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Upper Cenomanian-Lower Campanian Derdere and Karababa formations in the Çemberlitaş oil field, southeastern Turkey: their microfacies analyses, depositional environments, and sequence stratigraphy

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Abstract: The frontal belt of the southeastern Anatolia fold-thrust belt in Turkey contains several small to mid-size oilfields, producing from carbonate reservoirs of the Cretaceous Mardin group. Many of these fields are found along narrow, asymmetrical anticlinal structures, associated with the formation of the fold-thrust belt. The Çemberlitaş oil field in Adıyaman, southeastern Turkey, is one of the most important oilfields in the region. It produces from the Upper Cretaceous Derdere and Karababa formations of the Mardin group. We have conducted a detailed study of the microfacies, depositional environments, and sequence stratigraphy of the Karababa (Coniacian-lower Campanian) and Derdere (mid-Cenomanian-Turonian) formations in the oil field. Eight microfacies in the Karababa and Derdere formations have been identified; the microfacies in the Karababa formation are 1) mollusk-echinoid wackestone/packstone, 2) dolomitic planktonic foraminifera wackestone, 3) planktonic foraminifera bearing wackestone/packstone, and 4) phosphatic-glauconitic planktonic foraminifera bearing wackestone. The microfacies in the Derdere formation are 5) lime mudstone, 6) bioclastic wackestone/packstone, 7) medium-coarse crystalline dolomite, and 8) fine crystalline dolomite. These microfacies suggest that the Derdere formation was deposited in lagoonal to shelf depositional environments and the Karababa formation was deposited in a deep to shallow marine intrashelf basin. Two third-order sequence boundaries of late Turonian and early Campanian in age have been recognized in the reservoir interval. Depositional sequences contain transgressive and highstand systems tracts. These sequences are compared with those in other regions to differentiate the local, regional, and global factors that controlled sedimentation within the Çemberlitaş oil field area.

Key words: Derdere and Karababa formations, depositional environment, microfacies, sequence stratigraphy, Çemberlitaş oil field

1. Introduction

The Çemberlitaş oil field (Figure 1) is located in the frontal belt of the southeastern Anatolia fold-thrust belt near the city of Adıyaman in Turkey (Lisenbee, 1985; Wagner and Soylu, 1986; Perinçek and Çemen, 1992) and produces from the upper Cenomanian-lower Campanian carbonate reservoirs of the Mardin group, which has long been recognized as the main source and reservoir rock in the region. On the surface, the field area contains a large anticlinal feature, the Çemberlitaş Anticline, where the Çemberlitaş oil field includes a large anticlinal feature. The Middle to Upper Eocene Hoya formation is the oldest unit exposed along the crest of the anticline. The Upper Miocene Şelmo and Pliocene Lahti formations also outcrop along the flanks of the anticline. The Gebeli syncline and Çemberlitaş thrust fault are located to the north of the field (Figure 2).

In the Adıyaman area, most of the previous studies focused on the stratigraphy, lithology, and petrography of the Mardin group (Rigo de Righi and Cortesini, 1964; Cordey and Demirmen, 1971; Wagner and Pehlivanlı, 1985; Görür et al., 1987, 1991; Uygur and Aydemir, 1988; Çelikdemir and Dülger, 1990; Çelikdemir et al., 1991; Coşkun, 1992; Duran and Alaygut, 1992; Çoruh, 1993; Sayılı and Duran, 1994). The sequence stratigraphy of the Mardin group has remained relatively unstudied. The main objectives of the this study are 1) to provide a sequence-stratigraphic interpretation for the Karababa and Derdere formations of the Mardin group in the Çemberlitaş oil field area based on a detailed analysis of sedimentological and petrographic characteristics of the microfacies recognized in these middle Cenomanian-lower Campanian sequences and 2) to compare the sequence stratigraphy of the

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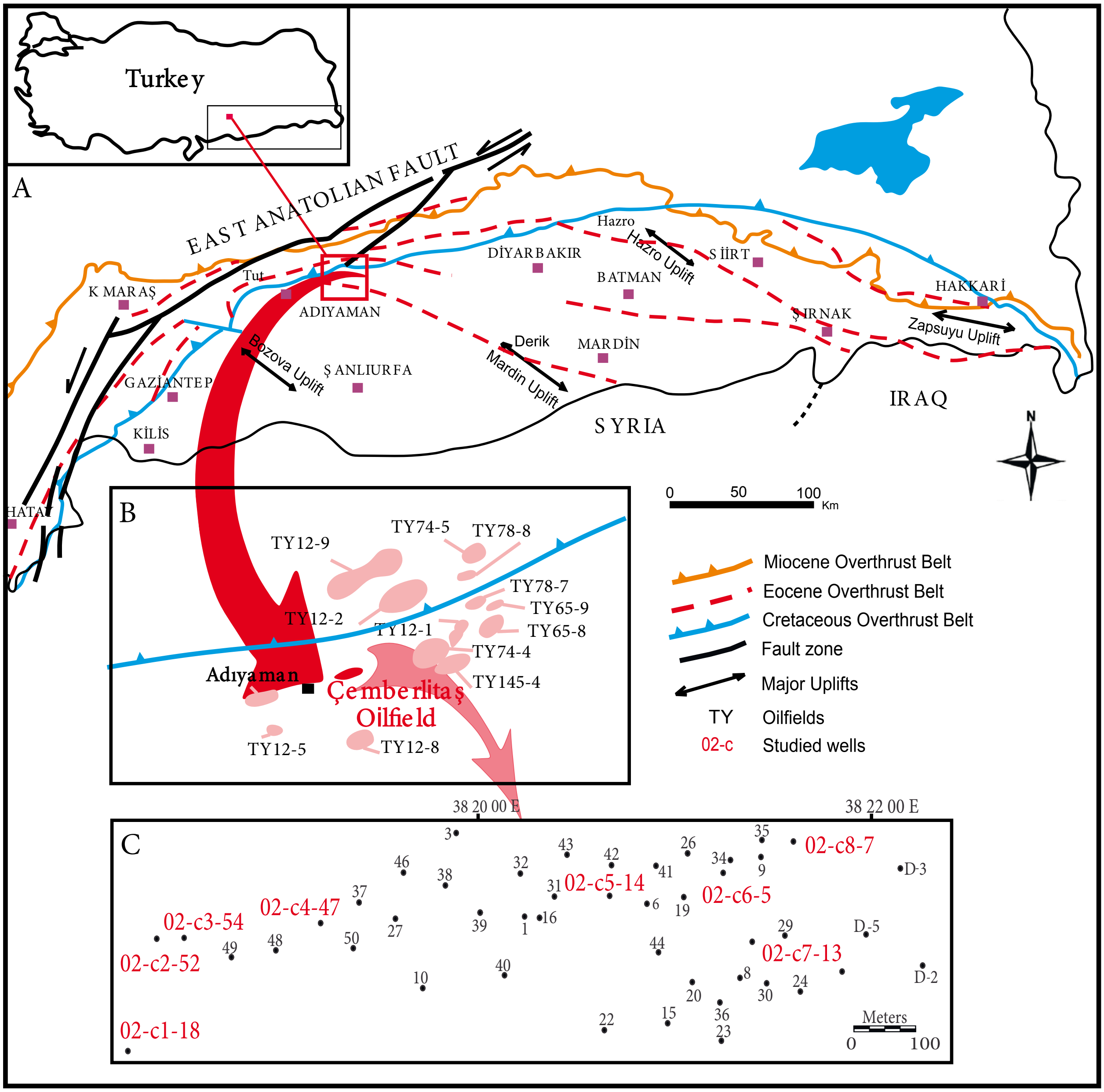

Figure 1. Index map of the study area showing tectonic units in SE Anatolia, A; location of the Çemberlitaş oil field, B; and well locations in the study area, C (modified from Aksu and Durukan, 2014). The insert map in the upper left corner shows the location of southeastern Anatolia, Turkey.

Karababa and Derdere formations with other regional sequence-stratigraphic studies (Lüning et al., 1998; Sharland et al., 2001; Schulze et al., 2003; Haq, 2014).

The southeastern Anatolia fold-thrust belt is a part of the Zagros fold thrust, which has experienced a complex structural development during the collision of the Arabian Plate with the Turkish plate since the Late Cretaceous. In this paper we will discuss only the sequence stratigraphy and depositional environments of the Karababa and Derdere formations based on our examination of the available limited cores and petrographic thin-section analysis from the Çemberlitaş oil field. For discussions on the structural/tectonic development of the Southeast Anatolia fold-thrust belt, the reader is referred to other sources (Şengör and Yılmaz, 1981; Çemen, 1987, 1990; Perinçek and Çemen, 1990, 1992; Yılmaz, 1993).

