

## Facies analysis and depositional environments of the Upper Cretaceous Sadr unit in the Nakhlak area, Central Iran

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### ABSTRACT

The up to 258 m thick, carbonate-siliciclastic Upper Cenomanian to Campanian rocks (Sadr unit), which crop out widely in the Nakhlak area of central Iran, consist of conglomerates, sandy limestones and dolostones, calcareous sandstones, sandy-argillaceous limestones and reefal limestones. The lower boundary of the studied section is an angular unconformity and its upper boundary is faulted. Sedimentological and palaeontological data indicate that Upper Cretaceous Sadr unit of Nakhlak area is equivalent to shallow carbonate platform successions of Upper Cretaceous rocks in central Iran, which belong to the central Iranian Plate and were deposited in marginal marine, shallow shelf and moderately deep marine environments. This geological unit can be divided into carbonates, siliciclastics, and mixed carbonate-siliciclastics groups. The siliciclastic facies group was deposited as shorelines, tidal flats, lagoons, and barrier bars indicating shallow shelf environments. The mixed carbonate-siliciclastics facies group was formed in a coastal-delta complex and the carbonate facies group took initially place on a homoclinal ramp which later developed into a rimmed platform due to the expansion of the rudist barrier facies.

Key words: siliciclastic, carbonates, homoclinal ramp, rimmed shelf, Cretaceous, Sadr unit, Nakhlak, Central Iran.

### RESUMEN

La unidad Sadr, que alcanza 258 m de espesor de carbonatos-siliciclásticos del Cenomaniano Superior al Campaniano, aflora ampliamente en el área de Nakhlak en Irán central y consiste de conglomerados, calizas arenosas y dolomitas, areniscas calcáreas, calizas areno-arcillosas y calizas arrecifales. El límite inferior de la sección de estudio es una discordancia angular y su límite superior se encuentra fallado. Datos sedimentológicos y paleontológicos indican que la unidad Sadr del Cretácico Superior en el área de Nakhlak es equivalente a sucesiones de plataforma carbonatada somera en Irán central, y pertenecen a la Plataforma de Irán central, y fueron depositados en ambientes marginales marinos, de plataforma somera y moderadamente profundos. Esta unidad geológica puede ser dividida en grupos de carbonatos, siliciclásticos y mezcla de carbonatos-siliciclásticos. El grupo de facies siliciclásticas fue depositado en costa, planicies de marea, lagunas y barras de margen, indicando ambientes de plataforma somera. El grupo de las facies mixtas de carbonatos-siliciclásticos, fue formado en un complejo costero-deltaico y el grupo de facies carbonatadas inició su depósito en una rampa homoclinal, que posteriormente se desarrolló en una plataforma cerrada, debido a la expansión de facies de barrera de rudistas.

Palabras clave: siliciclásticos, carbonatos, rampa homoclinal, plataforma cerrada, Cretácico, unidad Sadr, Nakhlak, Irán Central.

## INTRODUCTION

The Nakhlak area lies in a structural region of Central Iran and is situated north of the so-called Yazd Block. It covers an area between  $53^{\circ}45'N$  and  $53^{\circ}54'N$  and  $30^{\circ}30'E$  and  $33^{\circ}37'E$ . The area consists of pre-Triassic? ophiolites and a Triassic (Nakhlak Group; Alam, Baqoroq, and Ashin formations), Upper Cretaceous (Sadr unit) and Paleocene (Khaled unit) sedimentary cover. These sedimentary units exhibit considerable thickness (3250 m) and represent a range of environments (Figure 1).

The Nakhlak Group is an exotic Triassic succession in central Iran. Lithologically as well as palaeontologically, the Triassic strata of Nakhlak differ completely from the shallow-water carbonate platform successions of the Lower and Middle Triassic of Iran. The only Triassic succession

that lithologically and palaeontologically resembles the Nakhlak Group to some extent is the Triassic succession of the Aghdarband area in northeastern Iran (Davoudzadeh and Seyed-Emami, 1972; Ruttner, 1991; Alavi *et al.*, 1997; Vaziri, 1996, 2001, Vaziri and Fürsich, 2007; Balini *et al.*, 2009; Zanchi *et al.*, 2009), whereas lithological and palaeontological data indicate that the Cretaceous rocks of the Nakhlak area are equivalent to shallow carbonate platform successions of Upper Cretaceous rocks in central Iran, which belong to the central Iranian Plate (Vaziri *et al.*, 2005).

The relationship of this geological unit to Southern Iran, *i.e.* coastal Fars and the Arabian Plate sequences has not been described yet but maybe it can be correlated with some parts of the Lower Sarvak (Cenomanian), Ilam (Santonian-Campanian) and Tarbur (Campanian-Maastrichtian) formations in Zagros region and Inner Fars in Iran, Maudud and

