



The Frasnian-Famennian shelf deposits of the Bahram Formation in the Shams Abad section Kerman province, Central Iran: facies and sequence stratigraphy

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Abstract

Bahram Formation is a carbonate-clastic sequence of Late Devonian (Frasnian–Famennian) age and is deposited at the Central Iran sedimentary basin, Iran. In this investigation, Bahram Formation has been studied at Shams Abad section. Facies analysis and petrographic studies led to the recognition of 9 microfacies that are deposited in five facies belts: shore, tidal flat, lagoon, shoal and shallow open marine. The observed facies patterns indicate a mix carbonate-clastic shelf depositional environment. The shelf margin is formed as a result of tectonic activity associated with Hercynian orogeny passive margin in northeast Gondwana. Based on field observations, microfacies analysis and sequence stratigraphic concepts three, third-order sequences in this section. Sequences 3 joint with Hutk Formation (Carboniferous) are identified, on the basis of shallowing upward patterns. The transgressive deposits display a predominance of deep subtidal facies, while highstand deposits show shallow subtidal facies.

Introduction

This study is focused on the Bahram Formation, located in the Central Iran (South Tabas block) (Fig. 1a, b). The Bahram Formation covers the upper part of the Devonian succession. Devonian rocks are widely distributed and superbly exposed in the south-Tabas block of central Iran. Bahram Formation were deposited mainly in a shallow carbonate platform at the northern margin of Gondwana that is delineated by land areas in the north (eastern Alborz), south-east (Yazd Block), and southwest (Zagros) (Fig. 1a, b and c). The regional geology and stratigraphy of the Kerman area have been described by Huckriede et al. [28] and Wendt et al. [56, 57]. The fossil content of Bahram Formation have been illustrated by various authors: brachiopods [8], trilobites [34] crinoids [54], acritarchs and miospher [17] and conodont [18, 19, 20, 21 and 1]. Few previous studies focused on the depositional environments aspects of the Bahram Formation, especially in the Tabas block [22, 23 and 24]. The most comprehensive study on the Devonian rocks in Iran was carried out by Wendt et al., [55, 56 and 57]. So, the main objectives of this paper are (1) describing and interpreting the microfacies, interpret the depositional environments (2) and to describing and interpreting the sequence stratigraphy represented at Bahram Formation.