2. Geologic and stratigraphic overview

Southeast Anatolia, Turkey, constitutes the northernmost part of the Arabian Platform that formed as a part of the

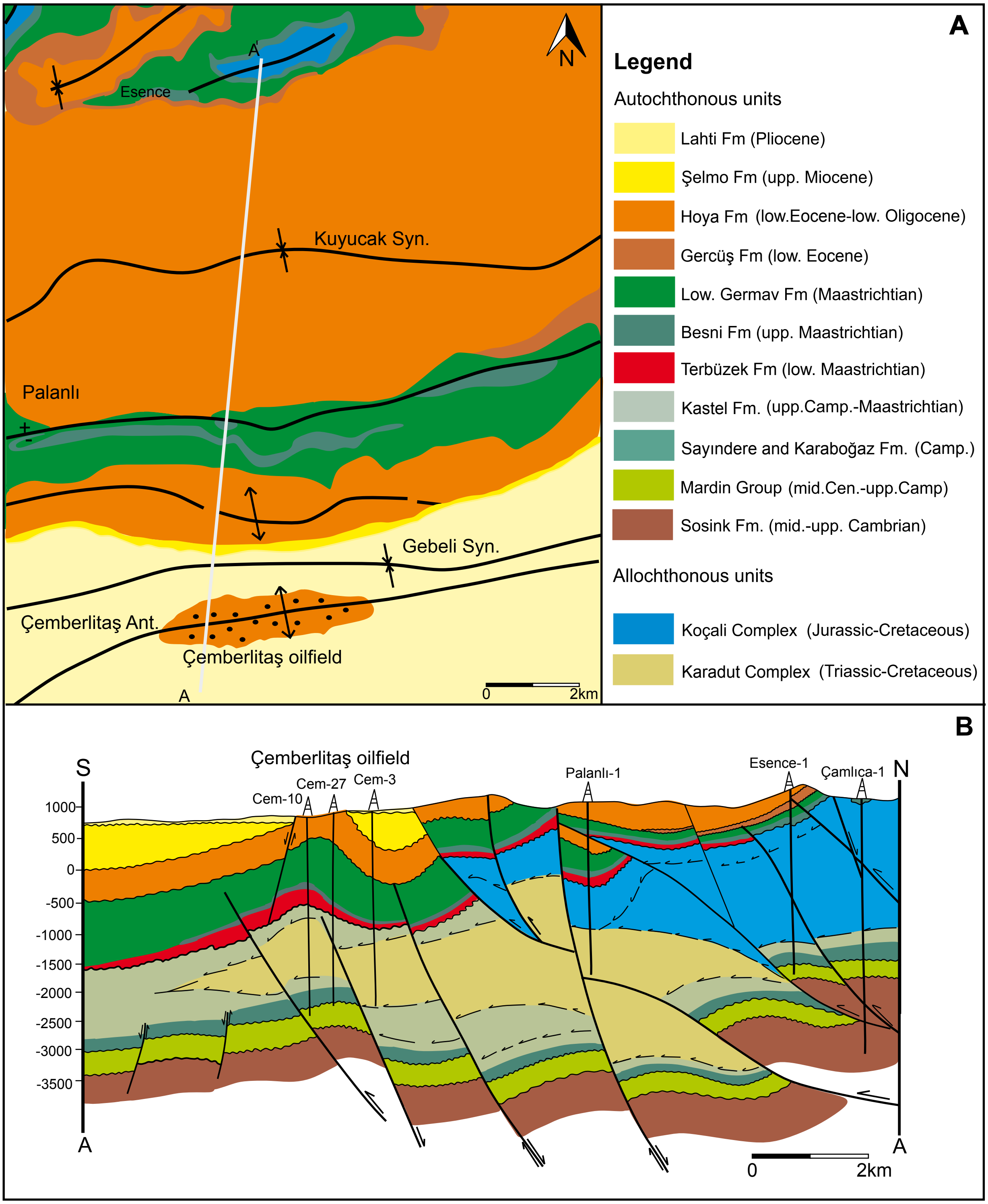

Figure 2. A) Simplified geologic map of the Çemberlitaş oil field area (modified from Aksu and Durukan, 2014). B) Simplified N-S structural cross-section along line A-A'.

north facing, passive Gondwanian margin of the southern branch of the Neotethys Ocean (Şengör and Yılmaz, 1981; Harris et al., 1984). Before the deposition of the Mardin carbonates, in the Late Jurassic to Early Cretaceous, the Arabian Platform experienced an extensional tectonics, which caused a block faulted terrain with structural highs and lows (Sungurlu, 1974; Ala and Moss, 1979; Sass and Bein, 1980). The extensional tectonics was roughly in the N-S direction and formed E-W-trending structural and topographic highs and lows (Yılmaz, 1993). As the transgression flooded the north-facing passive margin during the Aptian and Campanian, the Mardin carbonates were deposited (Görür et al., 1991). The Karababa and Derdere formations of group (middle Cenomanian-Campanian) were deposited in shelf and intrashelf basins along the north-facing passive margin of the Arabian Plate (Horstink, 1971; Uygur and Aydemir, 1988; Çelikdemir et al., 1991; Ziegler, 2001). During the early to mid-Cretaceous, the shelf area deepened northward into the southern branch of the Neo-Tethys Ocean. Relative sea-level changes in the ocean resulted in the development of two shallowing-upward depositional cycles, which together with a number of subcycles have been identified in the Mardin group succession (Görür et al., 1987). Erosional and nondepositional surfaces have also been identified within the group by sequence-stratigraphic analysis by Tardu (1991) and Mülayim (2013).

2.1. Stratigraphy of the Derdere Formation

The Derdere Formation comprises three units: dolomites at the base, dolomitic limestone in the middle, and bioclastic limestone in the upper parts (Figure 3). The unconformity between the Sabunsuyu and Derdere formations is mainly defined by environmental and lithological differences between the two formations. The exposed contact between them shows erosional features indicating an unconformity. In addition, cores from the top of the Sabunsuyu Formation show karstification features such as solution pipes, leaching, and brecciations (Wagner and Pehlivanlı, 1985; Çelikdemir et. al., 1991; Mülayim, 2013). These features indicate a subaerial exposure of the Sabunsuyu Formation (Görür et al. 1987) and support the existence of the unconformity. The Derdere Formation is regionally distributed and ranges from 5 to 84 m in thickness in the study area. The differences in thickness of the formation are probably due to predepositional paleotopography and the erosion on the postdepositional surface (Çelikdemir et al., 1991; Coşkun, 1992; Mülayim, 2013).

2.2. Stratigraphy of the Karababa Formation

The Karababa Formation consists of carbonates. It is unconformably underlain by the Derdere Formation and unconformably overlain by the Karaboğaz and Sayındere formations (Campanian). The Karababa Formation is

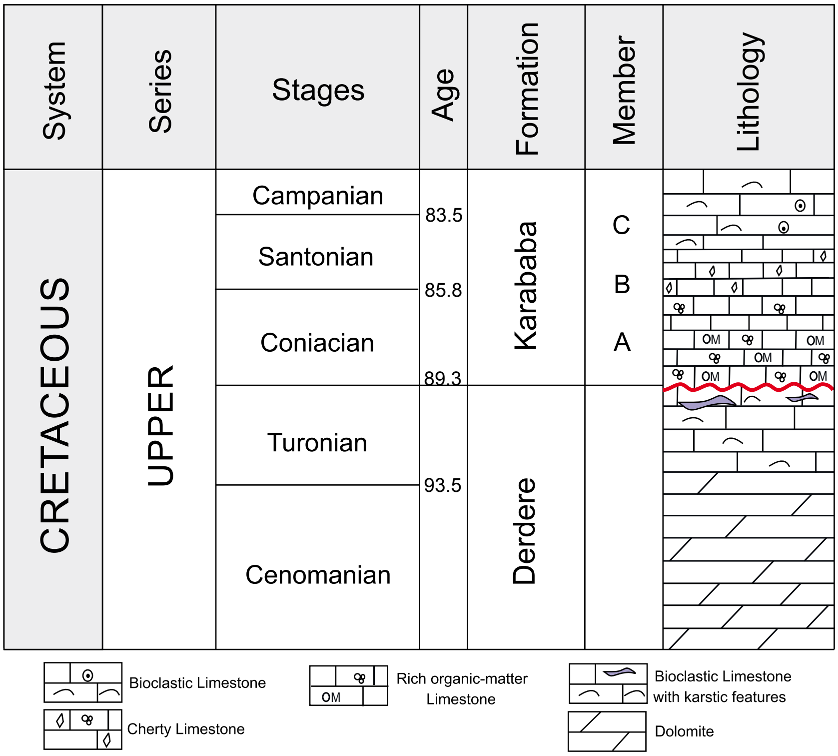

Figure 3. Upper Cretaceous subsurface lithostratigraphic units in the Çemberlitaş oil field (modified from Çelikdemir et al., 1991). No vertical scale is implied.

uniformly distributed throughout the study area. The thickness of the Karababa Formation ranges from 77 to 133 m and is irregular. This irregularity is attributed to the presence of intrashelf basins or depressions as depositional sites for the Karababa Formation (Wagner and Pehlivanlı, 1985; Çelikdemir et al., 1991; Mülayim, 2013). The formation consists of three members (Figure 3). The lower member (Karababa-A) is a dark brown gray, very fine-grained limestone. It contains rich-organic matter and abundant pelagic foraminifera. The Karababa-A member grades into the middle Karababa-B member. The upper Karababa-C member is a bioclastic limestone and partly dolomites. The unconformity between the Karababa and Derdere formations is characterized by nondeposition and erosion (lacuna) and is not regionally developed. The top of the Derdere Formation shows evidence of karstification. Cores taken from the top of the Derdere Formation display karstification features (Wagner and Pehlivanlı, 1985; Çelikdemir and Dülger, 1990).

