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GEOLOGY

The Middle Cretaceous Shallow to Deep Carbonates of the Sarvak Formation, Zagros Basin, Southwest Iran: Paleoenvironmental Reconstruction and Sequence Stratigraphy

Os Carbonatos Rasos a Profundos do Cretáceo Médio da Formação Sarvak, Bacia de Zagros, Sudoeste do Irã: reconstrução Paleoambiental e Estratigrafia de Sequência

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Abstract

The main purpose of this study is to investigate the sedimentary environment conditions and sedimentary characteristics of Sarvak Formation and therefore, due to the importance of Sarvak Formation in the Zagros Basin, in the present study, facies features, sedimentary environment and sequence stratigraphy of the mentioned formation were identified. In the present study, one stratigraphic section located in Bangestan Anticline (Tang-e-Sarvak) was studied to determine and analyze the facies types, depositional environment, and sequence stratigraphy characteristics of the Sarvak Formation in northwest of Behbahan city. This section is mainly composed of medium to thick-bedded and massive limestone. Facies analysis led to the recognition of 11 microfacies related to the pelagic, outer-ramp, middle-ramp, and inner-ramp environments. Facies frequency analysis of the microfacies and facies belt demonstrated that the most frequency was related to the MF2 belonging to the pelagic environment and the lowest frequency was related to the MF8 belonging to the inner ramp environment. Studying the changes of vertical facies and their comparison with their modern and ancient counterparts indicated that the Sarvak Formation has been deposited in a shallow carbonate ramp platform. The sequence stratigraphic assessments indicated that the Sarvak Formation consists of three third-order depositional sequences, each consisting of transgressive and highstand system tracts. Typical intervals, such as sequence boundaries, maximum flooding surfaces, stacking patterns, and system tracts were also distinguished.

Keywords: Depositional environment; Sarvak formation; Sequence stratigraphy

Resumo

O objetivo principal deste estudo é investigar as condições do ambiente sedimentar e as características sedimentares da Formação Sarvak e, portanto, devido à importância da Formação Sarvak na Bacia de Zagros, no presente estudo, características fácies, ambiente sedimentar e estratigrafia de sequência do mencionado formações foram identificadas. No presente estudo, uma seção estratigráfica localizada no Anticlinal do Bangestão (Tang-e-Sarvak) foi estudada para determinar e analisar os tipos de fácies, ambiente deposicional e características de estratigrafia de sequência da Formação Sarvak no noroeste da cidade de Behbahan. Esta secção é composta principalmente por calcário maciço e de estratificação média a espessa. A análise de fácies levou ao reconhecimento de 11 microfácies relacionadas aos ambientes pelágico, rampa externa, rampa intermediária e rampa interna. A análise de frequência de fácies da microfácies e cinturão de fácies demonstrou que a maior frequência estava relacionada ao MF2 pertencente ao ambiente pelágico e a menor frequência estava relacionada ao MF8 pertencente ao ambiente de rampa interna. O estudo das mudanças de fácies verticais e sua comparação com suas contrapartes modernas e antigas indicou que a Formação Sarvak foi depositada em uma plataforma rasa de rampa carbonática. As avaliações estratigráficas de sequência indicaram que a Formação Sarvak consiste em três sequências deposicionais de terceira ordem, cada uma consistindo em tratos de sistemas transgressivos e de nível alto. Intervalos típicos, como limites de sequência, superfícies de inundação máxima, padrões de empilhamento e setores do sistema também foram diferenciados.

Palavras-chave: Ambiente deposicional; Formação Sarvak; Estratigrafia de sequências

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1 Introduction

The Middle Cretaceous Sarvak Formation (Albian to Turonian) after the Oligo–Miocene Asmari petroleum system in the south of Iran (Zagros Basin) and in the Arabic Peninsula is of great importance as an oil formation (Beiranvand et al. 2007; Farzadi & Hesthmer 2007; Ghabeishavi et al. 2010; Rahimpour Bonab et al. 2012; Razin et al. 2010; Taghavi et al. 2006). The thickness of Sarvak Formation during the Cenomanian to Turonian in Zagros region is very variable due to tectonic activity (Ala 1974; Piryaei et al. 2010, 2011; Ricou 1971; Setudehnia 1978). Which varies from a maximum thickness in the Ahwaz area (900m) to total absence in the coastal fars area (Setudehnia 1978).

The type section of Sarvak Formation was measured (at Tang-e- Sarvak located in the south flank of kuh- e Bangestan). The lower 835 feet is composed of dark grey, nodular- bedded, argillaceous limestone with dark grey marl partings. This grades upwards into a massive, chalky white to buff limestone 360 feet with numerous brownish-red, siliceous nodules (James & Wynd 1965). The Zagros region, based on the facies varitions can be divided into four tectono- stratigraphic domains including: The Lurestan provice (western Zagros), The Dezful Embayment and The Izeh (central Zagros) and The Fars provice (interior Fars sub- Basin and coastal Fars sub- Basin) in eastern Zagros (Motiei 1993; Talbot & Alavi 1996).

In the studied section, Sarvak Formation overlies the Kazhdumi Formation and overlain by the Gurpi Formation. The upper contact of the Sarvak Formation is disconformity with Gurpi Formation and the lower boundary is gradational with the Kazhdumi Formation (James & Wynd 1965). According to Motiei (1993), and Wynd (1965), the Sarvak Formation has been deposited or formed during Albian to Turonian age. The Natih Formation (in Oman) and Wara, Ahmadi, and Mishrif Formations (in Saudi Arabia and Iraq) are equivalent to the Sarvak Formation (in Iran) (Alsharhan & Nairn 1990; Ghazban 2007; Van Buchem et al. 2002). Sarvak Formation is one of the principal stratigraphic units of the Bangestan Group mainly composed of the carbonate rocks. This formation has been deposited in a widespread carbonate platform system at the southern margin of the Paleo-Tethys Ocean (Motiei 1993; Setudehnia 1978).

Several studies including paleoenvironments, facies, diagenetic features, sequence stratigraphy, and reservoir quality have been done on the Sarvak Formation and various authors have studied the Bangestan Group in the Zagros Basin (e.g., Aleali 2017; Asadi Mehmandousti et al. 2013; Beiranvand et al. 2007; Farzipour-Saein et al. 2009; Ghabeishavi et al. 2009, 2010; Mahdi & Aqrawi, 2014; Mehrabi & Rahimpour Bonab 2013; Mehrabi et al. 2015; Reza 2018; Omidvar et al. 2014; Rahimpour Bonab et al. 2012, 2013; Razin et al. 2010; Sharp et al. 2010; Soleimani Asl & Aleali 2016; Soleimani et al. 2018). Ghabeishavi et al. 2009; Taghavi et al. 2006; Van Buchem et al. 2002; Van Buchem et al. 2010; Vincent et al. 2015; divided the Cenomanian sediments in the Tang-e Sarvak into three parts (Lower, Middle, and Upper) for the first time based on the Benthic foraminifera. Kiarostami et al. 2019, suggested the Albian- Cenomanian age for the Sarvak Formation in northwest of Behbahan. Mahmoudi and Taheri (2012) proposed the Upper Albian to Upper Cenomanian age for the Sarvak Succession in northeast of Gachsaran area. Omidvar et al. (2014) suggested the Cenomanian-Turonian age for the Sarvak Formation in Dezful Embayment.

Since, the Sarvak Formation in different places of the Zagros Basin exhibits significant changes in thickness, lithological and biological features, and facies types, detailed and comprehensive study on it can be a great help to increase our knowledge about this significant petroliferous reservoir. Therefore, , the main objective of this research is on the identification of the and analysis of the facies using the field and petrographic observations, identification of the depositional environment, recognition of the depositional cycles and sequences boundary of the Sarvak Formation in the type section, Tang-e Sarvak, and Bangestan Anticline.

2 Data and Methods

2.1 General Geological Information

Cretaceous in Zagros is divided into 3 parts: Lower Cretaceous, Middle Cretaceous and Upper Cretaceous (Aghanabati 2006). As the sea advances in the Middle Cretaceous, shale and calcareous sediments (Kazhdumi Formation) begin in Albian and as the sea shallows in the Late Albian to Cenomanian, shallow calcareous sediments are deposited in Sarvak Formation.

Regional uplift at the end of the Cenomanian has caused erosion of the upper parts of the calcareous sequence; the effects of this disconformity can be seen in the areas of the Fars and the Dezful Embayment. During the Turonian, the Fars region and the Dezful Embayment depression subside and the upper carbonates of the Sarvak Formation are formed (Motiei 1993). The top of the Sarvak is marked by a significant disconformity in Khuzestan and Fars provinces, which is less apparent in Lurestan where the formation is generally in the deeper water facies (James & Wynd 1965).

In the end of Turonian, all or part of the sediments belonging to Turonian have been removed due to the uplift of the area. In the Middle Cretaceous, three erosion phases have been proven: 1) the boundary of Aptian (Dariyan Formation) and Albian (Kazhdumi Formation) are a weathering zone including gluconite, siltstone, sandstone and iron. 2) At the end of Cenomanian, an erosion phase has caused the limestones of Sarvak Formation to be divided into 2 parts Cenomanian and Turonian, 3) Erosion phase after Turonian (Aghanabati 2006).

The Zagros area includes three zones, the Zagros suture-thrust zone, imbricated zone, and fold–thrust/simply fold belt (Alavi 1994, 2004; Falcon 1969). The Zagros Mountain (Zagros fold and thrust belt) with the NW-SE trend and width of about 1,800km is extended from the East Anatolian Fault in NE Turkey to northern Iraq and SW Iran (Falcon 1974; Haynes & McQuillan 1974). The Zagros Mountains (Zagros fold and thrust belt) are bounded by two faults on the northeast (Main Zagros Reverse Fault and Main Recent Fault) (McQuarrie 2004). The Main Zagros Reverse Fault (MZRF) is between the Arabian Plate and Eurasia (Dercourt et al. 1986; Parandavar & Hadavi 2019; Sengor 1984). The Zagros orogeny (Zagros fold and thrust belt) is divided into the zones of Lorestan, Izeh, Dezful Embayment, Fars, and High Zagros. These five zones are different in terms of sedimentary history and structural style (Berberian & King 1981; Falcon 1974; Motiei 1993; Stocklin 1968) (Figure 1A).

The study area is located in the Dezful Embayment. The Dezful Embayment is located within the Zagros Folded Belt and extends over ~75,000km^2. The Dezful Embayment is separated by a graben structure from the adjacent regions. Due to the rapid subsidence, this region is a depocentre (in Late Cenozoic) (Allen & Talebian 2011). The Dezful Embayment is bounded by the Balarud, Kazerun, and Mountain Front Faults. The Mountain Front Fault is between the Izeh zone and Dezful Embayment (Figure 1A). In the Aptian to Cenomanian interval, southwest Iran (the eastern part of the Arabian Plate) has been characterized by the large intra-shelf basins surrounded by the shallow-water platforms. The Sarvak Formation has been deposited on a carbonate platform in the passive margin of the Arabian Plate (Ziegler 2001).

