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ORIGINAL PAPER

THE UPPER CRETACEOUS SEDIMENTARY SEQUENCE IN NORTH- WEST IRAN: MICROFACIES AND GEOCHEMISTRY ANALYSIS, EVIDENCE OF NEOTETHYS

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ABSTRACT

The purpose of the research was to examine the Upper Cretaceous sedimentary sequence in northwest Iran, in particular, the Shahin Dezh geographical region in two stratigraphic sections, Godollu and Tark-e Viran, which revealed a thickness of 156 meters for the former and 114.5 meters for the latter. Field studies revealed that the lithological features and macroscopic characteristics of the rock sequence of the Godollu section can be divided into 12 lithological units. Sandstone petrofacies exhibit mature textural features and are classified as litharenites based on the composition of the main grains, reflecting sedimentation on a shallow marine shelf and slope. These studies also indicated that the carbonate sequence of the Tark-e Viran section can be divided into 11 separate lithological classes, and based on the laboratory studies, the microscopic samples consisted of three groups, namely, pelagic microfacies with mudstone bioclastic facies, Globotruncana wackestone, and Oligostegina packstone. These classifications are comparable to Flugel's SMF 3 and were deposited in the facies zone of FZ_1 and FZ_3, evoking the depositional environment of relatively deep seas. Geochemical studies on the elements of strontium, sodium, manganese, and iron revealed that the amount of strontium and sodium is very low while the amount of manganese and iron is higher than the carbonate equivalents of the present era. Due to the increased effect of late meteoric diagenesis, the amount of iron increases with the increase of manganese, and the changes of Sr/Ca compared to manganese represent an open diagenetic system reflecting that of the late meteoric diagenesis. As such, the studied limestones can be best classified as semi-polar types with the primary composition of calcite mineralogy.

1. INTRODUCTION

The current study sought to study the changes in facies of Upper Cretaceous clastic-carbonate rocks, the characteristics of their sedimentary environment, sequence stratigraphy, and geochemistry in an area located in the northwest of Iran and in the West Azarbaijan province, near Shahin Dezh city, which was a part of southeastern Laurasia at the time of sedimentation. The West Azarbaijan province of Iran is located between 45.0000°E longitude and 37.4550°N latitude, and Shahin Dezh city is between 46.5701°E longitude and 36.6741°N latitude at an elevation of 1345 meters above the sea. This city is situated 72 km northwest of Takab and 60 km southeast of Miandoab. The carbonate section is located in the village of Tark-e Viran, which can be accessed through the Shahin Dezh-Takab road. Furthermore, access to the studied sandstone section can be achieved through the Shahin Dezh-Hachesu road (Fig.1).

1.1. *RESEARCH BACKGROUND*

Regarding the corresponding literature on the northwest region of Iran, Rieben (1935) was the first author to offer systematic information on the geology of Azerbaijan. Kamenini and Mortimer (1975) studied the geological structure and metamorphic complexes of the Khoi area. Hassanipak and Ghazi (2000) examined the geochemistry, petrology, and tectonic setting of the Khoi ophiolitic complex. The biostratigraphy of Cretaceous sequences in the Merakan section were studied by Shetabi Fard (2012) who determined the age of these sequences to be Coniacian and Cenomanian. Regarding the northwestern region of Iran, Daghigh (2007) examined the Lower Cretaceous sedimentary settings of Azarshahr, while Abedini (2009) studied that of northwestern Tabriz. Evidence from the research indicated that the Cretaceous rocks in the northwest of the country are highly similar and recorded the alternation of continental and marine conditions in the region, The Cretaceous rocks of Merakan northeast of Khoi represent sedimentation in a marginal marine

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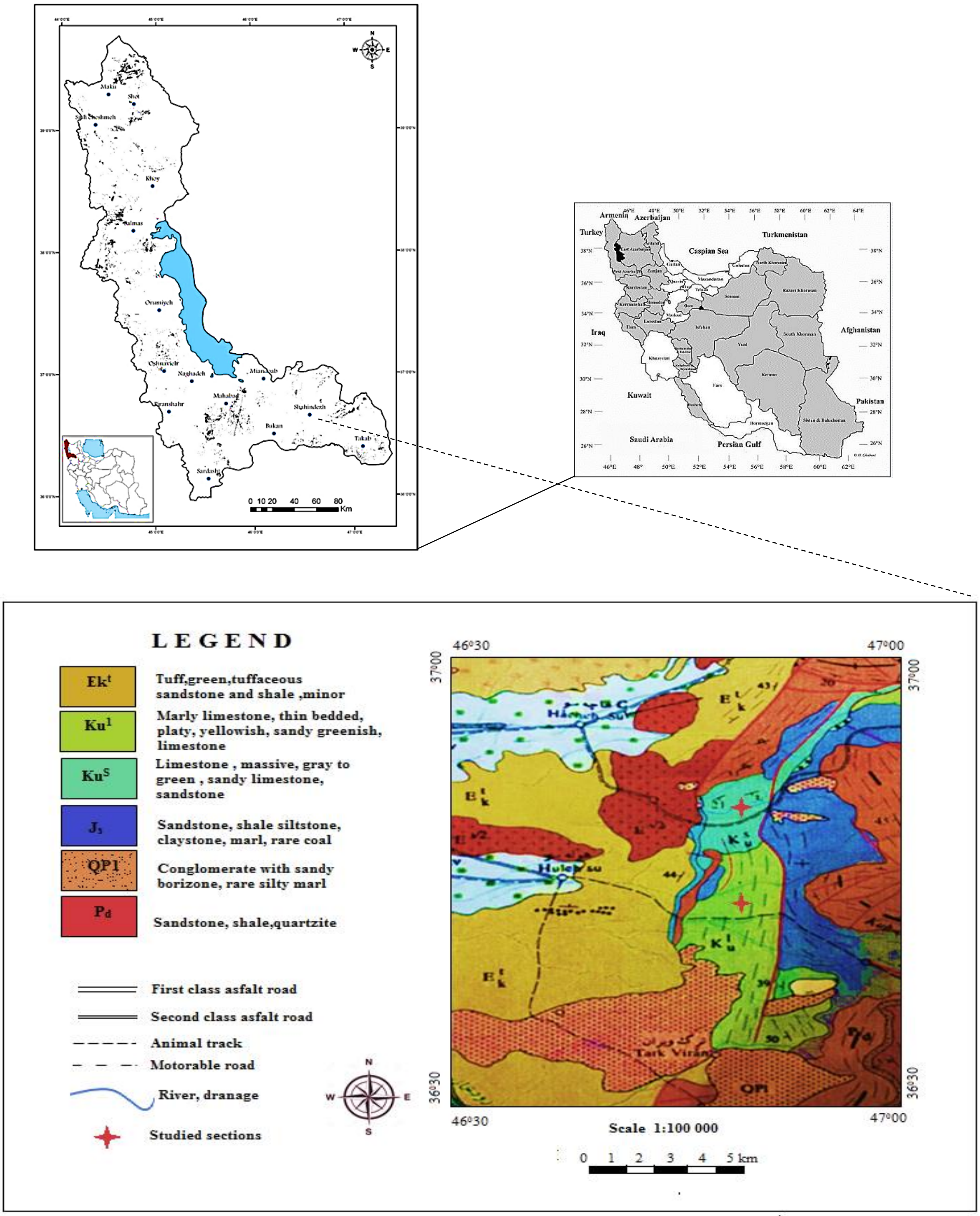


Fig. 1 Part of the geological map of the studied area in West Azarbaijan and Northwest Iran (adapted from Khalghi Khosraghi, 1994).

platform (Mahari et al., 2019). Moreover, a carbonate ramp system for the corresponding sequences was proposed by Rabani et al. (2019). The Cretaceous rock formations of northwest Iran can be divided into three main categories: siliciclastic, shallow carbonates, and pelagic rocks (Mahari et al., 2017). The results from examining Cretaceous facies in the north of Tabriz region best reflect the prevalence of semi-deep sea sedimentation, continental slope, deep sea, and sometimes shallow sea (Tagizadeh and Mahari, 2017). A deep marine environment influenced by turbidity currents has been suggested for the Cretaceous rocks of northeastern Tabriz (Namyar et al., 2012). The Lower Cretaceous deposits in the northwest of Tabriz represent a marginal carbonate shelf sedimentation environment (Abedini et al., 2009). Results from simulating the sedimentary environment and relative sea level fluctuations in the Cretaceous-Paleocene deposits of Central Alborz and Northern Iran suggest a near-shore sedimentary environment in a carbonate ramp system for the corresponding sequences (Rabani et al., 2019). The results from Upper Cretaceous strata of the Zagros area Gurpi Formation examined represents the presence of 12 genera and 27 species of planktonic foraminifera (Afghah, 2023).

1.2. *RESEARCH METHODOLOGY*

For the study, 100 samples from the carbonate stratigraphic section and 50 samples from the sandstone section of the area were collected for further detailed microscopic examinations. The methods of Wright (1992), Folk (1962), and Dunham (1962) were used for the classification and nomenclature of limestone microfacies., Flugel's (2010) method was used for the detection of environmental energy, and textural studies were based on Tucker (2001), The evidence of diagenesis and detection of energy and sedimentary environment were examined using the methods of Wilson (1975). Furthermore, the models presented by Hunt et al. (1992) were employed to distinguish the sequences and systems of tracts. Ultimately, the triangular diagrams of Dickinson et al. (1979) were used to determine the origin of sandstones, while the alkaline melting method was used for geochemical studies.

2. STRATIGRAPHY AND SEQUENCE STRATIGRAPHY OF UPPER CRETACEOUS CARBONATE SEQUENCE IN THE SHAHINDEZH AREA

Sequence stratigraphy consists of examining and studying sedimentary facies, their temporal and spatial changes, and identifying sedimentary environments dependent on the relative changes of sea level, and the sediment of a domain in the form of sequences that are located between discontinuities of the same width.

Each facies sequence or group is interpreted using relative sea level changes, which includes the facies category of low sea level, time of advance, and high sea level.

The microscopic facies and the shifts in sedimentation pattern of the main sequence surfaces, including the maximum water and progressive surfaces, the results from which revealed SB1 and SB2 sequence boundaries and the TST and HST sedimentary sections are shown in Figure 2.

The first sedimentary parasequence is composed of a progressive TST pattern with packstone and wackestone facies.

The second sedimentary parasequence is composed of an HST pattern above the sea water level and consists of wackestone and mudstone facies.

The third sedimentary parasequence is composed of a progressive TST pattern with packstone and wackestone facies.

The fourth sedimentary parasequence is composed of a HST pattern above sea level with mudstone and wackestone facies. The study of the lateral and vertical variation in the facies of the sedimentary environment indicates small and short-term regressions and transgressions over a large long-term progressive change which itself indicates the expansion of the Upper Cretaceous marine environment. The upper parts of the sequence indicate a relatively rapid retreat followed by extensive erosion, which corresponds to the end of the Mesozoic era and the closure of the Neotethys Ocean.