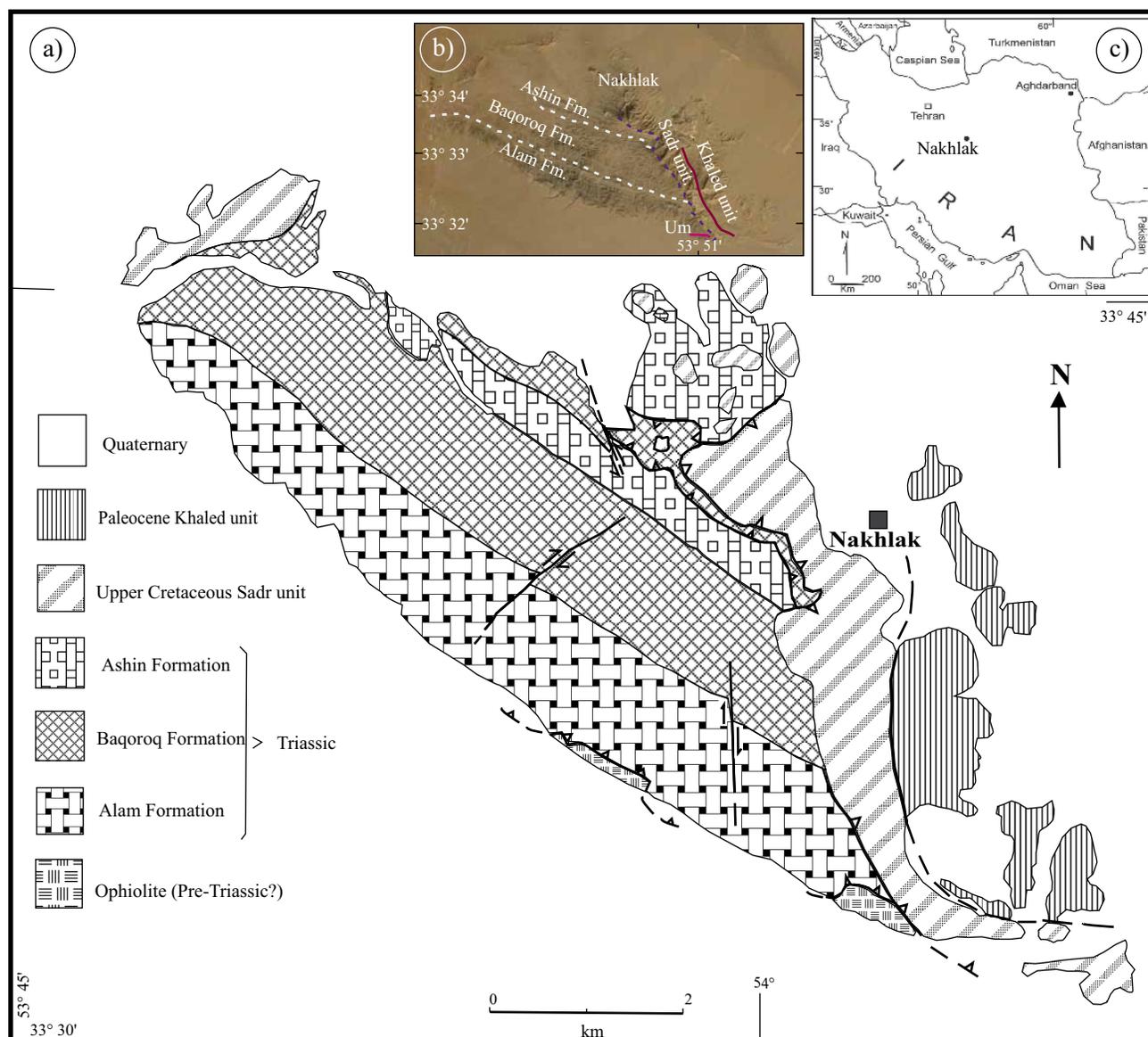


Figure 1. Geological map (a), satellite image (b, from Google Earth) and location (c) of the Nakhlak area, Central Iran.

Mishrif formations in the United Arab Emirates and Natih Formation in Oman (Razin *et al.*, 2010; van Buchem *et al.*, 2002). Khosrow-Tehrani (1977) indicated that Upper Cretaceous rocks of Nakhlak area can be correlated with those of Zagros region based on microfauna (foraminifera). This geological unit contains economically valuable minerals such as zinc and silver (Bariand, 1963; Burnol, 1968; Holzer and Ghassemipour, 1973; Cherepovsky *et al.*, 1982).

The main objectives of this paper are to describe and interpret the facies and depositional environments of the Upper Cretaceous Sadr unit in the Nakhlak area in order to understand the geological evolution of the area during that time interval.

## GEOLOGICAL SETTING

The Upper Cenomanian to Campanian rocks (Sadr unit) crop out across a large area of Nakhlak and reach a thickness of 258 m in the studied section (Figure. 1). This section is situated south of Nakhlak village (coordinates: N 33°32'09"; E 53°50'33") and consists of conglomerates, sandy limestones, calcareous sandstones, sandy dolostones, sandy-argillaceous limestones, sandy dolomitic limestones, and reefal limestones that have been subdivided into ten sub-units on the basis of their facies characteristics and described (Figure 2; Vaziri *et al.*, 2005). The rich foraminiferal assemblage from different sub-units of the studied section indicates a Late Cenomanian to Campanian age (Khosrow-Tehrani, 1977; Vaziri *et al.*, 2005). Biostratigraphic studies of the Upper Cretaceous rocks of the Nakhlak (Khosrow-Tehrani 1977; Vaziri *et al.*, 2005), Chooapanan and Haftoman areas (Khosrow-Tehrani, 1977), as well as of the Kerman area of east-central Iran (Faryabi, 2003) point to a hiatus during Turonian-Coniacian time.

The Upper Cretaceous Sadr unit overlies the Triassic rocks with an angular unconformity (Figures 3a-3c) and their top is faulted and overlain by Paleocene (Danian-Thanetian) rocks (Figure 3a, I; Vaziri, 1996; Vaziri and Fürsich, 2007; Balini *et al.*, 2009; Vaziri, 2011). Pebbles and fragments of Upper Cretaceous limestones in the basal red conglomerate and conglomeratic sandstone of the Paleocene sequence indicate a gap in sedimentation (disconformity) between the Upper Cretaceous and Paleocene rocks and that the fault contact is secondary.

## MATERIALS AND MEHTODS

During field work in the Nakhlak area, one stratigraphic section of the Upper Cretaceous Sadr unit was studied, 77 rock samples were collected and facies were studied along the layers trend, which indicated similar characteristics. Thin sections of collected samples were studied under a polarized microscope. For classification purposes the concepts of Folk (1974) have been used for siliciclastic

facies group (especially sandstones) and those of Dunham (1962) and Flügel (2004) for carbonate facies group. The petrography was subsequently studied at the GeoZentrum Nordbayern, University of Erlangen-Nürnberg, Germany within the framework of a DAAD-sponsored research stay.

## FACIES ANALYSIS AND DEPOSITIONAL ENVIRONMENTS

The lower part of Upper Cretaceous Sadr unit in the Nakhlak area is transgressive and consists of basal polymictic conglomerates occurring in pockets (Figure 3d), calcareous sandstones, and sandy limestones and dolostones, which are followed by dolostones, calcareous sandstones and shallow-water rudist-bearing limestones (Figures 3e-3h). The Sadr unit can be divided into carbonates, siliciclastics, and mixed carbonate-siliciclastics groups as follows, and there is no evidence of continental sedimentation.

### Mixed carbonate-siliciclastic facies group

Mixed carbonate-siliciclastic facies group have considerable extension and are observable in nearly all sub-units of the studied section. Sand- and gravel-sized detrital grains with fragmented and reworked allochems and a micritic to sparitic matrix indicate that the sedimentary basin frequently received detrital sediments from continental sources, brought in by rivers, and distributed and mixed by currents and storms. Sediments of the sub-units 1-3 of the Upper Cretaceous Sadr unit are mainly composed of these facies. The most important microfacies types are briefly described below:

#### *Pebbly to sandy bioclastic-packstone to fossiliferous pebbly sandstone*

Siliciclastic grains account for 30-40% and range in size from coarse sand to pebbles made up of monocrystalline quartz and meta-quartzite. Carbonate fragments account also for 30-40%, and consist especially of bioclasts such as brachiopods, bivalves (especially rudists), echinoids and gastropods fragments. The matrix consists of micrite and microsparite or sparite/sparry dolomite. Most carbonate grains are reworked and most likely are from within the basin. These facies can be observed in sub-units 3, 6, 7 and at the base of sub-unit 5 (Figures 4, 5d, 5e).