The study area (Bangestan Anticline) with an anticline structure is located about 7km from the town of Likak (Figure 1B). The Sarvak type section is located in Tang-e Sarvak in the south flank of Bangestan Anticline 57km in northwest of Behbahan (Khuzestan province). This section will be measured in detail at coordinates of 30˚ 58.98′ N and 50˚ 7.84 ′E in the following (Figure 1B). The Behbahan-Ramhormoz road can be used to have access to the area located 12km in northeast of Likak village.

2.2 Methodology and Study Area

This study was conducted in three steps. The first step was data collection, the second step was field studies and sampling, and the final step was related to the laboratory studies (studying the thin sections).

In the field studies, one section of Sarvak Formation (710 m thick) at type section area was chosen, described, measured, and sampled from all the layers in a systematic way. Then, a total of 166 thin sections were prepared and examined by the polarizing microscope. Facies were identified based on the microfacies characteristics, such as fossil content, depositional texture, grain composition, and grain size. The microfacies were named based on the classifications proposed by Dunham (1962) and Embry and Klovan (1971). The facies analysis and introduction of the sedimentary model were performed using the standard models (e.g., Burchette & Wright 1992; Buxton & Pedley 1989; Wilson 1975) For assessment of the sequence stratigraphy and their elements (such as sequence boundaries and system tracts), fundamental terminologies and concepts for interpretation were applied (e.g., Catuneanu 2006; Emery & Myers 1996; Sarg 1988; Vail et al. 1991).

3 Results and Discussion

3.1 Lithostratigraphy

Motiei (1993) believed that the Sarvak Formation has been deposited in a shallow marine environment during the Albian to Turonian age, with a depth from Fars and Persian Gulf towards the northwest of the basin (Lorestan). Based on James and Wynd (1965) and Setudehnia (1978), the Sarvak type section is subdivided into three units: the lower 254 m is composed of the fine-grained, dark grey, nodular-bedded, argillaceous limestone with thin, dark grey marl partings and observed small ammonite impressions are common throughout the unit.

The second unit consists of a 109 m thick massive, chalky white to buff limestone with numerous brownish-red, siliceous nodules. The third unit is composed of a 414 m thick very massive, cream to brown limestone containing abundant rudist debris, as well as low-angle clinoform (Figure 2A). The Sarvak Formation in the studied section rests on the Kazhdumi Formation conformably with gradational contact (black shales and black argillaceous limestone) and under the Gurpi Formation with disconformity boundary (Wynd 1965). Evidence such as the presence of iron oxide and bauxite in the upper part of the Sarvak Formation shows that the Sarvak Formation has experienced a local uplift during the Turonian age (Razin et al. 2010; Hajikazemi et al. 2010; Hollis 2011; Rahimpour-Bonab et al. 2013).

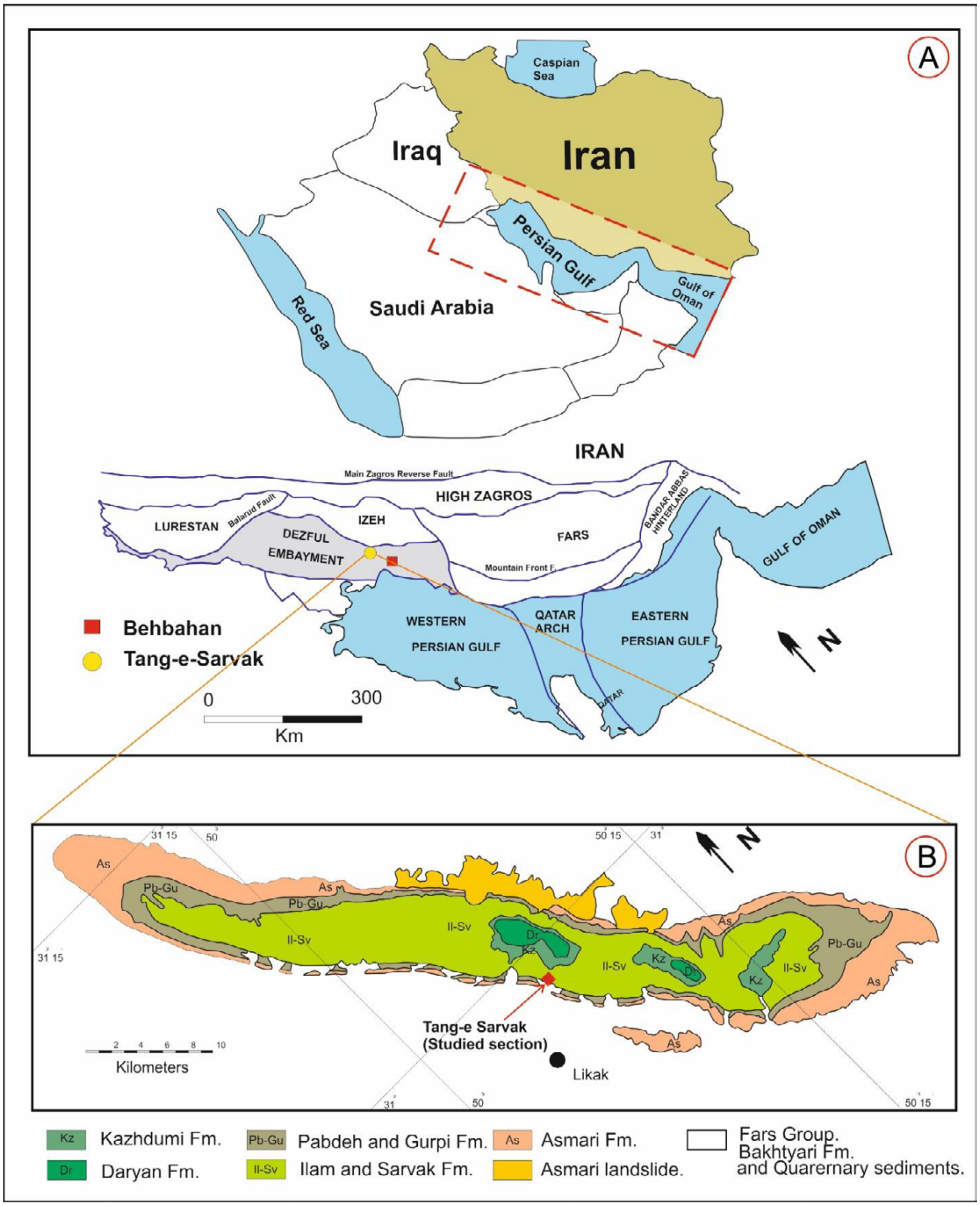

Figure 1 The Zagros orogeny is (Zagros fold and thrust belt) divided into five zones (Lorestan, Izeh, Dezful Embayment, Fars, and High Zagros), which are different in terms of sedimentary history and structural style. The Dezful Embayment is located within the Zagros Folded Belt and is separated by a graben structure from the adjacent regions: A. Principal geological and structural sub-divisions of southwestern Iran, Behbahan and the section Tang-e-Sarvak are labeled as red (adapted from the study by Omidvar et al., 2014); B. Geological map and related road map of the section Tang-e-Sarvak (adapted from the study by Ghabeishavi et al., 2010).

Given the performance of this erosional phase, the Turonian sediments are not present in the Sarvak type section due to the lack of deposition, exposure of sediments, and erosion. The Sarvak Formation in the studied section (type section) mainly consists of the limestone. This formation is located on the black shales of the Kazhdumi Formation (Aptian- Albian) with gradual boundary (Figure 2B). The top of Sarvak Formation in this section is composed of medium to thick-bedded limestone that is under the Gurpi Formation (Santonian) with disconformity boundary (Figure 2C).

The Sarvak Formation in the studied section (from base to top) is divided into four lithostratigraphic units (Figure 3): the first unit is comprised of a 140 m (from base of section) long dark gray medium-bedded argillaceous

Figure 2 Tang-e Sarvak outcrop section exposed in the Kuh-e Bangestan Anticline: A. This location shows the third unit of the Sarvak Formation in the study area. This unit consists of the low -angle clinoform; B. Detailed view of the Sarvak Formation shows that this formation rests on the Kazhdumi Formation (alternation of shale and limestone beds). White line marks the Sarvak and Kazhdumi Formations boundary in the type section; C. White line marks the Sarvak and Gurpi Formations boundary in the study area. The top of Sarvak Formation in this section is composed of limestone beds that are under the Gurpi Formation (Marl) with a disconformity boundary; D. The second unit of the Sarvak Formation in type section consists of light thick-bedded limestones with red-brown cherty.

limestone with dark gray thin-bedded marl interbeds. The second unit consists of a 100 m long light brown, thick-bedded limestone with red to brown cherty nodules (Figure 2D). The third unit is formed of a 170 m long light brown, thick-bedded limestone with abundant rudist debris. The fourth unit is composed of a 300 m long light brown, medium to thick-bedded limestone. The disconformity between Sarvak and Gurpi Formations is known by the presence of red iron nodules between these two formations (Figure 3).

3.2 Facies Analysis

The facies analysis and introduction of the sedimentary model were carried out using the standard models (e.g., Burchette & Wright 1992; Buxton & Pedley 1989; Wilson 1975). According to the petrographic studies on the Sarvak Formation including studies of carbonate components, depositional textures, microfauna's contents, and sedimentary features, 11 microfacies were distinguished belonging to various facies belts like pelagic, outer-ramp, middle-ramp, and inner-ramp environments (Table 1).

3.2.1. Pelagic Facies Group

This facies group consists of four microscopic facies (MF. 1, MF. 2, MF. 3, and MF. 4).

MF. 1: Radiolaria -Oligostegina Mudstone

The main components of this facies are the oligosteginids attendant by radiolaria in mud-supported textures. Subordinate grains are ostracods and rare bivalves. A large part of the Sarvak Formation is dedicated to these facies also MF. 1 lacks a shallow-water neritic fauna. This microfacies is characterized by the diagenesis processes, such as micritization and iron oxide.