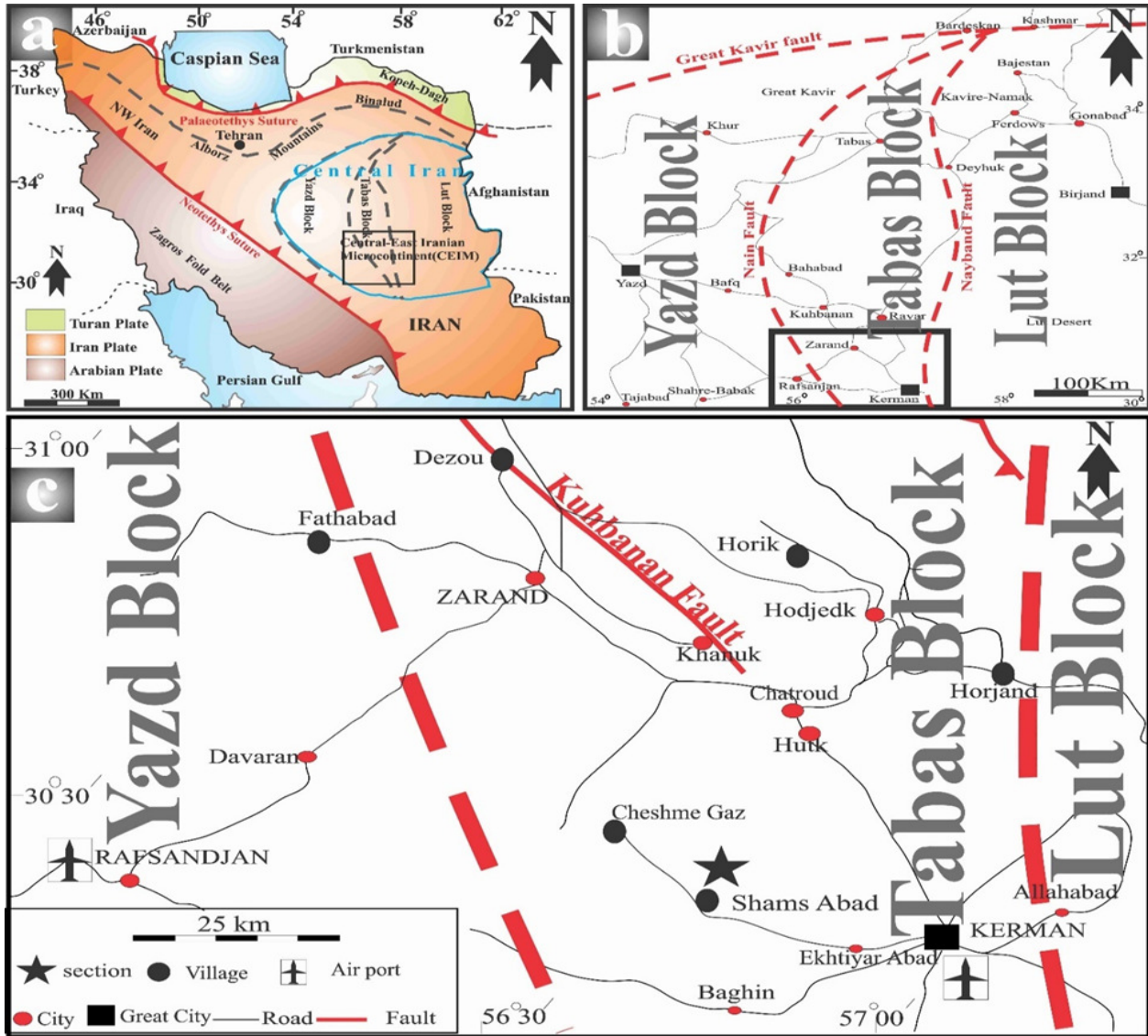


Fig. 1- Location map of the study area and measured stratigraphic sections in South Central Iran: (a) Structural and geographic framework of Iran showing the main sutures, structural units and geographic areas. (b) Close-up view of white square, South-Central Iran. Subdivisions of the Central Iran province and Location of the south Tabas block (modified from Wilmsen et al [58] and zand moghadam et al [62]). (C) Close-up view of white-square, the locations of measured sections in south Tabas block (modified from Wendt et al [56]).

Study area and methodology

The study area (Shams Abad section) is located about 1.5 km East of Shams Abad village and 40 km northwest of Kerman (Fig. 1c). In this study, the best place where the Bahram Formation could be measured is at the section with coordinations of $N30^{\circ}21'55.9''$ and $E56^{\circ}46'43.8''$ at the lower boundary and $N30^{\circ}21'49.9''$ and $E56^{\circ}46'49.5''$ at the upper boundary. The lower boundary of the Bahram Formation is exposed and underlain by the Rizu Series and the upper boundary is exposed and overlain by the Hutk Formation (Fig. 2, 3 and 4) [23, 1 and 57]. This study is based on the field and laboratory investigation of the Bahram Formation in the Tabas block region of Central Iran. Outcrop sections were studied to determine the sedimentary patterns, fossil, weathering profiles, size, color, lithology, relevant characteristics of the beds in vertical succession, lateral variations when there were changes in the sedimentation facies and bedding surfaces were described. Sedimentologic textures and structures are considered qualitatively. More than seventy thin sections are analyzed for definitions of facies. Some samples from the underlying Rizu Series and overlain Hutk Formation are also analyzed for comparison. All thin sections are checked under the microscope for petro/micro facies analysis. Facies definition is based on microfacies characteristics,

including depositional texture, grain size, grain composition and fossil content. Fossils and facies characteristics are described in thin sections from 70 samples were used for sequence stratigraphy analyses. The microfacies classification for carbonates is based on Dunham limestone classification Dunham [12] with the modifications of Embry and Klovan [14]. The petrographic description of the sandstones follows Pettijohn et al. [35]. The mud rocks classification follows the scheme of Dorrik [11]. Wilson [59] and Flugel [15] facies belts and sedimentary models are also used. For sequence stratigraphic interpretation, the concepts developed by many investigators [3, 4 and 14] are used. Field and petrographic studies are carried out for facies analysis, paleoenvironmental and change sea level reconstruction of the Bahram Formation.

Geology of the sampling localities

Palaeogeographic maps of the Late Ordovician to Late Devonian of northern Arabia suggest that north Africa and Arabia formed a broad stable continental shelf on the northern margin of the Gondwana supercontinent [29, 41, 56, 57, 40, 45, 25 and 10] bordering the Paleo-Tethys ocean (Fig. 9A &B). The study area is located in the central part of the Central-East Iranian Microcontinent in south Tabas block (CEIM; [43, 44], see Fig.1a). The CEIM consists of three north-south oriented structural units, called the Lut, Tabas, and Yazd blocks (Figs. 1b). The Tabas block is bounded by the Great Kavir fault in the north, the Nain Fault in the west and the Nayband fault in the east (Fig. 1c). Tectonically the area is part of a foreland basin filled dominantly with a thick sedimentary sequence of clastic and carbonate compositions. Long strike faults (which have cut the anticlines longitudinally and opened them laterally by erosion), short faults (which cut them widthwise) and lineaments which are of structural and stratigraphical origins are the similar structural elements in the regions exhibit a low morphology and more or less change in thicknesses. The older crustal blocks are relatively rigid, whereas the surrounding strata are more easily deformed into mountains and fault zones, a broken, mountainous belt separates the Tabas blocks. Early to Middle Cambrian volcanic rocks Rizu complex blanketed the oldest lithostratigraphic units in the studied area (Fig.3).