#### *Bioclastic-wackestone/sandy packstone to fossiliferous sandstone*

These mixed facies are finer-grained than the previous ones and the percentage of pebbles and carbonate grains is lower, and lithoclasts consist mostly of microfossils. The matrix is micrite and microspar, which indicates a lower energy level than in the previous facies (Figures 5f, 5g). As observed in the field, these mixed facies often occur

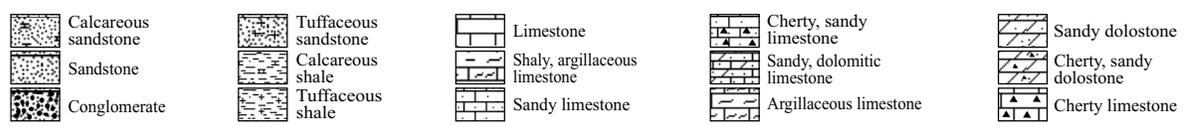
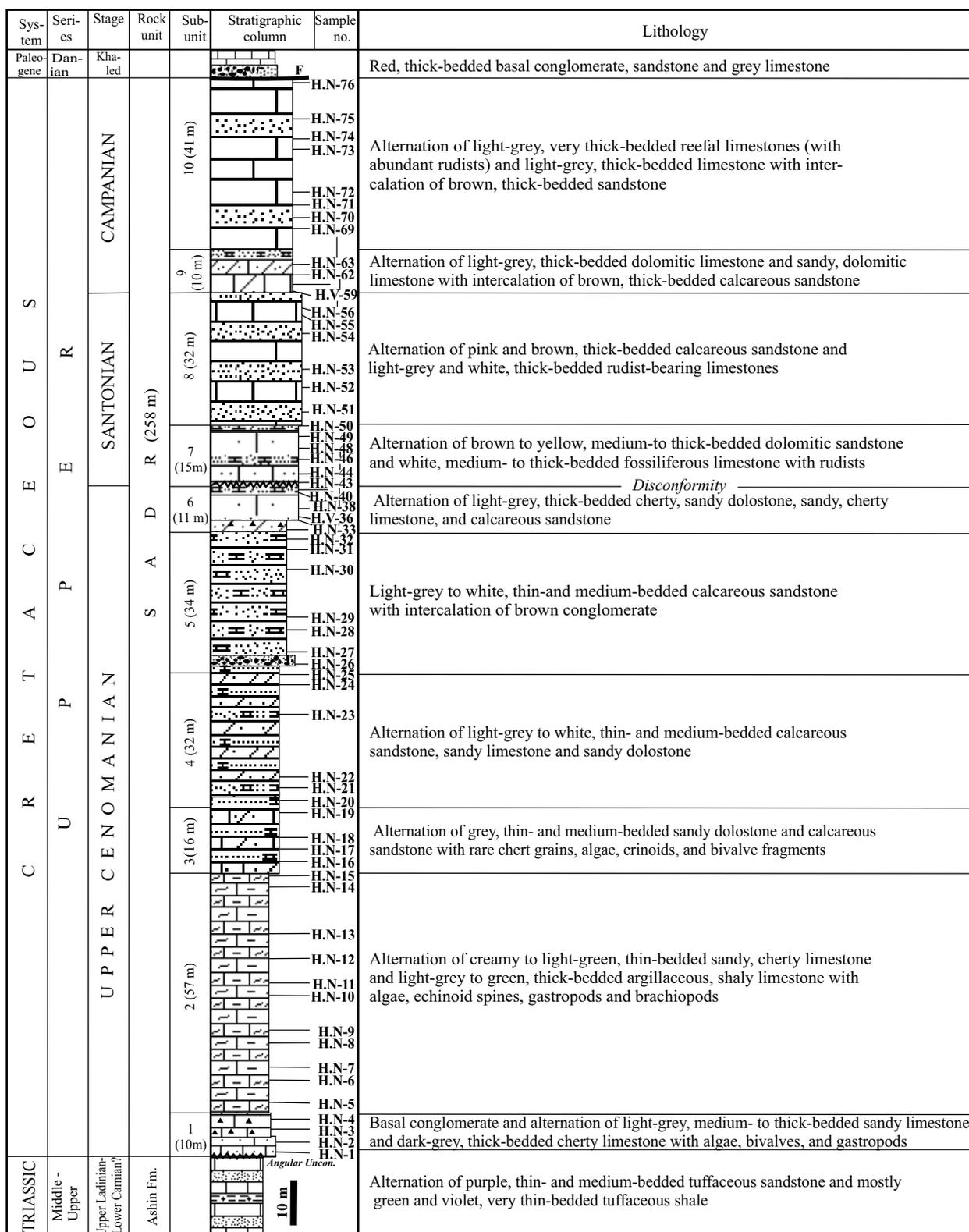


Figure 2. Lithological characteristics of the Upper Cretaceous succession (Sadr unit) in the Nakhlak area, Central Iran (modified from Vaziri et al., 2005).

as alternations of sandstone and carbonates. In sub-units 1-4 (Figure 4), mixed facies are very common and show thick coarsening-upward sedimentary cycles. Within these cycles thinner coarsening-upward cycles are also seen and the sediments are strongly bioturbated (Figure 6d). These mixed carbonate-siliciclastic facies mainly formed close to the shoreline and possibly in the vicinity of deltas.

#### ***Medium to coarse sandy dolostone to dolomitic sandstone***

Dolomite rhombs and detrital sand grains (monocrystalline quartz with undulose extinction) and a few cherts grains are observed. Commonly, the dolomite rhombs consist of ferric dolomite and have zonal structure (Figure 5h). With increasing percentage of quartz and decreasing percentage of dolomite crystals, this facies changes to dolomitic sandstone (sandstone of the sub-chert arenite group). In this facies, only shadows of allochems (crinoids and bivalves) can be seen, because primary texture has been affected by dolomitization. This facies is arranged in small fining-upward sedimentary cycles and reflect a gradual sea-level rise with increasing water depth. This facies can be observed in sub-units 3, 4, 6 and 9.

#### ***Interpretation***

Mixed carbonate-siliciclastic facies group consists mainly of pebbly to sandy limestones/or dolostones, calcareous sandstones and pebbly dolomitic sandstones. Detrital grains include meta-quartzites and chert granules. Carbonate components consist mainly of skeletal fragments of brachiopods, bivalves (e.g., rudists), echinoderms, algae, bryozoans, and foraminifera, in addition to some intraclasts, extraclasts, and peloids (Figures 5d-5g). Field and petrographic studies of the mixed carbonate-siliciclastic facies group, for example coarsening-upward cycles, large-scaled cross-beddings and grey-coloured sediments, show that these facies were formed in a coastal-delta complex. The coast is a spread area that includes deltas, beaches, barrier islands, cheniers and also coastal plains adjacent to the shoreline (Summerfield, 1991). Sedimentary shorelines can be divided into lobated and linear shorelines (e.g., Selley, 1996). The first set includes deltas and the second set mainly includes beach/barrier-lagoon complexes. The mixed carbonate-siliciclastic facies group of the Upper Cretaceous Sadr unit of the Nakhlak is probably belongs to linear shorelines (e.g., Selley, 1996).

The existence of pebble- and sand-sized (quartz, feldspar and chert) siliciclastic grains as well as the presence of various allochems, especially bioclasts, and the carbonate matrix indicates that these facies were affected by marine and continental processes. Variable textural maturity of the siliciclastic sediment samples, plenty of allochems and lime mud in other samples, coarsening upwards sedimentary cycles and plenty of biogenic structures show that these facies were deposited in various sub-environments of a shore-beach complex.

