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Facies analysis and paleoenvironmental reconstruction of Upper Cretaceous sequences in the eastern Para-Tethys Basin, NW Iran

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ABSTRACT

Upper Cretaceous mixed carbonate-siliciclastic sequences are among the most important targets for hydrocarbon exploration in the Moghan area, located in the eastern Para-Tethys Basin. Despite of their significance, little is known about their facies characteristics and depositional environments. Detailed facies analysis and paleoenvironmental reconstruction of these sequences have been carried out in eight surface sections. Accordingly, four siliciclastic facies, eight carbonate facies and one volcanic facies have been recognized. Detailed facies descriptions and interpretations, together with the results of facies frequency analysis, standard facies models and Upper Cretaceous depositional models of Para-Tethys Basin, have been integrated and a non-rimmed carbonate platform is presented. This platform was affected by siliciclastic influx, in the form of coastal fan delta and submarine fans in the shallow- to deep-marine parts, respectively. This model is interpreted to be shallower in the central and northeastern parts of the Moghan area. Toward the southeast and southwest, this shallow platform turns into deep marine settings along steep slopes without remarkable marginal barriers.

KEYWORDS **Sedimentary facies. Depositional model. Upper Cretaceous. Moghan. NW Iran.**

INTRODUCTION

Most of the Iranian oil and gas fields are located in the Mesopotamian depression, along the Zagros Fold and Thrust Belt (ZFTB), and reservoirs concentrated in some fields in the Central Iran. The second hydrocarbon bearing region is the South Caspian Basin, including the Moghan area of Iran, which is not yet thoroughly understood regarding its petroleum potential (Fig. 1).

In the Moghan area, the main oil- and gas-bearing interval is the so-called Clastic Productive Series of Middle Pliocene age. It includes about 90% of all the identified hydrocarbon reserves of Azerbaijan and adjacent offshore areas of the South Caspian Basin. During the last 20 years, a new type of reservoir rocks has been discovered in central and western Azerbaijan, mainly in the central portion of the Kura Depression (Fig. 1B, C). In this structural depression, commercial oil and gas reserves are also distinguished within fractured Upper Cretaceous rocks (Lerche *et al.*, 1997).

The Moghan area is located in the far most northwestern part of Iran in the Azerbaijan Province (Fig. 1A). The first petroleum geological studies of this area were done during the 1950's to the 1970's by the National Iranian

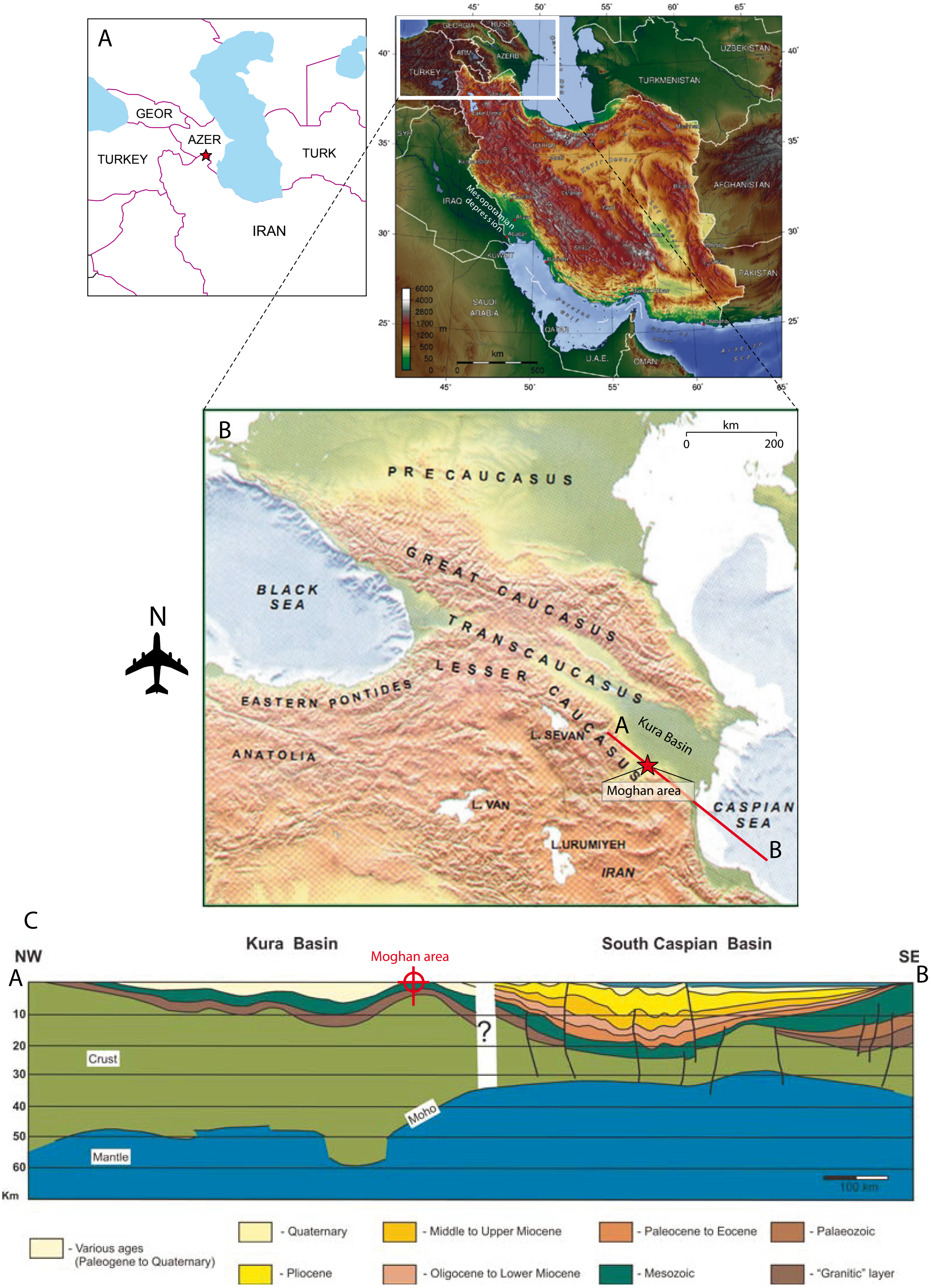

FIGURE 1. A, B) Location map of the Moghan area in northwestern part of Iran at southern margin of the Kura Depression. C) A schematic cross section across the Kura Depression and South Caspian Basin is also shown (compiled with some modifications from Adamia *et al.*, 2011; Baranova *et al.*, 1991; Mamedov, 1992).

Oil Company (NIOC) and the Institute Français du Petrole (IFP). These studies revealed that the Moghan area had potential for hydrocarbon exploration. Geophysical studies carried out from 1961 to 1965 (including gravimetry, geomagnetic and seismography) have shown that there are some important structural traps (anticlines) in this area (Fig. 1C).

In 1966, the first exploration well of this area was drilled on the Ortadagh anticline. Subsequently, seven additional wells were drilled. Geological mapping, structural geology, stratigraphy and source-rock potential of the Cretaceous and Cenozoic sequences were the subjects of subsequent works. Recently, geological modeling and exploration by Russian Lukoil Company and geophysical processing by Industria Nafte (INA) Company have been carried out in the Moghan area.

This study focuses on the Upper Cretaceous carbonate sequences of the Moghan area, considered as one of the most important intervals in view of their potential as reservoir rocks. Here, facies analysis and paleo-environmental reconstruction of these sequences are presented for the first time in eight surface sections across the study area.

GEOLOGICAL AND STRUCTURAL SETTING

It is mostly accepted that during the Paleozoic both Iranian and Arabian plates were attached together, forming part of the super-continent Gondwana. The Paleo-Tethys Ocean was formed as the result of separation between the Iranian and Touran plates during the early Paleozoic. Later during the late Paleozoic, the Neo-Tethys Ocean was formed by splitting between the Iranian and Arabian plates and the Paleo-Tethys starts to experienced subduction and closure (Berberian *et al.*, 1981; Eftekharnejad *et al.*, 1991). The Paleo-Tethys subduction beneath the Touran and Lesser Caucasus plates resulted in the formation of volcanic arcs and back-arc basins in the eastern and western parts, respectively. The collision occurred at the end of Triassic or early Jurassic times (Adamia, 2011).

The Moghan area (N38º 30' to 39º 42' and E46º 39' to 48º 10'), as a part of the Kura sedimentary-structural Basin, is located in the NW of Iran (Fig. 1). The geological and structural history of this area is related directly to its location in northern part of the Talysh-Lesser Caucasus folded and thrusted belt (Fig. 2; Adamia *et al.*, 1981, 2011). It is positioned at the collisional zone between the Eurasia and Africa-Arabian continental plates (Fig. 2). The convergence is active today, at an estimated rate of 20-30mm per year. The area is included in the world's largest continental collision zone, the Alpine-Himalayan belt, and is marked by intense compression and faulting (see Khain, 1975; Demets *et al.*, 1990).

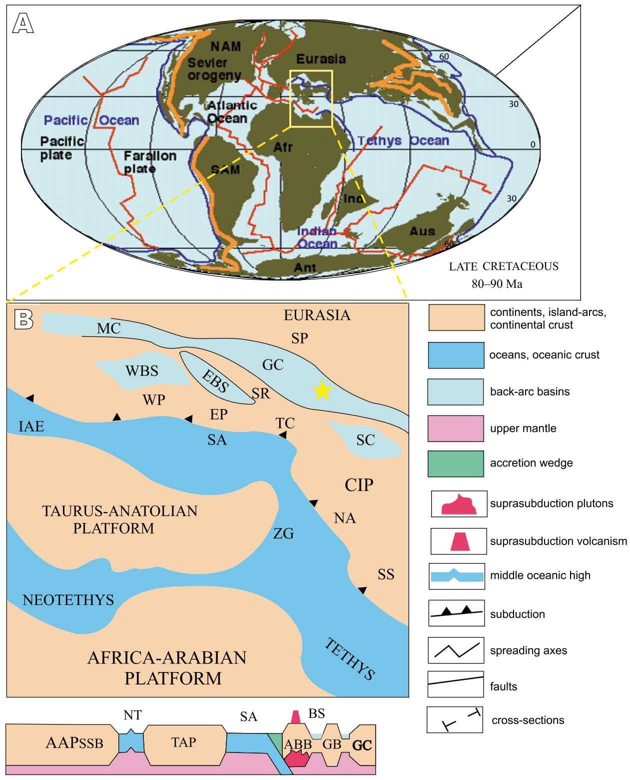

FIGURE 2. A) Paleogeographic map of the world in the Late Cretaceous (80–90Ma). As shown, the study area was located at 30–35º paleolatitude in northern hemisphere. B) Late Cretaceous tectonic reconstructions of the Tethyan region (from Adamia *et al.*, 2011). AAP: Africa-Arablan platform; ABB: Artvin-Bolnisi Block; Al: Alborz; An: Andrusov high; AT: Achara-Trialeti; BS: Black Sea; CIP: Central Iranian platform; EBS: Eastern Black Sea; EP: Eastern Pontides; GB: Georgian Block; GC: Great Caucasus; IAR: Ízmir-Ankara-Erzincan ocean; SC: South Caspian black-arc basin; SG: Srednogorie; SA: Sevan-Akera ocean; SP: Scythian platform; SPM: Serbian-Pelagonian massif; SR: Shatsky ridge; SS: Sanandaj-Sirjan volcanic arc; SSB: Southern Slope black-arc basin; MC: Mountainous Crimea basin; Na: Nakhchevan-South Armenia; NT: Neotethys; RM: Rhodope Massif; TAP: Taurus-Anatolian-Iranian platform; TI: Talysh; WBS: Western Black Sea; WP: Western Pontides; ZG: Zangezur-Garadagh ocean. Star indicates the study area.