3. SEDIMENTARY PETROLOGY

3.1. *SANDSTONE SECTION IN SHAHINDEZH AREA*

The studied section consists of sandstone and sandy limestone of Upper Cretaceous age in the Shahin Dezh area with a thickness of 156 meters (Fig. 3). Upper Cretaceous sandstones, sandy limestones, and limestones that of the Lar formation have the same slope disconformity as that of the Upper Jurassic age. That is, the studied carbonate-clastic section is placed on the sandstone-conglomerate at the base of the Upper Cretaceous. Photographs illustrating various facies are shown in Figure 4.

3.2. *PETROGRAPHIC STUDIES*

The petrography of the research samples were examined using the polarizing microscope, the results from which revealed that, regarding textural maturity and roundness, sandstone samples are mainly of very fine grain size, and are well-rounded, semi-angular, semi-rounded, and mature. Photomicrographs showing the main features are shown in Figure 6. Regarding mineralogy, the components of the rocks are as follows:

1. Quartz with semi-angular to semi-rounded monocrystalline sometimes polycrystalline grains with wavy to straight extinction, the highest abundance about point to linear contact boundary.
2. Lithic pieces including micritic limestone fragments, fossils, micro fossils, and chert, all of which are the most abundant after quartz.
3. Feldspar is characterized by polysynthetically-twinned plagioclase grains and potash feldspar.

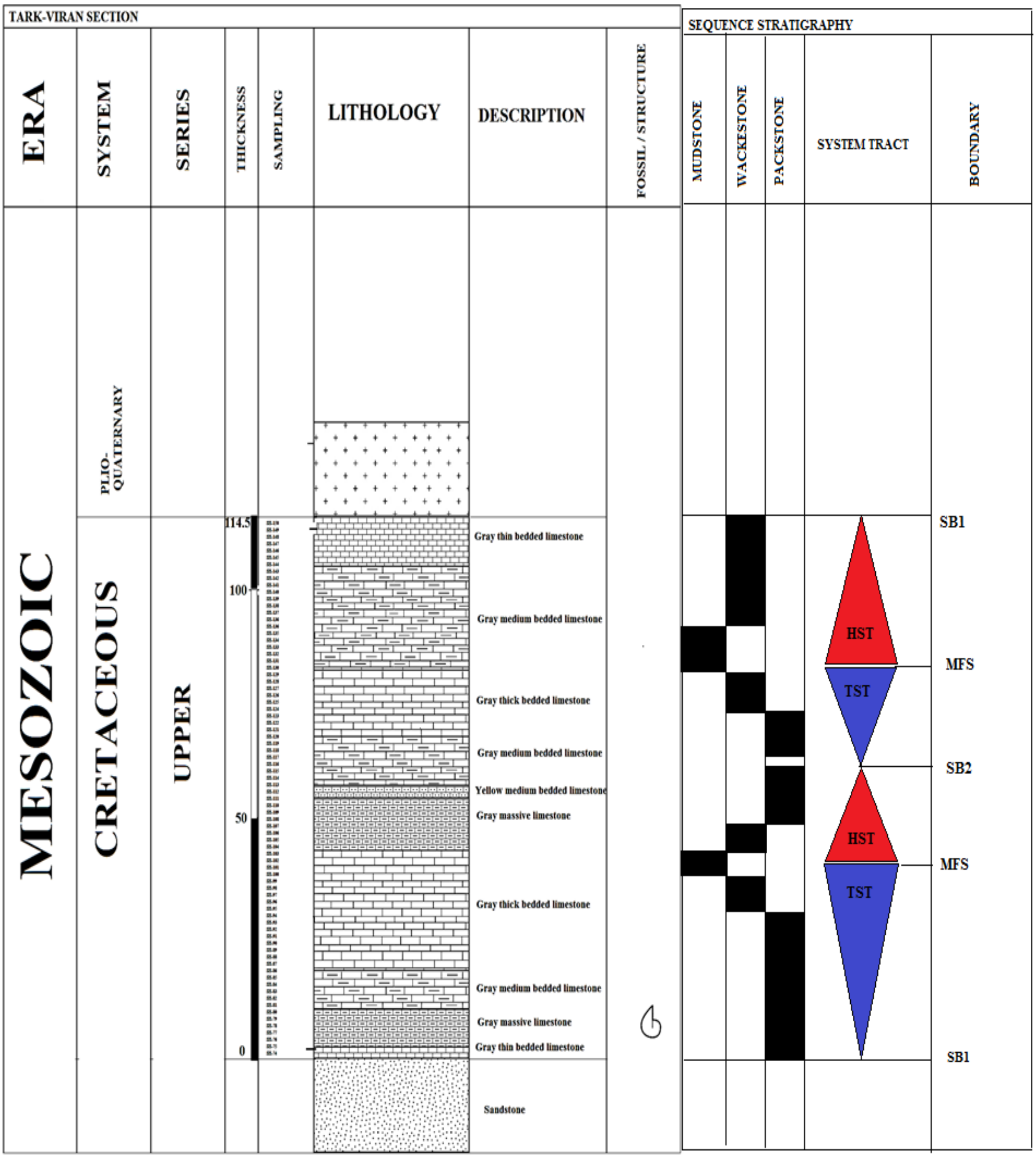


Fig. 2 Sedimentary sequence of the Upper Cretaceous carbonate section in Shahin Dezh area.

The microscopic studies of the samples collected in the area revealed that the grains mostly consisted of quartz and limestone fragments. Accessory minerals included tourmaline (Tu), zircon (Zr), chert (Ch), and muscovite (Ms) were identified in the samples. The studied sandstones are cemented by sparry calcite. Compositionally the samples are litharenites based on the classification of Folk (1980) and based on grain size and sorting can be described as texturally mature, very fine grained litharenites.

3.3. *THE TECTONIC SETTING OF THE UPPER CRETACEOUS SANDSTONE SEQUENCE IN SHAHINDEZH AREA (GODOLO)*

Dickinson et al. (1988) define tectonics as the component determining the global distribution of the source area of sediments and sedimentary basins, further stating that the composition of sandstones is strongly controlled by plate tectonics (Weltje et al., 2004). As such, the tectonic position can be readily determined by examining the composition and settings of the sandstones as well as their mineralogical composition (Dickinson and Suczek, 1979; Dickinson,

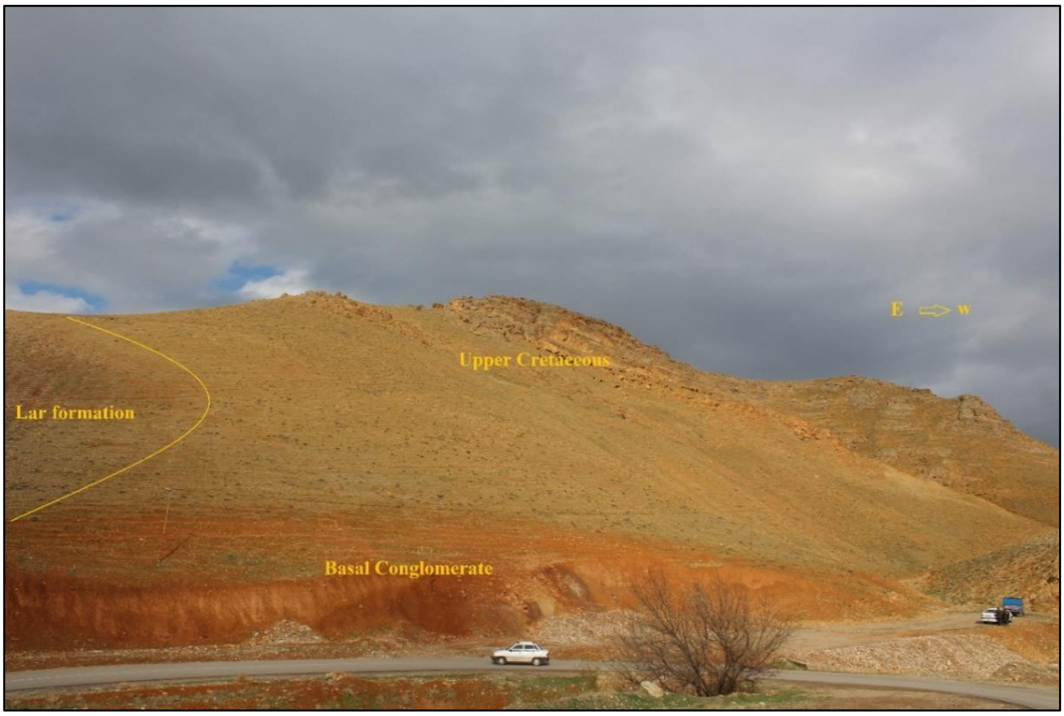


Fig. 3 The Cretaceous sequence in the clastic section in the Shahin Dezh area (Northwest Iran).