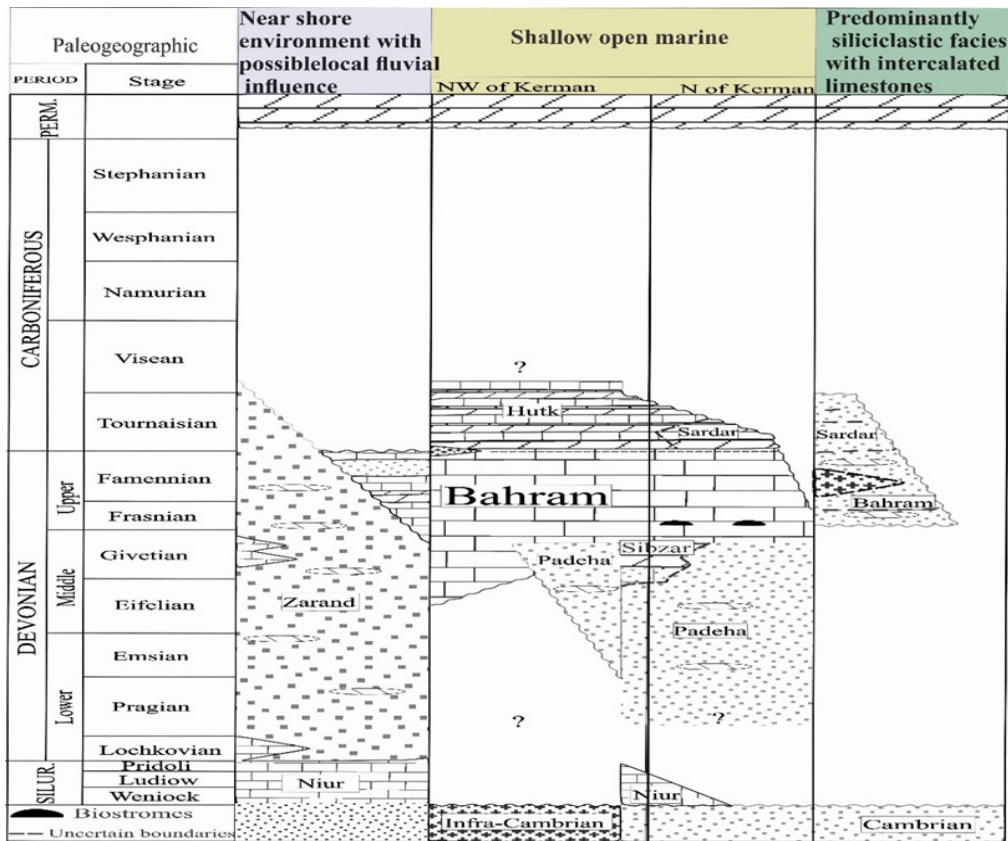


Fig. 2- Stratigraphic correlation chart of the Silurian to Permian units in the Kerman - Kuhbanan - Ravar area (with slightly modified after Wendt et al [56]). For legend see Text-fig. 4.

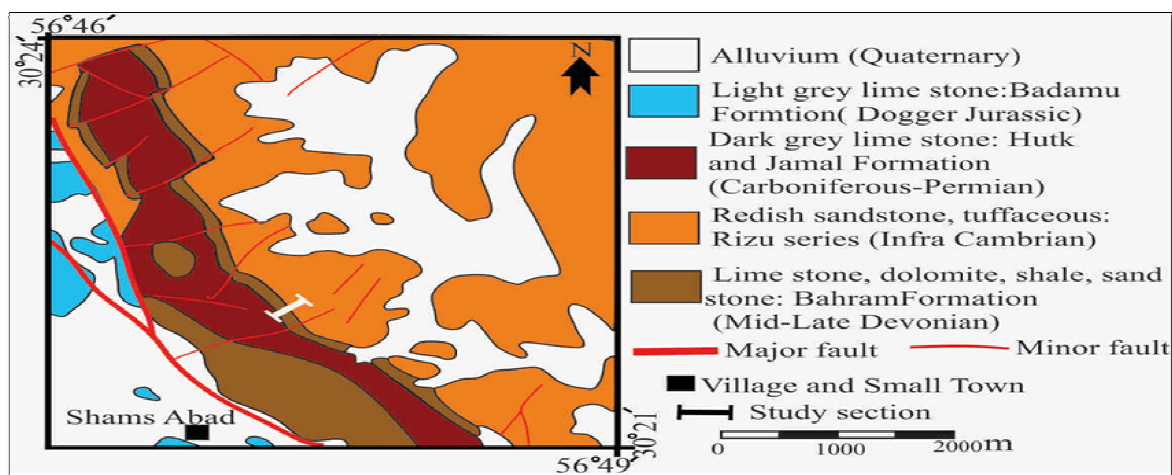


Fig. 3- Simplified geological maps of the study areas with locations of the studied section. Sheet 1:100,000 of Baghin by [9].