3. Methods

This study is based on data from eight exploration and production wells in the Çemberlitaş oil field. Samples were collected from the available cores in these wells near significant lithological changes within the stratigraphic succession of the Derdere and Karababa formations. Petrographic analysis is used to determine depositional facies (microfacies) of the Derdere and Karababa formations. The classification scheme used is that of Dunham (1962) with the modifications of Embry and Klovan (1971). The microfacies analysis was carried out using standard models and microfacies descriptions (Wilson, 1975; Flügel, 2004). Petrographic analysis of 160 thin sections (from cores and cuttings) from 8 wells resulted in the recognition of 8 microfacies. The sequence-stratigraphic model used in this study follows the approach and terminology of Emery and Myers (1996), Schlager (2005), and Catuneanu (2006). The sequence-stratigraphic tracts were then correlated with each other based on facies and depositional environments and finally related to the global sea-level curves of Haq (2014) for neighboring areas.

4. Microfacies analysis

Based on the composition and texture, the fabrics observed from petrographic thin-section study have been grouped into 8 different microfacies (MF) types, which are briefly described in the Table and illustrated in Figures 4a–4f and 5a–5f.

In the following section of the paper, first the microfacies of the Karababa Formation and their interpretations are discussed, and then the microfacies of the Derdere Formation and their interpretations are discussed.

4.1. Microfacies of the Karababa Formation

The sedimentary facies of the Karababa Formation are dominated by deep subtidal microfacies types; their depositional setting fundamentally differs from that of the Derdere Formation. Large parts of the Karababa Formation are represented by fossiliferous limestone beds (fine-grained wackestones/packstones) containing abundant planktonic foraminifera, thus indicating deep and open marine deposition below the storm wave base. In the upper parts of the unit, interbeds of skeletal and nonskeletal packstone and wackestone with bivalve, echinoids, and calcareous algae are found, suggesting intermittent shallow-water deposition characterized by transitions between deeper and shallower facies. Dolomite intercalations may be associated with emergent source areas. The four microfacies types of the Karababa formation are summarized in the Table.

Mollusk-Echinoid Wackestone/Packstone (MF1): Fossils in this microfacies include mollusks, echinoids, green algae (dasycladacean), and planktonic and benthic foraminifera. Only a few phosphatic grains are present in a single sample. The calcitic shells and tests of fossils can be seen as well preserved. Bivalve fragments and echinoids are well calcified. Some fossils, usually echinoids, can be seen as dolomitized and may be replaced by a single crystal of dolomite or by many fine rhombs.

Interpretation: Wackestones containing well-preserved bivalve fragments (Figures 4a and 4b) reflect a low-energy depositional environment below the fair-weather wave base. Preservation of these shells indicates that they are not reworked on the sea floor. Additionally, no preferential orientation of shells is observed in this microfacies. The echinoids found in this subtidal environment are broken and reworked, indicating transportation by wave energy. This microfacies can be correlated with the FZ 7 facies of Wilson (1975). The distribution of various fossil groups in Figures 4a and 4b shows the presence of filamentous fragments of dasycladacean algae and possible calcareous sponge spicules occurring in open shallow shelf and lagoonal environments.

Dolomitic Planktonic Foraminifera Wackestone (MF2): The matrix of this microfacies consists of dolomicrite and very fine-grained crystals and clear rhombic crystals. Where the cement is neomorphic calcite spar, it may consist entirely of extremely fine-grained calcite crystals, or it may be fine- to medium-grained, subhedral crystals. In some places the matrix has a texture similar to that of the dolomicrite of the lower cherty dolomitic limestone (Figure 4c) with extremely fine-grained anhedral crystals mixed with very fine- to fine-grained calcite rhombs. In places, clear, fine-grained, rhombic dolomites are present within these samples (Figures 4c and 4d). Fossils in this wackestone include planktonic foraminifers, echinoids,

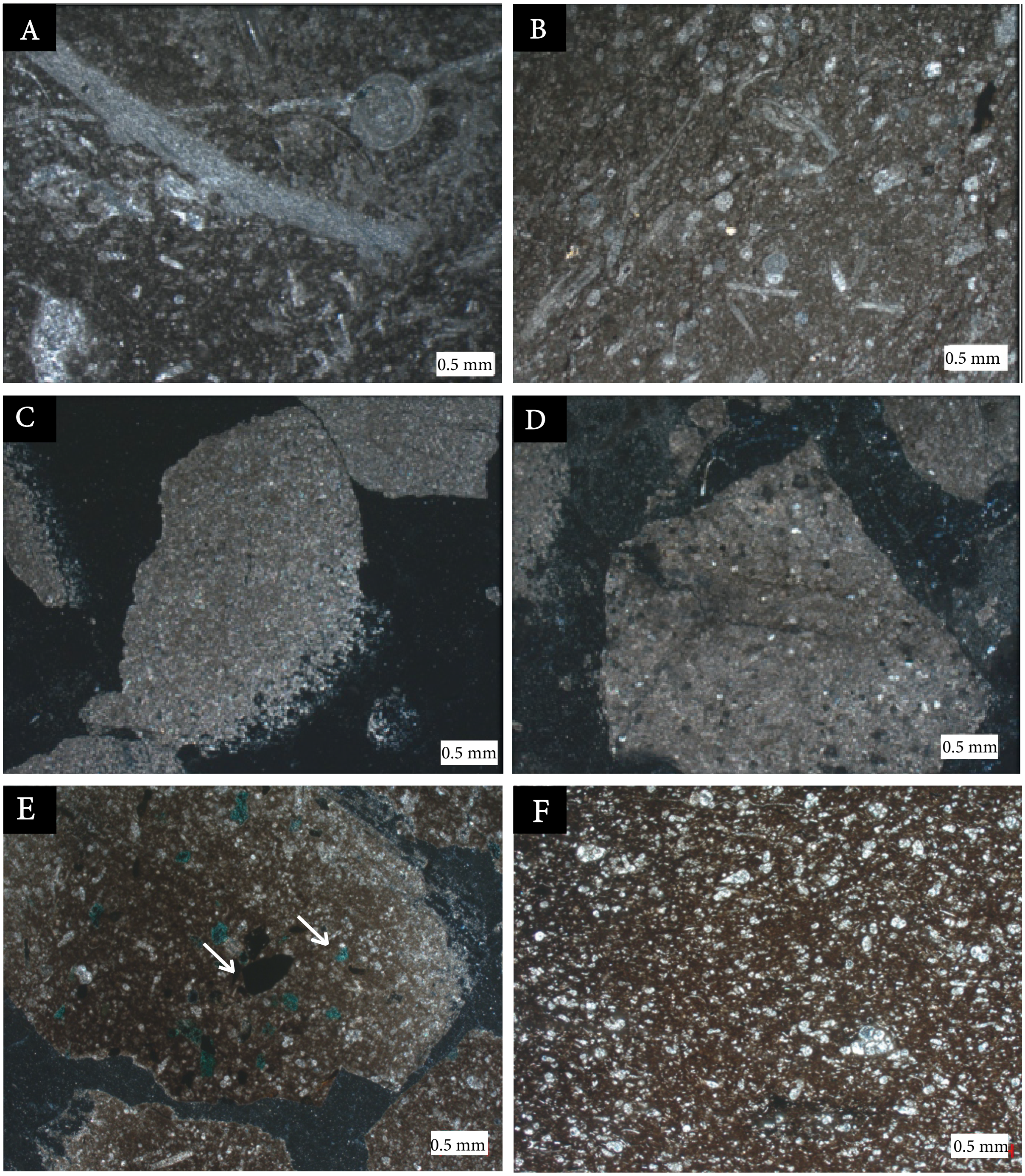

Figure 4. Microfacies of Coniacian-lower Campanian Karababa formation (scale bar = 0.5 mm). A and B) MF1, mollusk-echinoid wackestone/packstone, sample 082012-4, 02-c7-13, sample 082012-41, 02-c6-5; C and D) MF2, dolomitic planktonic foraminifera wackestone, sample 082012-15, 02-c1-18, sample 082012-10, 02-c1-18; E) MF4, phosphatic-glauconitic planktonic foraminifera bearing wackestone, sample 082012-15, 02-c8-7; F) MF3, planktonic foraminifera bearing wackestone/packstone, sample 082012-8, 02-c6-5.

and mollusk fragments. The shells are generally preserved but can be seen as partially or completely replaced by dolomite. The microfacies are partially dolomitized with the development of scattered subhedral to euhedral dolomite crystals, which form about 2% of the rock volume. The dolomite crystals range in size from 50 to 80

Table. The 8 MF types of the Karababa and Derdere formations in the Çemberlitaş oil field.