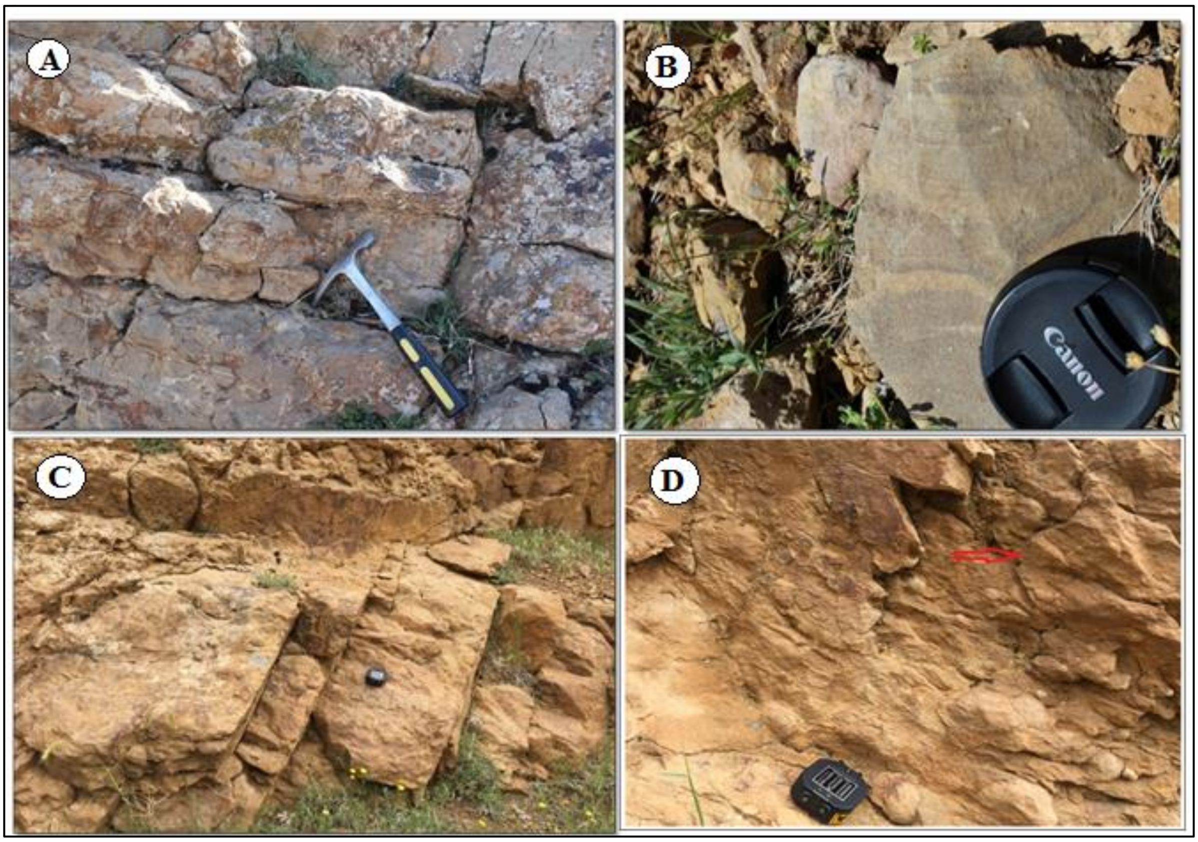


Fig. 4 A) Medium gray sandstones, B) The sedimentary structure of gradually fine-grained upward (parts of the Bouma sequence), C) Medium to thick yellowish limestones, D) Flute cast sedimentary structure, calcareous marls, E) Fossiliferous fine grained limestone, F) Medium sandy limestone of yellow layer.

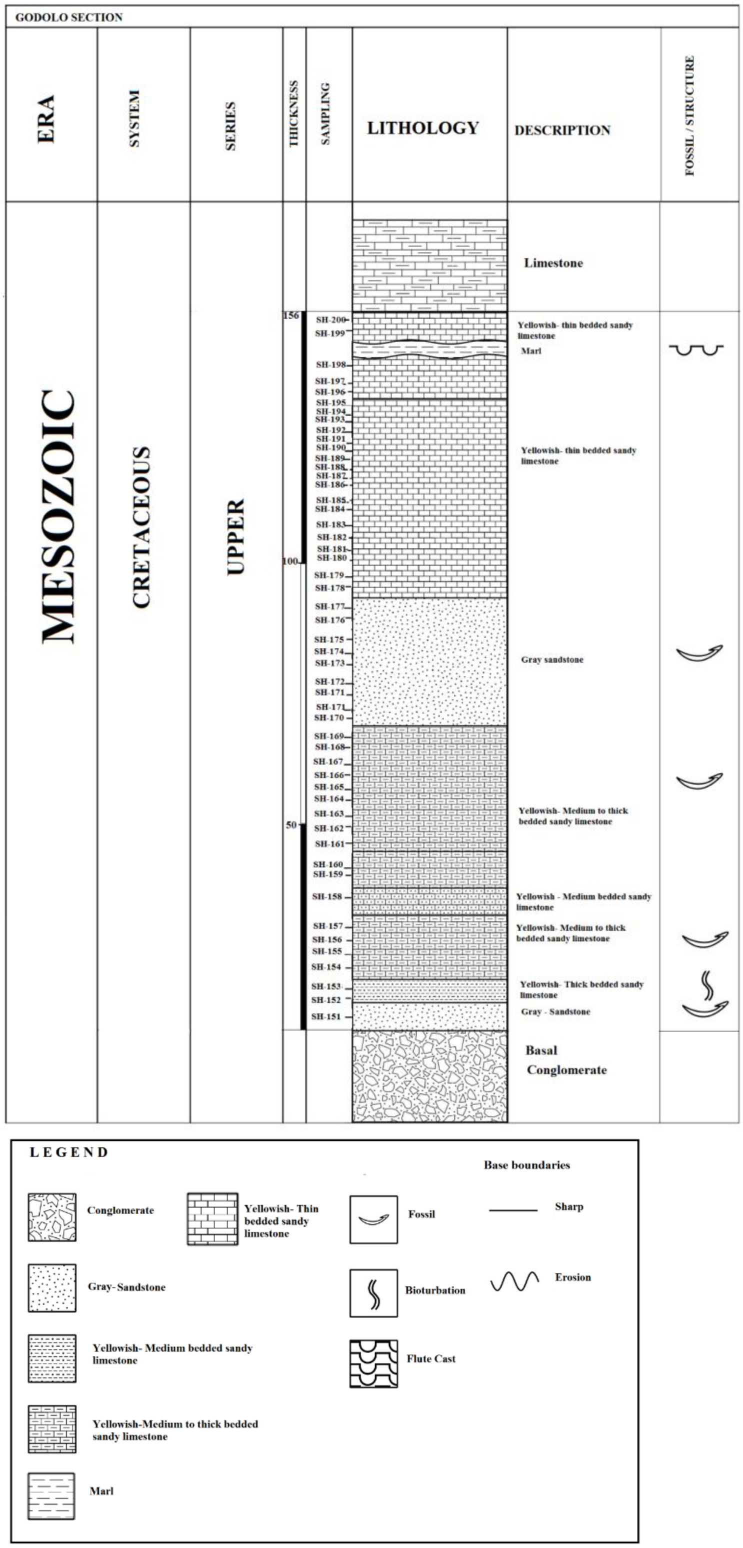


Fig. 5 Stratigraphic column of the clastic-carbonate section in the study area (northwest Iran).

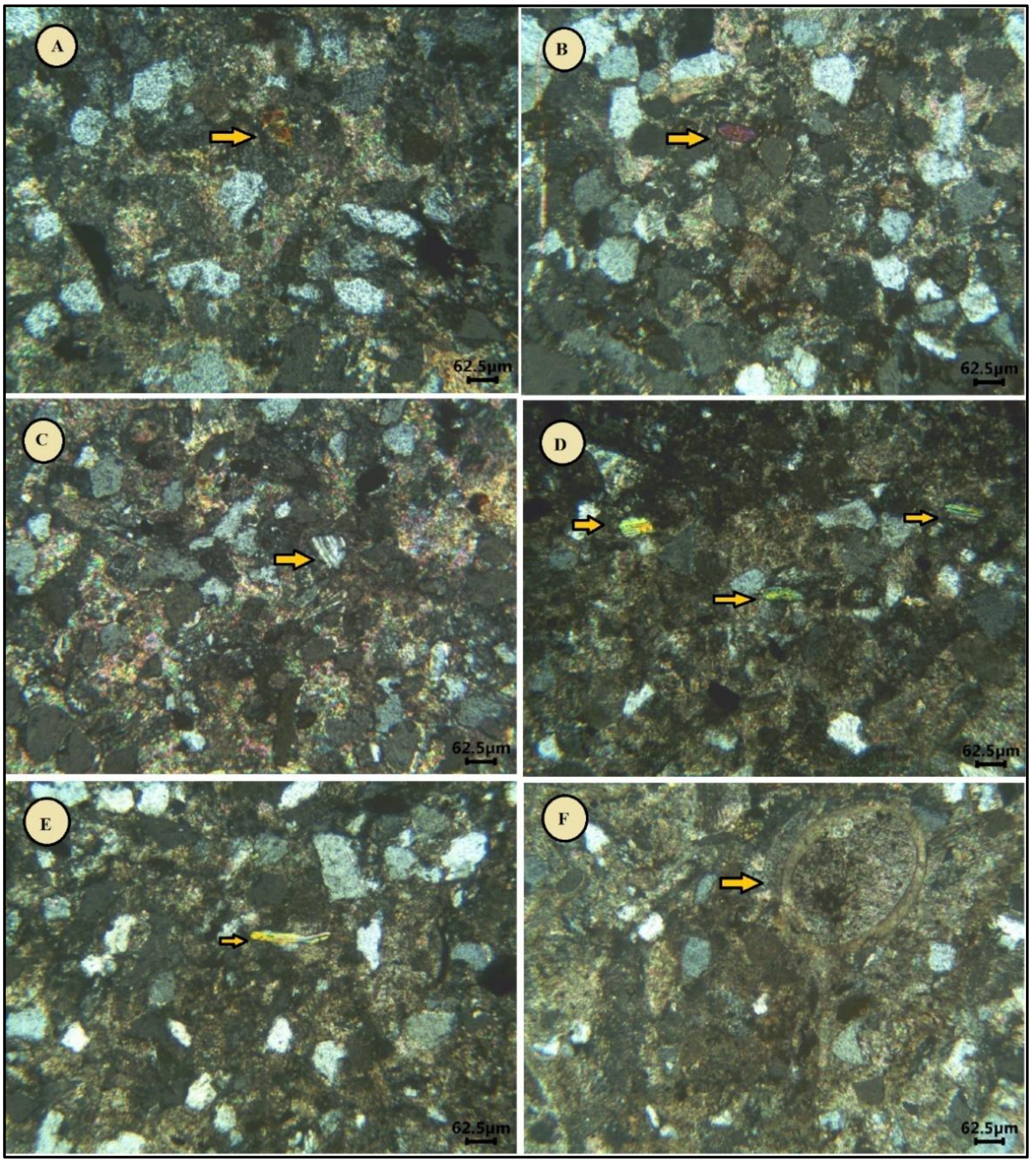


Fig. 6 Photomicrographs illustrating the carbonate cemented fine grained litharenite sandstones. A) Tourmaline, B) Zircon, C) Plagioclase, D) Muscovite, E) Muscovite, F) Bioclast.

1985). Research suggests that there is a correlation between the composition of sandstones and the depositional conditions of the area (that is, climate, weathering, tectonics, etc.), for which, the composition of clastic rocks can be used to interpret the tectonic position of the area (Dickinson et al., 1979; Mack, 1984; Dickinson, 1985; Dickinson et al., 2001). As previously stated, QFL compositional diagrams of Dickinson et al. (1979) were used to determine the origin of sandstones in the studied area. These diagrams are plotted to reflect the ratio of quartz, feldspar, and lithic fragments. The sandstones of the Upper Cretaceous clastic deposits in the studied area are within the range of orogenic re-cycles. Clastic grains originating from orogenic belts may belong to vast arrays of composition that reflect different types of orogeny. Sediments from orogenic recycling may fill adjacent foreland basins and remnant oceanic basins, or be transported to more distant basins in unrelated tectonic positions by major aquatic systems. Examining the relationship between the studied sandstones and the climate of the sedimentary basins indicates that the sedimentary basin where these sandstones were deposited must have had semi-arid to semi-humid climates. In the QtFL ternary diagram, the studied sandstone samples. fall within the orogenic recycling field (Fig. 6).

