminated Limestone

Packages of this facies are encountered at four levels (390, 424, 429 and 487 metres in Figure 7) as thin (5 cm) to relatively thick (150 cm) accumulations. These may be intercalated with calcareous mudstone, or may be, as in the level at 424 m, made up of very thin (mm-thick) flat-to-undulatory (commonly without interlayers) laminated limestone (Figure 8b). On a larger scale, they contain up to one-metre-high tepee structures, which partly determine the geometry of the overlying mudstone (Figure 8a). Under the microscope, very thin blue-green algae (i.e. Schyzophyceae) layers interbedded with silt-size carbonate fragments were observed. The algal layers in places show complicated disturbances and break-ups, and may even be reworked (Figure 8c). Burrowing is also seen. The facies locally contain small gastropods and bivalves. It passes upwards into either mudstone or a laminated, then nodular, gypsum facies.

Interpretation. It seems that these limestones represent shallower areas (than the mudstone facies), probably the intertidal zone. Thin-section observations indicate that algae played a key role in the deposition of this facies. There has been broad agreement on the role of blue-green algae in creating algal mats in the literature, although there are exceptions (Wray 1977). The typical algal-mat at 424 m accords well with the smooth-mat characteristics of the modern sediments that Kinsman & Park (1976) sampled from the Abu Dhabi coast. They reported that the smooth mats form 15-90 cm above low wave storm base and remarked that it has the highest preservation potential among all types. These researchers observed that this facies can occur in water depths less than 40 cm where salinity conditions are favourable. The example at 424 m probably formed partly under subaerial conditions since fragmentation (probably due to sporadic desiccation) is extensive, as seen under the microscope. However, the depositional site must have been drowned from time to time because it includes (in medial levels) some gastropod-rich intervals.

Facies E: Laminated Dolomite

Stratified dolomite was encountered at one level (470 m) as a 40-cm-thick interval atop the massive mudstone in the section. The facies extends laterally for more than 100 m. It is yellowish and includes partially coalified plant debris. Laminae are extremely deformed. This facies passes upwards into earthy/chalky, porous evaporitic rocks.

Interpretation. The dolomite probably formed as a secondary mineral after calcite in the studied sequence as it shows fine parallel lamination (resembling the algal-mat of Facies D), as well as contortions. Its position in the sequence (just below the nodular gypsum of Facies B and at the top of the mudstone, Facies A) reinforces this interpretation. Modern examples from Abu Dhabi sabkhas also indicate that the mineral normally forms as diagenetic mineral on the sabkha surface by replacement of aragonite, since the Mg^{+2}/Ca^{+2} ratio is high enough for the precipitation of gypsum in the same environment. Thus, it can be suggested that progradation of the evaporitic system across the algal-mat belt results in the replacement of calcareous algal mats by dolomites.

Facies F: Red/Green Non-fossiliferous Mudstone

This facies was observed at only one level (between 480-484 metres), overlying a 30-cm-thick, laminated mudstone. Red and green layers of mudstone alternate thrice in this interval. In turn, this facies is overlain by a one-metre-thick, white to yellow nodular gypsum unit. A very similar brick-red mudstone resting on the gypsum packet is also observed in exposures 3 km NE of Karaman village (Figure 5), and here is the lateral equivalent of the thick fluvial sandstone (subunit 3).

Interpretation. The position of the mudstone in the sequence, and especially the red colour of the mud, demonstrates subaerial deposition and resultant oxidation. The facies is situated in a more southerly position with respect to the nodular gypsum. Its lateral passage into fluvial facies to the NW provides additional evidence for subaerial deposition.

Facies Associations

The facies described above stack in characteristic patterns (i.e., facies associations), in space and time and that possess environmental significance, and these facies associations are the building blocks of the sedimentary record (Figure 9).

Facies Association I

This association is characterized by fossiliferous mudstone (Facies A) at the base, passing upward into laminated gypsum-mudstone alternations and then into finely laminated mudstone. A thin algal mat and overlying mud are generally succeeded by several metres of thick nodular gypsum (Facies B). The latter is sharply overlain by generally fossiliferous, grey-to-black, massive/laminated mudstones and marls.