Formation	Facies	Microfacies type (Mf)	Depositional setting
Karababa Fm.	Limestones	Mollusks-echinoid wackestone/packstone MF1	Open shallow shelf restricted lagoon
		Dolomitic planktonic foraminifera wackestone MF2	Deep open marine quiet water conditions
		Planktonic foraminifera bearing wackestone/packstone MF3	Deep marine restricted dysoxic
		Phosphatic glauconitic planktonic Foraminifera bearing wackestone MF4	Deep marine restricted dysoxic
Derdere Fm.	Limestones	Lime mudstone MF5	Shallow subtidal-restricted lagoon
		Bioclastic wackestone MF6	Shallow subtidal-restricted lagoon
	Dolostones	Medium-coarse crystalline dolomite MF7	Shallow subtidal to lower intertidal
		Fine crystalline dolomite MF8	Shallow subtidal to lower intertidal

µm (fine to medium crystalline). They are rarely zoned with turbid cores and clear peripheries.

Interpretation: The characteristics of the microfacies suggest deposition in shallow low-energy, open marine environments. Deposition probably took place in open circulation below the storm wave base and toe of slope FZ 3 of Wilson (1975). In general, the degree of dolomitization of the original matrix increases as the number of fossils decreases. This suggests that the depositional environment became more restricted, possibly due to differences in water circulation resulting in increases or decreases in salinity that promoted penecontemporaneous dolomitization.

Planktonic Foraminifera Bearing Wackestone/Packstone (MF3): This microfacies is common at several horizons in the Karababa-A member of the Karababa formation in the Çemberlitaş oil field. It consists mainly of dark brown and gray micrite containing organic rich material. It is slightly recrystallized into microspar, and it has few microfossils (Figures 4e–4f) and contains planktonic foraminifera and thin bivalve fragments, cemented by abundant micrite. Foraminifera are filled with fine sparry calcite and micrite cement. Phosphate grains are scarce (≤1%), and glauconite grains are absent. Microscale vertical size-grading occurs (Figure 4f). This microfacies is dominated by planktonic foraminifera, including the genera *Hedbergella* and *Heteroheliex*, which occur in homogeneous microcrystalline calcite. Many of the foraminiferal tests are replaced by subordinate sparry calcite such as *Globigerinelloidies*- and *Pithonella*-dominated calcispheres.

Interpretation: The sedimentary and fossil contents of the Karababa Formation indicate that it was deposited as a slope-to-basin environment and may correspond to FZ 1 of Wilson (1975), and it can be interpreted as deep-water carbonate deposits.

Phosphatic-Glauconitic Planktonic Foraminifera Bearing Wackestone (MF4): This microfacies is composed of planktonic foraminifera, bivalves, having less frequent glauconite and phosphate grains observed in the lower part of the Karababa Formation (Figure 4e). The facies is a recrystallized micrite or locally sparite containing argillaceous mud fragments that are irregularly scattered throughout both the matrix and cement. The matrix is dominated by small bivalve fragments and organic matter (Figure 4e). Small benthic foraminifera are less abundant than the planktonic foraminifera that dominate in the upper and lower levels. Planktonic fossils gradually decrease upwards in abundance in this microfacies. The grains deposited in this facies are observed to be of a green color that is also observed in some phosphatic wackestones. The abundance of glauconite and phosphate grains varies between 1% and 2% and between 2% and 3%, respectively.

Interpretation: This microfacies overlies the lime mudstone microfacies (MF4). It reflects deposition in a low-energy, deep marine environment. The high faunal abundance, and especially planktonic foraminifera, supports the interpretation of an open marine environment. The presence of echinoids and mud-supported fabrics (wackestone) indicates quiet water conditions.

4.2. Microfacies of the Derdere Formation

The Derdere Formation also contains four microfacies in the study area. They are (MF5) lime mudstone, (MF6) bioclastic wackestone, (MF7) medium-coarse crystalline dolomite, and (MF8) fine-crystalline dolomite (Table). These microfacies are in the middle and upper units of the Derdere Formation at the Çemberlitaş oil field. The four microfacies types of the Derdere Formation are summarized in the Table.

Lime-Mudstone (MF5): This microfacies occurs in the uppermost part of the Derdere Formation (Figure 5a). It is fine-textured, partly dolomitic, and dark to light gray in color. This microfacies is usually found in association with marls and fossiliferous limestone. Microscopic