3.4. *CARBONATE SECTION IN SHAHINDEZH AREA (TARK-E VIRAN)*

Upper Cretaceous carbonate sediments in the Tark-e Viran section have a thickness of 114.5 meters, which is located on Upper Cretaceous sandstone-limestone and finally leads to Plioquaternary

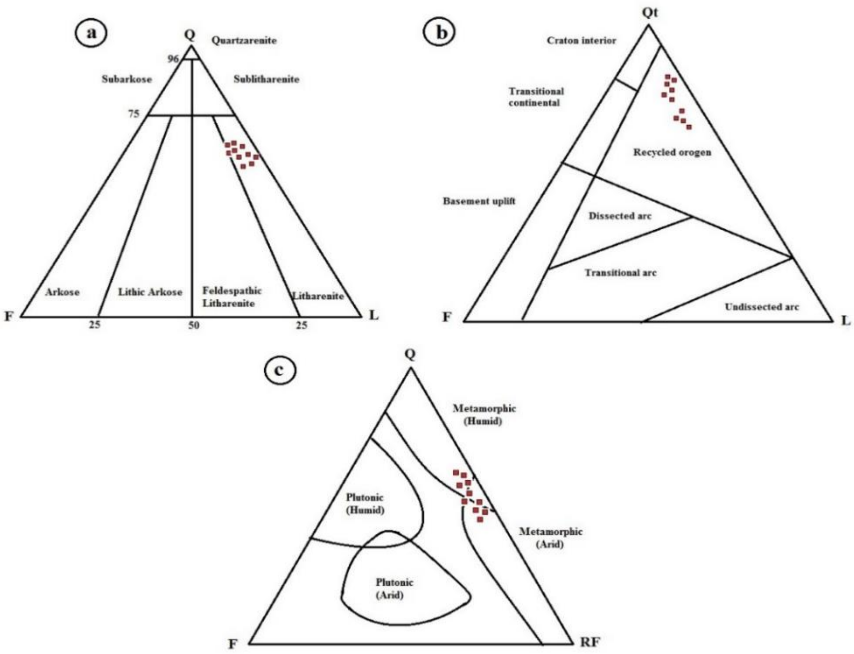
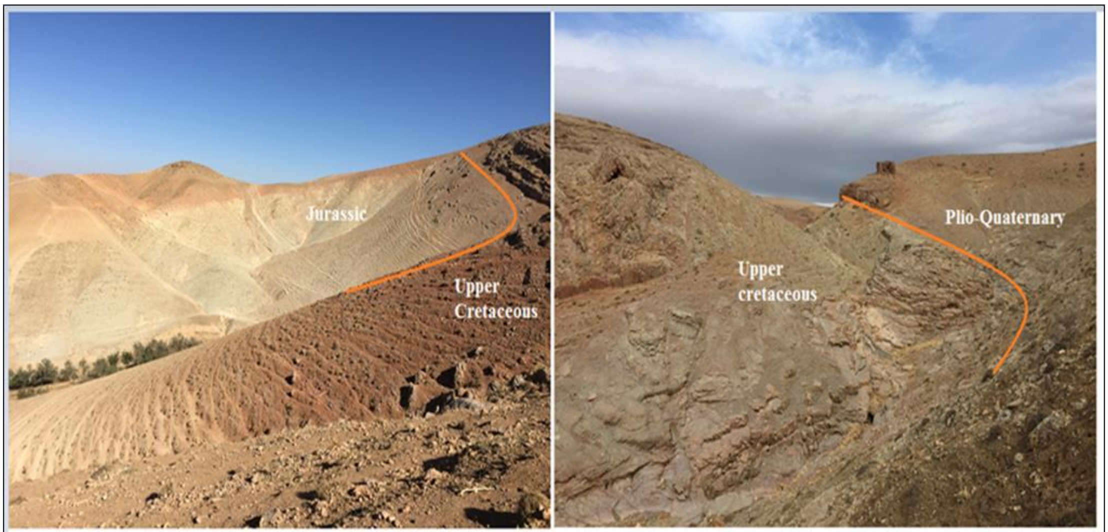


Fig. 7 a. The hierarchical position of the studied sandstones in the Folk (1980) diagram b. The hierarchical position of the studied sandstones in the QtFL diagram (Dickinson et al.,1983) c. The position of the sandstones according to the source area climate of sedimentary basins Suttner et al. (1981).



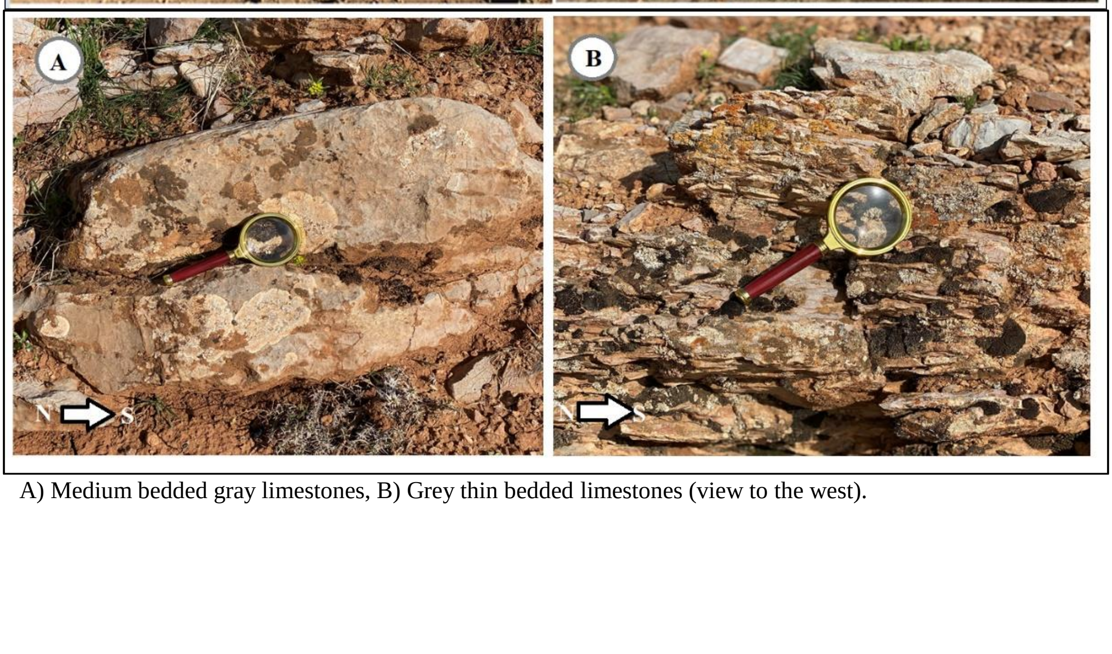


Fig. 9 A) Medium bedded gray limestones, B) Grey thin bedded limestones (view to the west).

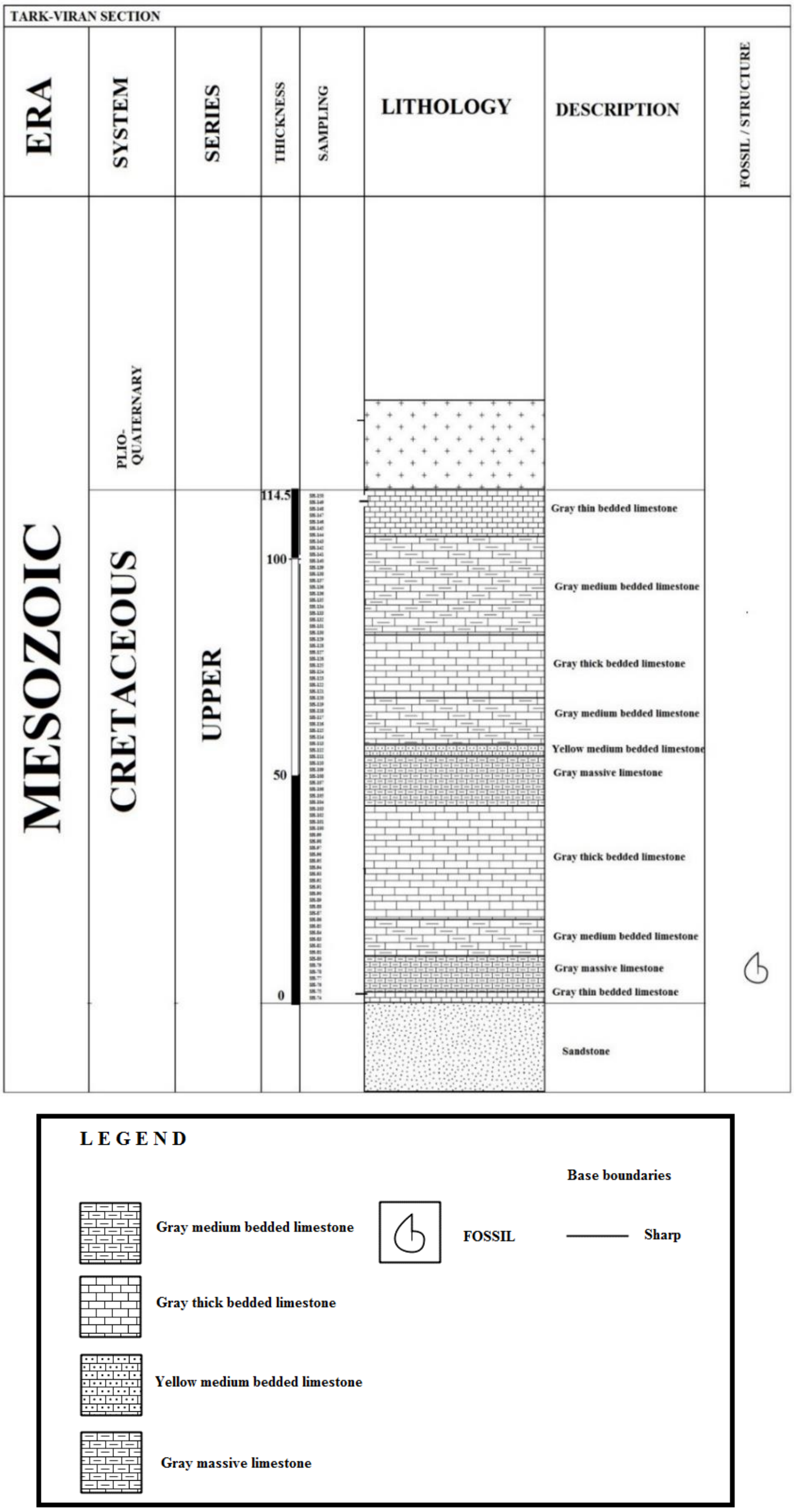


Fig. 10 Stratigraphic column of the carbonate sequences in the studied area.