The Moghan sedimentary Basin is part of the Para-Tethys Basin that formed in a back-arc and volcanic belt developed from southern France, in the Mediterranean to western China. Tectonic deformations during the Neogene favored the subdivision of Para-Tethys in three major subdomains namely the western, central and eastern Para-Tethys. The Moghan area is located in the eastern Para-Tethys Basin which was firstly defined by Laskarev (1924). The eastern Para-Tethys domain extends from the Carpathian foredeep in Romania to the Aral Lake in Kazakhstan, and includes the present-day Black Sea and Caspian Sea basins (Fig. 2). The study area is considered as part of the Kura Basin, bounded by the middle Caucasus towards the south (Fig. 1B). Sedimentary cover of the Moghan area consists of Upper Cretaceous and Tertiary

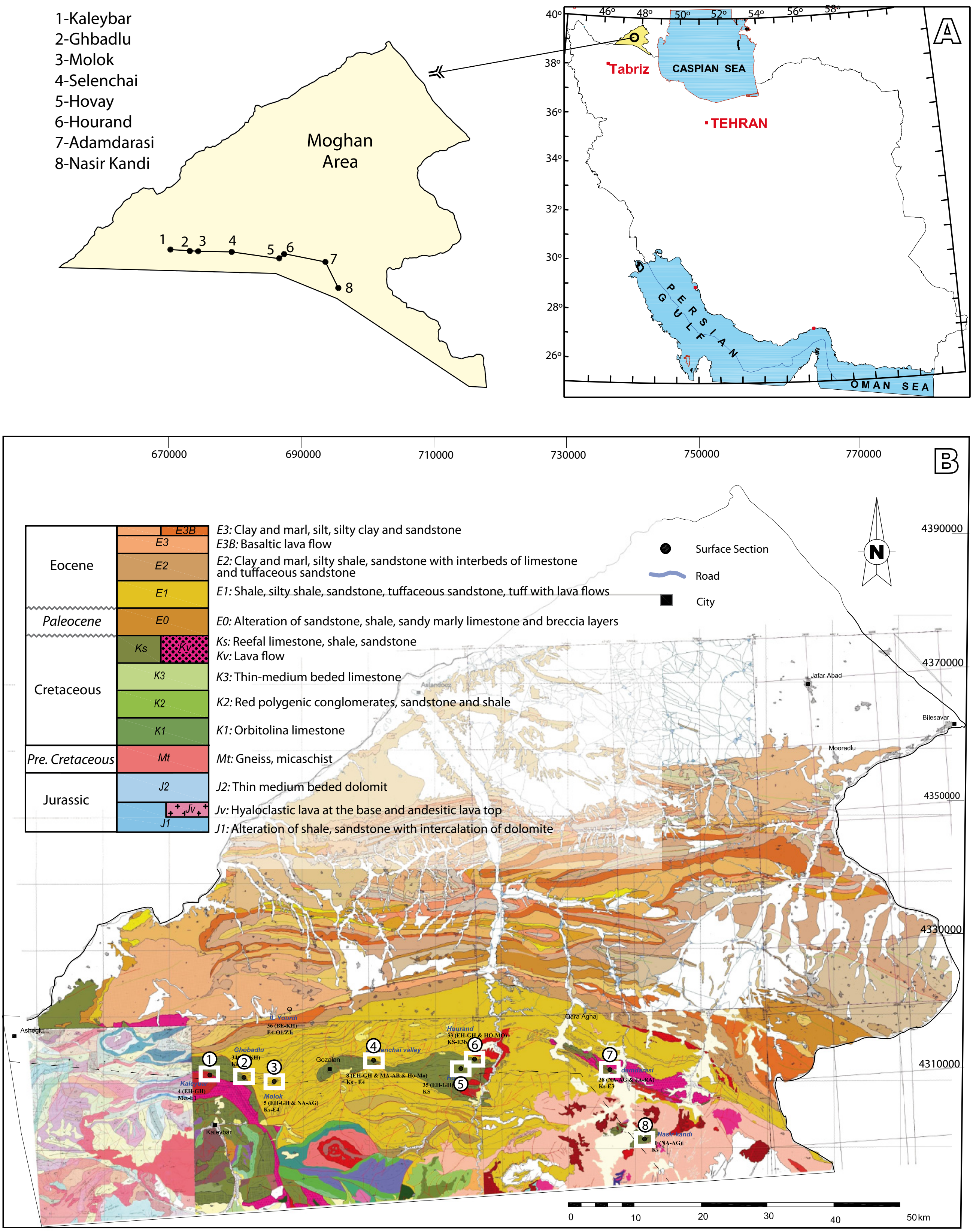

FIGURE 3. A) Location map of the Moghan area in northwestern part of Iran. B) Geological map and Jurassic-Eocene stratigraphy of the Moghan area (map from NIOC). As shown, the best outcrops of Upper Cretaceous sequences are located in the southern part of this area. Eight surface sections of these sequences (numbered as 1 to 8 and marked as white rectangles on the map) were selected for this study.

strata that experienced a major phase of folding and thrusting during the Alpine orogeny (Azizbekov, 1972; Devlin *et al*., 1999; Fig. 3).

MATERIALS AND METHODS

This study is based on the stratigraphic and petrographic analysis of Upper Cretaceous sedimentary sequences in 8 surface sections in the Moghan area, NW Iran (Fig. 3). A total of 3063 meters of sedimentary thickness were studied and logged in a W-E transect located in southern part of the study area, where Upper Cretaceous mixed carbonate-siliciclastic sequences are well-exposed (Fig. 3; Table 1). Lithological description, thickness variations and stratigraphy of the studied sequences are summarized in Table 1 for all measured sections.

Macroscopic field-features descriptions combined with the results of microscopic studies have been used for facies analysis and paleoenvironmental reconstruction (Fig. 3). In total, 1200 hand specimens were collected for subsequent studies. Sampling intervals were generally between 1 to 3 meters. Additional data, including macroscopic rock descriptions and biostratigraphic data, have been incorporated from NIOC and Pars Petro Zagros (PPZ) internal reports.

Petrographic facies analyses were carried out in 811 thin sections. The classification schemes of Dunham (1962) and Embry and Klovan (1971) were adopted for facies classification and textural descriptions of carbonates. Allochem grains identified and the relative frequency of all allochems and facies were determined and their vertical stacking patterns analyzed. Paleoenvironmental facies interpretations were made by using the well-known standard models based on microfacies distribution (*e.g*. Flügel 2013). From the available data, a regional depositional model for Upper Cretaceous sequences of the Moghan area is presented in the framework of paleogeographic setting of the eastern Para-Tethys Basin.

LITHOSTRATIGRAPHY

The Upper Cretaceous (Campanian–Maastrichtian) sequences of the Kura depression consist of hundreds of meters thick sequences of mixed carbonate-siliciclastic deposits interbedded with some volcanic-rocks (*i.e.* tuffaceous sands and pillow basalts). In the Lower Kura Depression of Azerbaijan drilled wells penetrated Upper Cretaceous clastic and carbonate rocks ranging in thickness from 300m to more than 730m (Lerche *et al*., 1997).

Upper Cretaceous sedimentary sequences of the Moghan area are composed of shallow- to deep marine (pelagic) carbonate rocks (mostly limestones) with some interbeds of sandstones, siltstones, conglomerates and volcanic rocks (Fig. 4). In the study area, they are informally named as the Kaleybar Formation (Bahramizadeh-Sajjadi, 2012). The name is adopted from the most complete surface section near the Kaleybar County in the East Azerbaijan Province of Iran (Fig. 4). In various parts of the Moghan area, the formation exhibits different thicknesses,

TABLE 1. Major stratigraphic features of the eight studied outcropping sections in the Moghan area of NW Iran

Section/location	Thickness (meters)	Lithology description	Lower boundary	Upper boundary
Kaleybar; western Moghan	1053	Limestone, sandy limestone, sandstone, siltstone	Non-conformity (187 meter-thick metamorphic rocks)	Disconformity (Qara-Su Formation; Paleocene)
Ghobadlu; western Moghan	205	Thin-bedded argillaceous limestone	Not known	Not known
Molok; western Moghan	60	Thin-bedded limestone	Not known	Disconformity (Qara-Su Formation; Paleocene)
Selenchai; western Moghan	220	Limestone with thin shale bed	Non-conformity (120 meter-thick volcanic rocks)	Disconformity (Qara-Aghash Formation; Eocene)
Hourand; central Moghan	189	Clean, thick-bedded limestone	Not known	Disconformity (Qara- Aghash Formation; Eocene)
Hovay; central Moghan	390	Clean, thick-bedded limestone; Conglomerate (12meter-thick) in middle part	Volcanic and metamorphic basement; non-conformity	Not known
Adamdarsi; eastern Moghan	103	Thin-bedded argillaceous (in parts) limestone	Not known	Disconformity (Qara- Aghash Formation; Eocene)
Nasirkandi; eastern Moghan	843	Thin-bedded argillaceous limestone	Not known	Disconformity (covered)