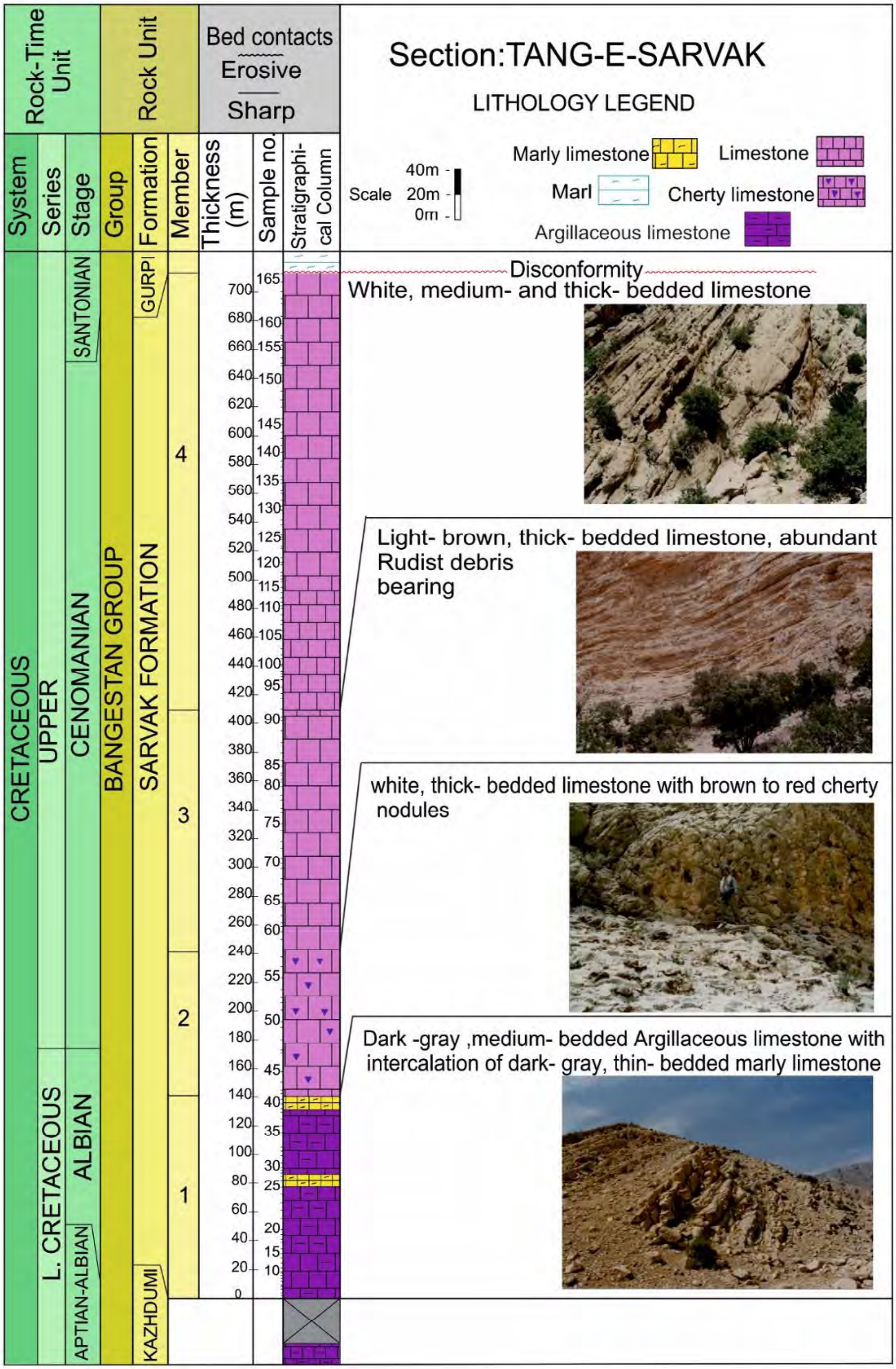

Figure 3 Stratigraphic column of Sarvak Formation in the Kuh-e Bangestan Anticline, northwest of Behbahan.

Table 1 The Microfacies Characteristics of Sarvak Formation in type section.

Facies code	Main components		Grain properties		Mineralogy and color	Energy level	Depositional environment
	Skeletal	Non- skeletal	Grain size	Sorting			
1	Oligosteginids, Radiolaria and ostracodes	--------	Very fine	poorly sorted	Calcite, Brown	Very low	Pelagic
2	Planktonic foraminifera, Oligosteginids, Radiolaria, sponge spicules and ostracodes	--------	Very fine	Poorly sorted	Calcite, Brown	Very low	Pelagic
3	Planktonic foraminifera, Oligosteginids, sponge spicules and ostracodes	--------	Very fine	well sorted	Calcite, Brown	Very low to low	Pelagic
4	Oligosteginids, echinoids, ostracodes	Peloids	Very fine to fine	well sorted	Calcite, Brown	Low	Pelagic
5	Rudist debris and Echinoids, ostracodes and algae	Peloids	Fine to medium	Modera-tely sorted	Calcite, light-brown	Low to medium	Outer ramp
6	Rudist debris, benthic foraminifera, bryozoan, miliolids and algae	Peloids	Medium to coares	Modera-te to well sorted	Calcite, Cream to light-brown	Moderate to high	Middle ramp
7	Rudist debris , large benthic foraminifera, orbitolinids, gastropods, Echinoids bryozoan, miliolids, algae and corals	--------	Medium to large	Modera-te to well sorted	Calcite, Cream to light-brown	Moderate to high	Middle ramp
8	Rudist debris, Echinoids, ostracodes and algae	Peloids	medium to coarse	Poorly sorted	Calcite, Cream to light-brown	Medium to high	Inner ramp (Shoal)
9	Benthic Foraminifera, echinoid debris, textularids, miliolids, ostracodes and algae	Peloids	Medium to large	Modera-tely to well sorted	Calcite, Light-cream to light brown	Moderate to high	Inner ramp (Shoal)
10	Diverse benthic foraminifera, rudist, sponge spicules, echinoids, bryozoan, algae and corals	--------	Medium	Modera-tely sorted	Calcite, Light-cream	Moderate	Inner ramp (Distal-middle lagoon)
11	Low Diversity Benthic Foraminifera, gastropods, echinoid fragments and miliolids	--------	Medium	Poorly sorted	Calcite, Light-cream	Low to moderate	Inner ramp (Proximal lagoon)

Interpretation: Evidence such as the abundance of radiolarian and oligosteginids, lack of shallow- water neritic fauna and the mud -dominated nature, in addition to the stratigraphic relationships with the MF2 (Flügel 2004; Wilson 1975) showed that the MF1 is situated in a very low- energy, calm pelagic environment, below the storm wave base (Figure 4A and Table 1). These facies can be considered equivalent to RMF5 (Flügel 2010) and is located in facies belt number of 1 in basin (Wilson 1975).

MF. 2: Oligosteginid and Planktonic Wackestone to Packstone

Planktonic foraminifera along with oligosteginids are the principal components. Subdominant grains are the sponge spicules and rare ostracods. The matrix of this facies is fine crystalline micrite. The stylolites, solution seams, and fracture porosity are the most important diagenesis processes in this microfacies. Stylolites and solution seams are the products of chemical compaction.

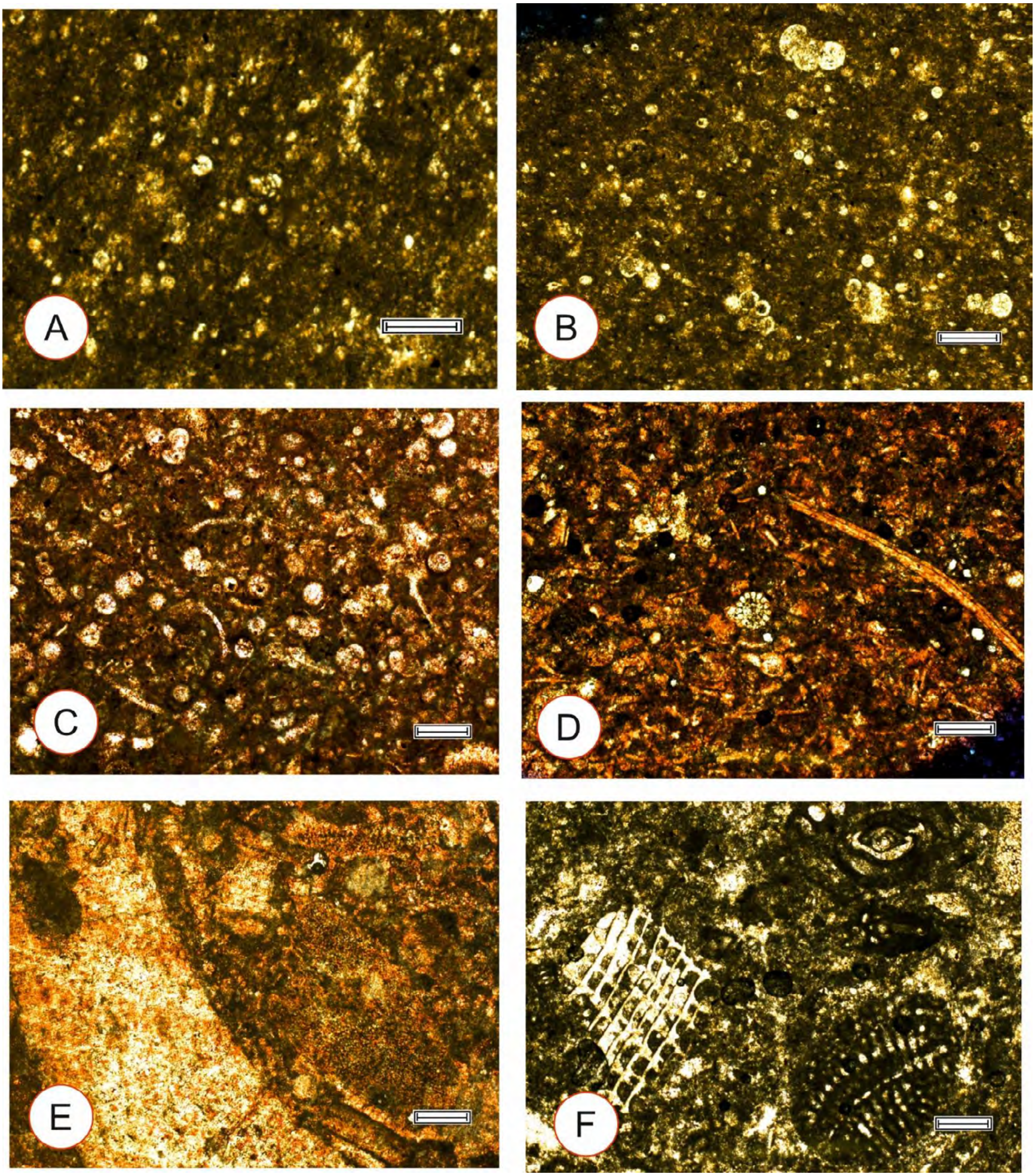

Figure 4 Microfacies of (MF.1 to MF.11) identified in the type section (Tang-e Sarvak): A. Microfacies MF.1, Radiolaria Oligostegina Mudstone; B. Microfacies MF.2, Oligosteginid and Planktonic Wackestone; C. Microfacies MF.3, Oligosteginid Packstone; D. Microfacies MF.4, Oligosteginid Packstone with Echinoderm; E. Microfacies MF.5, Bioclast Packstone bearing Rudist and Echinoderm; F. Microfacies MF.6, Rudist Packstone to Grainstone with Benthic Foraminifera (All figures 100μm).