Facies Association II

This association resembles association I, apart from reversed positions of the algal-mat and finely laminated gypsum in the sequence. Here again, the fossiliferous mudstone is at the base, and nodular gypsum is at the top of the sequence (Figure 9).

Facies association III

This association has a tripartite character. The lower part comprises fossiliferous grey massive/laminated mudstone, which passes upward into finely laminated limestone (algal-mat facies). This latter facies in turn, is overlain abruptly by the fossiliferous mudstone of Facies A (Figure 9).

Origin of the Cycles

Each of the facies associations in the studied section displays a shallowing-upward pattern interrupted by rapid relative rises of sea level following deposition of the subaerial and intertidal facies (Figure 10a & b). The shallowing-upward trend was likely produced by the progradation of subaerial facies towards the open sea (Figure 10c), instead of by a relative drop in sea level. If the latter had been the case, some reworking of older marine levels would have ensued, but such is not borne out by field observations. Hence it appears that the rate of sediment supply was greater than the rate of relative sea level rise at this stage in the cycle. Such a condition is generally satisfied during stillstands periods of sea level.

Modern examples from Abu Dhabi exhibit very similar vertical facies changes (Figure 9.20 in Till 1979). There, the carbonate mud which formed in the subtidal zone is situated at the base, while gastropod-bearing pellet sands and algal mats with gypsum residues follow upward. The uppermost division is made up of supratidal evaporites. Till (1979) interpreted this sequence as a regressive one, while Warren & Kendall (1985), emphasizing the progradational pattern, suggested that the coastal plain of the Abu Dhabi sabkha has advanced about 13 km during the last 6000 years. Warren & Kendall (1985) concluded that progradation rates in the subtidal succession, which is on the order of one-m-thick, are up to 2 km every 1000 years. Very similar types of vertical-facies stacking have been encountered in ancient evaporitic successions. Warren & Kendall (1985) for example, wrote that the full trinity (i.e. subtidal, intertidal and supratidal sediments, including laminated cryptalgal mats and sulphate-containing supratidal units) is critical in attributing an ancient body of sediment to a sabkha