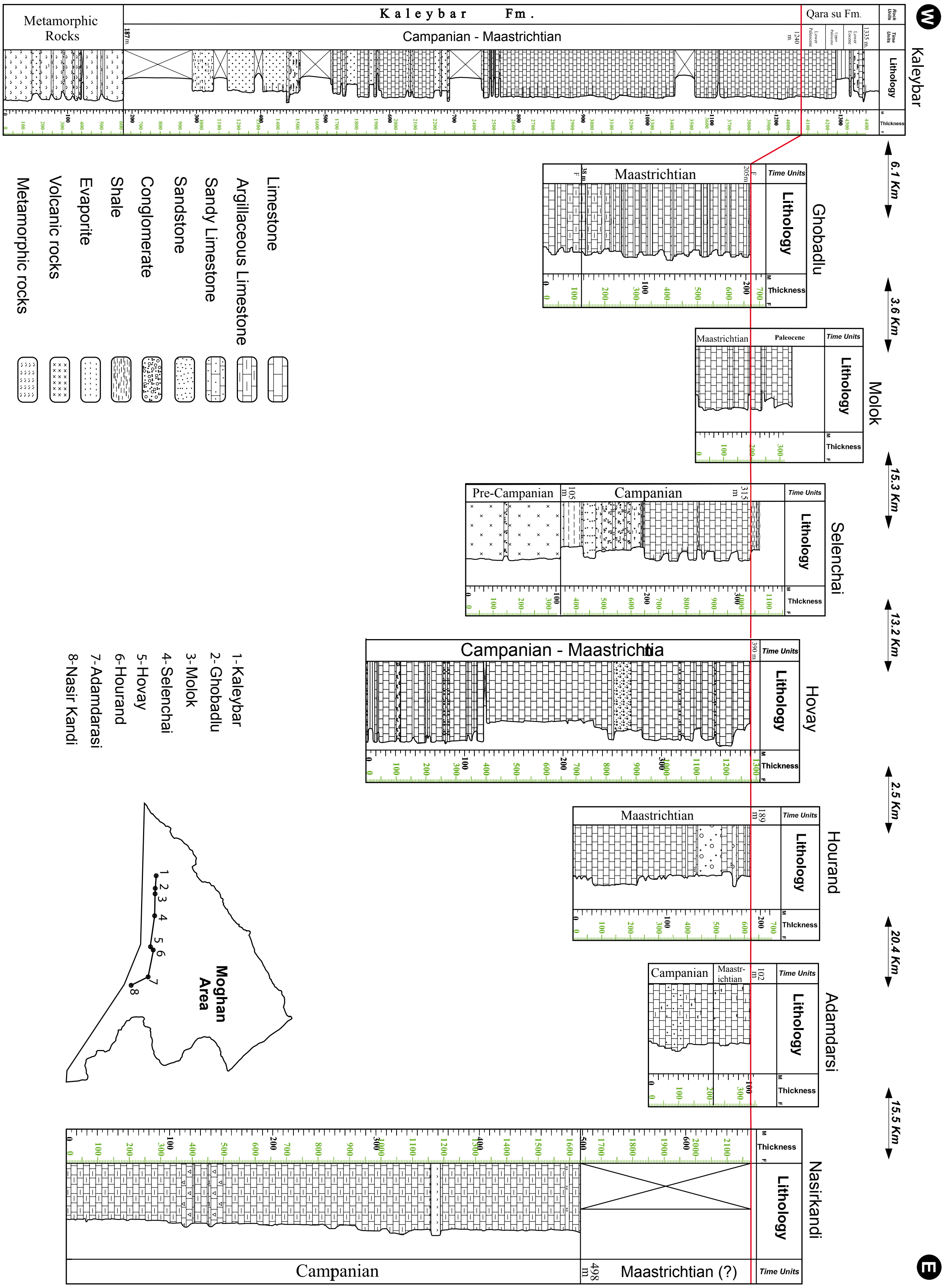

FIGURE 4. Lithostratigraphic correlation of Upper Cretaceous sequences in a west-east transect in the Moghan area. Relative ages from the archive of NIOC.

significant lithological variations and sharp facies changes (Fig. 4; Table 1).

In most of the studied sections, Upper Cretaceous sequences overlay metamorphic (serpentinized rocks and schists) and volcanic (pillow basalts) rocks along with pelagic limestones and red shales (Figs. 5E, F; 6A). Berberian *et al.* (1981) reported this rock complex as colored mélange and ophiolite remains and dated them as Senonian. The upper boundary of the Upper Cretaceous sequence is commonly marked by a disconformity surface, capped by the Paleocene Qara-Su Fm. (limestones, volcano-clastic sandstones, marls and volcanic rocks; Fig. 6B). The disconformity surface between the Kaleybar and Qara-Su formations is also marked by some brecciated and conglomeratic layers in which clasts of Cretaceous rocks are present (Figs. 5C; 6C).

Lithostratigraphic correlation between all measured surface sections (Nasirkandi, Adamdarsi, Hovay, Hourand, Selenchai, Molok, Ghobadlu, and Kaleybar sections) of the studied interval is presented in Figure 4. Best exposures are found at Qara-Dagh Mountains (Figs. 3; 4). A lithostratigraphic description of the Kaleybar Formation is summarized in Table 1.

In the Kaleybar section, the Upper Cretaceous sequences (total thickness: 1053 meters) can be lithologically subdivided into five parts from bottom to top (Fig. 4): i) 117 meter-thick interval covered by recent fluvial deposits, ii) 145 meter-thick interval of mixed carbonate-volcanoclastic rocks and gray-colored sandy siltstones, iii) 21 meter-thick polymictic conglomeratic interval with an erosional base and interbedded sandstones; this unit is overlain by a 50 meter-thick unit of recent fluvial deposits, iv) 265 meter-thick interval consisting of mixed carbonate-volcanoclastic and medium to thick-bedded argillaceous limestones. Shale interbeds are present in the upper part of this interval, v) 505 meter-thick interval of thick-bedded, gray, bioturbated and fractured limestones with thin shale interbeds at the topmost part.

There are lithological variations between the studied sections of the Moghan area. In both the western (*i.e.* Ghobadlu and Molok) and eastern (*i.e.* Adamdarsi and Nasirkandi) sections, the Kaleybar Formation is composed substantially of thin-bedded argillaceous limestones with some thin (less than 1 meter-thick) siltstone and sandstone interbeds (Fig. 4). In the Kaleybar section, the Upper Cretaceous sequences exhibit thin clastic (sandstones and conglomerates) and volcano-clastic layers, in the lowermost part (Fig. 4). In the Hovay and Hourand sections, in central Moghan, the sections mainly consist of pure limestones with some thin- to thick bedded sandstones and conglomerates (Table 1).

FACIES ANALYSIS

Sedimentological field studies combined with microscopic facies analysis of the Upper Cretaceous carbonate-siliciclastic sequences of the Moghan area have resulted in the recognition of 12 sedimentary facies and one volcanic facies (Table 2). Sedimentary facies are grouped into two main categories, based on their lithological characteristics and formation processes. They comprise eight carbonate facies/microfacies (MF's 1 to 8; Table 2) and four siliciclastic facies/petrofacies (PF's 1 to 4; Table 2).

The textural characteristics, grain and facies association, and depositional settings of the studied rocks are summarized in Table 2. First, facies description and environmental interpretation of depositional facies are discussed. Further details on sedimentary environments and regional depositional setting are provided in the following chapters.

Siliciclastic facies

Polymictic Conglomerate (PF1)

This facies is composed of sand to gravel, rounded volcanic and sedimentary particles (Fig. 7A). The terrigenous part of this facies is composed of quartz-, feldspar-, amphibole- and pyroxene-rich volcanic particles. Quartz grains are commonly monocrystalline and feldspars are substantially plagioclase. In most cases, the proportion of carbonate intraclasts and matrix may be significant. In case of high abundance (up to 50%) of carbonate component, it can be classified as a mixed carbonate-siliciclastic facies. In most conglomeratic samples, the matrix content, including the total percentage of sand-, silt- and clay-sized materials, is commonly less than 15 percent and, therefore, they have grain-supported textures. Consequently, they are classified as polymictic orthoconglomerates. This facies is recorded in the basal parts of the sequence in the Kaleybar section and in the uppermost parts in the Hourand section (see Fig. 6 C).

In the studied sections, the polymictic conglomerate facies has a close relationship and is associated with medium (sandstones; PF2) to fine grain siliciclastic deposits (siltstones and shales; PF's 3 and 4) and shallow marine carbonate facies (MF's 1 and 2; see Table 2; Fig. 6E). Such facies association and described textural characteristics all point to proximal parts of sedimentary bodies *i.e.* fan deltas located in a transitional, coastal sedimentary environment.

Lithic sandstone (PF2)

This facies is composed of poorly- to well-sorted and sub-rounded monocrystalline quartz grains, feldspars

FIGURE 5. Field photos (taken by NIOC and PPZ) of A, B) relatively thick-bedded argillaceous limestones in the Ghobadlu section, C) conglomeratic interval at top of the Hourand section, D) alternations of thick-bedded clean limestones and argillaceous limestones in the Hourand section and E, F) lithological boundary between red shales and limestones in basal parts of Upper Cretaceous sequences in the Hovay section.

and carbonate lithics. Volcanic particles are also present. Grains are commonly in the ranges of medium (0.25 to 0.5mm) to coarse (0.5 to 1mm; Krumbein, 1937) sand. Glauconite, heavy minerals, and rare shell fragments are subordinate grains in this facies (Fig. 7B). Considering the low amounts of rock matrix (<15%), high percentage of lithic grains (up to 50%) and lithic to feldspar ratios, commonly higher than 3:1, sandstone facies can be classified as litharenite (Folk, 1974). Sandstone facies are recorded in basal parts of Kaleybar and Selenchai