Interpretation: The abundance of planktonic foraminifera and oligosteginids in the fine-grained matrix suggests that the MF2 is situated in a very low-energy pelagic environment. The presence of planktonic foraminifers and the lack of larger foraminifers and red algae show that the MF2 has been deposited below the photic zone (Geel 2000). In addition, the presence of plagic foraminifers is indicative of open marine water and their abundance increase seaward (Geel 2000). The mud- supported nature and very fine grain- size of facies (MF.1, MF.2) strongly suggests that deposition occurred under very low- energy conditions. Observation of the glauconite in the matrix is a marker showing a deep marine environment with low oxygen and low sedimentation rate (Odin & Matter 1981). The pelagic environment (MF.1, MF.2) is characterized by the main components (such as oligosteginids, planktonic foraminifera, and radiolaria) the level energy (very low energy), mineralogy and color (calcite, brown), grain size (very fine), and sorting (poorly sorted) (Figure 4B, as shown in Figure 6 in the next section, and Table 1). These facies can be considered equivalent to RMF2 (Flügel 2010) and is located in facies belt number of 1 in basin (Wilson 1975).

MF. 3: Oligosteginid Packstone

The prevailing grains are the oligosteginids along with planktonic foraminifera, sponge spicules, and rare ostracods. The matrix of oligosteginid packstone is a dark carbonate micrite. The diagenesis processes observed in the MF. 3 are of iron oxide type.

Interpretation: The abundance of oligosteginids and planktonic foraminifera and the absence of neritic fauna, the mud-supported texture along with stratigraphic relationships indicate that the MF3 has been deposited in the low-energy sedimentary environment below the storm wave base (Flügel 1982, 2004; Geel 2000; Wilson 1975). The mud- supported nature and very fine grain size of this facies strongly suggests that deposition occurred under very low to low energy conditions. The pelagic environment (MF.3) is characterized by the main components (oligosteginids) the level energy (very low to low energy), mineralogy and color (calcite, brown), grain size (very fine), and sorting (well sorted) (Figure 4C and Table 1).

MF. 4: Oligosteginid Packstone with Echinoderm

The oligosteginid and echinoid located in the grain-supported textures are the major constituents of the oligosteginid packstone with echinoderm. The matrix of this facies is fine crystalline micrite. Subordinate grains are a small number of ostracods and bivalves. Peloids are present as non-skeletal components. The diagenesis processes observed in the MF. 3 are of micritization type.

Interpretation: The fossil components, textural features, and stratigraphy of the MF.3 show that this deposit is situated in a low-energy pelagic environment. The absence of photosymbiont- bearing taxa and sedimentary structure suggest that these facies located below the photic zone (Corda & Brandano 2003; Cosovic et al. 2004; Geel 2000; Romero et al. 2002). The pelagic environment (MF.4) is characterized by the main components (oligosteginids and echinoids), the level energy (low energy), mineralogy and color (calcite, brown), grain size (very fine to fine), and sorting (well sorted) (Figure 4D and Table 1).

3.2.2. *Outer -Ramp Facies Group*

This facies group consists of one microscopic facies (MF. 5).

MF. 5: Bioclast Wackestone to Packstone Bearing Rudist and Echinoderm

Rudist and echinoid debris are the dominant components and ostracods and algae are the subordinate grains encompassed by the fine crystalline lime mud (micrite). Rare peloids are present as non-skeletal components. The diagenesis processes including micritization, fracture porosity, and syntaxial cement are frequently observed in the MF. 5.

Interpretation**:** The fossil features**,** sedimentary characteristics (such as the presence of fine crystalline micritic matrix) and the presence of rudist and echinoid debris show that the MF5 has been formed in an outer-ramp environment below the fair-weather wave base. The presence of fine crystalline micritic matrix and generally fine to medium grain size in this facies strongly suggests that deposition occurred under low to medium energy conditions. This part of outer -ramp environment (MF. 5) is characterized by the main components (such as rudist debris, echinoid), the level energy (low to medium), mineralogy and color (calcite, light-brown), grain size (fine to medium), and sorting (moderately sorted) (Figure 4E, as shown inigure 6 in the next section, and Table 1). These facies can be considered equivalent to RMF8 (Flügel 2010).

3.2.3. *Middle -Ramp Facies Group*

This facies group consists of two microscopic facies (MF. 6 and MF. 7).

MF. 6: Rudist Packstone to Grainstone with Benthic Foraminifera

This facies is characterized by the presence of rudist debris and benthic foraminifera, such as alveolinids,

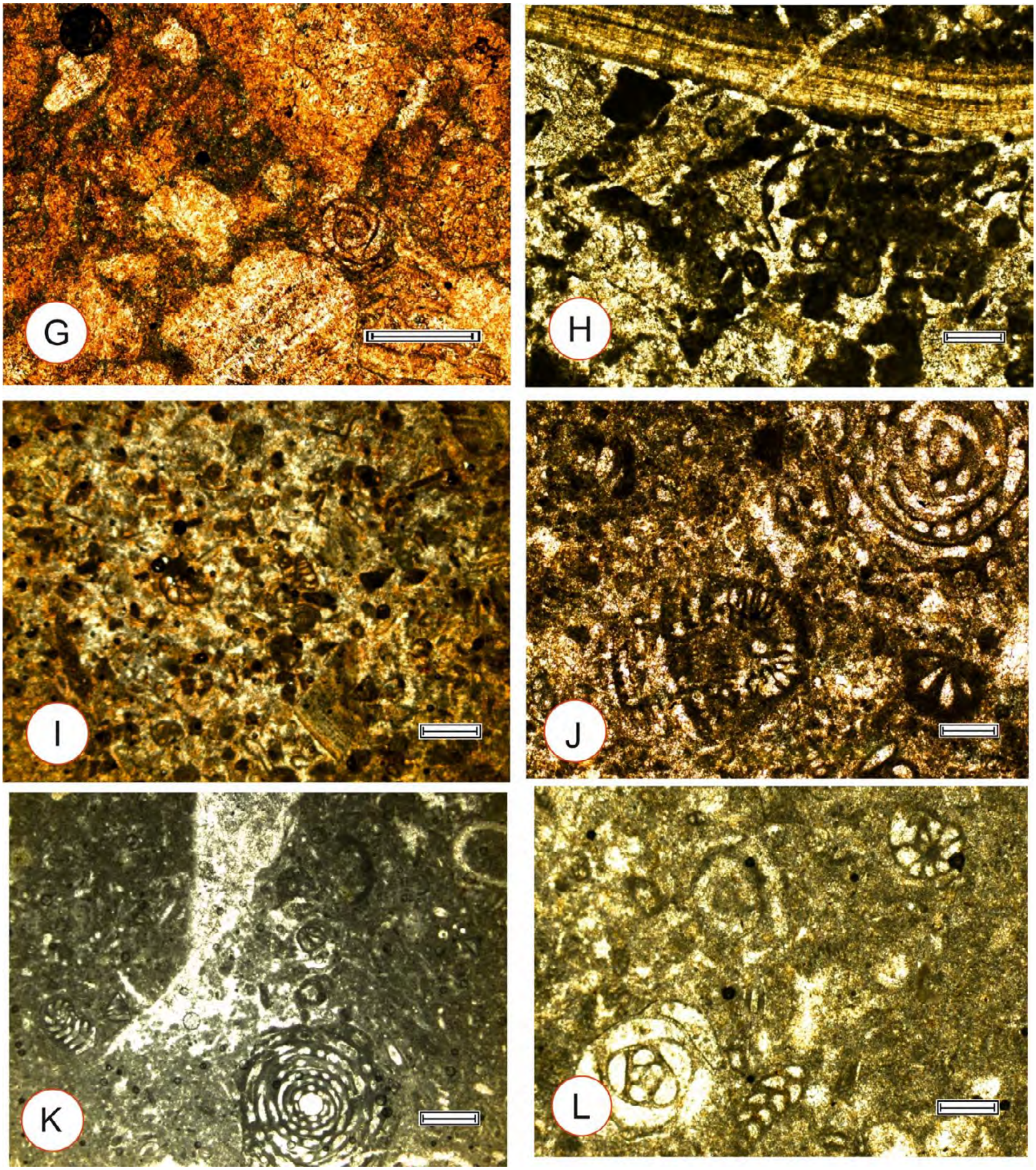

Figure 5 Microfacies of (MF.1 to MF.11) identified in the type section (Tang-e Sarvak): G. Microfacies MF.7, Large Benthic Foraminifera and Rudist Wackestone to Packstone; H. Microfacies MF.8, Bioclast Grainstone bearing Rudist and Echinoderm; I. Microfacies MF.9, Benthic Foraminifera and Echinoderm bioclast Grainstone; J. Microfacies MF.10, High Diversity Benthic Foraminifera Packstone to grainstone; K. Microfacies MF.10, High Diversity Benthic Foraminifera Wackestone; L. Microfacies MF.11, Low Diversity Benthic Foraminifera Wackestone to Packstone (All figures 100μm).