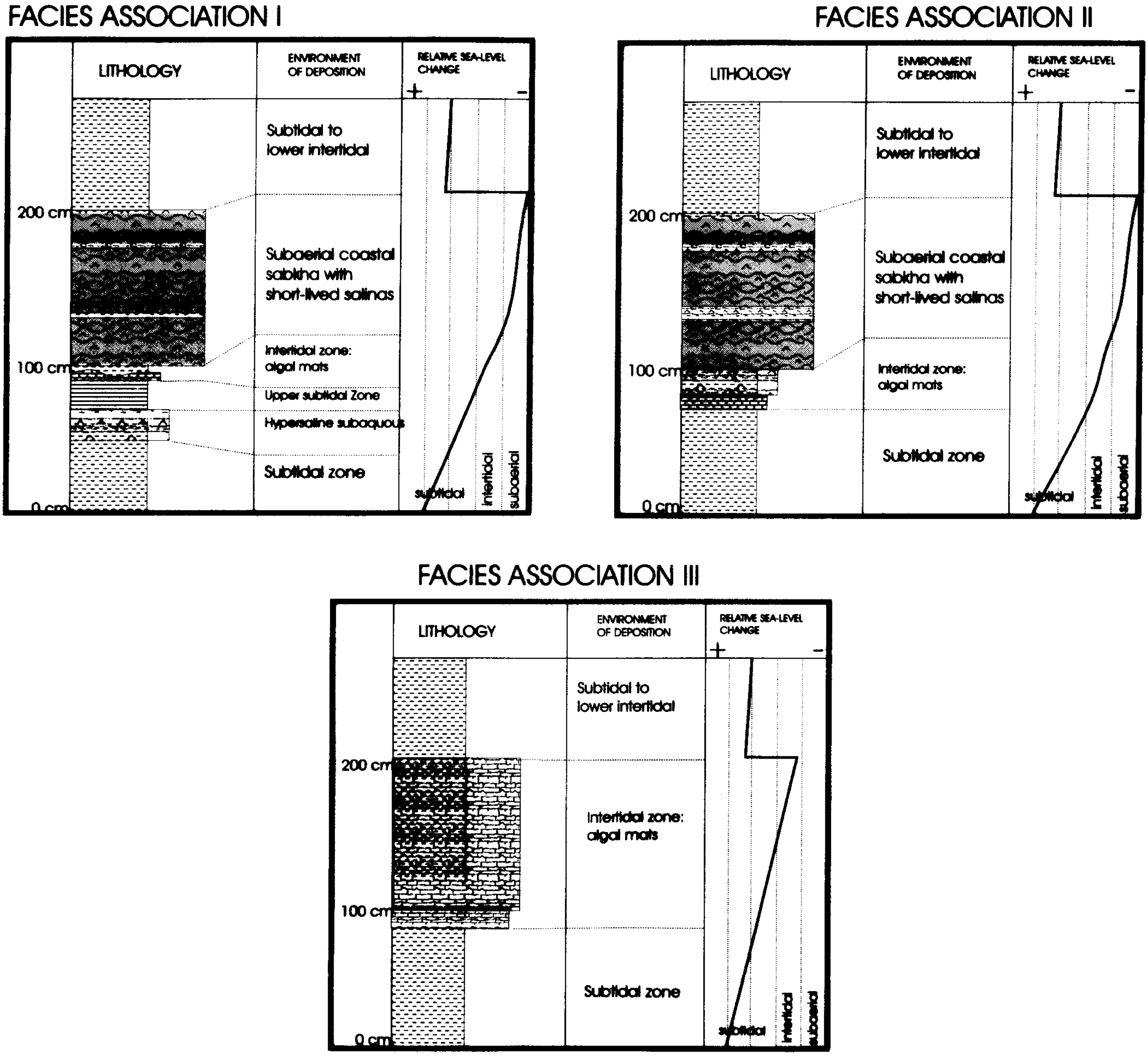

Figure 9. Facies associations in the studied evaporitic sequence (refer to Figure 7 for explanation of symbols).

setting. Garrison *et al.* (1978) investigated mudstone-to-nodular gypsum cycles of Messinian age that were recovered from Balearic and Ionian basins by DSDP (p. 585). They interpreted that the succession reflects a shoaling depositional environment, from subaqueous to mainly subaerial.

The cyclicity observed in the study area has many parallels with other documented progradational cycles. Aigner & Bachmann (1989) documented more than 15 small-scale (commonly one- to four-m-thick) trans/regressive cycles (i.e., a rapid rise at the base, and then a shallowing upwards trend) in the lower part of the Gypskeuper formation of Triassic age. A full Gypskeuper cycle begins with a subtidal facies (which is quite different from the example in this paper) at the base, and is capped by a supratidal facies. The authors, aided by the widespread lateral continuity of these exposures, discarded an autocyclic mechanism, and suggested that they can be regarded as astronomically-controlled parasequences (i.e., Milankovitch cycles). PACs