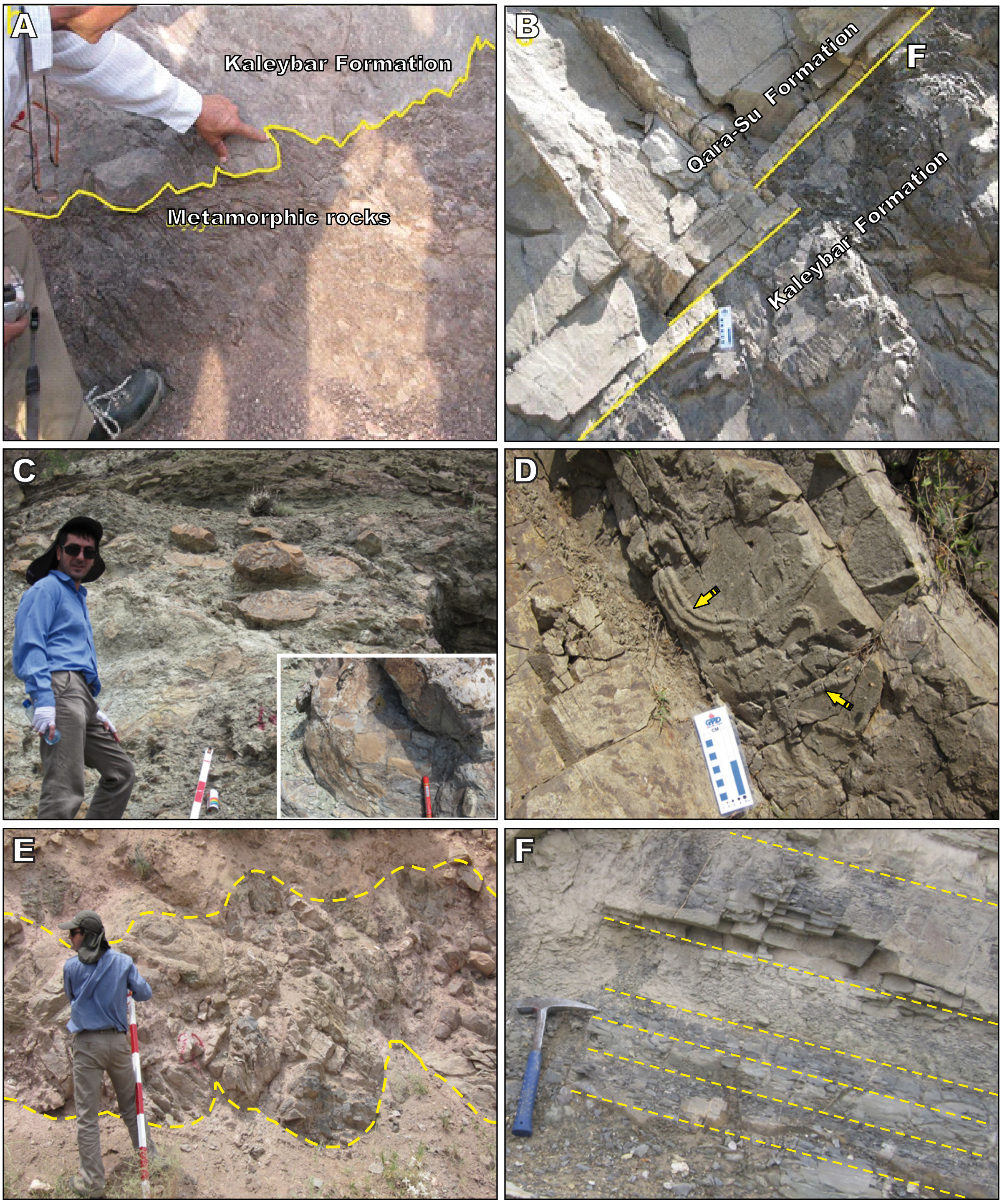

FIGURE 6. Field photos (taken by NIOC and PPZ) from upper and lower boundaries of Upper Cretaceous sequences in the studied sections. A) Lower boundary of limestones with older metamorphic rocks in the Kaleybar section. B) Upper boundary with overlying Cenozoic sequences (Qara-Su Formation) in the Kaleybar section (the detailed contact is locally displaced by small faults). C) Conglomeratic interval at the top of the Hourand section. D) Bioturbation/trace fossils. E) Channel fills conglomerates in middle parts of studied interval in the Hovay section. F) Lamination in siltstone beds in the Ghobadlu section.

sections and in upper parts in the Hovay section (see Fig. 4). Current-induced structures, such as cross-lamination and scour structures, along with bioturbation are notable sedimentary features that have been recorded in this facies. In case of abundance (up to 50%) of carbonate grains and matrix, it can be considered as a mixed carbonate-siliciclastic facies.

Lithic sandstones often form in a wide variety of sedimentary environments (including fluvial, deltaic, and alluvial sediments)

TABLE 2. Summarized data of depositional facies of Upper Cretaceous sequences in the Moghan area

Facies code	Facies name	Grains		Facies association	Depositional setting
		Skeletal	Non-skeletal		
PF1	Polymictic Conglomerate	--	Quartz, Volcanic rock fragments, Carbonate lithic	PF2, MF1, MF2	Proximal fan/channel
PF2	Sandstone (litharenite)	--	Quartz, Feldspar, Volcanic rock fragments, Carbonate lithics, Glauconite	PF1, PF3, PF4, VF1	Proximal fan
PF3	Siltstone	--	Quartz, Feldspar	PF2, PF4, MF6, MF7	Distal fan
PF4	Shale/Marl	--	--	PF2, PF3, MF6, MF7	Distal fan
VF1	Volcanic facies	--	Volcanic rock fragments and Shards	PF2	--
MF1	Benthic-foraminifera riched,bioclastic packstone/ grainstone	Bivalves, echinoderms, red algae, bryozoans, rudists, corals, benthic forams (*e.g.*, Orbitoides, Lepidorbitoides, Siderolithes, Pseudosiderolithes, Planorbulina, Pararotalia)	Quartz	MF2, MF3, PF1	Inner shelf
MF2	Intraclastic-bioclastic packstone/ grainstone	Echinoderms, bivalves, rudists, red algae, bryozoans	Intraclasts, Quartz	MF1, MF3, PF1	Inner shelf
MF3	Foraminifera-riched (benthic and planktonic), bioclastic wackestone/ packstone	Benthic and planktonic forams, bivalves, echinoderms, ostracoda, red algae	Quartz	MF1, MF2	Inner/outer shelf
MF4	Lime breccia	Rare planktonic foraminifera, echinoderm fragments	Intraclasts	MF6, MF7	Slope
MF5	Microbioclastic, planktonic foraminifer-Oligostegina packstone	Oligosteginids, echinoderm fragments, bivalves, and bryozoan debris,	Silt-grade quartz	MF4, MF6, MF7	Slope
MF6	Oligosteginids mudstone/ wackestone	Oligosteginids, rare planktonic foraminifera	--	MF4, MF5, MF7	Outer shelf/ Basin
MF7	Planktonic foraminifera mudstone/ wackestone	Globotruncanita, Gansserina, Globotruncana, Globotruncanella, Contusotruncana	--	MF6, MF8	Outer shelf/ Basin
MF8	Radiolarian wackestone/ packstone	Radiolarians	--	MF7	Basin

associated with active margins. This tectonic setting provides the source of lithic fragments, either through arc volcanism, thin-skinned faulting, continental collisions, un-roofing, and subduction roll-back (Pettijohn *et al*., 1987; Prothero and Schwab, 1996).

In the measured sequences, lithic sandstone facies (PF2) are mainly recorded in association with conglomeratic (PF1) and siltstone (PF3) facies. In these cases, they are interpreted as siliciclastic facies that have been deposited in a transitional depositional setting, close to the shore line, such as a delta and/or a fan-delta body. Such coastal sand bodies could develop in shoreline during the sea-level highstand.

In the Kaleybar section, sandstone facies are associated with deep marine (pelagic) mudstones. Close association of sandstone facies with deep-marine (pelagic) carbonate facies indicates deposition in deeper parts of carbonate platforms. These sandstones could be formed as deep marine sand-bodies or fans resulting from the increase in siliciclastics influx during the falling stages in relative sea-level.

Siltstone (PF3)

This facies is composed of silt-sized quartz and lithic (sedimentary and volcanic) grains. Opaque and heavy

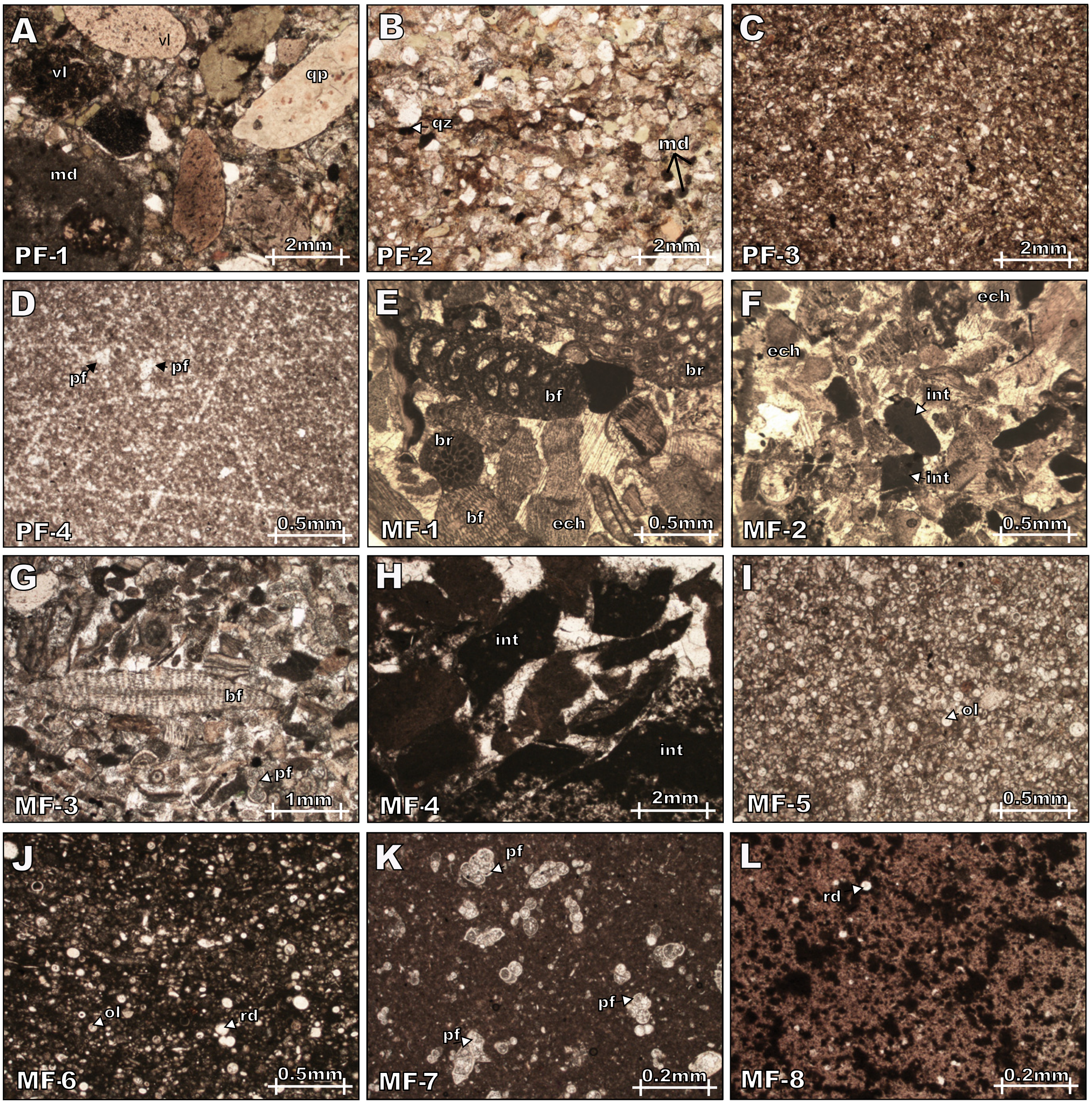

FIGURE 7. Photomicrographs of depositional facies of Upper Cretaceous sequences in the studied sections of Moghan area. They comprise both A-D) siliciclastic and E-L) carbonate microfacies. See Table 2 for facies characteristics and depositional settings (md: mud clast, vl: volcanic lithic, qp: polycrystalline quartz, qz: quartz, bf: benthic foraminifer, br: bryozoan, ech: echinoderm, int: intraclast, pf: planktonic foraminifer, ol: oligosteginids, rd: radiolarian).

minerals, plant debris and glauconite are also present as subordinate grains. In some cases, pelagic fauna (*e.g.* planktonic foraminifera) are distinguished within this facies. Various amounts of carbonate matrix are present (Fig. 7C). Lamination and bioturbation are two important sedimentary features in this facies (Fig. 6D, F). It is recorded in lower parts of the measured intervals in the Kaleybar and Selenchai sections (Fig. 4). In these localities, siltstone facies have close association with sandstone (PF2), shale (PF4) and pelagic mudstone (MF's 6 and 7) facies (Figs. 8; 9).