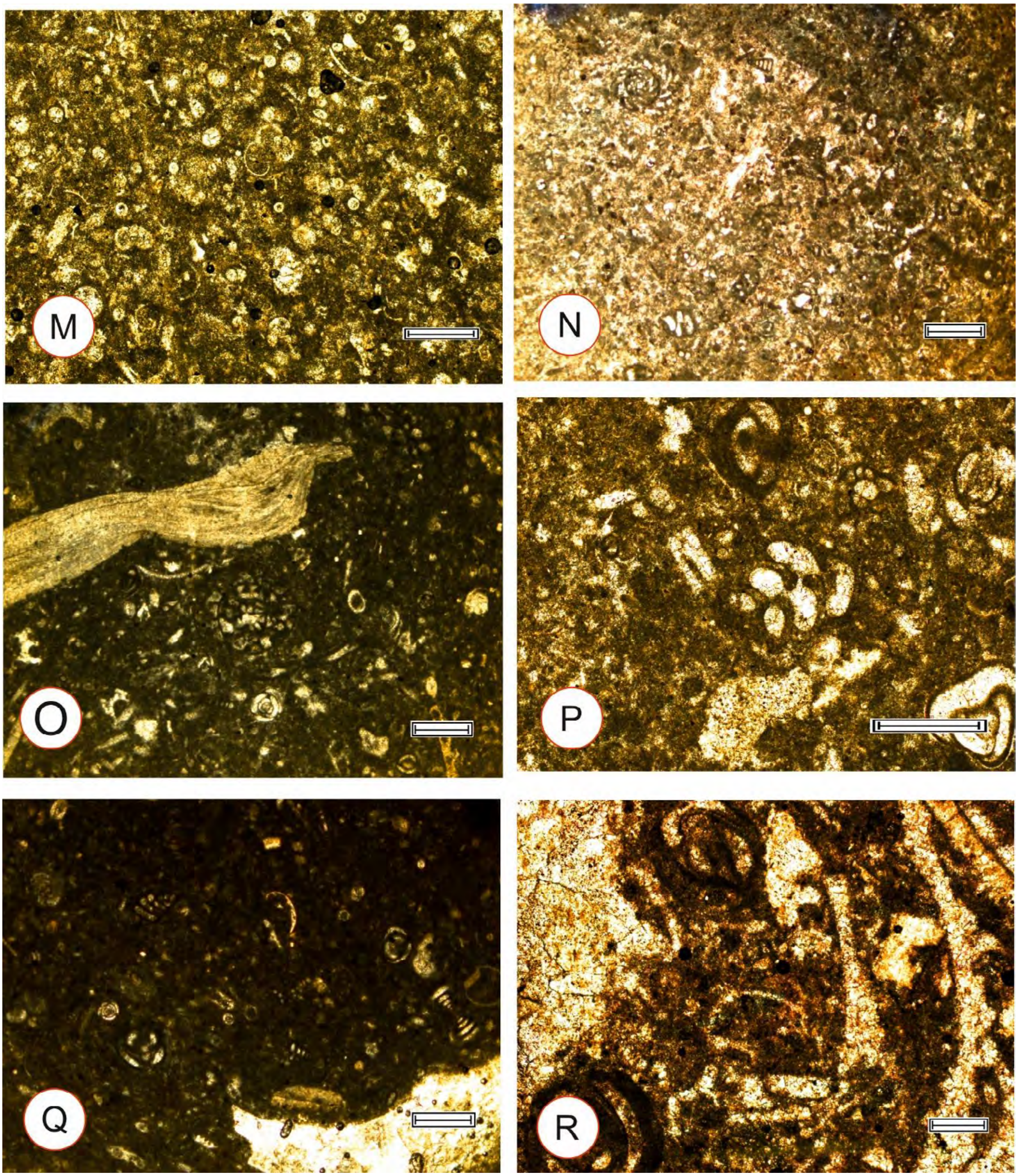

Figure 6 Microfacies of (MF.1 to MF.11) identified in the type section (Tang-e Sarvak): M. Microfacies MF.2, Oligosteginid and Planktonic Packestone; N. Microfacies MF.10, High Diversity Benthic Foraminifera Packstone to Grainstone; O. Microfacies MF.7, Large Benthic Foraminifera and Rudist Wackestone; P. Microfacies MF.5, Bioclast Wackestone to Packstone bearing Rudist and Echinoderm; Q. Microfacies MF.11, Low Diversity Benthic Foraminifera Wackestone; R. Microfacies MF.11, Low Diversity Benthic Foraminifera Packstone (All figures 100µm).

Nezzazata, and miliolids. Other components including bryozoan and algae are the subordinate allochems. Rare orbitolinids are also present. Peloids are present as non-skeletal components. The matrix of this facies is a combination of micrite and sparite. The syntaxial cement, micritization, and bladed calcite cement are the most important diagenesis processes in this microfacies.

Interpretation: The presence of rudist debris and benthic foraminifera's fauna and grain-supported texture, and stratigraphic relationships with the MF.5 represent that the MF6 is placed in moderate to high-energy middle-ramp environment. This facies is located in the middle ramp; the middle ramp is the zone between fair weather wave base and storm wave base (Burchette & Wright 1992). The grain- supported nature and medium to coarse grain size of facies strongly suggests that deposition occurred under moderate to high energy conditions. MF.6 is characterized by the main components (Rudist debris and benthic foraminifera), the level energy (moderate to high), mineralogy and color (calcite, cream to light-brown), grain size (medium to coarse), and sorting (moderate to well sorted) (Figure 4F and Table 1).

MF. 7: Large Benthic Foraminifera and Rudist Wackestone to Packstone

This wackestone to packstone is characterized by the fine crystalline lime matrix (micrite) as well as the occurrence of rudist debris and benthic foraminifera. Large benthic foraminifera include the alveolinids, *Nezzazata*, and miliolids. Rare orbitolinids, gastropods, bryozoan, algae, and corals are also present. The main porosity observed in the microfacies 7 is interaparticle porosity as observed in the calcite-filling fractures of the MF. 7.

Interpretation**:** The abundance of larger benthic foraminifers along with benthic fauna (rudist debris, echinoid, bryozoan) implies that the MF7 has been originated from the oligophotic zone of middle-ramp environment (Bassi et al. 2007; Brandano et al. 2009; Geel 2000; Nebelsick et al. 2005). The presence of fine crystalline micritic matrix and generally medium to large grain size in this facies strongly suggests that deposition occurred under moderate to high energy conditions. The diverse fauna (larger benthic foraminifers) suggests that deposition located in a marine environment of normal salinity. MF.7 is characterized by the main components (larger benthic foraminifers and rudist debris), the level energy (moderate to high energy), mineralogy and color (calcite, cream to light brown), grain size (medium to large), and sorting (moderate to well sorted) (Figures 5G and 6O and Table 1). These facies can be considered equivalent to RMF13 (Flügel 2010).

3.2.4. *Inner -Ramp Facies Group*

This facies group consists of four microscopic facies (MF. 8, MF. 9, MF. 10, and MF. 11).

MF. 8: Bioclast Grainstone Bearing Rudist and Echinoderm

Rudist debris and echinoids are the main components and ostracods and algae are other grains surrounded by the coarse crystalline sparry calcite cement. The non-skeletal components consist of the peloids. The fracture porosity and syntaxial cement are the most important diagenesis processes in this microfacies.

Interpretation: The fossil contents**,** the grain-supported nature, the lack of lime mud, presence of sparry calcite cement, and also stratigraphic relationships with the MF. 7 and MF. 9 demonstrate that the MF8 has been formed in the energetic parts of the inner-ramp facies under medium to high- energy conditions. Medium to high energy conditions indicated by the presence of sparry calcite cement and the abundance of ruddiest debris. The inner ramp located between the upper shoreface and the fair-weather wave base in euphotic zone (Burchette & Wright 1992). The middle ramp is separated from the inner ramp by a bioclastic shoal facies. This part of inner-ramp environment (MF.8) is characterized by the main components (ruddiest debris and echinoids) the level energy (medium to high energy), mineralogy and color (calcite, cream to light-brown), grain size (medium to coarse), and sorting (poorly sorted) (Figure 5H and Table 1).

MF. 9: Benthic Foraminifera and Echinoderm Bioclast Grainstone

The substantial allochems are benthic foraminifera, such as *Nezzazata*, miliolids*, textularia*, and echinoid debris surrounded by the grain-supported textures (sparite). Rare peloids are present as non-skeletal components. Ostracods, algae, and bivalves are subordinate allochems. The most important cement has been formed in the microfacies under study, and interaparticle porosity was also the main porosity observed in the syntaxial cement and bladed calcite cement. The vuggy porosity was the second major type of porosity observed in thin sections.

Interpretation: The abundance of benthic foraminifers (*Nezzazata*, miliolids, and *textularia*) and echinoid debris in the grain-supported textures suggests that the MF9 is situated in a moderate to high-energy part of inner-ramp environment (Fournier et al., 2004). Observation of benthic foraminifers (*Nezzazata*, miliolids, and *textularia*) and grain-supported matrix indicates that this facies is situated at platform margin (in shoal) (Amirshahkarami et al.

2007). The absence of micrite and moderate to well sorted fragmented fauna suggest located of the sediments under shallow water (Flügel 2004; Wilson 1975). Moreover, the presence of small miliolids together with ostracods are indicators of a restricted peritidal setting. Also, the algae (dasycladacean green), suggest deposition in a shallow marine environment (Curry 1999). The grain- supported nature, the presence of sparry calcite cement and medium to large grain size of facies strongly suggests that deposition occurred under moderate to high energy conditions. MF.9 is characterized by the main components (benthic foraminifers and echinoid debris), the level energy (moderate to high), mineralogy and color (calcite, light- cream to light brown), grain size (medium to large), and sorting (moderately to well sorted) (Figure 5I and Table 1).

MF. 10: High -Diversity Benthic Foraminifera Packstone to Grainstone

The occurrence of diverse benthic foraminifera (alveolinids, *Nezzazata, Chrysalidina*, and *Daxia*) in the mud-supported textures is the main feature of this packstone to grainstone. Rudist debris, bryozoan, echinoid/crinoid fragments, sponge spicules, algae and corals are among other components. The most important cement has been formed in the microfacies under study, and interparticle porosity was also the main porosity observed in the syntaxial cement and bladed calcite cement. The vuggy porosity was the second major type of porosity observed in thin sections. Micritization and calcite-filling fractures were other diagenesis processes of the MF. 10.

Interpretation: the stratigraphic relationships with the MF.9 and MF.11, the medium grain size, the diverse benthic foraminifera and mud-dominated nature indicate that the MF10 has been formed in inner-ramp environment (distal-middle lagoon) with moderate energy environment. In addition, these facies have been deposited within the euphotic zone (Bassi et al. 2007; Corda & Brandano 2003; Rasser et al. 2005). The presence of marine perforate foraminifera along with platform interior imperforate foraminifera an expression the absence of a barrier between inner ramp and middle ramp (Geel 2000; Romero et al. 2002). In other words, a co-occurrence of these fauna indicates that deposition located in an open shelf lagoon in the euphotic zone (Nebelsick et al. 2001; Rasser & Nebelsick 2003). MF10 is characterized by the main components (high-diversity benthic foraminifera), the level energy (moderate), mineralogy and color (calcite, light- cream), grain size (medium), and sorting (moderately sorted) (Figures 5J-K and 6N and Table 1).

MF. 11: Low -Diversity Benthic Foraminifera Wackestone to Packstone

This facies is characterized by the low diversity of benthic foraminifera (miliolids and *Nezzazata*) along with minor bivalve fragments, gastropod and echinoid fragments. The matrix of this facies is fine crystalline micrite. The micritization, interaparticle porosity, fracture porosity, and calcite-filling fractures were the main porosity observed in the microfacies 11.