#### **Siliciclastic facies group**

This facies group consists mainly of siliciclastic and other detrital grains derived from Triassic rocks of the Nakhlak area. The grains consist of quartz and reworked carbonate grains such as carbonate lithoclasts and eroded allochems. This facies group is composed of a variety of gravel-, sand-, and silt-sized grains and exhibit sedimentary structures such as horizontal lamination, lenticular bedding, and flaser bedding, normal and reverses graded bedding, mud cracks, casts of evaporite minerals, plant roots and remains of paleosoil (caliche). Sandstone and conglomerate beds alternate and exhibit numerous sedimentary structures such as imbrications and trough cross bedding. Siliciclastic mudstones are seen between the sandstone beds. Chert arenite and quartzarenite facies have good textural maturity and mineralogy and may display parallel lamination and cross-bedding. The most important facies types are as follows:

#### ***Brown, fine-grained oligomictic conglomerate***

This gravel facies is intercalated between sandstones in sub-unit 5 (Figure 4) and occurs partly as orthoconglomerate and partly as paraconglomerate. Gravel grains consist of meta-quartzite, monocrystalline quartz and chert, and are light-coloured. The sorting of grains is good but their rounding usually is poor to moderate. The conglomerate is variably sandy and occasionally grades into gravely sandstone. Its brown colour is caused by the dolomitized carbonate cement with hematite impregnation (Figure 6a). The conglomerate has a wide lateral extension and, according to its lithological and petrographic features such as textural and compositional maturity, flat bedding, fining-upward graded bedding and marine fauna, is interpreted as shoreline facies.

#### ***Fossiliferous, mature sub-chert arenite with dolomitic-calcareous cement***

In this facies, quartz and chert grains are cemented by carbonate. Commonly, grains are medium in size, and their rounding and sorting are not good. The cement is impregnated with hematite. Quartz and chert pebbles and macro- and microfossil fragments are characteristic elements of this facies (Figures 5a, 5b). The general colour of this facies is brownish and small detrital grains can be seen (Figure 6b). The conglomeratic facies has been deposited at relatively high-energy shorelines. Textural maturity and fragments of echinoderms, bivalves, foraminifera, and algae support this interpretation. This facies mostly occurs in sub-units 5, 6, 7, and 8 (Figure 4).

#### ***Cross-bedded chert-arenite to mature, coarse-grained quartzarenite with dolomitic-calcareous cement***

This siliciclastic facies includes coarse- to very coarse-grained sandstones and some conglomerates. The percentage of chert grains varies from very low to 30%. Other grains are composed of monocrystalline quartz and meta-quartzite. Most quartz grains have undulose extinction and metamor-

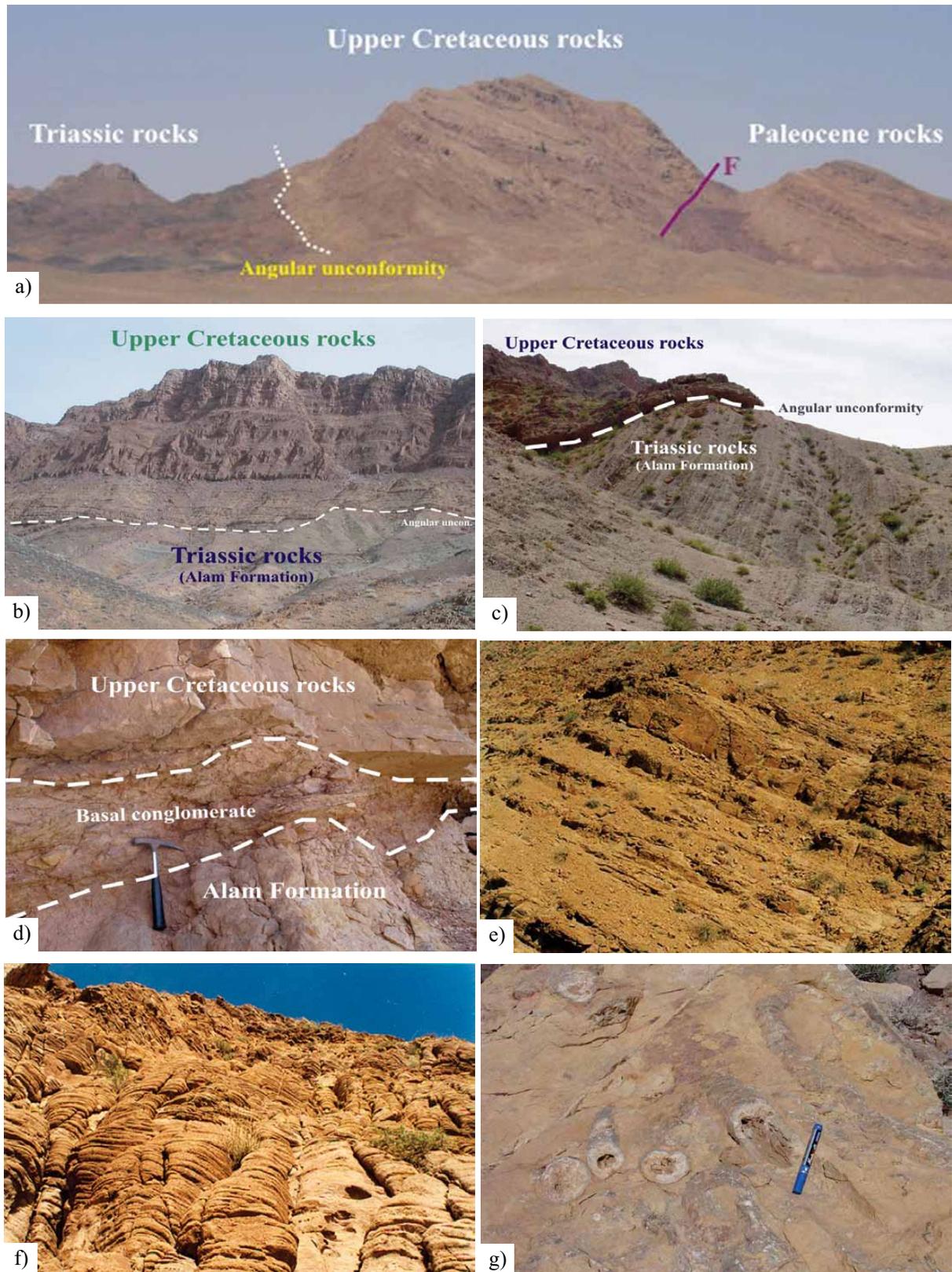


Figure 3. a: The Upper Cretaceous Sadr unit of the Nakhlak area and their lower and upper boundary with Triassic and Paleocene rocks, respectively. View to the north. b: Section point of the Upper Cretaceous Sadr unit and its angular unconformity with Triassic rocks (Alam Formation), view to the east. c: Angular unconformable contact between the Triassic rocks (Alam Formation) and the Upper Cretaceous Sadr unit, view to the southeast. d: Transgressive polymictic conglomerate at the base of the Upper Cretaceous rocks. e: Alternating sandy, cherty limestones and argillaceous, shaly limestones of sub-unit 2. f: Calcareous sandstones of sub-unit 5. g: Rudist-bearing limestone of sub-unit 10.

phic or plutonic sources. The components are embedded in rhombohedral ferric dolomitic or granular, blocky and poikilotopic calcite cements (Figure 5c). The sandstone beds show light-gray to white, medium and thick beds with large scale cross stratifications. Both field and petrographic evidence suggest that this facies represents sand waves organized in barrier bars. This facies attains considerable thickness in sub-unit 5 (32 m) (Figure 4).

### **Mudstone**

Fine-grained siliciclastic facies include mudstone and shale. Some of the mudstones are brownish or yellowish and exhibit mud cracks (Figure 6c), burrows and lamination. These deposits represent tidal flats, in particular supratidal areas. Some other mudstones are black and are composed of thin fining-upward cycles overlying sandy deposits. Very probably, these mudstones were formed during transgressive events, because of fining-upward cycles and black coloured representing deposition under reduce conditions.