Textural characteristics and facies association indicate that siltstone facies were formed in two different depositional environments. They are interpreted to have deposited in distal parts of a transitional siliciclastics setting, where they are associated with coarse sandstones and shale, (*i.e.* fan-delta; Pettijohn *et al.*, 1987). In some stratigraphic intervals, they are accompanied with pelagic carbonate facies. In these intervals, they have high amounts of carbonate matrix and contain pelagic fauna. Therefore, they are attributed to submarine fans which were formed in outer parts of platform (Flügel, 2013).

Shale/Marl (PF4)

This facies is characterized by its dark-color and brittle appearance in macroscopic view. Lamination is the main sedimentary structure. It contains opaque minerals, phosphate, glauconite, rare plant debris and planktonic foraminifera (Fig. 7D). In some cases, this facies occurs as a homogenous, non-fissile mudstone with high amounts (up to 50%) of carbonate. These samples are classified as marl facies (Weaver, 1989).

In the Selenchai section, shale/marl facies are recorded as relatively thick intervals (5 to 25 meter in thickness) in three different stratigraphic positions in the Upper Cretaceous sequences (see Fig. 9). A thin shale bed is also detected in basal parts of this formation in the Hovay section (see Fig. 8).

This facies shows close association with siltstone (PF3), sandstone (PF2) and deep marine carbonate facies (MF's 5, 6 and 7; see Table 2). It is attributed to distal parts of transitional depositional setting (*i.e.* coastal fan/delta setting). In case of association with pelagic carbonate facies and presence of pelagic fauna, they are attributed to the distal parts of submarine fans in deep-water environments (Flügel, 2013).

Carbonate facies (microfacies)

Benthic foraminifera bioclastic packstone/grainstone (MF1)

This grain dominated facies contains benthic foraminifera (*e.g.* Orbitoides, Lepidorbitoides, Siderolithes, Pseudosiderolithes, Planorbulina and Pararotalia) and some other bioclasts (*e.g.* rudists, echinoderms, red algae, bryozoans and corals) as main allochems. Peloids and rare quartz grains are also present as subordinate grains. It has packstone to grainstone textures in which fine cross lamination is the only notable sedimentary structure (Fig. 7E). Micritization and marine cementation are two notable early diagenetic features. In many cases, frequent (up to 40%) large bioclasts (>2mm in diameter) including echinoderms, red algae and bryozoans are present yielding a rudstone texture. This facies is commonly associated to other grain- to mud-dominated facies from inner platform settings (*i.e.* MF's 2 and 3; Table 2). It is mainly recorded in the Hovay, Adamdarsi and Hourand sections and, with a lesser extent, in the Nasirkandi section.

Grain-dominated textures along with well sorted, abraded and highly cemented fabrics indicate deposition in high-energy condition. Facies of similar characteristics are commonly found in shoal complexes developed in high-energy settings, around fair-weather wave base in both old and recent carbonate platforms (*e.g.* Harris *et al.*, 2009; Flügel, 2013). It can be considered as equivalent of RMF7 (bioclastic packstone with abundant echinoderm, bivalve, foraminifer, and skeletal grains) and SMF10 (bioclastic packstone with skeletal grains) of microfacies types of Flügel (2013) found in ramp and shelf carbonate platforms. The above-mentioned facies are positioned in middle ramp and open marine shelf settings, respectively (see Flügel, 2013 for more details). Here, we consider this facies in shallow inner shelf setting, around the fair-weather wave base.

Intraclastic/bioclastic packstone/grainstone (MF2)

This grain-dominated facies contains intraclasts and bioclasts as main constituents. Bioclasts are from echinoderms, bivalves and bryozoans (Fig. 7F). Intraclasts occur in various sizes (from 2mm up to 5cm) and frequencies (20 to 50%). Benthic (*e.g.* Orbitoides, Lepidorbitoides, Siderolithes, Pseudosiderolithes) and planktonic (*e.g.* Globotruncana, Globotruncanita, Heterohelix) foraminifera, peloids and ostracods are subordinate allochems.

Fine cross lamination is a common sedimentary structure in grainstone facies. In some samples, sand- to silt-sized quartz grains and heavy minerals are scattered within the facies. This facies is recorded in the Nasirkandi, Hovay and Ghobadlu sections in association with pelagic facies from outer platform settings (*i.e.* MF's 6 and 7; Table 2).

Grain-dominated textures and presence of benthic fauna (*i.e.* benthic foraminifera, bivalves and algae) point to a shallow, high-energy setting. Whereas, facies association with pelagic mudstones and wackestones of outer platform together with the presence of planktonic foraminifera all indicate deposition in deep marine settings. Such duality in facies characteristics and allochem content along with the presence of intraclasts led us to consider this facies as re-sedimented deposits formed below the storm wave base (Molina *et al.*, 1997; Pérez-López and Pérez-Valera, 2012). They probably represent storm (tempestite) deposits. This facies can be considered as equivalent to the RMF8 (packstone and grainstone with various skeletal grains and intraclasts) facies of Flügel (2013) that has been attributed to a middle-ramp depositional setting.

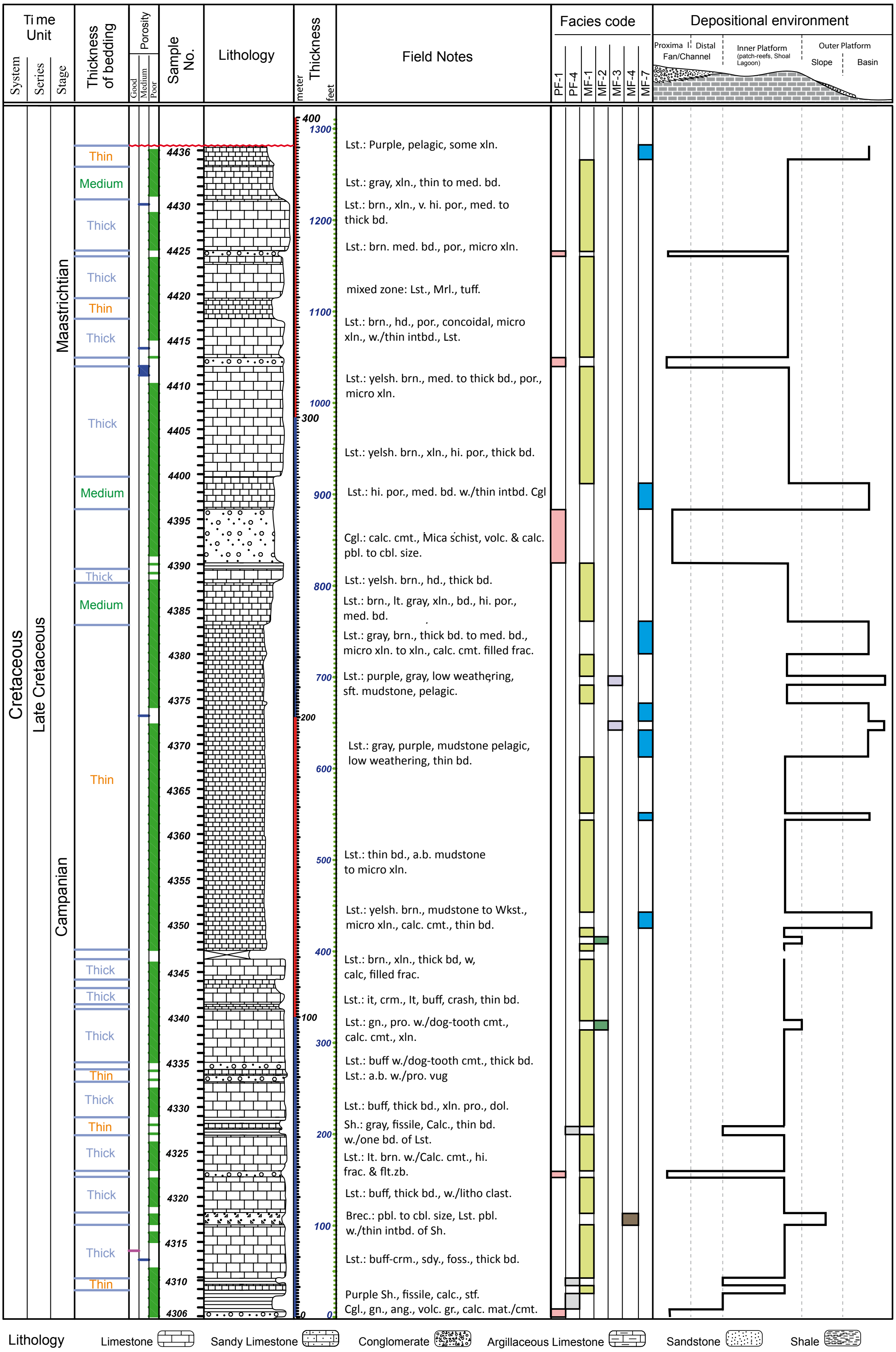

FIGURE 8. Sedimentological log of Upper Cretaceous sequences in the Hovay section in central part of the Moghan area. Lithological variations, field descriptions (including the beddings and sedimentary structures), sedimentary facies and depositional settings of these sequences are included in this log.