Interpretation: The low taxonomic diversity including benthic foraminifera in the mud-supported textures indicates that the MF11 has been deposited in the low to moderate- energy of inner-ramp environment (proximal lagoon). The low diversity of benthic foraminifera indicates the shallowest part inner ramp environment and makes suitable conditions for the living foraminifera (Murray 2006).The MF.11 is characterized by the main components (low diversity of benthic foraminifera), the level energy (low to moderate energy) in the environment, mineralogy and color (calcite, light-cream), grain size (medium), and sorting (poorly sorted) (Figures 5L and 6Q-R and Table 1).

3.3 Sedimentary Environment

Carbonate deposits are formed at various marine environments from shallow to deep water (Flügel 2004). Most of the previous studies on the Sarvak Formation and its equivalent deposits in the adjacent regions (Arabic Plate) have mentioned that the Sarvak Formation has been deposited on a carbonate ramp (e.g., Aqrawi et al. 1998; Burchette and Britton 1985; Mehrabi & Rahimpour Bonab et al. 2013; Rahimpour Bonab et al. 2012; Scott 2007).

Mehmandosti et al. (2013) believed that the Sarvak deposits of the Central Zagros (Izeh Zone) have been created in a ramp-type platform composed of various facies associations containing tidal flat, lagoonal, shoal, and open marine. Mehrabi and Rahimpour-Bonab (2013) believed that the Sarvak Succession has been established on the ramp-type depositional system (platform) in a warm, humid tropical climate with constant rainfall. Solemani Asl and Aleali (2016) in the Abadan Plain (Azadegan Oilfield) and Aleali (2017) in the Izeh Zone investigated the facies features and depositional settings of the Sarvak Formation. They pointed out to deposition of the Middle Cretaceous Sarvak Formation occurring in the homoclinal ramp- like depositional regime with gentle slope (Figure 7).

The facies analysis and introduction of the sedimentary model were carried out using the standard

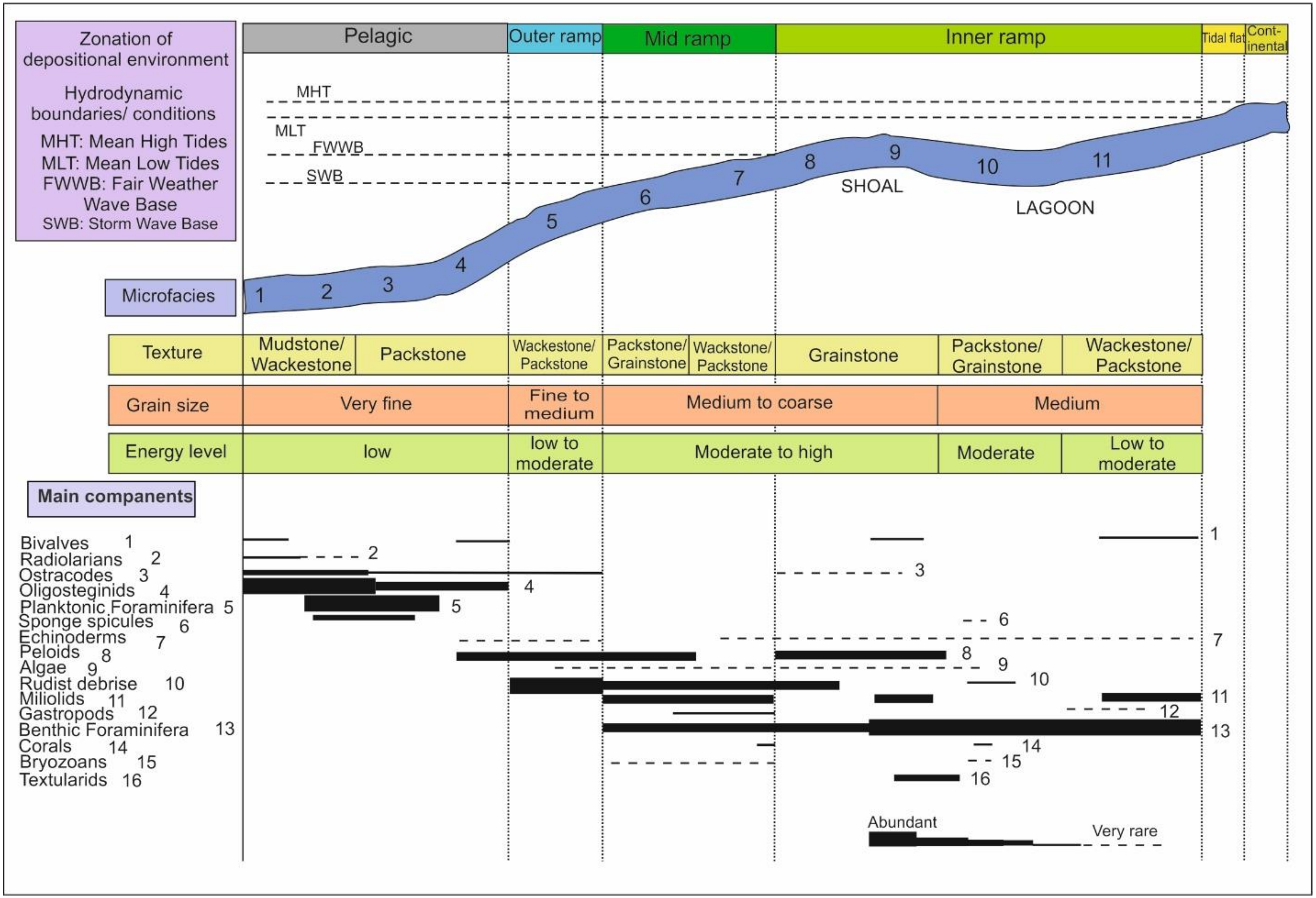

Figure 7 The column shows the deposition model, distribution, and frequency of the main companents within various sedimentary environments of the Sarvak Formation in the Bangestan area (type section). The interpretation was done based on the study by Flügel (2004). Abbreviations: FWWB: Fair-weather wave base; SWB: Storm wave base.

models (e.g., Burchette & Wright 1992; Buxton & Pedley 1989; Wilson 1975).

In this study, identified microfacies were categorized into four main facies groups including the inner-ramp, middle-ramp, outer-ramp, and pelagic. Evidence such as the lack of any marginal reef development, extension of low boundstone facies and framestone facies (Alsharhan 2006; Burchette & Wright 1992; Ehrenberg 2006), the absence of a major break in the slope and the presence of high-energy grainstone facies (Flügel 2004; Tucker et al. 1993), gradual changes in the facies and the absence of talus, mass flow ,and calciturbidite (Flügel 2004; Lee et al. 2001; Wilson 1975) shows that the Sarvak Formation at type section has been deposited on a homoclinal carbonate ramp system with a very gentle slope.

Sedimentation of the inner-ramp (euphotic zone) is situated between the upper offshore (middle-ramp) and coastal line (tidal flat) (Burchette & Wright 1992). In the studied succession, the inner-ramp environment includes the lagoon (proximal, distal, and middle) and the shoal environments. The proximal lagoon environment (MF11) is characterized by low taxonomic diversity however; the middle to distal lagoon environment (MF.10) is characterized by high-diversity benthic foraminifera. Sadeghi et al. (2010) believed that appropriate conditions including the presence of enough oxygen and normal circulation of waters can cause a high diversity of fauna. The shoal facies is situated at the platform margin, separating the upper offshore from the shoreface (MF.8 and MF.9). The grain -supported nature and the well-sorted grain size indicate high-energy shoal and deposition in a shallow shoreface zone (Schulze et al. 2005). The presence of rudist and benthic foraminifera indicates the deposition of the middle -ramp environment (MF6 and MF 7). MF7 has been separated based on the amount of micritic matrix and size of the components. The occurrence of algae and large foraminifera confirms that these facies have been formed in the middle-ramp (mesophotic zone) environment (Pomar 2001; Pomar et al. 2004; Pomar et al. 2012). Microfacies 5 is characterized by the occurrence of the bioclasts, rudist debris, and echinoid fragments. Abundant oligosteginids and sponge spicules illustrate the pelagic environment facies (MF4) also; high amounts of oligosteginids, planktonic foraminifers, and radiolaria demonstrate the facies of pelagic environment (MF.1 to MF.3).

Facies frequency analysis of the microfacies and facies belt demonstrated that the most frequency was related to the MF2 (29%) belonging to the pelagic environment and the lowest frequency was related to the MF8 (1%) belonging to the inner-ramp environment (Figures 8 and 9A). Furthermore, the frequency assessment of the facies belt indicated that among all the facies belts, pelagic environment was the most frequent facies belt and middle-ramp environment was the least frequent facies belt (Figures 8 and 9B).

3.4 Sequence Stratigraphy

Based on Lasemi (2000), the sequence has been formed in the relative sea-level change (rise and fall). Each sequence has two boundaries**,** unconformity boundaries (SB1) and/or their correlative conformity boundaries (SB2) (Emery & Myers 1996; Van Wagoner et al. 1988). According to the field observations, biostratigraphy assessments, facies analysis and environmental changes, three third-order depositional sequences were recognized in the Sarvak Formation. The results of studying the Sarvak Formation at type section are in accordance with other studies in the areas of SW Iran and the Arabic Platform (e.g., Razin et al. 2010; Taghavi et al. 2006; Van Buchem et al. 1996). In the studied section, the sequences include the transgressive systems tract (TST), the highstand systems tract (HST) and do not include the lowstand systems tract (LST) (Figure 10). Identified sequences are compared with the sequences introduced in the studies by Haq, Hardenbol & Vail (1988), and Hardenbol et al. (1998) in the European Basins.

3.4.1. Sequence 1

The sequence 1 with a thickness around 140 m is the thinnest interval in the lower part of the Sarvak Formation. The TST of the first sequence starts in the Kazhdumi Formation and has thinnest interval (30 m) in the Sarvak Formation. The TST package of this sequence is specified by the pelagic facies consisting of planktonic foraminifera, oligosteginids with the packstone texture (MF.3) and indicates the progradational stacking pattern (Figure 10).

The lower and upper boundaries of this sequence are of type 2 sequence boundary (SB2) due to the lack of sediments coming out of the sea and also the continuation of the sediments. The upper sequence boundary is situated at the base of a cherty limestone unit including fauna of the pelagic environment and this boundary is coinciding with the (MFS) of sequences of Al 5 introduced in the literature (Hardenbol et al. 1998; Figure 11).