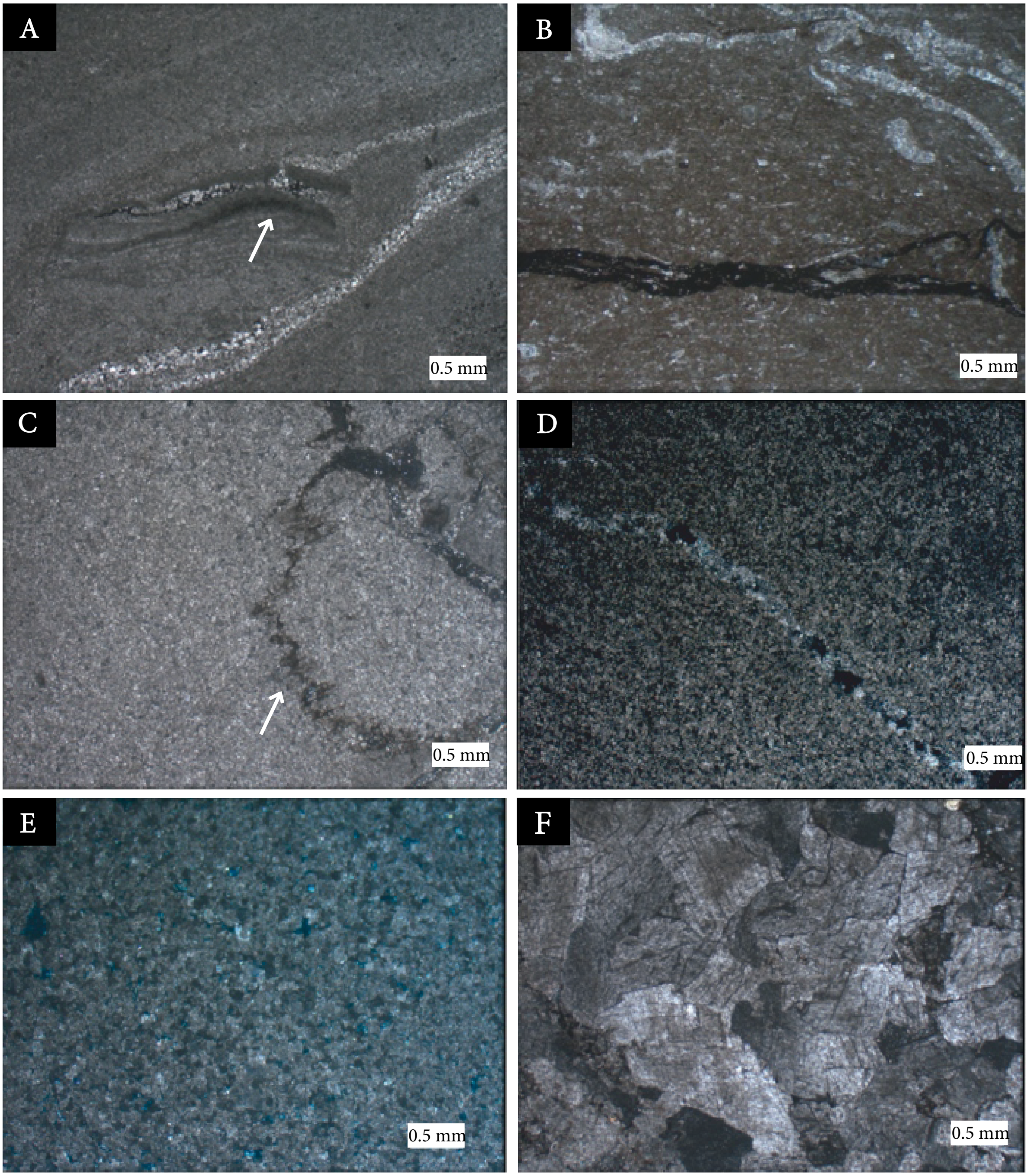

Figure 5. Microfacies of mid-Cenomanian-Turonian Derdere formation (scale bar = 0.5 mm). A) MF5, lime mudstone sample 082012-12, 02-c1-18; B) MF6, bioclastic wackestone, sample 082012-15, 02-c6-5; C and D) MF8, fine crystalline dolomite, sample 082012-6, 02-c5-14; E and F) MF7, medium-coarse crystalline dolomite, sample 082012-3, 02-c6-5, sample 082012-8, 02-c6-5, sample 082012-4 02-c1-18.

investigations show that these lime-mudstones are composed of dense micrite (95%) with rare shell debris (1%–2%).

Interpretation: The lime-mudstone microfacies has been deposited in low-energy environments with low faunal abundance (benthic foraminifera and calcareous algae). It contains fine dark gray lamination, which is common for deposition in shallow lagoons characterized by calm conditions with no or little water circulation (Flügel, 1982; Pittet et al., 2002), or in shallow marine carbonate shelf environments with low wave and current energy. The low faunal diversity reflects the restricted conditions in this setting. This microfacies may correspond to FZ 8 of Wilson (1975). Therefore, the sparsely fossiliferous lime-mudstone at the Çemberlitaş oil field indicates deposition in a shallow subtidal zone of a lagoon. The abundance of the stylolites in horizontal seams in this microfacies indicates dissolution and chemical compaction. The stylolite zones act as impermeable barriers inhibiting the movement of fluids perpendicular to the plane of the stylolites, but they serve as conduits to facilitate fluid movement parallel to the stylolite seams (Figure 5a).

Bioclastic Wackestone (MF6): This microfacies is mud-supported and contains around 30% to 40% skeletal material as seen in most thin sections. These allochems are diverse and include mollusk and echinoids fragments, calcareous algae, and ostracods. The shell fragments are highly recrystallized, consisting of calcite spar characterized by high birefringence (Figure 5b).

Interpretation: This microfacies is comparable to the FZ 7 and 8 facies of Wilson (1975) and the SMF 12 facies of Flügel (2004). These facies represent deposition in shelf lagoons. The predominance of bioclastic shell fragments in this microfacies indicates a shallow subtidal environment with limited circulation. These deposits also record short-term periods of sea-level fluctuation or storm events as indicated by reworking and transportation. Bioclasts in this microfacies are benthic foraminifera (uniserial and biserial), micritic algae, and bivalve shell fragments.

Medium-Coarse Crystalline Dolomite (MF7): This microfacies is the most abundant type of dolostones by volume in the Derdere formation. It consists mainly of interlocked calcitized dolomite rhombs (Figures 5e and f). No fossils are found in this microfacies, while dissolution vugs and fractures are locally present. No replacement textures are observed.

Interpretation: The occurrence of coarse crystalline dolomite facies suggests a progressive shallowing of sea level (Mutti and Simo, 1994). The medium-coarse crystalline dolomites have been interpreted as deposited in a shallow subtidal to lower intertidal setting.

Fine Crystalline Dolomite (MF8): This microfacies consists mainly of idiotopic interlocked fine dolomite rhombs (Figure 5c). Some dolomite rhombs become calcitized into light calcite ones. The dense mosaics contain no recognizable allochems. Stylolites are common in the dolostones (Figures 5c and 5d).

Interpretation: The fine-grained rhombs of dolomite can probably be attributed to replacement of the original calcium carbonate mud (Al-Aasm and Packard, 2000). The fine crystalline dolomites have been interpreted as a result of penecontemporaneous dolomitization of precursor micrite in supratidal flat sediments during the regressive phase in an upper intertidal to supratidal setting (Warren, 2000). The presence of finely crystalline dolomites with no evaporates suggests that the microfacies was deposited in a shallow subtidal to lower intertidal zone in platform carbonate depositional settings that were formed during sea-level fall (Abu El-Hassan and Wanas, 2005).

5. Depositional environments

Based on the microfacies described above, and the fact that the Derdere and Karababa formations are separated by a major unconformity (Coşkun, 1992; Wagner and Soylu, 1986), two separate depositional models are proposed in this paper for the two formations. The model for the Karababa Formation is an intrashelf complex (Figure 6). The model for the Derdere Formation is a shallow shelf-lagoonal system (Figure 7). Similar facies models for the Mardin group of the Adıyaman area were proposed by Görür et al. (1987, 1991), Uygur and Aydemir (1988), Duran and Alaygut (1992), and Sayılı and Duran (1994).

5.1. Karababa Formation

Intrashelf basins were common on the shallow northern margins of the Arabian Plate in Cenomanian-Turonian time. The infill of the intrashelf basins often consists of storm-generated sequences of sediments derived from the surrounding platform (Read et al., 1986). In deeper parts of the basins, organic-rich sediments may have accumulated, which can form source rocks for hydrocarbons (Ayres et al., 1982).

The Karababa Formation is in general a shallowing upward sequence of wide lateral extent with an initially deposition in a deep-water basin. It has been subdivided into A, B, and C members to reflect differences in depositional environments up-section (deep to shallow marine) in which the Karababa Formation consists of organic-rich limestones and is considered to be one of the major source rocks in southeastern Turkey (Görür, 1991). The deposition of the Karababa source rock took place in an intrashelf basin, which is interpreted as an anoxic silled basin (Demaison and Moore, 1980). Karababa-A represents an anoxic deeper part of the basin and the Karababa-B and -C represent the overlying more oxygenated sediments (Figure 6).

The Karababa-A member is a dark, muddy carbonate

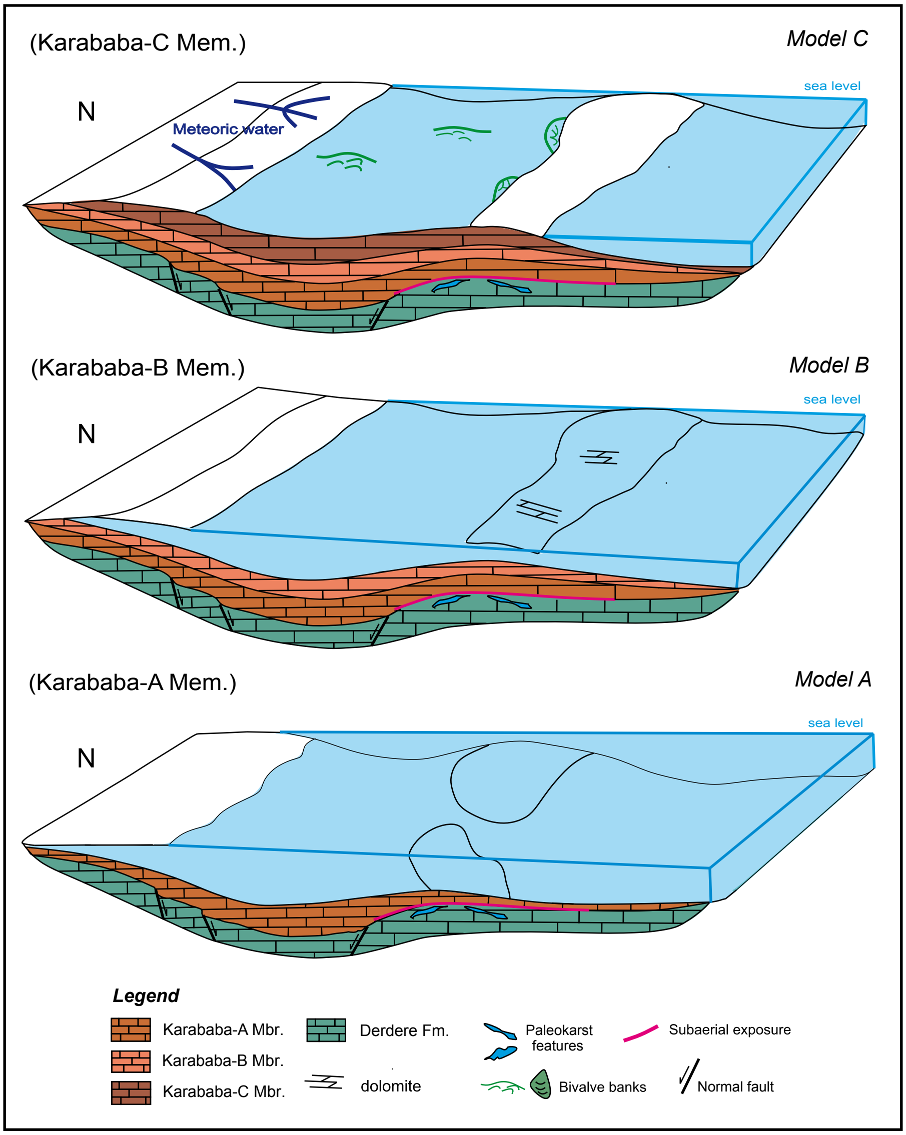

Figure 6. Depositional models of the three members of the Karababa formation in the Çemberlitaş oil field area.