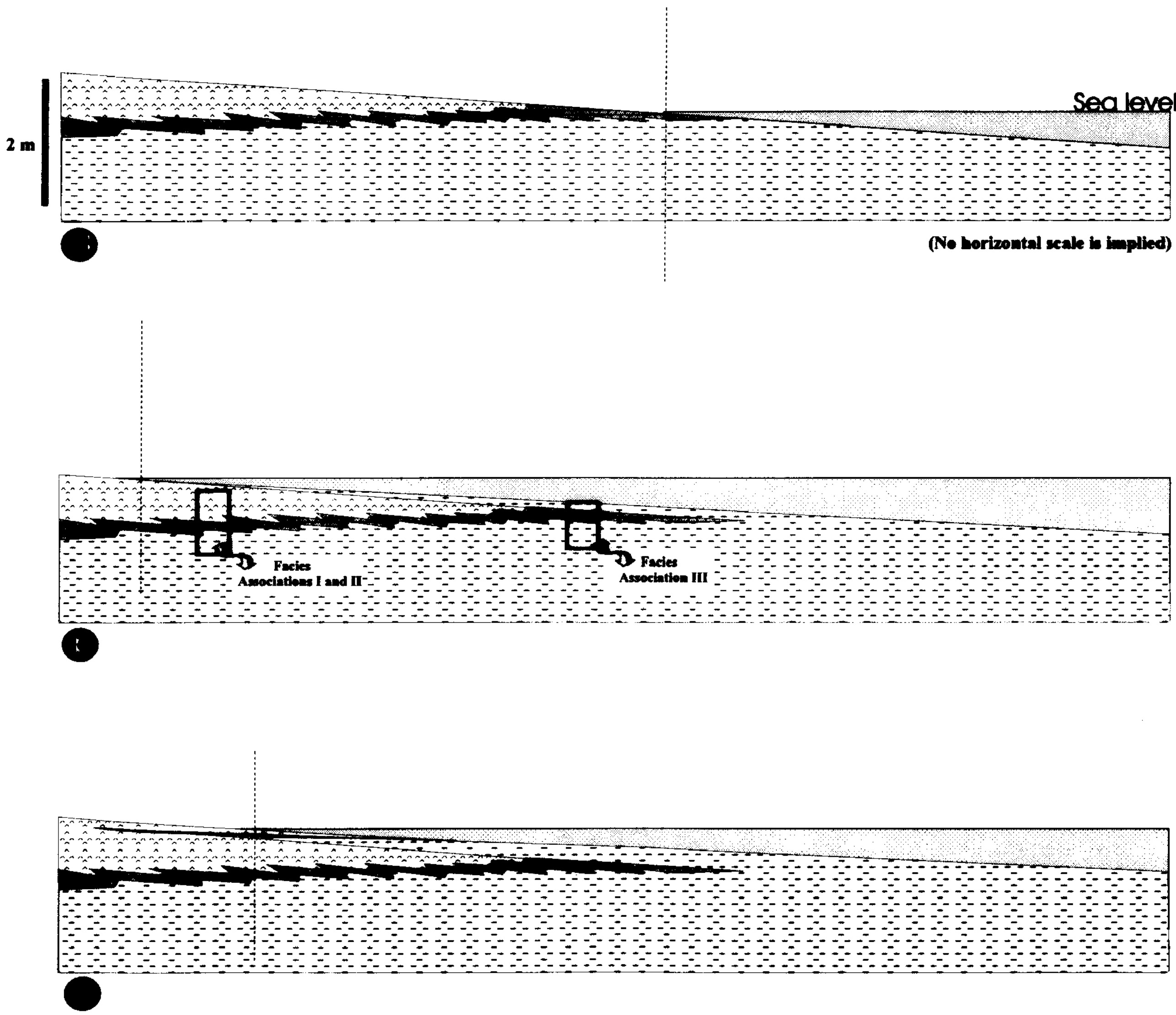

Figure 10. Modes of formation of the defined facies associations. **(a)** progradation of coastal sabkha system towards shelf, **(b)** transgression, resulting in the formation of several types of facies associations, **(c)** renewed progradation of coastal sabkha basinwards.

(Punctuated Aggradational Cycles) first described by Goodwin & Anderson (1985) are another similar (if not identical) type of sequence that are frequently observed in carbonate rocks. These one- to five-m-thick shallowing-upward cycles are defined at the base by an isochronous boundary (also a non-depositional surface), which is generated by a geologically instantaneous sea-level rise (Goodwin & Anderson 1985, p. 517, Figure 2). Here again, the researchers regarded glacial eustacy as the driving factor.

In view of the scale and facies stacking style of the Karacaören cycles described above, I suggest that the cycles in the present study represent Milankovitch cycles (i.e. parasequences).

Significance in Distribution of the Studied Evaporitic Succession in the Sivas Basin

Figure 4 shows the distribution of marine Miocene units (i.e., the Karacaören Formation) in the central and eastern parts of the Sivas Basin. For areas II and III in

Figure 4, there is no doubt about the uniqueness of the marine unit (sandwiched between continental deposits), while for the westernmost area diverse stratigraphic columns have been erected by various authors (Çiner & Koşun 1996; Gökçe & Ceyhan 1988; Poisson *et al.* 1996), probably due to confusing tectonic deformation. For this sector, I adopt the stratigraphy (with only one marine Miocene level) proposed by Poisson *et al.* (1996). In Figure 4, the underlying sedimentary rocks of the Karacaören Formation are shown as two separate units [Eocene volcanogenic flysch and Oligocene (?Lowest Miocene) sedimentary rocks] in order to test the degree of Miocene onlap.