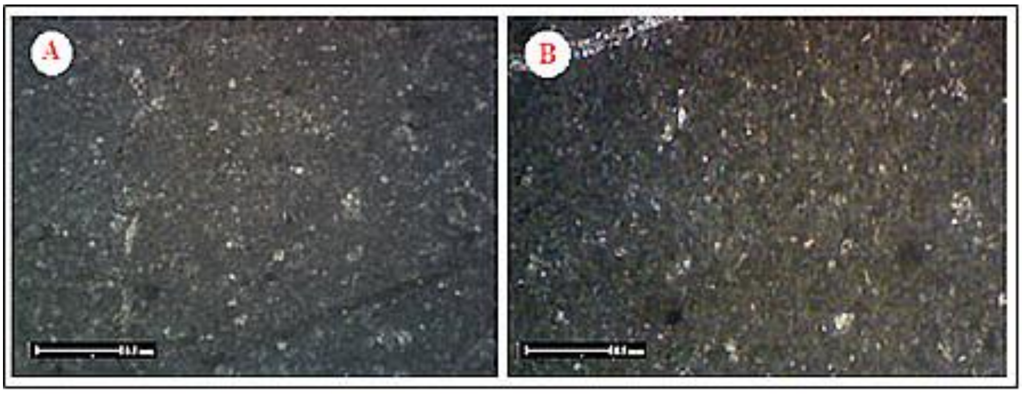


Fig. 11 Mudstone bioclastic microfacies. The microfacies consist of fine-grained and dark micrite matrix, in which plankton microfossils, especially foraminifera, globotruncanids, calcispheres, and fragments of benthic foraminifera are scattered.

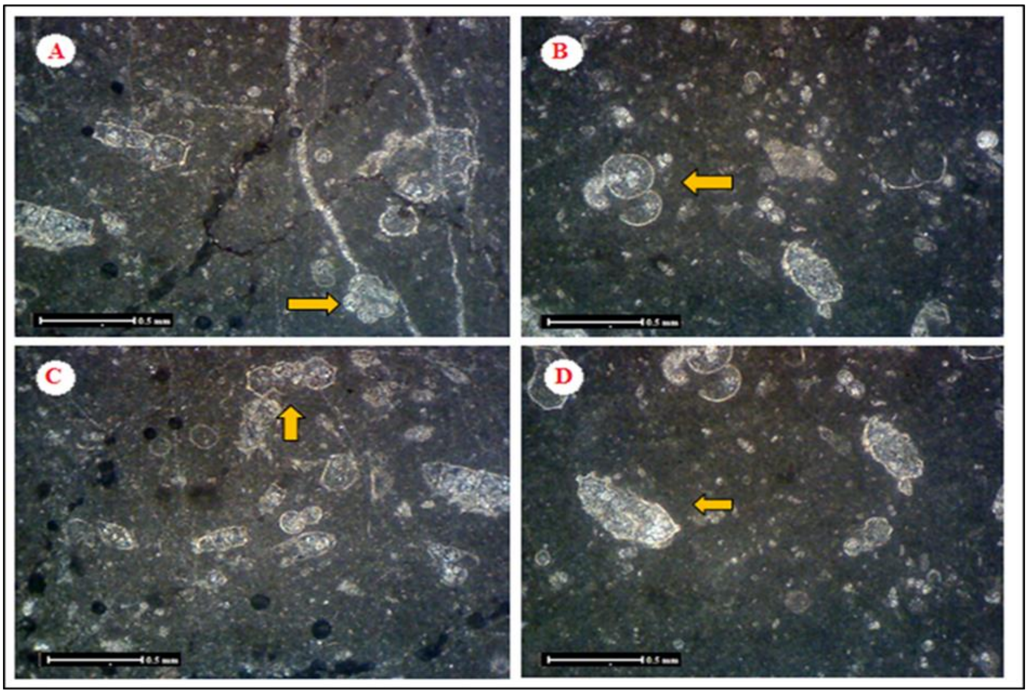


Fig. 12 Microfacies of bioclastic wackestone; (A) Globotruncana wackestone; (B) Globigerinoides wackestone; (C) Globotruncana wackestone (D) Globigerinoides wackestone.

sediments (Fig. 8). The sediments of this section have facies with regular layering and mainly consist of yellow to gray limestones and in some parts are fossiliferous (Fig. 9).

The stratigraphic column for this section is shown in Figure 10.

4. MICROFACIES OF THE UPPER CRETACEOUS SEQUENCE IN TARK-E VIRAN STRATIGRAPHIC SECTION

Field and laboratory investigations of the Upper Cretaceous carbonate sequence in the Tark-e Viran stratigraphic section have led to the identification of three layers of microfacies, namely, bioclastic mudstone, bioclastic wackestone, and bioclastic packstones, which are explained in detail below:

4.1. *MUDSTONE BIOCLAST*

This microfacies consists of a fine-grained and dark micrite matrix, in which plankton microfossils, especially foraminifera, globotruncanids, calci-spheres, and fragments of benthic foraminifera are scattered. The lamination structure can be seen in some sections. The diagenetic processes in these microfacies include the formation of calcite veins, crystallization, dissolution, and replacement.

4.2. *GLOBOTRUNCANA WACKESTONE*

The main components of these microfacies include various species of planktonic foraminifers such as Heterohelix and Globotruncana. The ground rock is of micrite, which is shown to be deposited in a low-energy environment owing to the abundance of

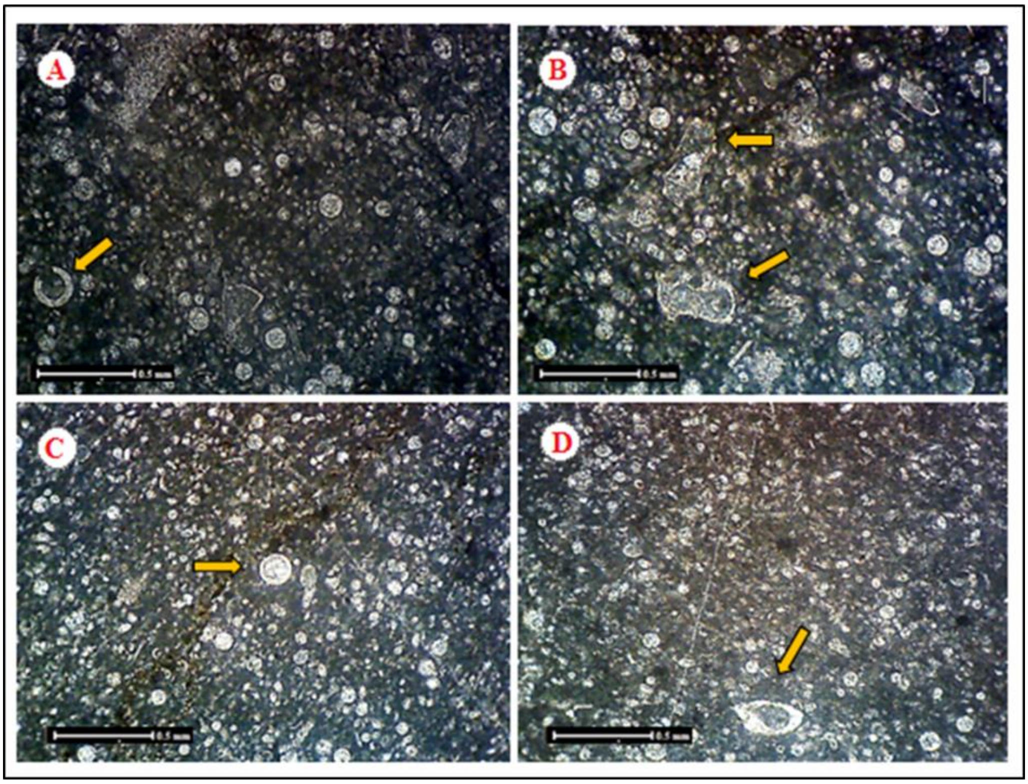


Fig.13 (A) Oligostegina packestone; (B) Oligostegina packestone; (C) Oligostegina packestone; (D) Foraminifer packestone.

mud (Jamalian et al., 2015; Adabi et al., 2016). Calcite veins are spread in these microfacies. The most important diagenesis processes in these microfacies can be called crystallization, dissolution, and replacement. It is comparable to the standard SMF 3 facies of Flugel (2010). These facies are attributed to the external ramp environment due to the presence of pelagic foraminifers.

The matrix is micrite with calcite veins spread in this microfacies, the most important diagenetic processes in this microfacies are crystallization, dissolution, and replacement.

4.3. *OLIGOSTEGINA PACKESTONE*

These microfacies include planktonic foraminifers such as Oligostegina, which are allochems with good sorting in the micrite matrix. These micro-facies are attributed to the outer ramp and is consistent with Flugel's (2010) RMF3 standard.

4.4. *MICROFACIES ENVIRONMENT*

The laboratory studies revealed that the microscopic samples include 3 groups of pelagic microfacies with mudstone, wackestone, and packstone facies, which is highly similar to that of Flugel's SMF, indicating sedimentation in a relatively deep sea environment.

The results from field studies and those of lithology, paleontology, and microfacies constituents of the Upper Cretaceous limestones in the Tark-e Viran section indicate that FZ-1 and FZ-3 facies belts are the best candidates to represent the formation of these deposits. (see Figure 14).