Lithology

In the study area in Shams Abad, the thickness of the Bahram Formation is 122 m (Fig. 4). It is composed of thick to massive bedded limestone, dolomite, shale and sandstone. The Bahram Formation in the sections angular unconformity overlies the Rezu Series and with a transitional contact and also underlies Hutk Formation (equivalent Shishto Formation) paraconformably. The conodont fauna collected in this section allows to assigning a late Frasnian- middle Famennian age to the Bahram Formation [56 and 1]. According to this observation, the following are brief stratigraphy and lithological descriptions of subjective study sequences which are summarized in Figs. 4.

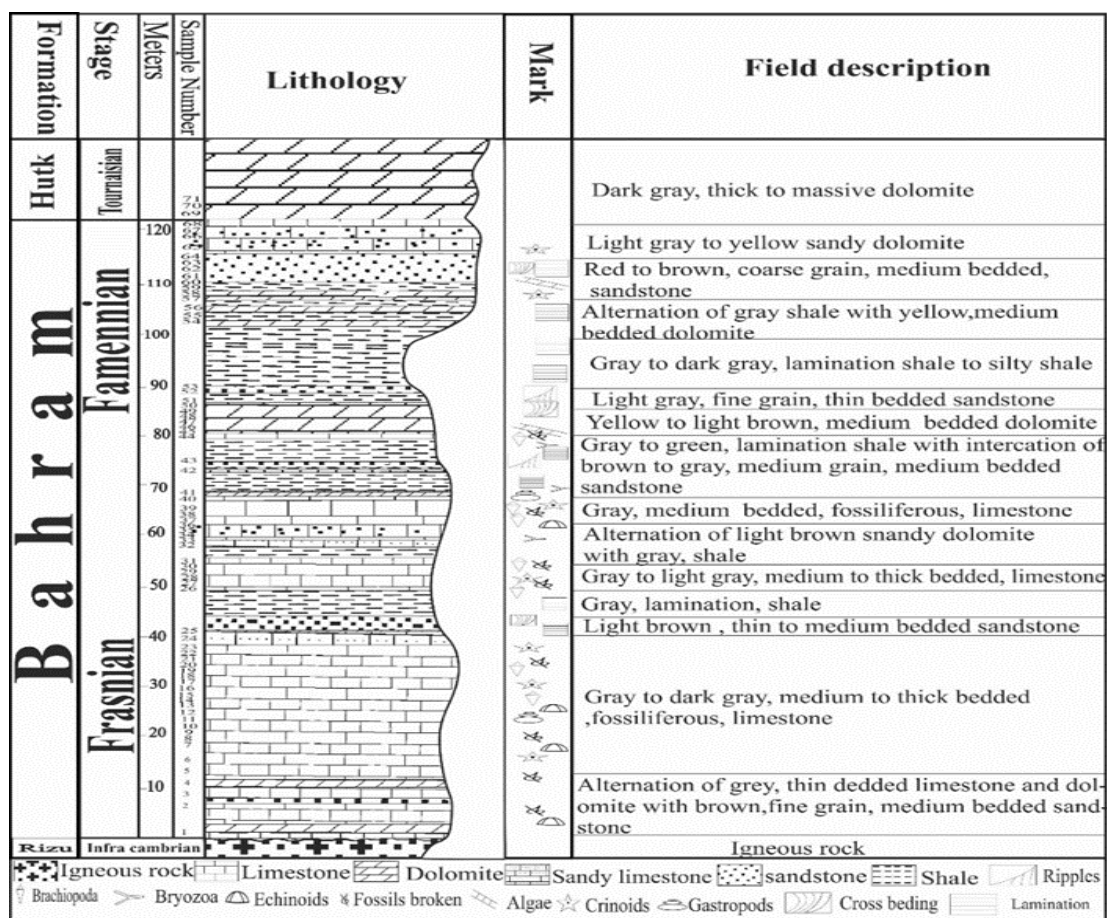


Fig.4- Lithostratigraphic column of the Bahram Formation in the Shams Abad section (according to field observation).