The maximum flooding surface (MFS) is marked by the occurrence of pelagic facies consisting of the planktonic foraminifera and oligosteginids with wackestone texture. The MFS of sequence 1 is equivalent to the (MFS) of sequences Al 2 introduced in the literature (Hardenbol et al. 1998; Figure 11). HST is characterized by the

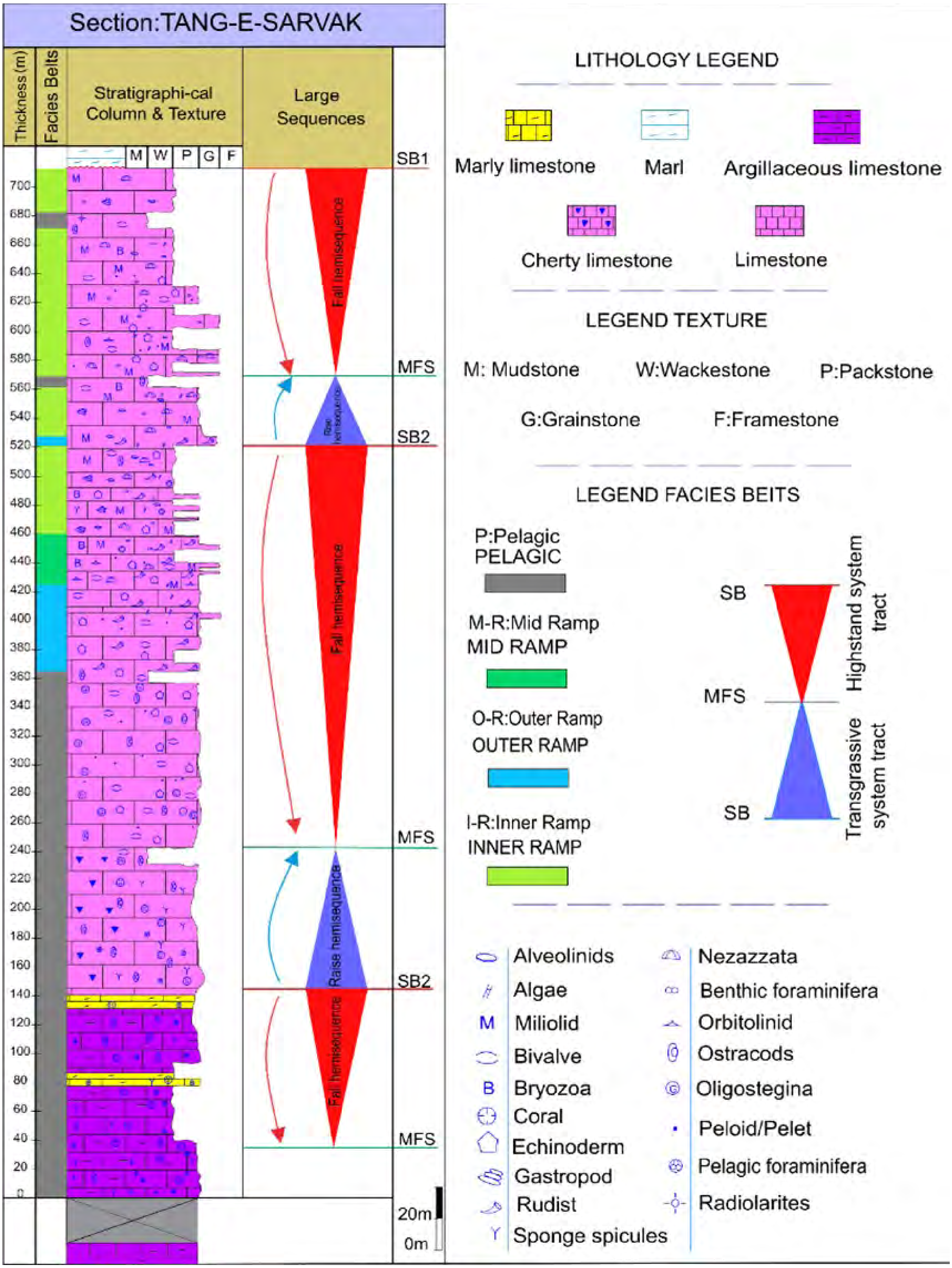

Figure 8 Shematic sketch showing idealized third- order sequences model of the Sarvak Formation.

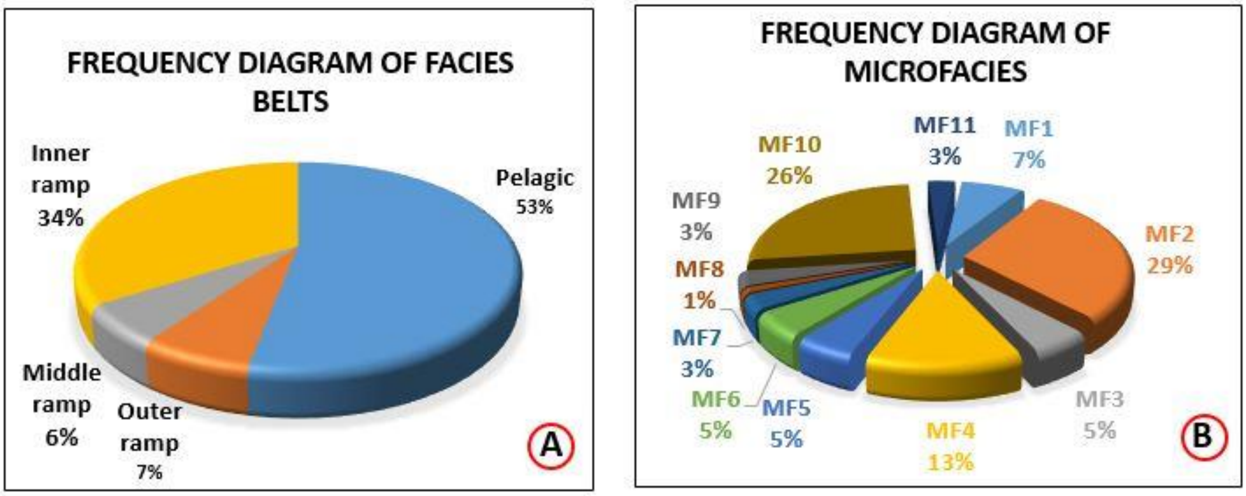

Figure 9 Diagrams of frequency percentage of microfacies A. and facies belt B. of the Sarvak Formation in type section.

pelagic facies consisting of the planktonic foraminifera and oligosteginids composed of wackestone to packstone texture (MF.2). Depositions of the HST have been formed with a retrogradational stacking pattern.

3.4.2. Sequence 2

The thickness of this sequence is around 380 m. The upper boundary of this sequence is of type 2 sequence boundary (SB2) due to the lack of sediments coming out of the sea and also the continuation of the sediments, and is identified by the outer-ramp facies. The lower boundary is characterized by a packstone texture consisting of planktonic foraminifera and oligosteginids (MF.3).

The lower boundary of this sequence coincides with the (MFS) of sequences of Al 5 introduced in the study by Hardenbol et al. (1998) and the upper boundary of this sequence is analogous to the boundary between sequences of Al 11 and Ce 1 proposed in the literature (Hardenbol et al. 1998; Figure 11). This sequence starts with a 100 m thick TST package, consisting of pelagic facies (planktonic foraminifera, oligosteginids) and composed of packstone texture (MF.3).

The maximum flooding surface is located at the top of the cherty limestone of the lower part of the sequence and is marked by the existence of pelagic facies consisting of radiolaria and oligosteginids with mudstone texture (MF.1). The MFS of sequence 2 is equivalent to the (MFS) of sequences of Al 6 introduced in the literature (Hardenbol et al. 1998; Figure 11).

The HST is determined by the pelagic facies (consisting of oligosteginids, echinoderm) composed of packstone texture (MF.4), outer -ramp facies (consisting of rudist debris and echinoderm) composed of wackestone to packstone texture (MF.5), middle -ramp facies (consisting of rudist and benthic foraminifera) comprised of wackestone to grainstone texture (MF.6, MF.7), and inner -ramp facies (consisting of benthic foraminifera and echinoderm) made of wackestone to grainstone texture (MF.8, MF.9, MF.10, and MF.11). This sequence includes a relatively thick HST (280 m) in the studied type section. Depositions of the TST package sequence 2 have been formed with a progradational stacking pattern and HST package has been formed with a retrogradational stacking pattern (Figure 10).

This sequence can be divided into two small sequences so that, the (MFS) of the first small sequence is comparable to the (MFS) of sequences of Al 6 and (MFS) of small sequence 2 is comparable to the (MFS) of sequences of Al 8 introduced in the literature (Hardenbol et al. 1998; Figure 11).

3.4.3. Sequence 3

The thickness of this sequence is around 190 m. The lower boundary is of type 2 sequence boundary (SB2) due to the lack of sediments coming out of the sea and also the continuation of the sediments. The lower boundary of this sequence is similar to the boundary between the sequences of the Al 11 and Ce 1 introduced in the study by Hardenbol et al. (1998) and also upper boundary of this sequence coincides with the upper boundary of sequences of Ce 5 proposed in the literature (Haq, Hardenbol & Vail 1988; Figure 11).

The third sequence of TST is characterized by the relatively low thickness of the carbonate deposits (around 50 m of thickness) of inner - ramp facies including benthic