5. GEOCHEMICAL STUDIES

The type and amount of shellfish (skeletal and biological) and non-shellfish (inorganic) components and the abundance of different carbonate minerals are among the major factors influencing the content levels of secondary elements in carbonates (Tucker et al., 1990; Morse et al., 1990). The mineralogy and composition of carbonates move towards more stability during progressive stages of diagenetic, and carbonate minerals such as aragonite and unstable magnesium calcite change to low magnesium calcite and stable dolomite during the stages of diagenesis. Geochemical information is only employed for facies diagenesis when the diagenesis processes and the corresponding lithological features are known. If the types of facies are defined using major facies criteria, the matching of geochemical data and microfacies will result in insightful conclusions (Flugel, 2004). Table 1 shows the values of major and minor elements of carbonate samples of the Upper Cretaceous sequence in the study area. Some researchers argue that the mineralogy of carbonates was different during the Phanerozoic period, and calcite was introduced as the main mineral forming carbonates in the early and

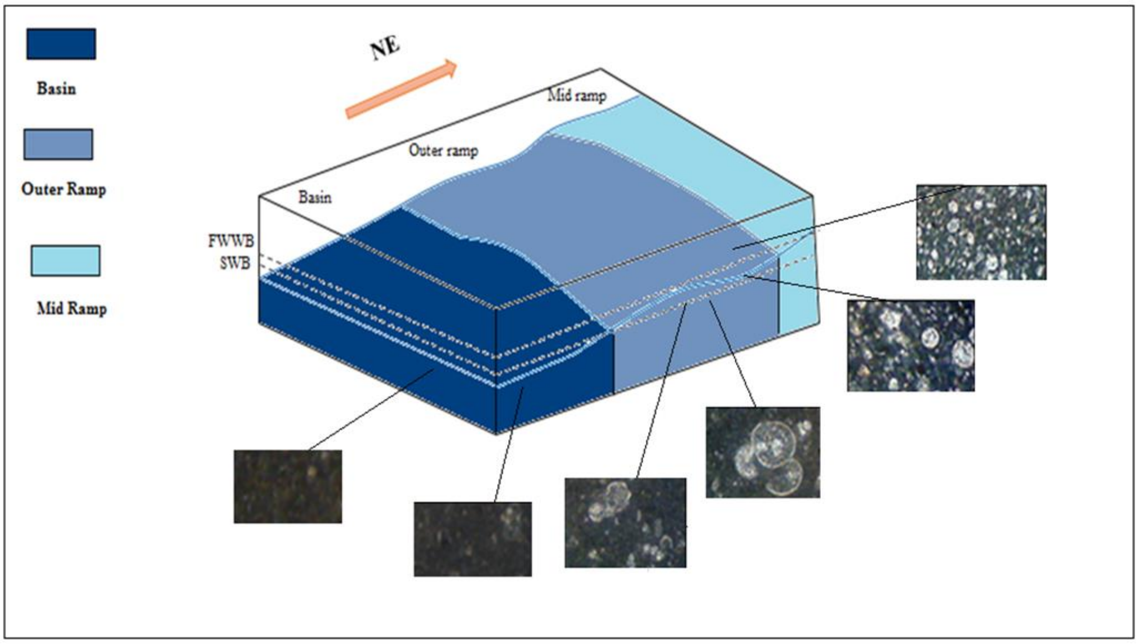


Fig.14 Sedimentary pattern of Cretaceous deposits in the Shahin Dezh region.

Table 1 Results of geochemical analysis.

Sample	Fe	Mn	Mg	Na	Sr	Ca
64	2662	156	0.58	238	434	51.72
110	1406	590	0.52	192	633	52.04
115	4816	534	0.56	182	677	51.32
123	2675	360	0.5	203	660	50.34
124	5550	464	0.57	182	681	49.68
125	3462	327	0.57	213	665	51.54
133	2178	381	0.5	195	671	47.25
144	6609	556	0.57	210	994	46.14
148	7291	592	0.57	252	915	44.83

middle Paleozoic and Jurassic periods. As such, this research sought to examine the primary mineralogy of Cretaceous limestones in the Tark-e Viran section located in Shahin Dezh. In this model, aragonite and calcite with high magnesium (an important carbonate mineral in Late Precambrian-Early Cambrian, Middle Carboniferous to Triassic, and Tertiary to the present era) have been introduced as the main mineral forming carbonates in Middle Paleozoic and the Jurassic period (Wilkinson et al., 1985) The primary mineralogy of Upper Cretaceous limestones is established using elemental studies and its primary calcite mineralogy, and the results are compared with the ranges of present-day carbonates in the tropical and temperate regions (Millimam, 1974; Rao et al., 1992; Rao et al., 1995), warm Ordovician carbonates and cold subpolar Permian carbonates with calcite mineralogy located in the state of Tasmania in Australia (Rao,1991).

5.1. *STRONTIUM (SR)*

The amount of strontium in bulk carbonate samples of the tropical regions of the present era varies between 8000 and 10000 ppm (Milliman, 1974), while the same parameter for the bulk carbonate samples of the temperate regions of the present era stands in the relatively low range of between 1642 and 5007 ppm (average 3270 ppm) (Fig. 15). The amount of Sr varies according to the mineralogy of carbonates. As such, the amount of Sr increases with an increase in the amount of aragonite and decreases with an increase in the amount of calcite (Rao et al., 1992). The abundance of Sr is also directly correlated to the increase in seawater temperature (Morse et al., 1990). Semi-stable Caco3 minerals are usually changed to calcite during meteoric diagenesis or burial, and therefore the amount of Sr in diagenetic calcite mainly depends on the partition coefficient and their concentration in diagenetic solutions. Since the distribution coefficient of Sr is less than 1 and its concentration in meteoric waters is insignificant, the resulting diagenetic calcite are presumed to have a low concentration of Sr. The amount of Sr in the limestones of the studied area varies between 434 and 994 ppm (average 627 ppm). This low concentration

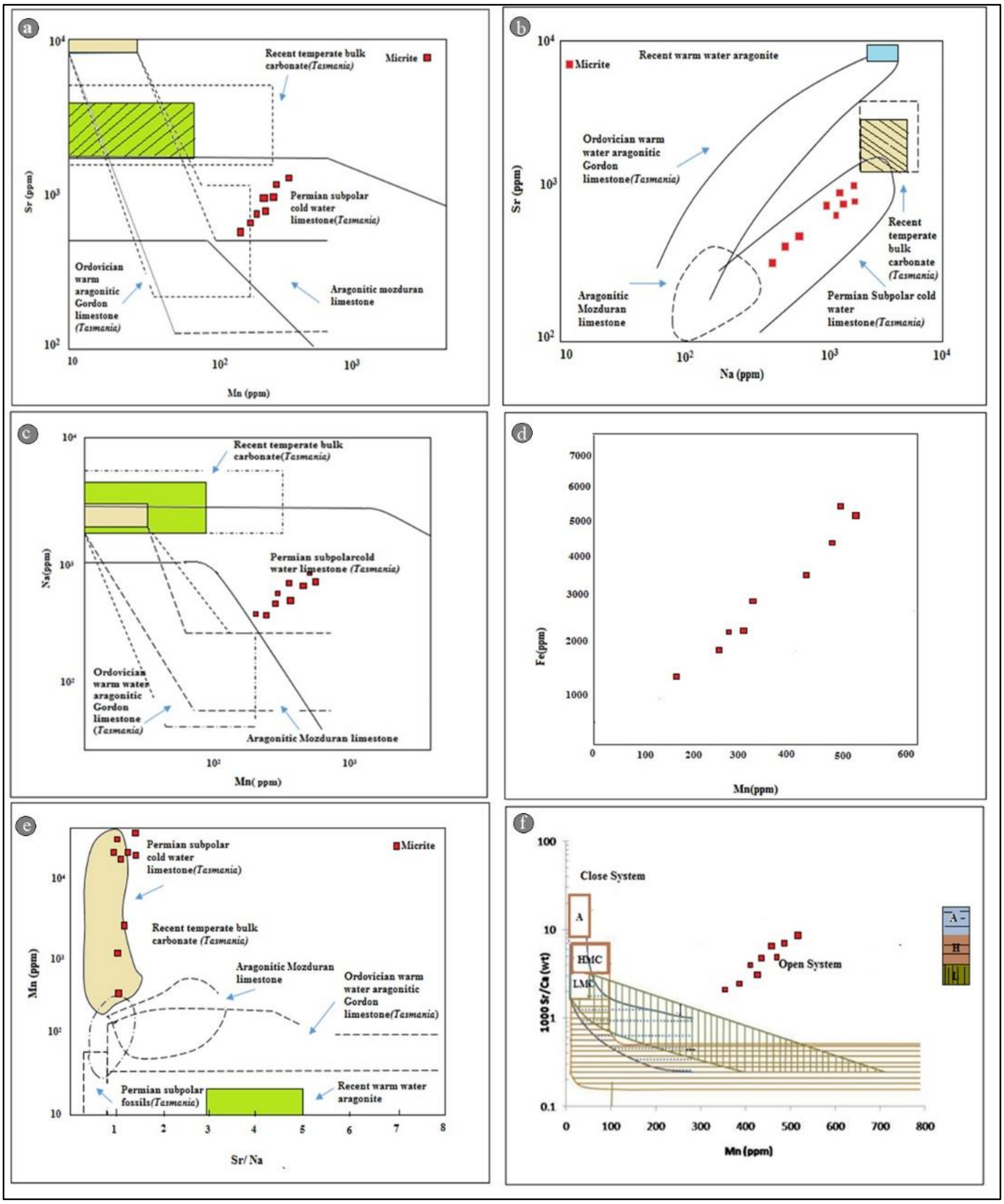


Fig. 15 a) Comparison of Sr and Mn content values, accompanied with alteration of Mn against Sr values in the regional samples which are compared, for the study, with the bulk carbonate samples of the temperate regions of the present age, the range of subpolar limestones of Permian Tasmania and the range of Ordovician carbonates of Tasmania sub-tropical warm waters. The samples of the studied area are hence attributed to subpolar limestones of Tasmania with calcite mineralogy (Adabi, 2004), b) Alterations of Sr and Na in the Upper Cretaceous limestones of the study section. In this figure, four areas have been identified, the areas related to the warm waters of the present age, the subpolar Permian limestones of Tasmania, the Ordovician carbonates of the warm subtropical waters of Tasmania, and the aragonitic limestones of Mazduran formation. The samples of the studied area can be attributed to the Permian subpolar limestones of Tasmania with calcite mineralogy (Adabi, 2004), c) Alteration of Mn and Na in the Upper Cretaceous limestones of the study section. The samples related to the studied area can be attributed to the subpolar Permian limestones of Tasmania with calcite mineralogy (Adabi, 2004), d) Changes of Fe and Mn in the limestones e) Graph of Sr/Ca against Mn, which shows the high impact of meteoric diagenesis in an open diagenetic system, f) The scatter of the data in the chart shows the open sea.

of Sr in these samples can be attributed to the increase of calcite mineralogy (HMC + LMC) compared to that of aragonite mineralogy (Rao et al., 1992).

5.2. *SODIUM (NA)*

Evidence from previous research has established that there are conclusive differences between the sodium carbonates of the present era, the carbonates of the temperate regions of the present era, the tropical limestones of the Ordovician period, and the limestones of the cold semi-polar regions of the Permian era (Fig. 15). The amount of sodium in abiotic tropical aragonite limestones of the present era varies between 1500 and 2700 ppm (average 2500 ppm), while it is in the range of 270 ppm low-magnesium abiotic calcites of temperate regions. The amount of sodium in calcitic bryozoans (that is, of LMC and HMC type), which are the most abundant organisms in carbonates of temperate regions (average about 4500 ppm), is perceivably far higher than that of aragonite and abiotic low magnesium calcite (LMC) (Rao et al., 1995) which is often attributed to biochemical fractionation (Land et al., 1973). Sodium content levels in carbonate sediments depend on the degree of salinity, biological reduction, kinetic effects and crystal defects, mineralogy, and water depth. The number of sodium increases with the increase of salinity and depth of water and the amount of aragonite. The amount of sodium in the limestone samples are much lower than their carbonate equivalents, as sodium decreases significantly following the increase in the impact of meteoric waters (Adabi, 1991). Sodium has a distribution coefficient of less than 1 and has a low concentration in meteoric waters; hence its contents will be low in carbonate rocks that are affected by diagenetic processes. As such, plotting Sr-Na values in these limes indicates a regular decrease in the amount of the two elements Sr and Na in the region, which can be partially attributed to the increase in delayed atmospheric diagenesis (Brand et al., 1980) (Fig. 15).