Microfacies and sedimentary environments

Identification and description of sedimentary facies are the most important factors for interpreting the sedimentary paleoenvironmental conditions [51]. Bahram Formation consists of carbonate and clastic rocks with a high variety of skeletal and non-skeletal grains, calcite cements, micrite, late diagenetic dolomites and sedimentary structures. Based on lithology, textures and fossil contents of outcrop samples from the study area, there are ten micro/petrofacies types in the Bahram Formation. Five main facies belts are distinguished from distal to proximal, these are: shallow open marine, shoal, lagoon, tidal flat and shore (Fig. 8). These facies belts are described briefly below:

1. Quartzarenite

The siliciclastic sediments are widely distributed in the studied formations. Quartz is the dominating framework grain in the studied thin sections (Fig.5A). The quartz sandstone facies consists of brownish gray, medium beds of fine to coarse grained, moderately to angular to subrounded, sand-sized monocrystalline quartz. Recycled micritic grains are moderately sorted, with a grain-supported texture, set in calcite spar. The high compositional and textural maturity in the Bahram Formation quartzarenite, as well as trough and planar cross-bedding, ripple marks (Mega ripple) that are symmetric and laminations indicate a high energy depositional environment for this facies (Fig. 5 B, C, D & E). These types of ripple marks are known to be characteristic of a coastal environment [32]. Vertical grading of the quartzarenite to lithic sandstone, cross bedding, and a vertical association of the clastic facies with carbonate tidal facies point to sedimentation in a shallow supratidal to an upper intertidal (foreshore to shoreface) environment [15]. In general, fining upward cycles of sandstone with features such as wavy and interference ripplemarks and cross-bedding shows that the petrofacies in the studied area was deposited in a coastal environment [5].

2. Shale

Shale layers show thickness of less than 1 m and are intercalated with carbonates and sandstones (Fig. 5F). There is typically a delicate and visible lamination in which individual lamina is characterized by normal grading and an erosional base. The shales show two different colors including light brown fissile with horizontal lamination (silty sand) and grey to dark grey (calcareous biogenics) shale form. Laminated shale contains very fine to fine, angular to sub-angular quartz grains, clay lamina and bioclastic debris. Fine quartz grains are abundant (<10%) in some parts silty sand shale form. The calcareous biogenics shale form include bioclastic debris and bioturbations. Fine to medium grained quartz, bioclastic debris and bioturbations in shale form show normal marine condition in a lower shoreface environment (such as mud flat). Shale units are deposited from suspension because of the absence of current and wave formed structures. The grain size, bioturbations and bioclastic debris indicate that the light brown and gray shales were deposited in a low energy marine setting in an intermediate continental marine environment [54]. Also the bioturbated shales that are intercalated with sandstones indicate mixed mud-sand tidal flat deposition [38].

3. Dolostone

The dolostones are dark gray in color, very hard and alternate with shales. Dolomite bed thicknesses are variable. Primary structures are rare but some faint laminations are present in some horizons. The faint laminations in some dolostones are probably owing to microbial binding. Petrographically, the dolostone is composed three types of dolomite crystals were identified in the Bahram Formation (very fine crystalline, fine crystalline, medium crystalline (Figs. 6 A, B and C)). The relics of original allochems including crinoid stems and brachiopod shells are also present (Fig. 6D). Given the texture and fine crystal in the dolomites, the retention of the presence of quartz grains scattered and iron oxide (hematitized) in the very fine crystalline dolostone of the Bahram Formation. In some dolostone samples due to the obliteration of fossils and sedimentary structures, it is difficult to determine the depositional environment of dolostones. However, [28] and [15] placed such facies in supratidal–intertidal zones.

4. Dolomitized fenestral lime mudstone

This facies is characterised by yellow– light brown, medium to thick bedded, fine grain dolomite without any fossils or sign of fossils (Fig. 5I). Fenestrate structures are well developed. Birdseye or fenestral structures are typical products of shrinkage and expansion, gas bubble formation, and air escape during flooding, or may even result from burrowing activity of worms or insects [42]. Due to fine grain crystals, lack of fossils, and the presence of bird's eye structure, this facies was accumulated in low-energy tidal flat environment. This dolomite formed under near surface, low energy conditions, possibly in a tidal flat setting [15 and 60].

5. Silty lime mudstone

This microfacies is composed of dense lime mudstones. In this microfacies, scattered silt to sand size quartz grains are present (Fig. 5G, H). Bioclasts and sedimentary structures are lacking. This facies occurs in the middle and upper parts of the Bahram Formation. When the environmental energy is low and then increases abruptly, thin layers of silty and sandstone formed between the mud-sized sediments. The fine grained nature, the presence of quartz grains and the lack of fauna in this microfacies suggest that deposition occurs in a low-energy, restricted environment. According to Flugel [15], sediments composed of a mixture of carbonate and siliciclastic material are common in near coast and inner shelf settings as well as at high latitudes. Increased proportion of sand in mudstone units, present locally, might represent prograding levels of associated tidal channels [52 and 6]. The overall fining-upward trend (Fig. 2) probably resulted from the progradation of the tidal depositional system [37]. Silt-size quartz grains indicate eolian influence and nearness to the shore.