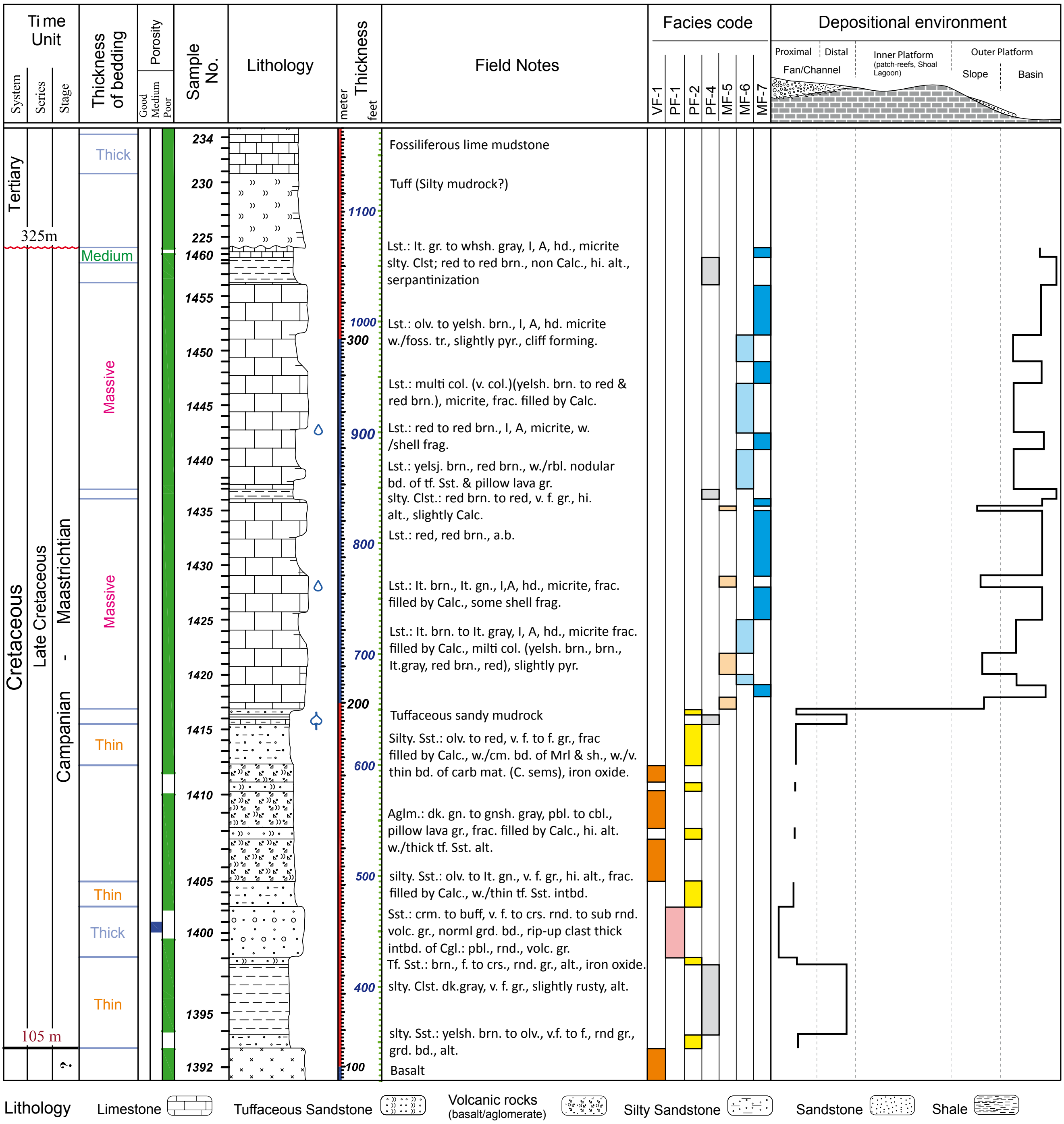

FIGURE 9. Sedimentological log of Upper Cretaceous sequences in the Selenchai section in western part of the Moghan area.

Foraminifer-rich (benthic and planktonic) bioclastic wackestone/packstone (MF3)

This facies encompasses a spectrum of mud- to grain-dominated textures in which benthic (*e.g.* Lepidorbitoides, Pararotalia, Lenticulina, Gaudriyna) and planktonic (Globotruncana and Heterohelix) foraminifera are present in various frequencies. Clasts of bivalves, echinoderms, ostracoda and red algae are also present (Fig. 7G). Oligosteginids and fine quartz grains are accessory grains of this facies. Phosphate and glauconite are two non-carbonate constituents. This facies is recorded in upper part of the studied sequences in the Nasirkandi section, lower parts of the Hovay section and in the Hourand

and Adamdarsi sections. It is commonly associated with benthic foraminifer bioclastic packstone/grainstone facies (MF1). It is also in close association with outer platform facies (MF's 6 and 7; Table 2) in Nasirkandi section.

Facies characteristics including depositional textures (wackestone to packstone), skeletal and non-skeletal components, and facies association indicate deposition of this facies in a transitional environment between the middle and outer platform settings. Co-occurrence of benthic and planktonic foraminifera, as the main constituent allochems of this facies, along with its association with both inner and outer platform facies backed this interpretation. Similar interpretation has been given for comparable facies in carbonate platforms of both Mesozoic and Cenozoic ages (see Slatt and Zavala, 2011 for more details). This facies is like the RMF7 of Flügel (2013) (bioclastic packstone with abundant foraminifera) that has been attributed to distal middle ramp settings.

Lime breccia (MF4)

In macroscopic field descriptions this facies is recorded as a lime breccia containing large (several centimeters) irregular and angular carbonate clasts. Microscopic petrographic studies revealed that these clasts are from pelagic mudstones and wackestones which were deposited in outer platform settings and, were subsequently eroded, reworked and re-deposited as lime breccias (Fig. 7H).

Intergranular spaces are commonly filled by calcite cements and/or pelagic lime mud. This facies is very minor in most of the studied sections and is largely recorded in the Nasirkandi section, located in westernmost parts of the Moghan area. With a lesser extent, it is also encountered in the Kaleybar section, in the easternmost part of the study area. In both of these sections, lime breccia facies are in close association with pelagic mudstones and wackestones of outer platform and basinal settings (MF's 6, 7 and 8; Table 2).

Lime breccias can formed as a result of both depositional and post-depositional processes (Blount and Moore, 1969). They comprise tectonic breccias, solution-collapsed breccias associated with evaporites and karstified sequences, and depositional breccias that formed by mass transport processes. The latter types include turbidite, debris-flow and gravity-flow deposits (Scholle *et al.*, 1983; Craig Shipp *et al.*, 2011; Flügel, 2013).

In our case, as deduced from described characteristics, lime breccias originated from depositional processes. Similarity between intra-clast and matrix, absence of fracturing and associated facies all support this interpretation. This facies can be considered as equivalent to the RMF's 9 and 10 types from outer parts of distally-steepened ramp settings and to standard microfacies SMF4 from slope setting in shelf-type carbonate platforms (Flügel, 2013). In addition, some tectonic breccias are also recorded in the studied sequences. They are associated with slickensides and intense fracturing and are not considered for paleoenvironmental interpretations.

Microbioclastic, planktonic-foraminifer Oligostegina packstone (MF5)

This is a grain-dominated facies containing oligosteginids, planktonic foraminifera (*e.g.* Globotruncanita and Gansserina), and other fine-grained bioclasts (microbioclasts) as main allochems. Microbioclasts are from echinoderms, bivalves and bryozoan (Fig. 7I). Very fine sand and silt-sized quartz and glauconite are also present as subordinate grains. Fine cross- lamination is the only important sedimentary structure in this facies. This facies is found in the Kaleybar, Ghobadlu, Hourand and Nasirkandi sections of Moghan area. This facies is in close association and has sharp contact with other deep, outer-platform facies (*i.e.* MF's 6 and 7; Table 2).

Grain-supported texture of this facies indicates its deposition under high-energy (agitated) conditions. Close association with pelagic mudstones and wackestones points to deep marine deposition in an outer platform setting. Grains association and faunal content also support deep sedimentation. Existence of fine lamination indicates current actions.

Similar facies are also reported from ancient carbonate platforms all around the world (*e.g.* Tucker and Wright, 1990; Molina *et al.*, 1997). Molina *et al.* (1997) have reported calcareous grain-dominated, fine-grained deposits in pelagic facies of Jurassic sequences in southern Spain. They considered these laminated and wavy bedded sand- to silt-sized bioclastic facies (packstone and grainstone in texture) as storm-induced deposits (tempestite). Flügel (2013) has also interpreted cross-stratified pack- and grainstones occurring as 0.1 to about 2 meter-364 thick units interbedded with pelagic lime mudstones and wackestones as tempestite. He categorized these facies as a distinct microfacies type, RMF6 (graded, laminated and finely cross-bedded bioclastic and peloidal packstones and grainstones; see Flügel, 2013 for more details).

Oligosteginid mudstone/wackestone (MF6)

This mud-dominated facies is defined by mudstone and wackestone textures in which oligosteginids are notable constituents. Besides, planktonic foraminifera, other fine-grained skeletal debris (including echinoderms and ostracods) and opaque minerals are present as accessory grains (Fig. 7J). No sedimentary structure is recorded in this facies. Maximum frequency of oligosteginids facies is encountered in lower part of the studied sequences in the Kaleybar section and in the upper part of the Nasirkandi and Ghobadlu sections. It is also recorded in all the Selenchai section. This facies has close association with pelagic mudstones and wackestones of outer platform and basinal settings (*i.e.* MF's 5 and 7; Table 2).

Textural characteristics and fossil association point to deep-marine deposition well below the storm wave base. Oligostegina-bearing facies have been reported from outer ramp and basinal settings of Cretaceous carbonate platforms of the Tethyan realm (*e.g.* Adams *et al.*, 1967; Alsharhan and Nairn, 1988; Aqrawi *et al.*, 1998; Sharp *et al.*, 2010; Rahimpour-Bonab *et al.*, 2012; Omidvar *et al.*, 2014). In most paleontology and paleoecology published works, oligosteginids are positioned in outer shelf and distal slope environments (*e.g.* Wynn Jones, 2006). This facies is comparable with RMF2 (argillaceous mudstone/wackestone) and SMF3 (pelagic mudstone/wackestone) that have been attributed to outer ramp and basinal/deep shelf settings, respectively (Flügel, 2013).

Planktonic foraminifer mudstone/wackestone (MF7)

This facies consists of mudstones and wackestones containing various types of planktonic foraminifera as main faunal elements (Fig. 7K). Major types are Globotruncanita, Gansserina, Globotruncana, Globotruncanella, and Contusotruncana. Moreover, rare oligosteginids and other fine-grained skeletal debris are present. Very thin parallel lamination is the only sedimentary structure exhibited by this facies. This facies is recorded in most of studied sections of the Moghan area. It forms a major part of the Upper Cretaceous sequences in the Molok, Kaleybar and Nasirkandi sections. It is also one of the most important depositional facies in the Selenchai, Hourand and Ghobadlu sections and occurs as a subordinate facies in the middle parts of the Hovay section. It shows a close association with MF's 5, 6 and 8 (see Table 2; Fig. 9).