5.3. *MANGANESE (MN)*

The amount of Mn in the limestones of the section varied between 156 and 592 ppm (average 440 ppm). Aragonite carbonates located in warm and shallow seas have low Mn content (less than 20 ppm), while the Mn content of the bulk carbonate samples in the temperate regions of the present age is higher than 300 ppm (Rao et al., 1992). Furthermore, the amount of Mn increases with the influence of meteoric diagenesis (Brand et al., 1980; Rao, 1990), because the distribution coefficient of Mn is about 15 and it has a very high concentration in meteoric waters (Pingitore, 1978). A clear decrease of Sr and Na is accompanied by a slight increase of Mn. The diagram of changes of Sr-Mn and Na-Mn in the studied limestones (Adabi et al., 1991) indicated that calcite was the dominant mineralogy within the basin (Fig. 15).

5.4. *IRON (FE)*

The amount of iron in the rock in the limestones of the section varied between 1406 and 7291 ppm (average 4079 ppm). As such, given the increased effect of meteoric diagenesis, the amount of iron increases as the amount of manganese heightens (Fig. 15). Moreover, the concentration of iron usually increases with the increase of the percentage of insoluble matter (IR) in the acid, because iron may be added to the solution through the dissolution of the insoluble matter in the acid.

5.5. *SR /NA RATIO*

Paleotropical and modern carbonates can be distinguished from their non-tropical equivalents by Sr/Na ratio and Mn content (Rao, 1981; Adabi et al., 1991; Adabi et al., 2008; Adabi et al., 2010). In tropical aragonite limestones of the present era, the Mn content is low and the Sr/Na ratio is high (about 3 to 5), while in the calcitic limestones of the temperate regions of the present era, the Mn content is high and the Sr/Na ratio is low (about 1). The graph of changes of Sr/Na against Mn (Fig. 15) indicates that the samples retrieved from the studied area are attributable to the subpolar Permian limestones of Tasmania with calcite mineralogy (Adabi, 2004).

6. DIAGENETIC PROCESSES

Diagenesis can be defined as the alterations that occur in the features and composition of sediments from the moment they are deposited in the sedimentation environment to lithification, right before entering the metamorphic environment (Moore, 2001; Machel, 1999). It is widely believed to encompass a wide range of post-depositional physical, chemical, and biological processes in which primary sediments react with pore water in the sedimentary basin to achieve a stable textural and geochemical equilibrium with the environment (Schmid et al., 2004). As such, gaining knowledge on the processes of diagenesis is of utmost significance to the characteristics of microfacies. Sediment composition and texture, burial history, and intergranular water chemistry within the sedimentation basin are among the most important factors affecting diagenesis (Kim et al., 2007). The age of the sediments and the geometric shape of the layers, climate, and sedimentation environment, and facies are pivotal to diagenesis (Tucker, 2001; Parcerisa et al., 2006).

6.1. *DIAGENETIC PROCESSES OF TARK -E VIRAN CARBONATE SECTION*

In the studied area, various processes of diagenesis have been effective on carbonate rocks. The most important of them are drusy and block cementation, neomorphism, mechanical and chemical compression, dolomitization, pyritization, dissolution, and protrusion. In this section, the identified diagenetic processes are described, and finally, based

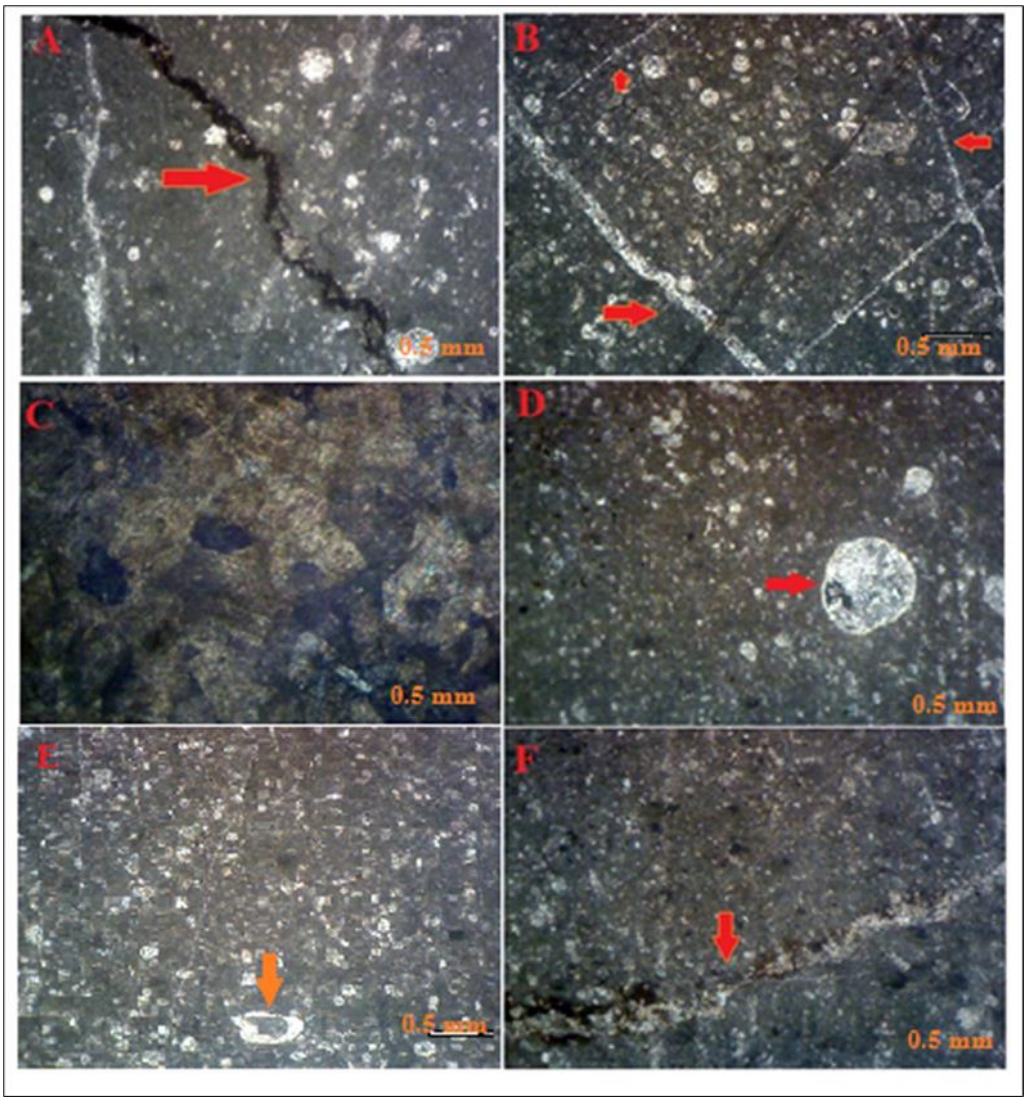
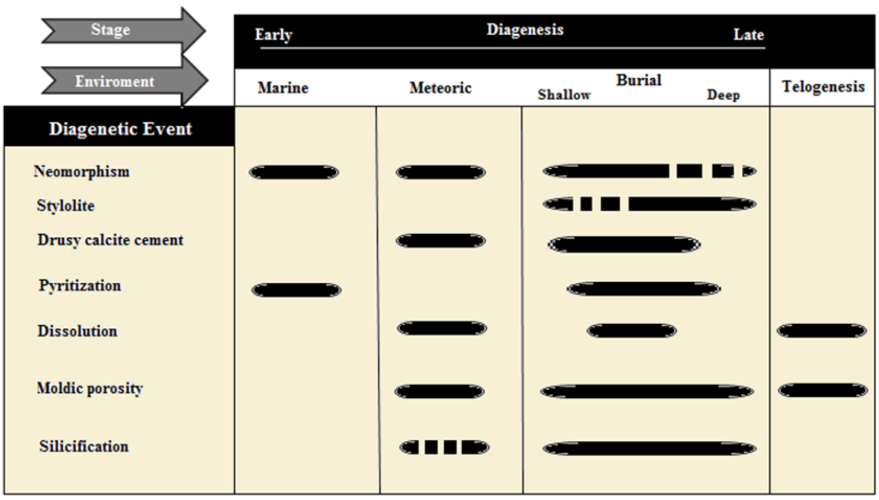


Fig.16 Diagenetic processes of the Tark-e Viran section (A) Stylolitization and silicification interrupted by stylolith; (B) Cavity filling cement; (C) Burial cement; (D) Cement filling the dissolution mold; (E) Incremental neomorphism; (F) Pyrite replacement in the context of compressive dissolution.

Table 2 Paragenetic sequence of Tark-e Viran carbonate section in the studied area.



on the observed textures and temporal relationship between the phenomena, the diagenetic history of carbonate sediments and their paragenetic sequence are presented.

6.1.1. DIAGENETIC SEQUENCE

Diagenesis processes have affected the Upper Cretaceous carbonate sediments during three sub-stages, namely (1) eogenesis, (2) mesogenesis, and (3) telogenesis. The eogenesis is the first stage in which the diagenesis processes influence the sediments. It can occur after sedimentation or during sedimentation and before the deep burial stage, applicable to both marine and atmospheric environments. The atmosphere of the sediments is under the influence of atmospheric waters, which has caused long-point contact, dissolution, drusy cement, and pyritization in this environment. Following eogenesis, sediments are affected by intermediate diagenesis processes during the mesogenesis. The diagenesis processes in this stage affect the temperature, pressure, and depth of different sediments during burial. The main processes in this stage include stylolite, Longitudinal-point contact, drusy calcite cement, convex-concave contact, dissolution, cavity-filling dolomite cement, and pyritization. The last stage of the impact of diagenesis processes on sediments takes place in the telogenesis stage. Fractures are created when the rocks rise at this stage. The impact of atmospheric waters on the hardened sediments results in porosity and mold dissolution.

6.2. *DIAGENETIC PROCESSES OF GODOLO STRATIGRAPHIC SECTION*

In the formation of any sandstone, the sequence of genetic events can be carried out in a simple manner of the deposition of one mineral (Tucker, 2001) or a very complex manner, in several stages of deposition, replacement, and dissolution. The elements controlling the process of diagenesis in sandstones include the depositional environment, the composition and texture of the sediment, the biochemistry of the water inside the pores, the burial depth, and the rise time, among others. As such, this section seeks to outline the identified diagenetic processes and hence present, based on the observed textures and the temporal relationship between the phenomena, the diagenetic history of clastic sediments, and their paragenetic sequence. Among the diagenetic processes identified in Upper Cretaceous sandstones include physical compression, cementation (drusy, same dimension) pyritisation, dolomitization, and types of contacts, being longitudinal, convex-concave, which will be explained and interpreted in the following.