### **Shale**

Shaly facies alongside with creamy to light-green carbonates represent open marine conditions deposited below the storm wave-base.

### **Interpretation**

The siliciclastic facies group of the Upper Cretaceous Sadr unit of the Nakhlak area were deposited in various sub-environments of siliciclastic shorelines, especially tidal flats, lagoonal, sandy barriers, and open marine areas. These facies were formed on a shallow shelf during a relative sea-level highstand. During that time, the carbonates were highly diluted by abundant input of land-derived siliciclastic material. Sedimentation took place along linear shorelines in a warm and dry climate which is supported by the presence of mud cracks and casts of evaporate minerals. In this setting, deltas are common, but barrier islands situated parallel to the shores are widespread. These sandy islands may have separated lagoons from the open sea and may have been cut by a few tidal dissected channels. This complicated system may have formed whenever carbonate regime changed to a siliciclastic regime in connection with a relative fall in sea level or evolution of continental environments to coastal environments during a transgressive phase and relative sea-level rise. Shales are highly bioturbated and intercalated between sandstones of the shore face sub-environment. They are interpreted to represent offshore and open marine environments.

### **Carbonate facies group**

Thick-bedded limestones account for a considerable part of sub-unit 10 (Figure 4). In other sub-units, carbonate beds (calcareous or dolomitic) generally occur alternating or interbedded with siliciclastic rocks or mixed carbonate-

siliciclastic facies group. The most important facies types are as follows:

#### ***Dolomitic-lime mudstone to laminar dolomudstone with casts of evaporite minerals***

These facies include all samples that are composed of finely crystalline dolostone (Figure 7j); do not have allochems and only rare peloids and intraclasts. Calcium carbonate mud was changed during diagenesis to microspar. The most important structures and fabrics of these sediments include lamination, mud cracks, casts of evaporate minerals and fenestral fabrics (Figure 7j). These fenestral fabrics can be observed as birds eyes and usually form fenestral porosities while the others have been filled with sparry calcite. These thin- to medium-bedded sediments can be attributed to inter- and supratidal environments (Gebelin, 1977; James, 1979; Shinn, 1968, 1983; Sellwood, 1991) (Figure 5e). Erosional sedimentary structures such as scour and fill structures occurring in some beds are common on tidal flats (Reineck and Singh, 1980; Elliott, 1991; Reading and Collinson, 1996). Similar sediments form at present day on supratidal flats of Florida and the Bahama and on sabkha flats of the Persian Gulf (Shinn, 1986).

#### ***Lime mudstone to bioclastic-wackestone with casts of evaporite minerals***

This facies contains bioclasts (1–15 %), some quartz grains, and a few peloids. Bioclasts include foraminifera and rarely ostracods. The pore spaces were filled with sparite. In some samples, a geopetal fabric formed in these cavities (Figures 7a, 7b).

#### ***Peloidal bioclastic wackestone***

In this facies, peloids account for 10% and fine-grained bioclasts including benthic foraminifera and ostracods for approximately 5–10% of the total rock volume. Locally, the micritic matrix has been converted to microspar and pseudospar (Figure 7c). All evidence such as plenty of lime mud, fragments of foraminifera from offshore environments and peloids indicate a quiet environment.

#### ***Peloidal bioclastic packstone to grainstone***

This facies differs from the former facies by its higher amount of allochems and type of matrix. The facies contains 20–25% bioclasts (foraminifera, ostracods and bivalves) and 20–25% peloids. The size of the bioclasts is fine- to medium-grained sand and the fabric is grain-supported (Figure 7d). This indicates that the sediment has been deposited under elevated energy conditions.

Field and petrographic evidence suggests that the three above facies represent restricted shallow-water inner platform areas resembling recent inner platforms such as the Persian Gulf, Florida, and the Bahamas (Bathurst, 1975; Shinn, 1986; Purser and Evans, 1973). Abundant lime mud is evidence of sedimentation in a low-energy environment. In some of the facies, a bioturbation fabric (mottling) and

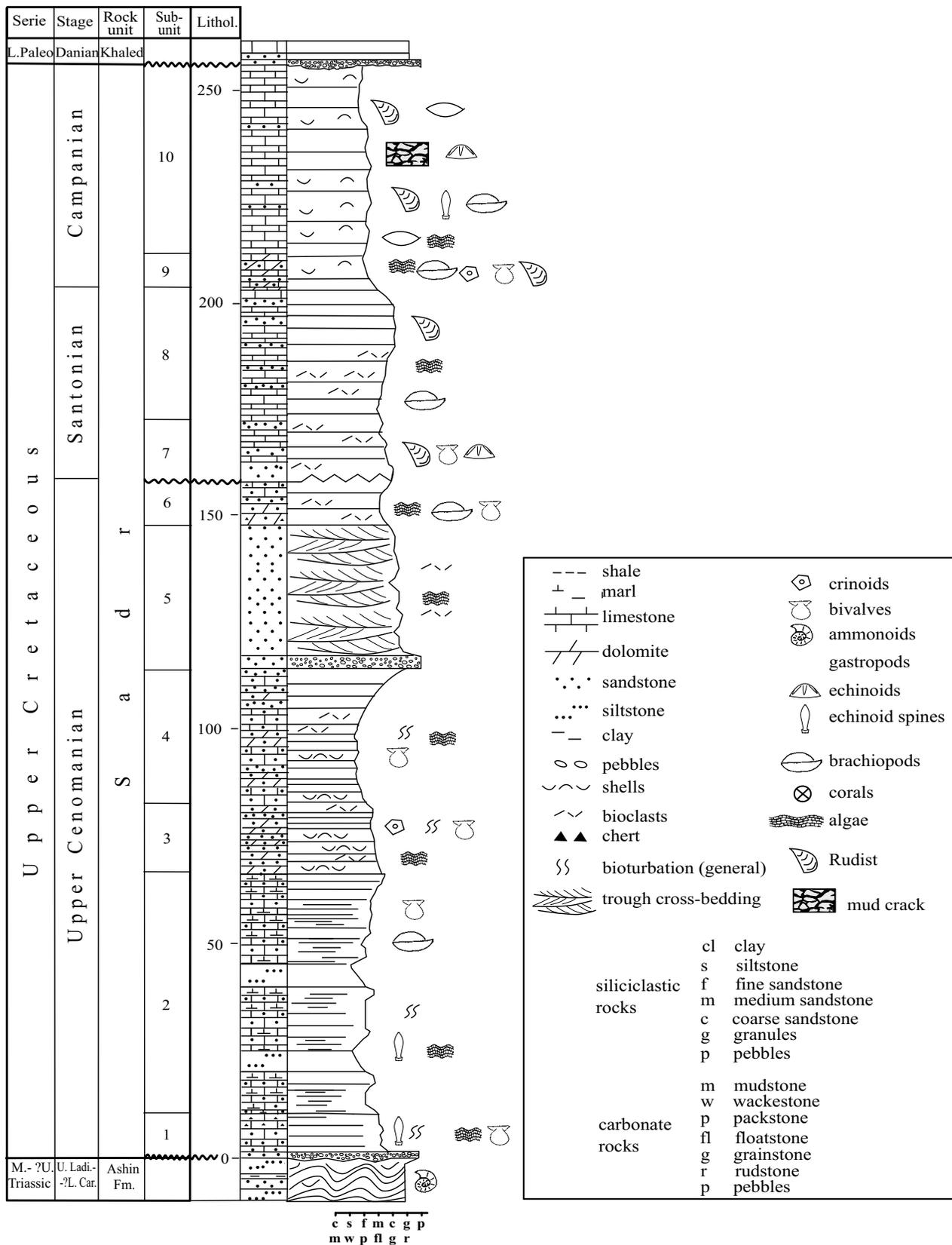


Figure 4. Sedimentary succession and fossil content of the Upper Cretaceous Sadr unit of the Nakhlak area.