of rich organic matter. The presence of abundant pelagic foraminifera indicates a deep water environment. This suggests that a fast sea-level rise occurred in the Santonian. The Karababa-A member is composed of *Heterohelix*-bearing strata that may reflect variable nutrient levels and fluctuating sea level during the deposition (Figure 6). The association of nonkeeled planktonic foraminifera such as *Globigerinelloides* and calcispheres represents a planktonic assemblage that colonized shallow as well as deeper neritic and open marine environments. This facies is interpreted as the deepest intrashelf basinal environment with an estimated water depth of approximately 60–150 m. Bottom-water conditions in this setting fluctuated from well oxygenated to dysaerobic (Van Buchem et al., 2010). The abundance of the *Heterohelix* forms and calcispheres indicates transgressive episodes. The *Heterohelix* and *Globigerinelloides* forams and calcispheres dominate the limestone and are considered as indicators of eutrophic conditions (Omaña et al., 2012).

The Karababa-B member is planktonic, including dolomite rhombs and micritic carbonate. Its microfaunal content suggests deposition in a water depth that was somewhat shallower than the one in which Karababa-A was deposited. The Karababa-C member is a bioclastic carbonate containing mollusks, echinoids fragments, green algae, and small benthic foraminifera, indicating a shallow marine environment. This facies occurs in the regressive part of the third-order sequences that are

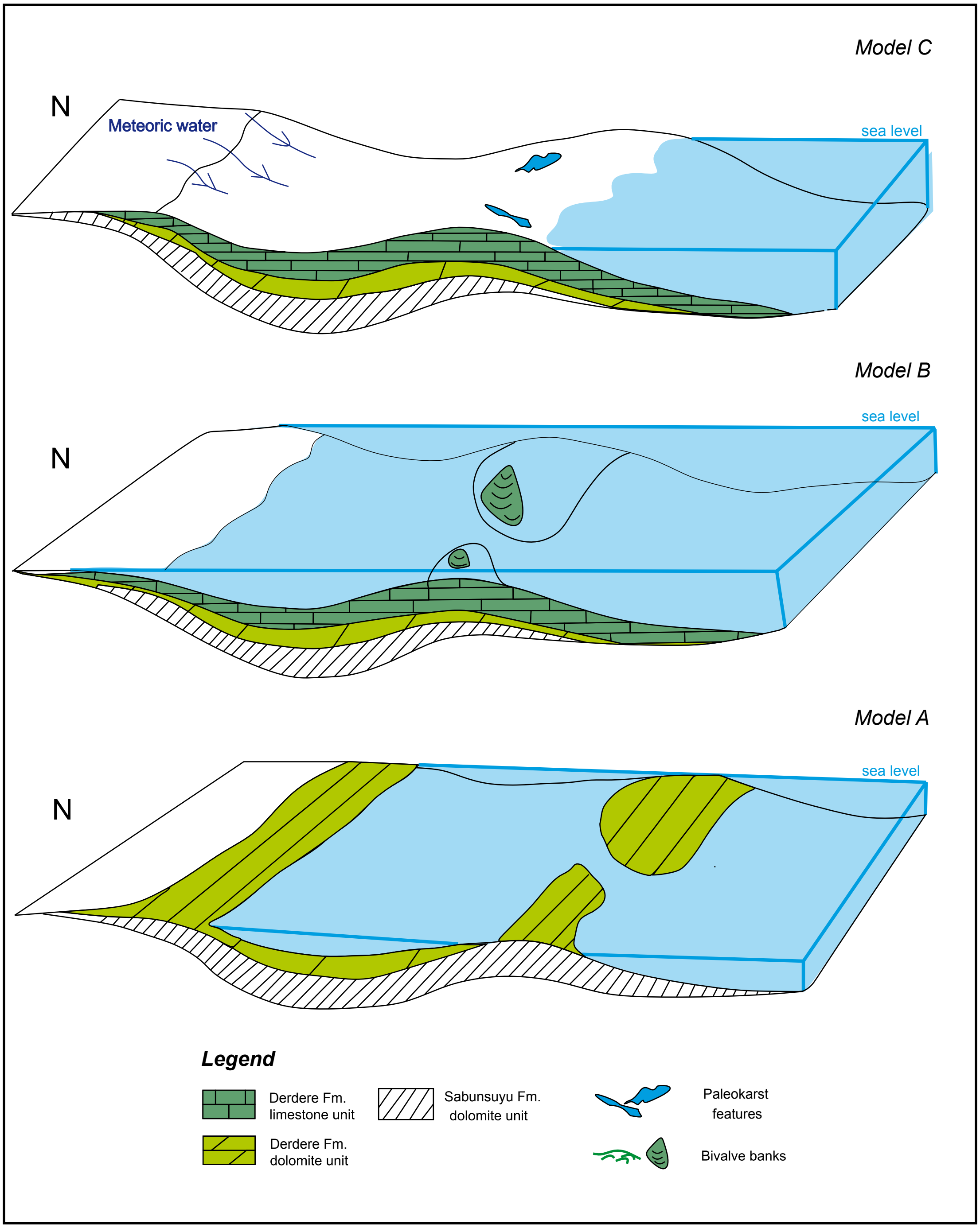

Figure 7. Depositional environment models of Derdere formation in the Çemberlitaş oil field. A) Depositional environment during middle Cenomanian (dolomite unit). B) Depositional environment during early Turonian (limestone unit). C) Development of paleokarst features on the top of the limestone unit in the early Turonian.

characterized by water depths just above or around the storm wave base. Therefore, this facies is interpreted as being deposited in a shallow water, well-oxygenated, intrashelf basinal environment, with an estimated water depth of about 10–40 m. Karababa-C also suffered early meteoric water leaching. This is suggested by the presence of strongly solution-widened fractures and secondary intraskeletal porosity. However, in comparison to the Derdere Formation, the exposure of Karababa-C to surface conditions was for a shorter period.

5.2. Derdere Formation

The characteristics of the microfacies of the Derdere Formation suggest deposition in a shallow shelf to marine lagoonal depositional environment. In this setting, calcareous green algae are common in chlorozoan assemblages (Lees, 1975). The formation locally contains lime mudstone microfacies. The absence of larger planktonic foraminifera, textulariids, and open marine fauna is consistent with a shallow shelf to marine lagoonal environment (Figure 7). The lagoonal conditions were widespread and probably occurred in an epeiric shallow shelf setting that included local protected areas on the shelf associated with bivalve banks (Figure 7). Depositional conditions for the Derdere sediment accumulation in the photic zone included shallow water depths, warm temperatures, normal salinities, and low to moderate water energy as evidenced by the presence of a high content of euphotic and stenohaline organisms, such as calcareous algae (dasyclads), ostracods, and bivalves. Such a faunal assemblage is characteristic of shallow marine deposition. The relative abundance of suspension- and deposit-feeding macrobenthos of bivalves and echinoids indicates eutrophic conditions (Wilmsen and Nagm, 2002). Absence of macrofauna and the occurrence of low-diversity microfauna predominated by benthic foraminifera (miliolids) suggest that the uppermost part of the Derdere Formation represents a slightly restricted environment characterized by elevated salinities and a very shallow water environment. Due to the shallow water nature of the Derdere Formation it may contain some exposure structures such as paleokarstic features associated with low sea-level conditions.

6. Sequence stratigraphy

The carbonate microfacies of the Derdere and Karababa formations contain a distinctive assemblage of facies and stratigraphic surfaces that can be used to define depositional sequences and systems tracts. During this study, special attention was given to the recognition of an abrupt change in the vertical succession of facies. The sequence-stratigraphic terminology of Van Wagoner et al. (1988) and Sarg (1988) was used together with the concepts developed by Catuneanu (2002) and Schlager (2005).