As seen in the Figure 4, the Karacaören Formation extends widely but patchily atop of the Oligocene sediments, especially in the northern part. The lack of preservation of significant exposures in the northern areas is directly related to post-Middle Miocene tectonic uplift and subsequent deep erosion (Poisson *et al.* 1996; Ocakoğlu 1999) since recent palaeogeographic reconstructions reveal that those areas were a site of relatively deep shelfal mud and carbonate accumulation at that time (Poisson *et al.* 1997).

The geographical extent of the studied evaporitic succession is also shown in Figure 4. One can suggest that the distribution is non-uniform and, that there are two distinct areas within which marine evaporite deposition focussed. Those features are separated from each other by a palaeogeographic high, where the Miocene carbonate rocks unconformably overlie the Oligocene Selimiye Formation, while on both the western and eastern sides of the uplift the stratigraphic record is more or less continuous throughout the Miocene. On the other hand, the northern limit of evaporite deposition is clearly defined by a boundary situated between Yolören and İmranlı, and Karayün and Hafik (Figure 4). The facies north of this boundary consists of marine mudstones and carbonate rocks while the southern area encompasses evaporitic facies. Even though detailed sedimentologic data are currently lacking, thick, aggrading packages of nodular gypsum that perhaps were interbedded with alluvial (though not marine) facies are expected to characterise the more southern evaporitic succession. As with the northern boundary, it is likely that this marks the maximum basinward progradation of the evaporitic system.

Two further questions require answering to have a complete picture of Miocene evaporitic deposition in the Sivas Basin. Does the studied evaporitic succession correspond to a basinwide (or regional) salinity crisis? If so, what is the driving mechanism for this? A previous geochemical evaluation performed by Baysal & Ataman (1980) showed the absence of abnormally high evaporative conditions during the deposition of evaporites in the Sivas Basin, since they are characterized by low levels of F, Li and Sr; this implies inhibition of free circulation with adjacent larger seas due to palaeogeographic obstacles. The analyzed samples were collected from six different locations in the basin, and are assigned to the Lower to Middle Miocene. Baysal & Ataman (1980) suggest a marine influence since they include some marine fossiliferous levels. One of the sampled localities is the same as one mentioned by Kurtman (1961). Previous studies point to a narrow connection in the eastern part of the basin. For example, Poisson *et al.* (1997) have drawn a palaeogeography in which the open marine facies are distributed in the north (around Sivas), while restricted marine and fluvial facies occur in the south. They suggested that the Mediterranean connection of the study area was provided by a passage situated further east from the Oligocene sediments. Luttig & Stefens (1976) proposed an E-W trending Langhian-Serravalian trough extending from Sivas to Van and farther east, and suggested that it was periodically flooded by the sea. Hence, at the present level of knowledge about the palaeogeography of the Sivas Basin and easterly connected basins, it can be suggested that this geologically relatively short period in the Late Burdigalian (may be Serravalian), when coastal evaporite deposition occurred, is a time of little or no connection with the eastern Mediterranean.

Conclusions

The following conclusions can be drawn from analysis of the 100-m-thick evaporitic succession in the Zara area: (1) The evaporitic succession was deposited mainly during a generally transgressive segment of the local relative sea-level change curve. (2) The studied evaporite sequence is characterized by a facies trinity, which is also common in some modern coastal evaporitic settings such as in Abu Dhabi. The elements of this facies association are typically fossiliferous subtidal mudstone at the base, intertidal limestone and laminated gypsum in the middle, and nodular gypsum of a coastal sabkha environment at the top. (3) The facies succeed each other vertically in a predictable manner, so that a general shoaling upward pattern (with 5 m average thickness) results in each cycle. The great lateral extent, similar internal architecture, and the average thickness of these cycles closely resemble parasequences described in the literature. (4) The formation of 100-m-thick gypsum-bearing coastal evaporites within the ca. 1000-m-thick marine sediments could be related to their formation in marginal, restricted conditions with little or no connection to an open marine environment.

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