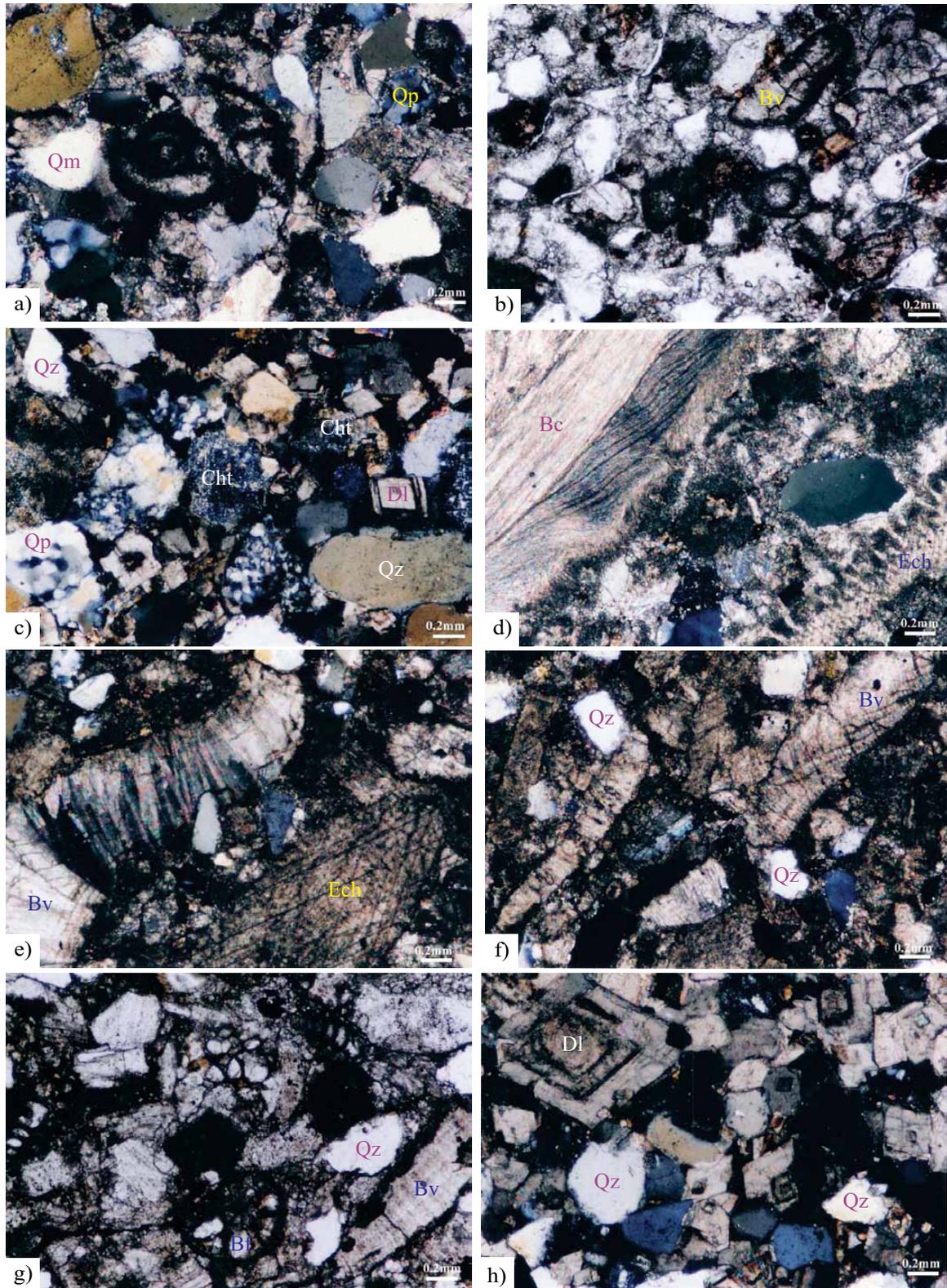


Figure 5. Thin-section photographs of siliciclastic and mixed carbonate-siliciclastic facies of the Upper Cretaceous Sadr unit of Nakhlak. a, b: Fossiliferous, mature sub-chert sandstone with carbonate cement of sub-unit 8. c: Mature, chert-arenite with ferric dolomitic cement of sub-unit 5. d: Mixed carbonate-siliciclastic facies containing quartz grains, peloids, and brachiopod and echinoderms fragments of sub-unit 2. e: Mixed carbonate-siliciclastic facies containing bivalves and echinoderm fragments of sub-unit 3. f: Mixed carbonate-siliciclastic facies, containing quartz grains and bivalves fragments of sub-unit 3. g: Mixed carbonate-siliciclastic facies containing mainly foraminifera of sub-unit 2. h: Medium to coarse-grained sandy dolostone of sub-unit 6. Symbols: (Qz) quartz; (Qm) monocrystalline quartz; (Qp) polycrystalline quartz; (Bf) benthic foraminifera; (Ech) echinoderm; (Bv) bivalve; (Bc) brachiopod; (Rd) rudist; (Cht) chert; (Dl) dolomite rhombs.

micritization of skeletal grains occur, which resulted from the activity of endolithic organisms in quiet environments such as lagoons (Flügel, 2004). Plenty of peloids and tests of benthic foraminifera such as miliolids and algae also support sedimentation of these facies in lagoonal environments (Tucker and Wright, 1990; Wright and Burchette, 1996).

#### ***Intraclastic to bioclastic grainstone***

The allochems are coarse sand- to gravel-sized and set in a sparry calcite cement. The most important bioclasts are foraminifera, echinoderm, brachiopod, bryozoan and bivalve fragments (Figures 7e, 7f). Granular cement between allochems and syntaxial rim cement around echinoderm fragments are the most important cement fabrics. This facies is not widely distributed. Skeletal grains and lack of lime mud indicate turbulent environments such as shoals. Intraclasts were formed in tidal flat channels or estuary channels.

#### ***Rudist boundstone***

Boundstones occur mainly in sub-unit 10 (Figure 4). The light-grey, thick-bedded deposits contain rudists in growth position (Figures 3h, 5f). Apart from rudist fragments, some echinoderm, brachiopod, and foraminiferal fragments occur. These deposits change in thickness laterally and alternate with lagoonal and open marine facies (Figure 6g). The intraclastic bioclastic grainstone and rudist boundstone are here interpreted as bioclastic barriers and rudist biostromes/reef, respectively on platform margins or high-energy areas of the inner platform. Texture of the grainstone facies (lack of matrix) indicates that the sediment formed in high-energy areas. Similarly, the coarse sizes of calcareous grains support deposition in a turbulent environment (Irwin, 1965). At present day, bioclastic barriers can be observed in the Persian Gulf (Purser and Evans, 1973) and on the Bahamas Platform (Harris *et al.*, 1985). Rudists at the margins of carbonate platforms commonly formed biostromes/reefal barriers (Ross and Skelton, 1993).