The Derdere and Karababa formations in the subsurface can be subdivided into two third-order sequences that were deposited from the middle Cenomanian to the early Campanian (Tardu, 1991). Each depositional sequence is bounded by an unconformity and contains transgressive and highstand systems. Within each sequence, a deepening upward trend defines the transgressive systems tract (TST), and a shallowing upward trend in water depth defines the highstand systems tract (HST). Transitional beds between the systems tracts show a deepening to shallowing succession that represents a condensed section, which is interpreted as a maximum flooding surface (MFS) (Figure 8).

6.1. Depositional sequences and sequence boundaries

The Karababa and Derdere formations in the Çemberlitaş oil field include parts of two depositional sequences formed in response to tectono-eustasy changes (Figure 8). The sequences are divided by distinctive sequence boundaries that were recognized by abrupt facies changes in the stratigraphic record, such as hardgrounds or subaerial exposure structures and development of facies representing shallowing or deepening upward sedimentary environment conditions.

6.1.1. Depositional Sequence-1

This partial sequence includes the middle and upper parts of the Derdere formation. Its lower part is not observed in the study area. Its upper boundary is marked by SB1 in the Çemberlitaş oil field (Figure 8). It is correlated with S2 and S3 (TuJo2/TuJo3) of Schulze et al. (2003) in Jordan (Figure 8) and with TuSin (S1) of Lüning et al. (1998) in central-eastern Sinai. Deposits of the TST of this sequence were not recognized in the study area. However, deposits of the HST of this sequence are recognized in the Çemberlitaş oil field area. They are composed of a shallowing upward section that formed as a result of a sea-level highstand. The top of the HST in the area is marked by transition from shallow subtidal to intertidal facies, which reflects the overall shallowing upward trend during this regressive phase. The occurrence of dolomites below the shallow subtidal carbonate platform unit has been interpreted to be related with a relative progressive shallowing of water depths due to a decrease in the rate of sea-level rise.

6.1.2. Depositional Sequence-2

This sequence includes the entire Karababa formation with all of its three members (i.e. A, B, and C members) and is defined by sequence boundary 1 (SB1) at its base and sequence boundary 2 (SB2) at its top (Figure 8). Sequence 2 contains TST (member A) and HST deposits (members B and C). The transgressive surface at the base of this TST in parts of the basin coincides with SB1. The TST interval of this sequence consists of sediments of deep subtidal limestone and foraminifera bearing wackestone/packstone beds. The MFS is identified at the top of the deep subtidal units. The MFS is recognized by a facies change from the underlying deepening upward trend observed in the foraminiferal wackestone facies below a shallowing upward trend seen in the overlying beds (Figure 8). This HST section constitutes the uppermost part of the middle (Karababa B) and the entire upper part (Karababa C) of the formation. The HST strata are overlain by thick aggradational shallow subtidal units. These shallowing upward units represent HST deposits that formed due to

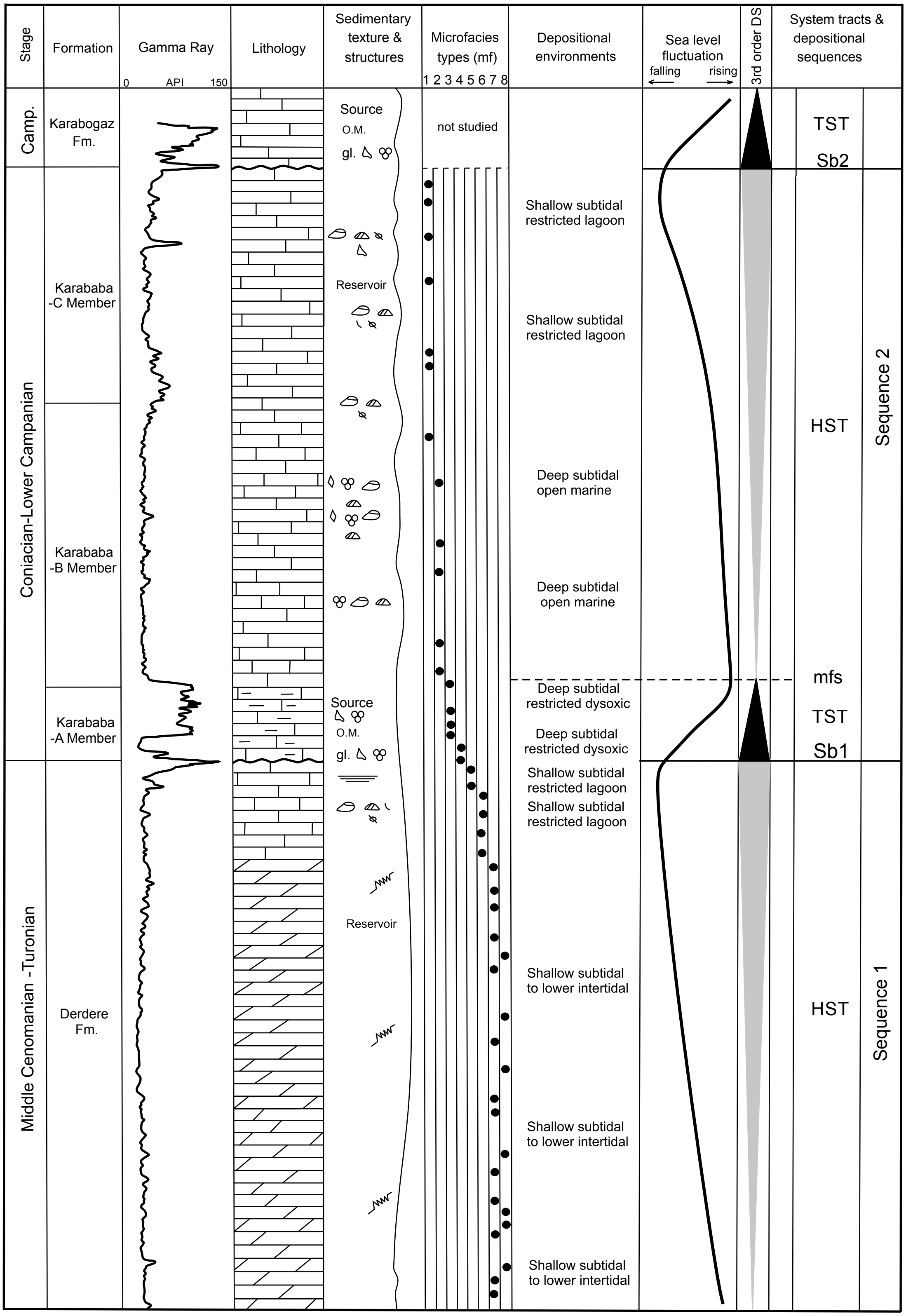

Figure 8. Representative general stratigraphic sections in the Çemberlitaş oil field showing the microfacies, depositional environments, relative sea-level curve, depositional sequence, system tracts, and boundaries of the Karababa and Derdere formations.

a normal regression associated with a sea-level highstand. This HST interval consists of shallow subtidal units of members B and C deposited at the top. Such an occurrence of dolomites above intertidal-shallow subtidal carbonate platform beds has been interpreted here to suggest to a progressive shallowing of sea level.

SB1 is recognized at the top of the Derdere Formation as the base of Depositional Sequence-2. It separates the shallow carbonate deposits (lagoon) of the middle Cenomanian Derdere Formation and the deep subtidal (intrashelf) carbonate deposits of the overlying Coniacian-lower Campanian Karababa Formation (Figure 8). The boundary contains features suggesting solution-enhanced fractures, collapse breccia, vugs, and cave floor deposits (Wagner and Pehlivanlı, 1985) that developed at the time of subaerial exposure. This boundary is recognized as a subaerial unconformity. This interpretation is consistent with the sequence boundaries described in Jurassic and Cretaceous shallow-marine strata associated with the carbonate platform of France and Oman by Hillgaertner (1998) and Immenhauser et al. (2001), respectively. They attributed the brecciation in the carbonate platforms to karstification during an episode of sea-level fall and exposure to surface. Furthermore, the occurrence of deep subtidal sediments, containing planktonic foraminifera, above this subaerial unconformity represents a transgressive surface (Van Wagoner et al., 1988) or a ravinement surface (Catuneanu, 2002). Glaucony transportation could involve tidal ravinement processes from a deep water environment towards a shallow marine environment during transgression (Catuneanu, 2006). High maturity of glaucony in the study area indicates a break in sedimentation on the order of a hundred thousand years or so (Odin and Matter, 1981). This suggests that glaucony development started at the onset of transgression and that the green grains were removed after a long period of maturation that encompassed a significant portion of the TST. Penecontemporaneous remobilization of glaucony by traction currents is common within a variety of shallow marine to deep water settings (McCracken et al., 1996; Amorosi, 1997). In the study area, the lower sequence boundary is delineated in the Karababa-A member (Figure 8). However, instead of very shallow water facies such as stromatolites, or mudstones with ostracods and charophytes, bioclastic facies with shallow biota, facies with glauconite, phosphate, and planktonic forams may indicate an effect of rapid subsidence, which may be tectonically controlled.