6. Ooid grainstone

This facies consists of thick-bedded, fine to coarse grained ooid grainstone. This microfacies is characterized by a high abundance of ooids with concentric structure (Fig. 6G). Ooids have been influenced dolomitization and hematitization (Fig. 6G). To create ooids, it needs saline and energetic environment [15]. The ooid grainstone represents shallowing-upward upper ramp shoals [36]. They are usually used as proxies for warm water environments or tropical settings [30]. The good sorting of grains and the absence of a fine matrix indicates high-energy condition for deposition of this microfacies. In accordance with the standard microfacies type described by [59] and [15], this microfacies is interpreted as a shoal and beaches environment above the normal wave base, separating the open marine from the more restricted marine environments.

7. Bioclastic grainstone

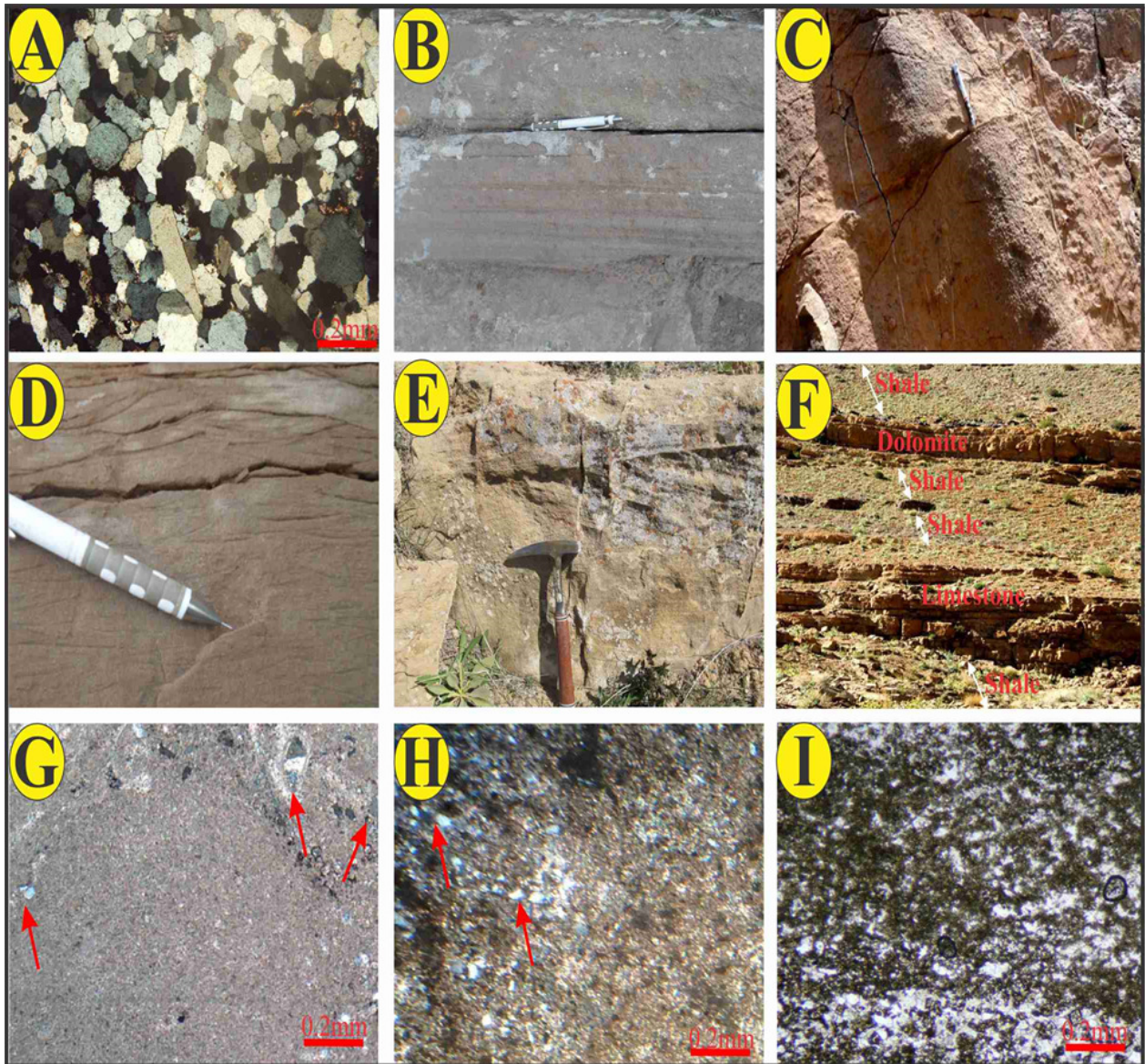
This facies consists of grayish brown to dark gray, medium to thick bedded, fossiliferous beds and is characterized by the abundance of bioclasts. Bioclasts of this microfacies belong to gastropods, brachiopods, coral and echinoderms (Fig. 6E, F). Grainstone texture and the absence of micritic matrix points, in these facies belt are indicators of high energy environment [61, 39 and 15] Such high energy deposits are typically associated with carbonate shoals and bars on or near the seaward edge of platforms [15, 59 and 48].