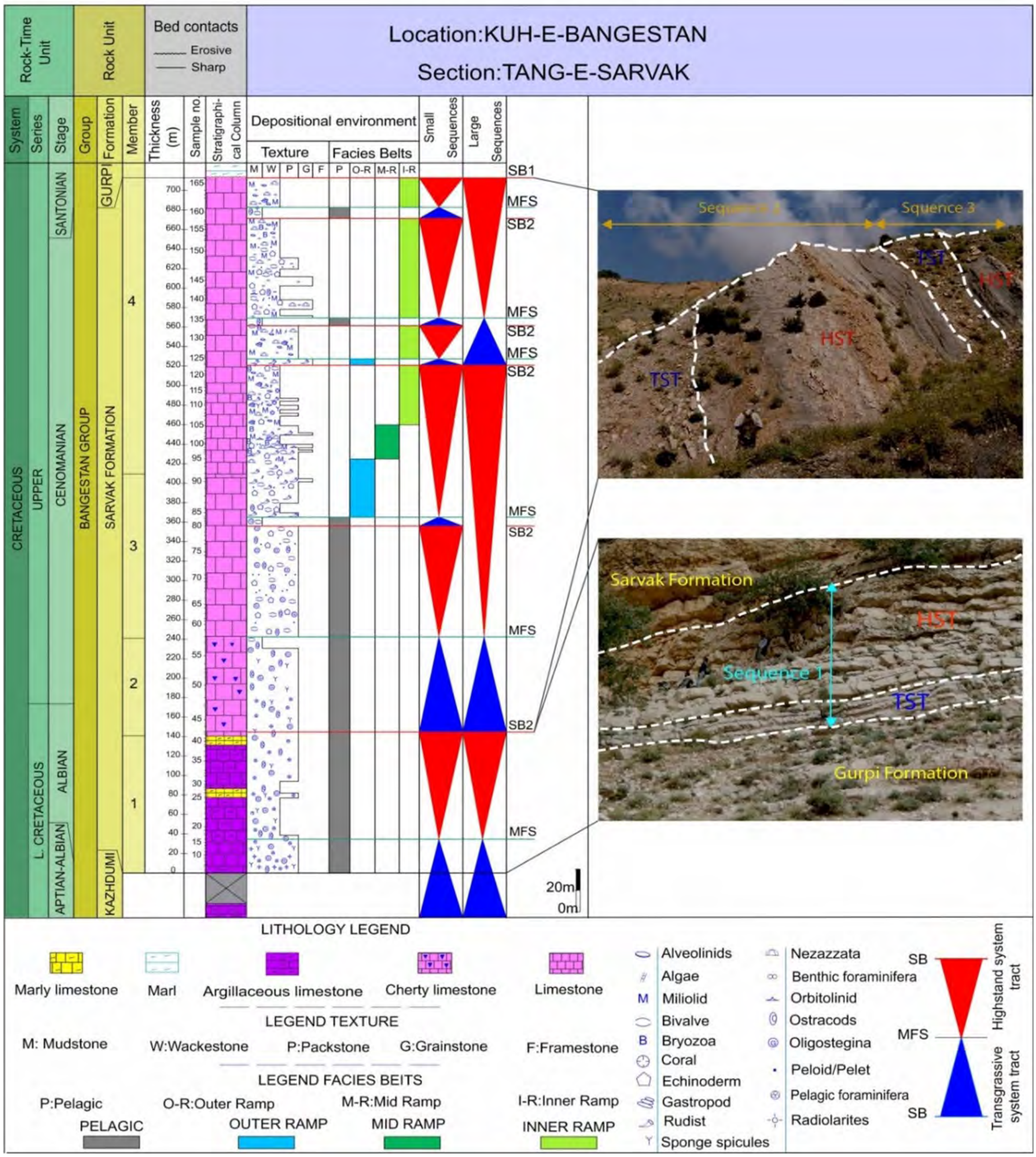

Figure 10 Sequence stratigraphy diagram of the Sarvak Formation in type section (Tang-e Sarvak). Below picture: The lower parts of the Sarvak Formation in type section (Tang-e Sarvak) showing Medium-bedded argillaceous limestone along with interbedded thin-bedded marl limestone. Above picture: middle and upper parts of the section, showing the sequences in the Sarvak Formation.

foraminifera, echinoderm along with wackestone - packstone - to grainstone texture (MF.8, MF.9, MF.10, and MF.11). Sedimentation pattern of the TST package is progradational stacking pattern. The maximum transgression is recognized by the presence of pelagic facies consisting of radiolaria and oligosteginids with mudstone texture (MF.1).

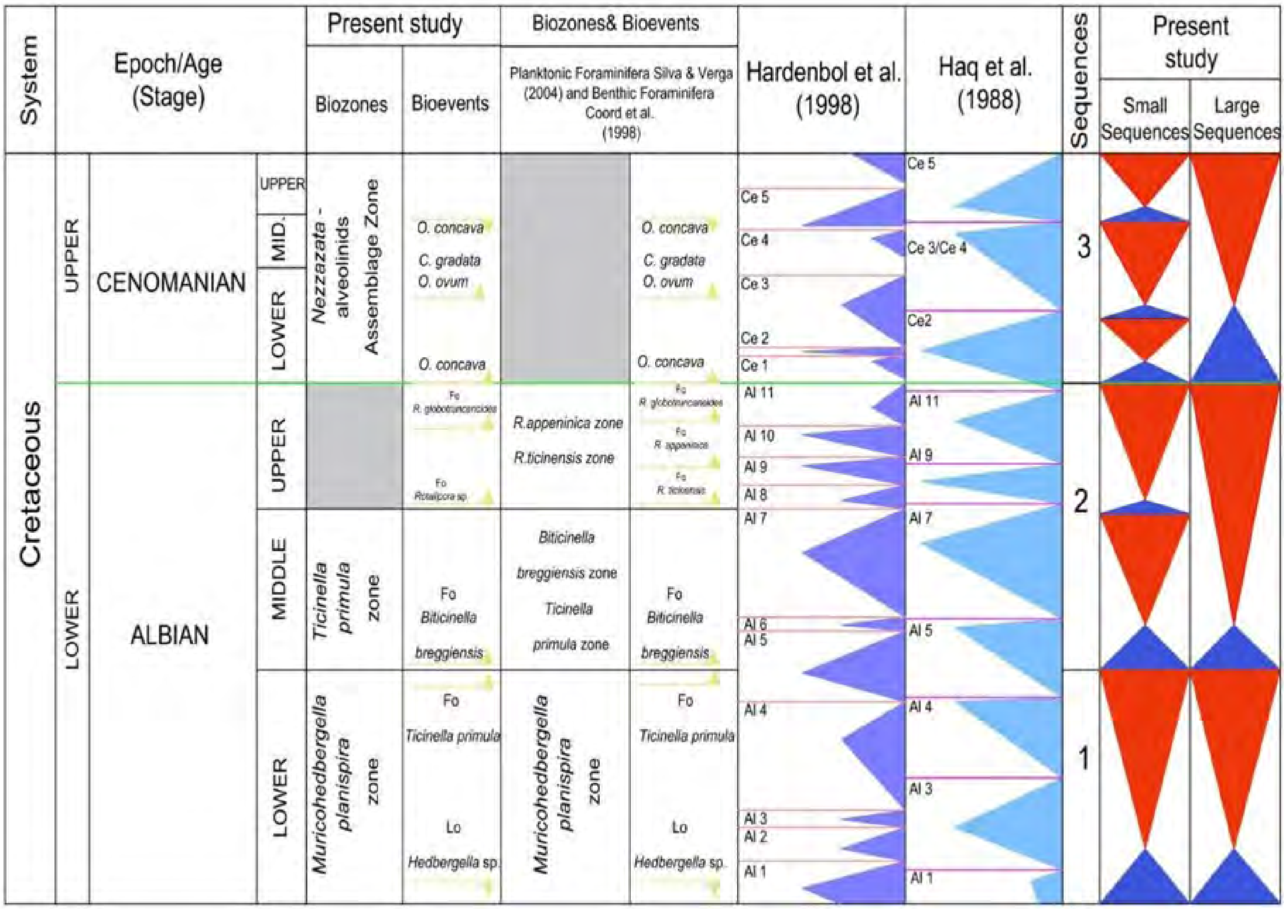

Figure 11 Correlation between the identified sequences in the present study and carried out sequences of Haq et al. (1988) and Hardenbol et al. (1998) in European Basin.

The MFS of sequence 3 is equivalent to the boundary between sequences of Ce 2 and Ce 3/ Ce 4 identified in the study by Haq, Hardenbol & Vail (1988) and the (MFS) of sequences of Ce 3 identified in the literature (Hardenbol et al. 1998; Figure 11). The (HST) package is defined by the inner - ramp facies consisting of benthic foraminifera, echinoderm, and wackestone-packstone to grainstone texture (MF.8, MF.9, MF.10, and MF.11).

The sedimentation pattern of the HST package is retrogradational stacking pattern. The upper sequence boundary of sequence 3 is located on top of white, thick-bedded limestone including the abundant benthic foraminifera with wackestone texture. Deposits of the Turonian have been eroded in the Sarvak Formation. Therefore, the upper boundary of the Sarvak Formation with the Gurpi Formation is in the form of disconformity. Evidence shows the sea level has declined for a long time and the sediments have come out of the sea as a result, the upper boundary of sequence 3 is of type 1 sequence boundary (SB1). This unconformity was recorded in the Lorestan, Dezful Embayment and Fars regions (James & Wynd 1965).

The presence of erosion surface, iron oxide effects, and bauxite intervals in the upper boundary of the Sarvak Formation indicates that this boundary has been subjected to the long-time erosion. The upper boundary of the third sequence marked by iron oxide red spots at the end of Sarvak Formation (Figure 10). Sequence 3 can be divided into three small sequences so that, the (MFS) of the first small sequence is analogous to the (MFS) of sequences of Ce1 and the (MFS) of the second small sequences coincides with the (MFS) of sequences of Ce3 introduced in the study by Hardenbol et al. (1998). Also, the (MFS) of the third small sequences is comparable to the (MFS) of sequences of Ce 5 proposed in the literature (Haq, Hardenbol & Vail 1988; Figure 11).

4 Conclusions

The lithostratigraphy studies on the Sarvak Formation in type section (Tang-e Sarvak, northwest of Behbahan) showed that this formation with 710 m of thicknesses could be divided into four lithostratigraphic units

The facies analyses of the Sarvak Formation, such as grain properties, texture, fauna, and energy level of the environment led to recognition of 11 microfacies formed on a homoclinal carbonate ramp environment with a gentle slope. The absence of a major break in the slope and the presence of high-energy grainstone facies, gradual changes in the facies and the absence of talus, mass flow, and calciturbidite shows that the Sarvak Formation at type section has been deposited on a homoclinal carbonate ramp system with a very gentle slope.

The facies belts included an inner-ramp, middle-ramp, outer-ramp, and pelagic. Facies frequency analysis of the microfacies and facies belt demonstrated that the most frequency was related to the MF.2 (29%) belonging to the pelagic environment and the lowest frequency was related to the MF.8 (1%) belonging to the inner -ramp environment.

The sequence stratigraphic assessments showed that the Sarvak Formation includes three third-order depositional sequences, each consisting of TST and HST. The first sequence starts in the Kazhdumi Formation and the upper boundary of the third sequence was between boundaries Sarvak and Gurpi Formations. Lower and upper boundaries of the first and second sequences were of type 2 sequence boundary "SB2", due to the lack of sediments coming out of the sea and the continuation of the sediments. Unlike, the upper boundary of the third sequence was of type 1 sequence boundary "SB1", due to the boundary has been subjected to the long-time erosion and was characterized by the surface erosion (iron oxide and bauxite) and erosional disconformity in the Turonian age. Furthermore, the identified sequences in the present study coincided with the sequences introduced in the studies by Haq, Hardenbol & Vail (1988) and Hardenbol et al. (1998) in the European Basins and the sequences of Sarvak Formation in the study area correspond to the global curve of sea level changes. Accordingly, the first sequence age Lower Albian, the second sequence age Middle- Upper Albian and the third sequence age is Cenomanian.

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Kiana Kiarostami: conceptualization; formal analysis; methodology; validation; writing-original draft; writing – review and editing; visualization. **Mohsen Aleali:** conceptualization; formal analysis; methodology; validation; writing-original draft; writing – review and editing; visualization. **Ali Aghanabati:** supervision.

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