SB2 is Campanian in age and defines the top of Depositional Sequence-2 (Figure 8). It separates the shallow marine carbonate units of the upper part of the Karababa Formation and the deep marine units of the overlying Campanian Karaboğaz Formation. The contact is marked by a well-developed hardground surface. This boundary can be in correlation with the sea-level curve of Luning et al. (1998) for the central-eastern Sinai area with the sea-level rises associated with the Campanian boundary (Figure 8). The MFS coincides with the abundant organic-rich sediment occurrence (Figure 8). The SB2 surface that marks the boundary between the Karaboğaz and Karababa formations could be the transgressive surface in parts of the study area. This boundary could be associated with the drowning/sudden subsidence event associated with regional tectonics.

6.2. Sequence-stratigraphic comparison

The sequence-stratigraphic framework of the middle Cenomanian-lower Campanian succession in the Çemberlitaş oil field has been compared with schemes proposed by Haq (2014), Lüning et al. (1998), and Schulze et al. (2003) (Figure 9). The MFSs recognized in this study are also compared to those of the Arabian Plate (Sharland et al., 2001). These comparisons facilitate the reconstruction of relative sea-level fluctuations and their imprints on the sedimentary architecture within shelf areas. The middle Cenomanian to lower Campanian stratigraphic successions of several areas of the Arabian Plate were correlated by Sharland et al. (2001). Their correlation incorporates the stratigraphic succession of the Çemberlitaş oil field and the positions of the MFSs recognized in the study area. The MFSs were dated by Sharland et al. (2001) on the basis of biostratigraphic and sedimentological sequence-stratigraphic analyses. We integrated these surfaces into the chronostratigraphic scheme of Ogg and Hinnov (2012) and compared them with the MFS observed in southeastern Turkey. This correlation is problematic, because the ages assigned by Sharland et al. (2001) do not always correspond with the stratigraphic position of the sequence boundary surfaces in southeastern Turkey, as evidenced by the work of Wagner and Pehlivan (1987) and Cater and Gillcrist (1994). For example, the K150 MFS is identified above the major middle Turonian unconformity (Haq, 2014). The fall in relative sea level producing this unconformity is primarily the result of tectonics events, such as inversion due to ophiolite obduction (Cater and Gillcrist, 1994). As suggested by Wagner and Pehlivan (1987), this may be due to lack of accommodation space during the development of this unconformity in southeastern Turkey. The K160 MFS was formed as part of a marine flooding event and accommodation space associated with this event was available in an intrashelf basin in southeastern Turkey (Wagner and Pehlivan, 1987). Therefore, this marine flooding event is represented by the sediments of the Karababa-A member (Cater and Gillcrist, 1994), which includes organic-rich carbonates characterized by a high gamma ray signature found at the base of the Karababa-A

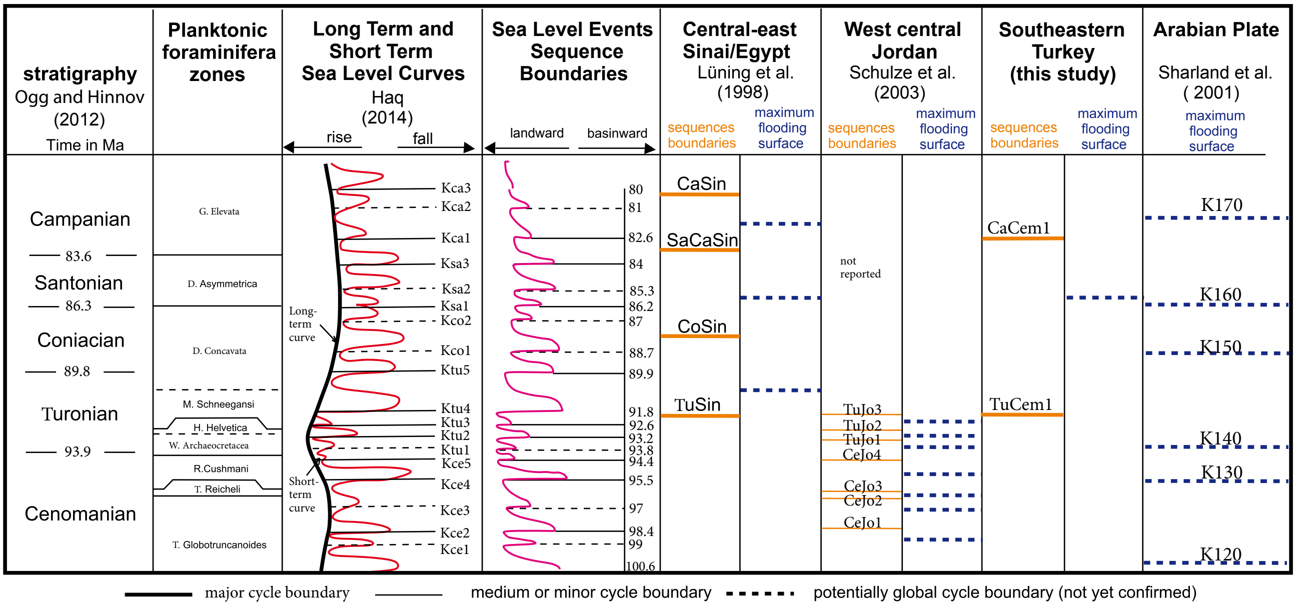

Figure 9. Relative sea-level curves of the Karababa-Derdere formations exposed in the Çemberlitaş oil field and its correlation with surrounding areas (modified from Haq, 2014).

member of the Karababa Formation in the available wireline logs examined during this investigation. This MFS may correlate with the 86-ma MFS described by Haq (2014).

7. Discussion

During this study, eight microfacies were recognized in the Derdere and Karababa (middle Cenomanian-lower Campanian) carbonate reservoirs of the Çemberlitaş oil field area. Four of these microfacies characterize the Karababa formation and include 1) mollusk-echinoid wackestone/packstone, (2) dolomitic planktonic foraminifera wackestone, 3) planktonic foraminifera bearing wackestone/packstone, and 4) phosphatic-glauconitic planktonic foraminifera bearing wackestone. The other four characterize the Derdere formation and include 5) lime mudstone, 6) bioclastic wackestone/packstone, 7) medium-coarse crystalline dolomite, and 8) fine crystalline dolomite. These microfacies suggest that the Derdere Formation was deposited in a shallow marine lagoonal to shelf depositional environment and the Karababa formation was deposited in a deep to shallow marine intrashelf depositional environment.

Our interpretation of the subsurface stratigraphic section of the Derdere and Karababa formations of the Mardin group in the study area suggests the presence of parts of two third-order depositional sequences bounded by an unconformity in the lower Campanian. The basal sequence boundary of Depositional Sequence-1 was not observed. Its upper boundary is marked by SB1 in the Çemberlitaş oil field. Deposits of the TST of this sequence were not recognized in the study area. However, deposits of HST of this sequence were recognized in the Çemberlitaş oil field area and represented by dolomitic MF7 to MF8 at the bottom and nondolomitized MF6-5 at the top of this interval. The top of the HST in the area is marked by transition from shallow subtidal to intertidal facies, which reflect the overall shallowing upward trend during this regressive phase. The occurrence of dolomites below the shallow subtidal carbonate platform unit has been interpreted to be related to a relative progressive shallowing of water depths due to a decrease in the rate of sea-level rise.

The lower boundary of Depositional Sequence-2 is marked by an unconformity in the middle Turonian. The upper boundary of this sequence is defined by a lower Campanian unconformity in the Çemberlitaş oil field area. The facies patterns in these sequences primarily reflect changes in relative sea level. The TST deposits include a predominance of deep subtidal facies, while sediments of the HST consist of shallow subtidal to intertidal facies.

Comparisons of the sequence-stratigraphic framework determined during this study with surrounding regions (Arabian Platform, Jordan, and Sinai) suggest that there are regional and local sedimentological differences although major similarities also exist. The differences are interpreted to be a result of a combination of variations in relative sea-level and regional-local tectonic events that affected depositional conditions and patterns in the shallow-shelf and intrashelf areas.

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