8. Interclastic bioclast grainstone

Intraclasts (20%) and peloids (35%) are the dominant components of this microfacies (Fig. 6H). Intraclasts are well rounded with 500 μ m to 4 mm in size. Bioclast include green algae, brachiopods, gastropods, echinoderms, and bi-valves. Some intraclasts are internally homogeneous and consist of micrites, while others display internal compositions such as fossils. The presence of allochems in sparry calcite cement and the absence of micritic matrix points to high-energy conditions. Intraclast grainstones are often interpreted as deposits formed by storm wave erosion, tidal currents and reworking of various sediment types occurring in shallow-marine environments [15]. The sediments would have been deposited in a shoal environment which separating the open marine from more restricted marine environment [15].

9. Bioclastic wackestone/packstone

The bioclast wackestone packstone is composed of thin-bedded, light to dark gray fossiliferous, beds. The skeletal grains include echinoderms, debris fossil and brachiopods that are with a micritic mud matrix (Fig. 6I). The occurrence of thin bedding in a bioclastic wackestone/packstone is characteristic of low rates of sedimentation and a high-energy depositional environment. This facies was deposited in the distal part of a carbonate platform or a shallower part of an open marine environment. Presence of micrite and lack of detrital grains and strati-graphic position demonstrate to deposit it under wave base and conditions of still environment [7].