Mud-dominated texture and thin, parallel lamination indicate deposition in low-energy conditions from suspension load (Tucker and Wright, 1990). Presence of planktonic foraminifera, as the main faunal elements in this facies, indicates deep marine deposition in outer platform and basinal settings, well below the storm wave base (Flügel, 2013). This facies is equivalent to the SMF3 and RMF5 of Flügel (2013), both of them characterizing deep shelf and outer ramp settings.

Radiolarian wackestone/packstone (MF8)

This facies is recorded as mud- to grain-dominated textures in which radiolarians are only skeletal components present (Fig. 7L). Lithology of this facies varies from argillaceous limestone to siliceous mudstone or marl. No sedimentary structure is recorded in this facies. The facies has occurred in middle parts in the Nasirkandi section in association with MF7 (planktonic foraminifer mudstone/wackestone; see Table 2).

Radiolarian assemblages are important paleoenvironmental indicators that accumulate on the sea-floor as the result of deposition from suspension load. Modern radiolarians are abundant in deep-sea sediments, particularly in Pacific equatorial regions where productivity is high in the overlying water column (Flügel, 2013). Significant accumulations of radiolarian tests commonly occurred in depths below the Carbonate Compensation Depth (CCD), which ranges from 4 to 5 kilometers in depth (Kruglikova, 1989; Harold and Trujillo, 2004). However, they have also been reported from shallower parts of basinal, slope and even lagoonal settings associated with shallow-water carbonate facies of platform settings (see Blendinger, 1985; Racki and Cordey, 2000). In our study, high carbonate content in radiolarian facies together with close association of these facies with pelagic limestones of outer platform settings all point to a deep marine outer platform to basin depositional environment.

Depositional facies, facies characteristics and their depositional environments are summarized in Table 2. Sedimentological logs of the studied sequences are presented in Figures 8 and 9 for the Hovay and Selenchai sections.

Depositional model

Based on the facies description and interpretation, deposition of Upper Cretaceous sequences is assumed to have occurred in various sedimentary environments that include transitional siliciclastic settings grading basinwards into shallow carbonate platforms deep-marine fans and pelagic carbonates (Fig. 10). The carbonate platform comprised inner and outer parts in which shallow to deep pelagic facies were deposited. The lack of barrier reef facies (*i.e.* organic boundstones) points to a non-rimmed carbonate platform with a steep slope in front (Fig. 10).

Carbonate depositional facies include high-energy facies of shoal complexes (MF1), debrites accumulated in the transition to the basin at the toe of slope and tempestites deposited around the storm wave base, respectively. The presence of abundant lime breccias, microbioclastic and intraclastic facies (MF's 4 and 5) indicate that there was steep slope in the frontal part of carbonate platform (Fig. 10).

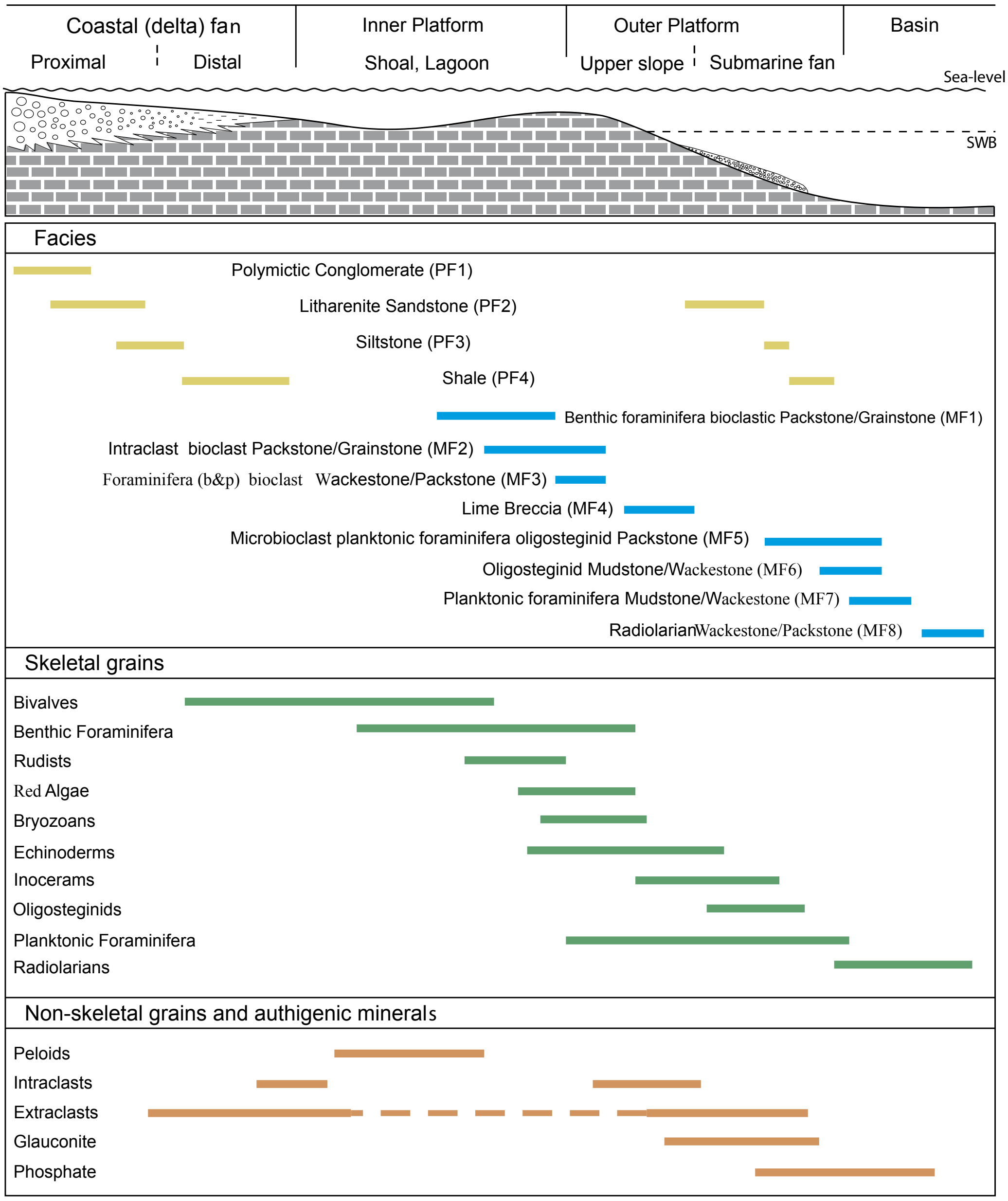

FIGURE 10. Schematic cross-section of depositional setting of Upper Cretaceous sequences in the Moghan area. Topographic variations, depositional sub-environments, major energy levels, and lateral distributions of depositional facies and grain associations (skeletal and non- skeletal) are also shown.

The presence of remains of potential reef-builders such as rudists, bryozoan and red algae, points to the possibility of existence of some potential, un-continuous (patchy) reefs in innermost parts of platform. Nevertheless, in-situ boundstones and whole fossils of these organisms have not been found in the studied sections. There are two possibilities; they were either not encountered in our studied sections because of their paleogeographic distribution in the paleo-platform and could exist in other parts of the Moghan area or they couldn't provide stable and rigid structures against the wave and storm actions and, therefore, they only acted as important sources of grains for bioclastic sand shoals and other facies belts.

This platform was affected by siliciclastic influx during the phases of eustatic sea-level changes and/or uplifting/ subsidence of hinterland. These terrigenous (land-derived) sediments were deposited as fan deltas and turbidities in shallow to deep marine parts of this platform, respectively (Fig. 10). Conglomeratic and coarse sandstone facies (PF's 1 and 2; Table 2) were deposited in coastal parts and, fine sands, siltstones and shale facies (PF's 3 and 4;

Table 2) were formed as submarine fans in deep-water settings. They show some evidence of a classic Bouma sequence in the Kaleybar and Ghobadlu outcrop sections (Fig. 6E, F). A sharp fining-upward trend is recorded in the studied interval that includes massive sandstones and conglomerates with erosional surfaces at the base (Fig. 6E) and change to cross-laminated sandstones and horizontal-laminated siltstones and mudstones at the top (Fig. 6F). Some channels are assumed to cut the inner parts of carbonate platform and transport terrigenous sediments into deeper parts, and deposited them as submarine fans in toes of slope (Fig. 11). In the case of submarine fans, close association of such siliciclastic facies with pelagic mudstones and wackestones of outer platform and basinal environments (*i.e.* MF's 5, 6 and 7; Table 2; Fig. 9) and lime breccias of upper slope (MF4) indicate their deposition in deep marine settings (Fig. 10). Evidence of channeling, such as erosional surfaces and overlying conglomerates, and channel-shape sand bodies have been reported in field descriptions and are illustrated in Figure 6E.

FACIES FREQUENCY ANALYSIS

Frequency analysis was carried out on depositional facies of Upper Cretaceous sequences in all studied sections and results are presented in Figure 12. As shown, there are some meaningful trends in frequency variations of depositional facies among the measured sections. To get a better understanding about these trends, depositional facies have been grouped into five facies associations/belts. They comprise inner platform facies (MF's 1 and 2), platform slope facies (MF's 4 and 5) and outer platform and basinal facies (MF's 6, 7 and 8). Likewise, siliciclastic facies of this formation are classified as shallow coastal and deep-marine fans/deltas, based on their textural characteristics, sedimentary structures and associated facies (Fig. 12).

Maximum frequencies of shallow, high-energy inner platform facies are recorded in the Adamdarsi and Hovay sections as 94% and 81%, respectively. These facies are also determined as 35% frequency in the Hourand section. Deeper marine outer platform and slope facies are the dominant facies in the Molok, Selenchai, Ghobadlu and Kaleybar sections, respectively (Fig. 12). Siliciclastic facies are also present as one of the important facies of this formation in the Kaleybar and Selenchai sections. In the Kaleybar section, they are mostly present as coarse- to medium-grained clastic rocks (*i.e.* sandstones and conglomerates; PF's 1 and 2) deposited in coastal fan (delta) settings (Fig. 12A). On the contrary, they are commonly recorded as fine siliciclastic deposits (siltstone and shale; PF's 3 and 4) associated with pelagic carbonates in the Selenchai section, which are interpreted as deep submarine fans (Figs. 9; 12D).