6.2.1. DIAGENETIC SEQUENCE

Diagenesis processes have affected the Upper Cretaceous sediments during three sub-stages, namely (1) eogenesis, (2) mesogenesis, and (3) telogenesis. The eogenesis is the first stage in which the diagenesis processes influence the sediments. It can occur after sedimentation or during sedimentation and before the deep burial stage, applicable to both marine and atmospheric environments. The atmosphere of the sediments is under the influence of atmospheric waters, which has caused long-point contact, dissolution, drusy cement, and pyritization in this environment. Following eogenesis, sediments are affected by intermediate diagenesis processes during the mesogenesis. The diagenesis processes in this stage affect the temperature, pressure, and depth of different sediments during burial. The main processes in this stage include stylolite, Longitudinal-point contact, drusy calcite cement, convex-concave contact, dissolution, cavity-filling dolomite cement, and pyritization. The last stage of the impact of diagenesis processes on sediments takes place in the telogenesis stage. This stage is where protrusions are formed as a result of rising rocks. The impact of atmospheric waters on the hardened sediments results in cavity-filling dolomitic cements and dissolution.

7. CONCLUSIONS

Upper Cretaceous clastic and carbonate deposits have extensive facies in the Shahin Dezh area. The Upper Cretaceous deposits of Shahin Dezh consist of clastic and carbonate parts. Clastic deposits are discontinuously situated on the Late Jurassic Lar limestone formation and are covered with Pleistocene-quaternary sediments on top of the carbonate sediments. The clastic section is made up of sandstone, sandy limestone, and marl and has a thickness of 156 meters. Field studies revealed that the lithological characteristics and macroscopic characteristics of the studied detrital sequence could be divided into 12 lithological units, which mostly include petrofacies of sandstone, limestone, and sandy limestone with interlayers of marl and limestone. Sandstone petrofacies often exhibit coarse textural features and are classified as sedarenite-type litharenites based on the composition of the main grains, and the carbonate part has a thickness of 114.5 meters, which is a sequence of carbonate sedimentary rocks, mostly medium to thick layers. Field studies also indicated that the lithological and macroscopic characteristics of the carbonate sequence of the studied section can be divided into 11 separate lithological classes, and based on the laboratory studies, the microscopic samples consisted of three groups, namely, Pelagic microfacies with mudstone bioclastic facies, Globotruncana wackestone, and Oligostegina packstone. The groups are comparable to Flugel's SMF 3 and were deposited in the facies zone of FZ_1 and FZ_3, evoking the depositional environment of relatively deep seas. The sedimentation conditions and environment of the clastic facies of the shallow and semi-deep seas are reminiscent of the turbulent sloping seas, while the sedimentation environment of the carbonate facies best evokes the relatively deep open seas at the edge

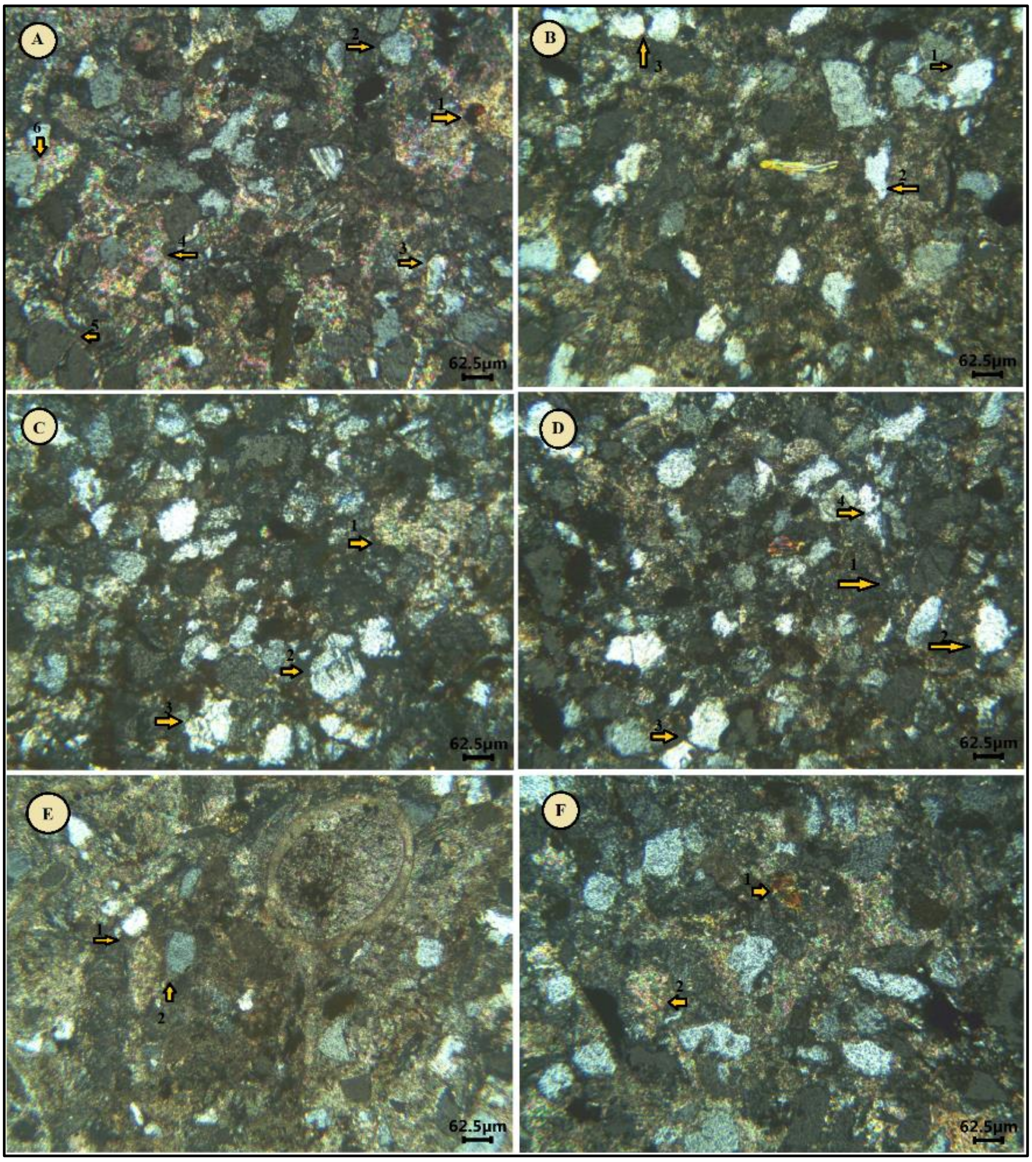


Fig. 17 A: (1) Pyritization, (2) convex-concave contact boundary, (3) Dimensional cement, (4) Dolomitization, Drusy cement that filled the empty cavity, (5) linear contact boundary between grains, (6) Rough boundary between grains

B: (1) Drusy cement that filled the empty cavity, (2) convex-concave contact boundary, (3) Drusy cementation in the form of cavity filling, point contact boundary between grains

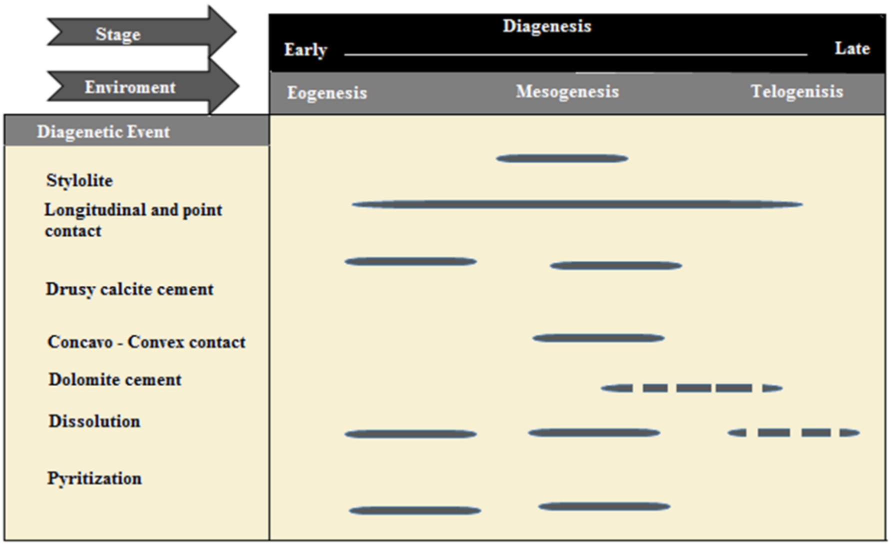
C: (1) Dolomitization, (2) Same-dimension cement, convex-concave contact boundary, (3) Drusy cementation in the form of cavity filling

D: (1) Stylolite, (2) Drusy cementation in the form of cavity filling, (3) linear contact boundary between grains, (4) convex-concave contact boundary, high density and compression in the studied section, which has caused grains to sink into each other and create various boundaries between grains

E: (1) point contact boundary between grains, drusy cementation in the form of cavity filling; (2) Pyritization, point contact boundary between grains

F: (1) Pyritization, (2) Dolomitization, high density and compression in the studied section, which has caused grains to sink into each other and create various boundaries between grains.

Table 3 Paragenetic sequence of Godolo clastic section in the studied area.



of the young Tethys ocean. Geochemical studies on the elements of strontium, sodium, manganese, and iron revealed that the amount of strontium and sodium is very low while the amount of manganese and iron is higher than the carbonate equivalents of the present era. Due to the increased effect of late meteoric diagenesis, the number of iron increases with the increase of manganese, and the changes of Sr/Ca compared to manganese represent an open diagenetic system reflecting that of the late meteoric diagenesis. The studied limestones can be inferred from the mentioned characteristics to be as semi-polar with the primary composition of calcite mineralogy. Examining the shifts in vertical and lateral facies and their arrangement in the depositional environment suggests small and short-term regressions and progressions embedded in a large long-term progressive sequence, itself reflecting the expansion of marine and oceanic environments during the Late Cretaceous, although the erosion of the upper parts of the sequence and the last lithological layers of the whole Mesozoic era indicate a relatively rapid regression followed by extensive erosion, which corresponds to the end of the Mesozoic era and the closure of the Tethys ocean.

SUGGESTION

It is suggested that other studies of Upper Cretaceous deposits in other regions of northwestern Iran should investigated and compared in order to make a detailed analysis of Cretaceous sedimentation in this area.

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