#### ***Rudist floatstone to rudstone***

This facies is composed of matrix made of lime mud, and more than 50% of fine and coarse shell fragments. Bioclasts consist of rudists and some foraminifera, echinoderms, and brachiopods. Such floatstones and rudstones commonly form on reefal flanks as reefal debris (Figures 7f, 7g).

#### ***Lime mudstone to bioclastic-wackestone***

This facies represents the deepest carbonate facies of the Upper Cretaceous rocks of the Nakhlak area and alternates with other carbonate facies or with open marine shales. The main allochems are pelagic foraminifera such as *Hedbergella delrioensis*, *H. planispira*, *H. simplex* and *Globotrancana* sp. (approximately 15%). Other allochems include fragments of echinoderms, small brachiopods, and thin and fragile bivalves (Figure 7h). Rarely, the rocks ex-

hibit a nodular texture. Plenty of lime mud, fossils, and the thin-bedding suggest deposition below storm wave-base in an open marine environment.

#### ***Interpretation***

The rudist float- to rudstones and the mud- to bioclastic-wackestones probably formed in moderate energy, shallow- to deep-water, quiet open platforms. Such conditions usually exist on mid to outer ramps and on open shelves and basinal areas. Rudist fragments resulted from demolition of marginal platform reefs by waves and storms. The sediment accumulated as biostromes/reef talus in reefal barriers and on slope areas of the platform margin. In summary, field and petrographic studies indicate that the carbonates facies formed in tidal flats to open marine areas (Figure 8). Some beds exhibiting a detrital base and graded bedding probably represent storm deposits (Figure 6h).

## **CONCLUSIONS**

The detailed study of the Upper Cretaceous Sadr unit of the Nakhlak area indicates a range of siliciclastic and carbonate environments, which frequently changed through time. Siliciclastic facies were deposited in marginal marine environments during a relative sea-level highstand such as tidal flats, lagoons and barrier islands. Some finer-grained facies including mudstones and shales belong to somewhat deeper shelf areas. The carbonate facies formed on a homoclinal ramp. At times, these platforms were rimmed by barrier bars. The facies show various sedimentary structures and textural characteristics such as lamination, evaporate pseudomorphs, fenestral fabrics, and mud cracks indicative of intertidal to supratidal conditions. Some facies contain macrofossils such as rudists which formed patch reefs, alternating with some shales and marls deposited below storm wave-base. The mixed facies types are related to mixed carbonate-siliciclastic shelf environments where abundant intraclasts of carbonate rocks have been produced and a great number of quartz and chert grains, and pebbles have been delivered from a terrestrial source. Field and petrographic studies indicate that these facies were formed in a coastal-delta complex and are probably belong to linear shorelines.

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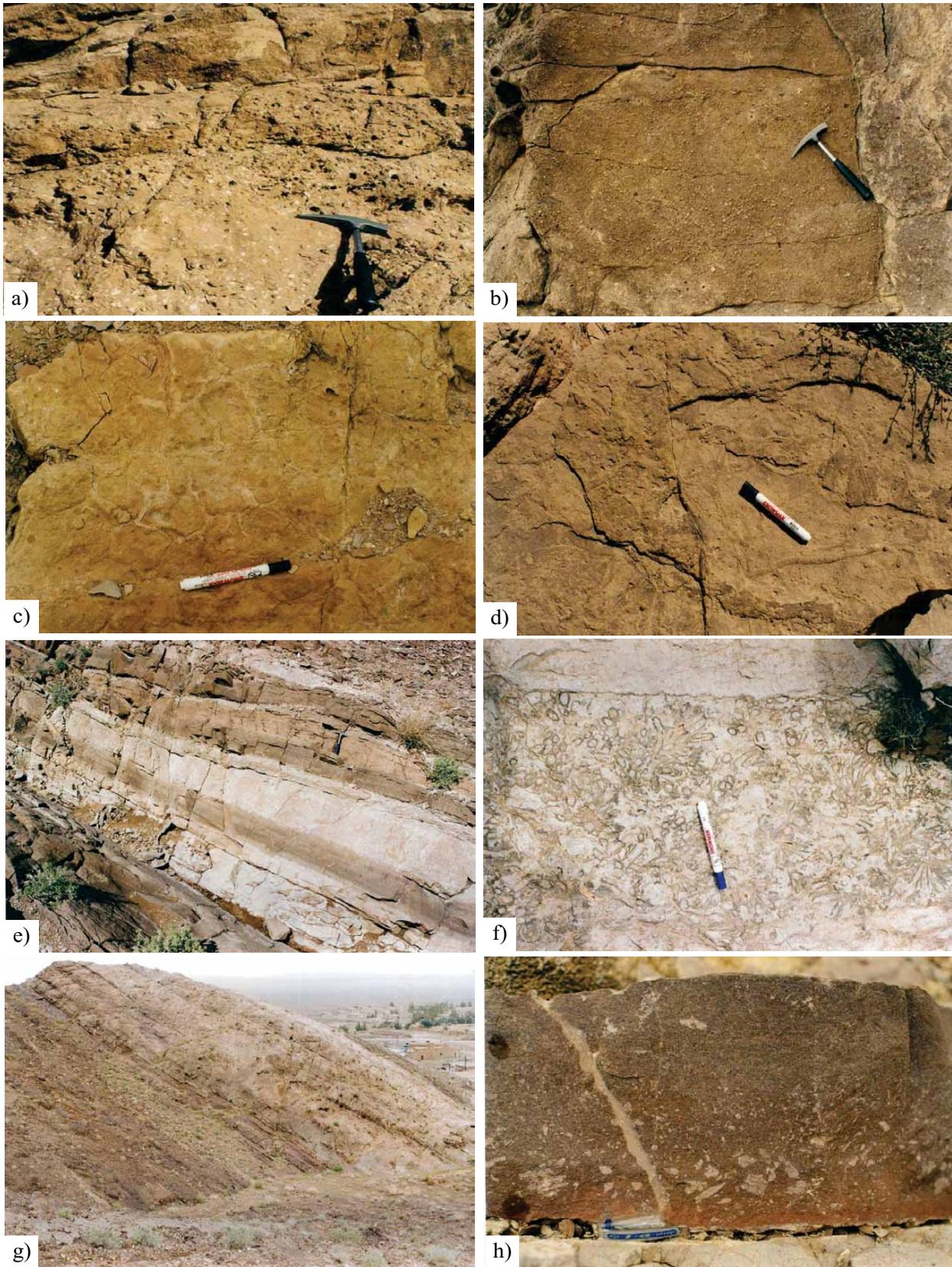


Figure 6. a: Fine-grained, brown oligomictic conglomerate of sub-unit 5. b: Pebbly, fossiliferous chert-arenite with carbonate cement of sub-unit 8. c: Mud cracks on the lower surface of carbonate mudstones of sub-unit 10. d: Horizontal burrows (*Taenidium* isp.) in mixed carbonate-siliciclastic facies of sub-unit 2. e: Dolomiticrite representing supratidal and intertidal environments of sub-unit 10. f: Rudist boundstone of sub-unit 10. g: Rudist-bearing limestones of sub-unit 10, view to the north. h: Graded bedding of storm origin, sub-unit 10.