DISCUSSION

Upper Cretaceous paleogeographic maps from the eastern part of the Para-Tethys Basin indicate that the Moghan area was located at 30-35º paleolatitude in northern hemisphere (see Fig. 2A). During this time, sea-level was at one of its higher levels in geological history and carbonate platforms developed on continental margins all around the Tethyan realm (Miller *et al.*, 2004). Shallow- to deep marine carbonates were deposited in such platforms in a tectonically active back-arc basin simultaneously to volcanic activity and siliciclastic influx (Fig. 11A). Based on it paleolatitude location, a temperate to cool subtropical

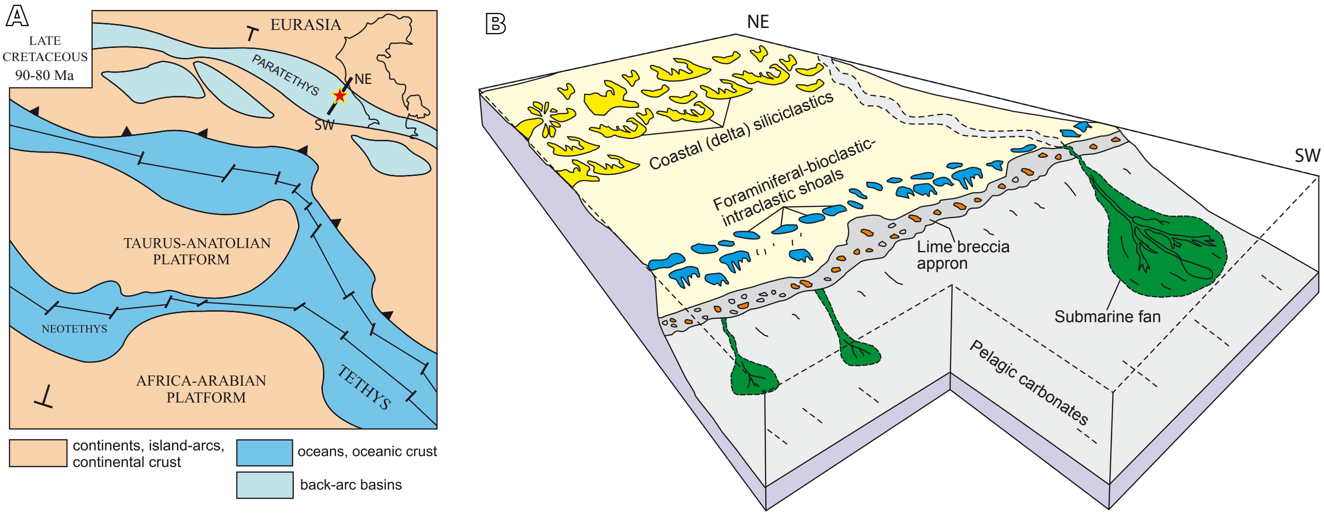

FIGURE 11. Conceptual depositional model of Upper Cretaceous sequences in paleogeographic framework of the Moghan area (adopted and compiled with some modifications from Adamia *et al.*, 2011; Handford and Loucks, 1993).

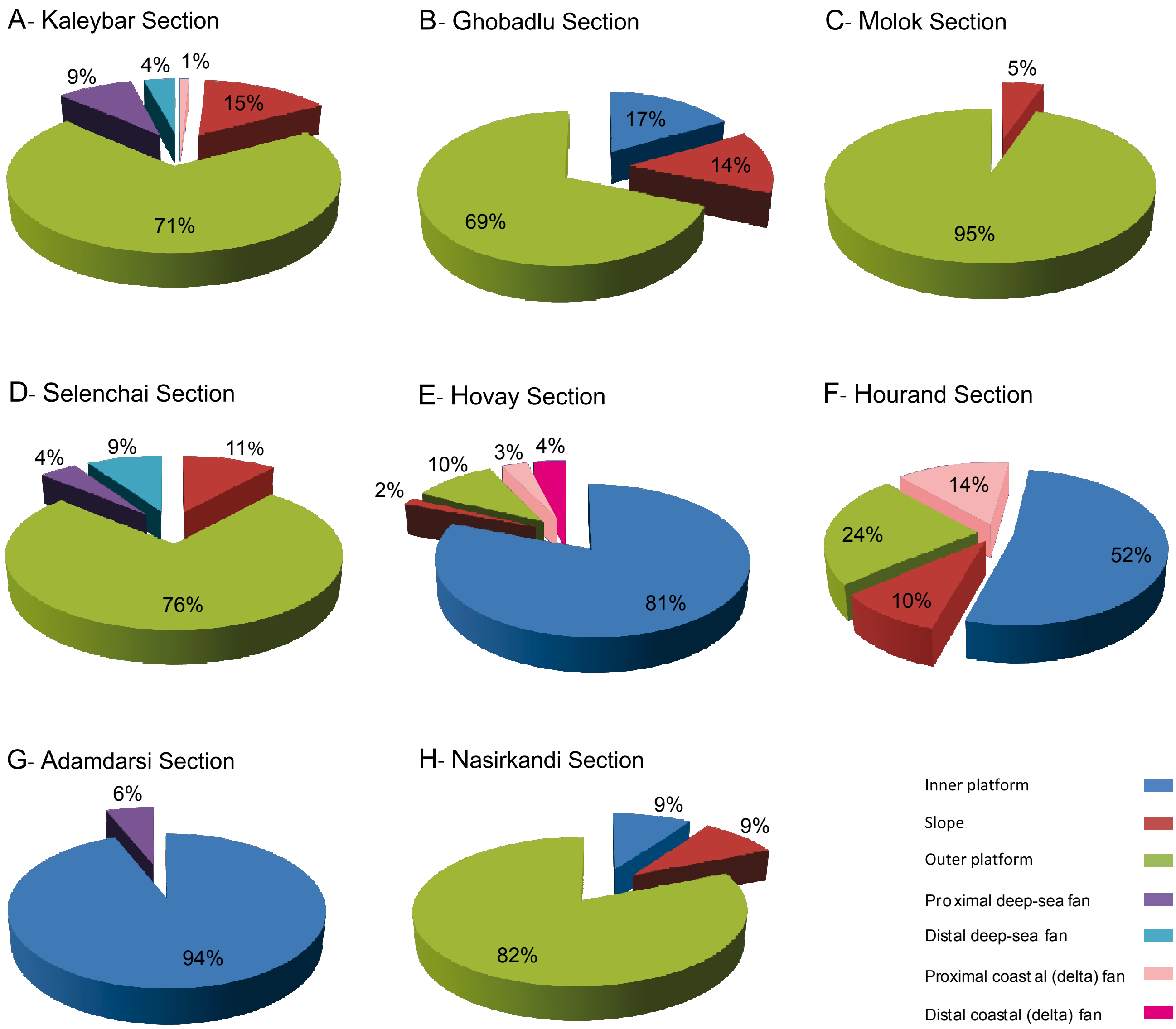

FIGURE 12. Pie diagrams illustrating frequencies of various facies associations in eight studied sections of the Moghan area.

paleoclimatic condition could be considered for this area. This interpretation is also supported by our observations, especially regarding the grain association (skeletal and non-skeletal) of the studied sequences.

Faunal and floral association of this formation (including rudists, other bivalves, echinoderms, benthic and planktonic foraminifera, red algae and bryozoan) represents a foraminiferal-mollusk (foramol) or bryozoan-mollusk (bryomol) association (Coffey and Read, 2007; Einsele, 2013). These communities live in temperate and cold waters and also at deeper settings in comparison to the tropical chlorozoan association (Lees, 1975; Flügel, 2013).

Depositional environments of the foramol association vary significantly in both modern and ancient platforms (Jones and Desrochers, 1992; Einsele, 2013). They are recorded in shallow subtidal settings of high latitudes to deep outer shelf environments in low latitudes (Henrich *et al*., 1996; Betzler *et al*., 1997).

On the other hand, regional depositional model of the Kaleybar Formation (*i.e.* un-rimmed shelf; Fig. 10) is thoroughly compatible with described active tectonic setting of the studied area during the Upper Cretaceous. Such steep slopes could have been formed as the result of block-faulting in the back-arc sedimentary basin in southern margin of the Kura Depression (see geological setting part and Berberian *et al*., 1981; Adamia *et al*., 2011 for more details).

Facies frequency analysis and lithostratigraphic descriptions show that in the Hovay, Hourand and Adamdarsi sections, located in the central parts of study area, shallow neritic carbonate facies are dominant (Figs. 11; 12). By contrast, in the other five studied sections including the Kaleybar, Ghobadlu, Molok and Selenchai sections located in the eastern part, and in Nasirkandi section in westernmost part of the Moghan area, deep-marine pelagic facies are the dominant facies types (Figs. 11; 12). Therefore, it seems that the shallow inner parts of the Upper Cretaceous platform were located in the central parts of Moghan area. This shallow platform turns into deep marine settings with a steep slope and without any remarkable marginal barrier, to the southeast and southwest (Fig. 11).

SUMMARY AND CONCLUSIONS

Integrated field descriptions and microscopic petrographic analysis of the Upper Cretaceous mixed carbonate-siliciclastic sequences, named informally as the Kaleybar Fm., have been carried out in eight surface sections in the southern part of the Moghan area, located in the Kura Depression of eastern Para-Tethys Basin. Stratigraphic measurements and lithostratigraphic studies revealed that these sequences developed throughout the study area with different thicknesses (ranging from 60 to more than 1000 meters), intense lithological variations and sharp facies changes.

Lithologically, they consist mainly of clean to argillaceous limestones and some inter-beds of siliciclastic (conglomerate, sandstone, siltstone and shale) and volcanic (tuff and basalt) rocks. The lower boundary of this formation is marked by an unconformity, with the Upper Cretaceous sedimentary rocks lying directly upon older metamorphic rocks. Some clasts of these metamorphic rocks are found in the basal parts of the studied formation. The upper boundary is marked by a disconformity surface and an associated conglomeratic interval.

Facies analysis have shown that this formation is composed of four siliciclastic facies (petrofacies) that are interpreted to have been deposited in proximal to distal parts of clastic channels and fans. Carbonate intervals of this formation comprise eight microfacies that have been attributed to inner platform, outer platform, slope and basinal settings. Frequency analysis of facies associations carried out in all studied sections allows placing each section of the Moghan area within the framework of an Upper Cretaceous conceptual depositional model. Depositional setting of the studied, mixed siliciclastic-carbonate sediments is interpreted to have been shallower in the central and northeastern parts of the Moghan area. Toward the southeast and southwest, the shallow carbonate platform turns into a deep marine setting through a steep slope and without any remarkable marginal barrier (Fig. 11B).

Consequently, Upper Cretaceous paleoenvironmental model of the Moghan area is interpreted as a distally-steepened non-rimmed carbonate platform with predominant bioclastic (foraminifer-, bryozoan-, red alga- and rudist-riched) sedimentation and bioclastic shoals in the inner parts. Lime breccias and microbioclastic packstones in slope aprons, and planktonic foraminifera and radiolarian wackestones and mudstones in outer platform and basinal environments. This platform was affected by siliciclastic influxes that supplied the terrigenous sediment accumulating in local fan deltas and submarine fans. This regional model is thoroughly compatible with paleogeographic setting and tectonic history of the Moghan area during the Upper Cretaceous.

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