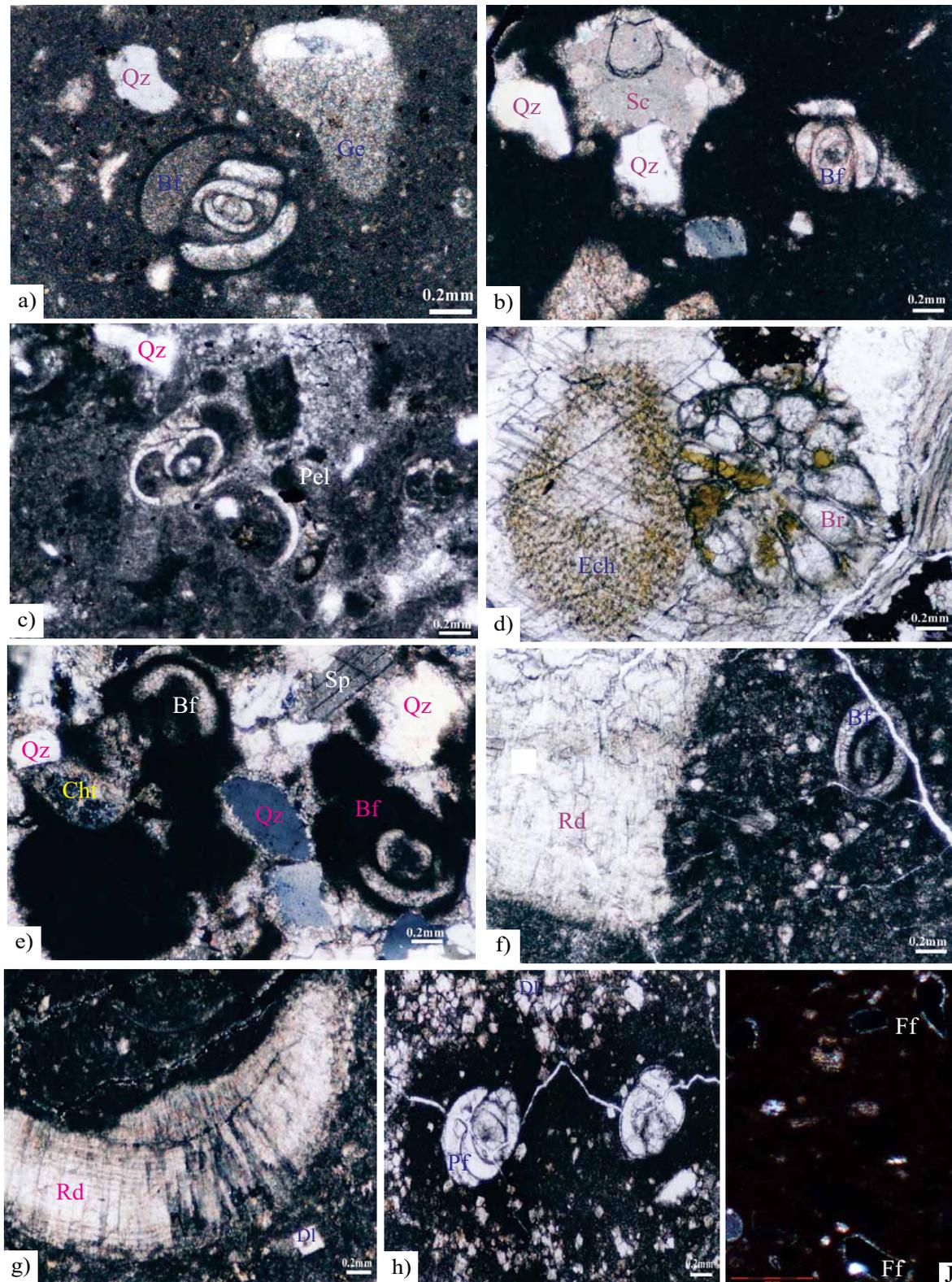


Figure 7. Thin-section photographs of carbonate facies of sub-unit 10 of the Upper Cretaceous Sadr unit of Nakhlak. a: Mudstone to bio-wackestone with geopetal cavities and quartz grains. b: Carbonate mudstone with rare benthic foraminifers, detrital quartz, and pore-filling sparry calcite. c: Pel-bio-wackestone of lagoonal origin. d: Intra-bio-grainstone, with echinoderm, bryozoan and brachiopod bioclasts. e: Intra-bio-grainstone, with intraclasts, peloids, and foraminifer tests. f, g: Bio-floatstone with rudist fragments and also foraminifer test (in f), fore-reef debris. h: Mudstone to bio-wackestone with abundant dolomite rhombs of the open shelf. Symbols: (Qz) quartz; (Ge) geopetal fabric; (Pel) peloids; (Sc) pore-filling sparry calcite; (Bf) benthic foraminifer; (Pf) pelagic foraminifer; (Ech) echinoderm; (Bv) bivalve; (Br) bryozoan; (Rd) rudist; (Cht) chert; (Dl) dolomite rhombs; (Sp) sparry calcite; (Ff) fenestral fabric.

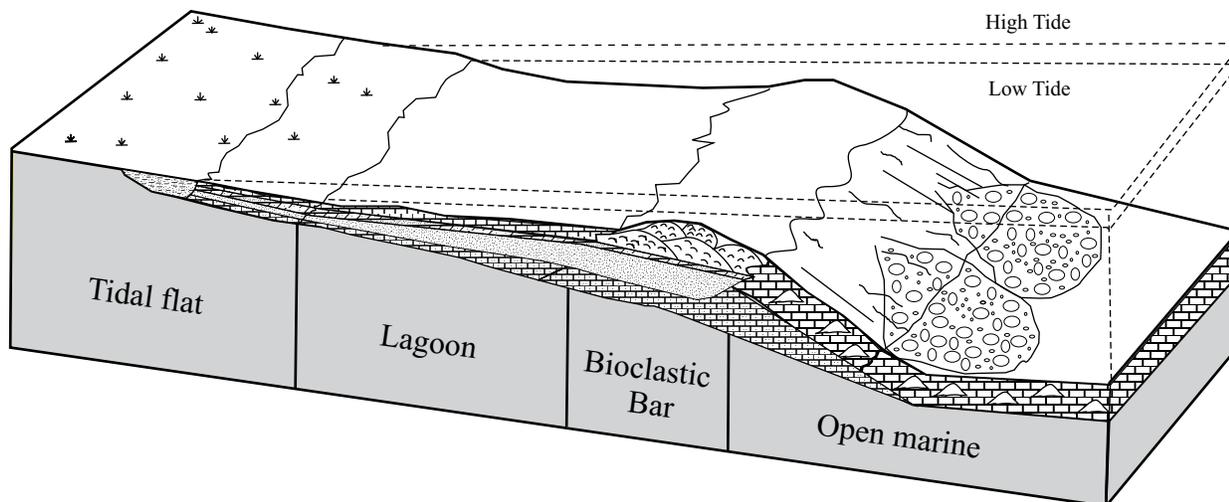


Figure 8. Depositional model for carbonate facies of the Upper Cretaceous Sadr unit of the Nakhlak area.

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