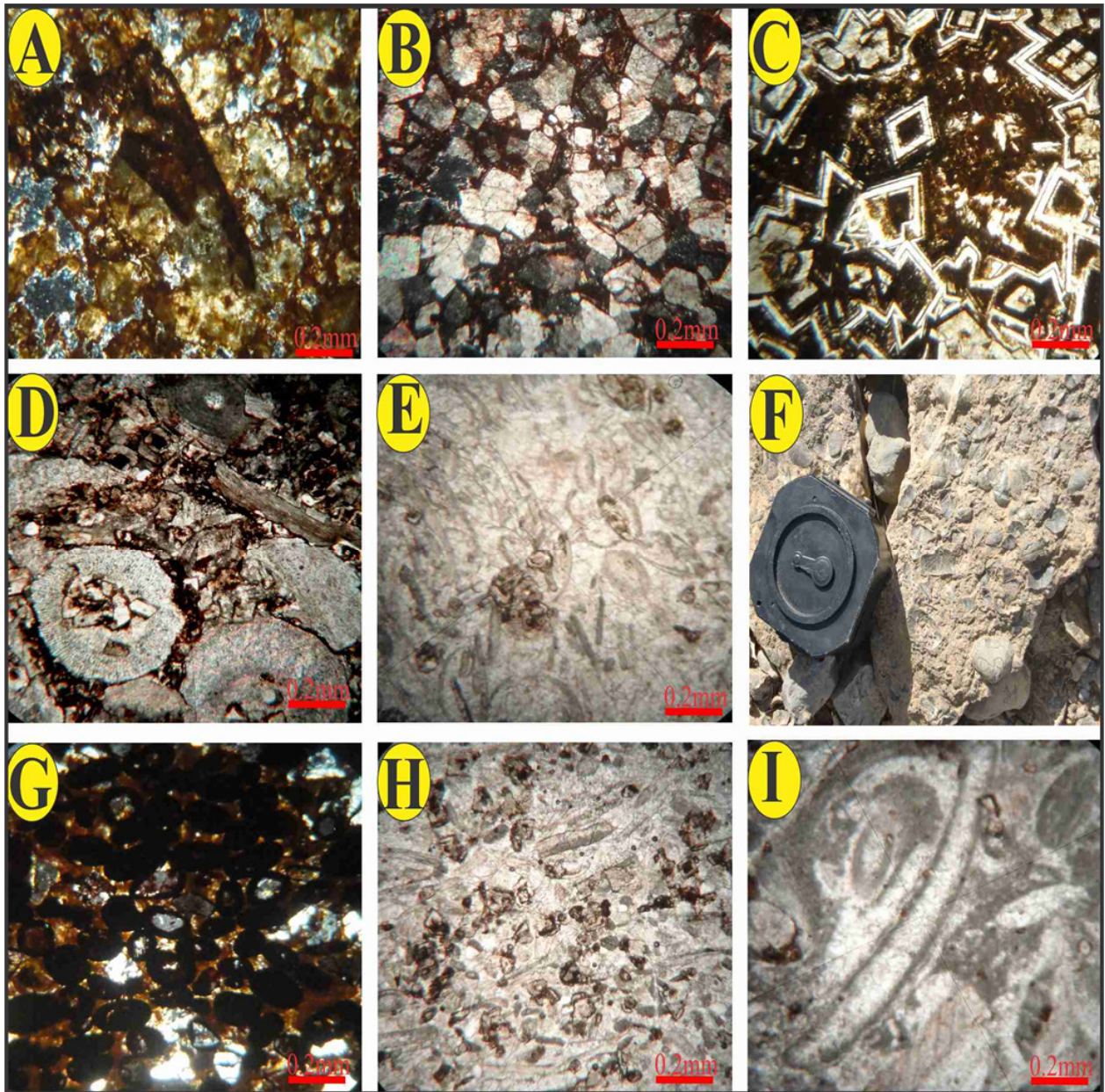


Figs.5- (A) Photomicrograph quartzarenite petrofacies with quartz grain, XPL. (B) Lamination in the quartzarenite. (C) Mega ripple mark in Sandstone bed. (D) Succession quartzarenite with trough cross-bedding. (E) Succession of planar cross-bedding (arrows) in the quartzarenite. (F) Succession alternation shale, dolomite and sandstone. (G) (H) Photomicrograph silt size quartz grain mudstone microfacies with silt size quartz grain (arrows), XPL. (I) Photomicrograph fenestral dolomitic mudstone, XPL.

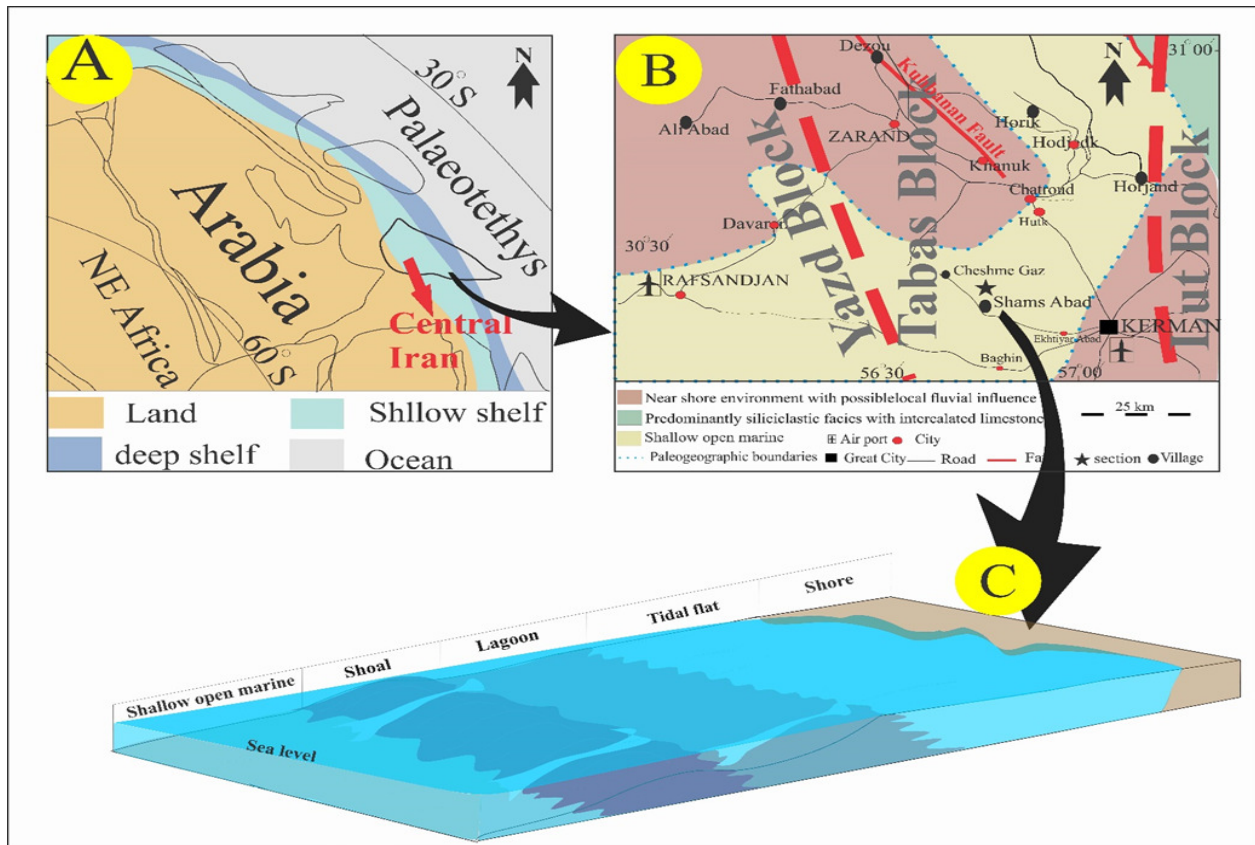
Facies association and depositional model

This model provides a reference for the interpretation of vertical facies changes in terms of Walther's Law of succession of facies [33]. This facies model should be regarded as a predictive tool and not as a paleogeographic reconstruction for a certain time interval. Palaeogeographic maps of the Late Ordovician to

Late Devonian of northern Arabia suggest that north Africa and Arabia formed a broad stable continental shelf on the northern margin of the Gondwana supercontinent [29, 41, 56, 57, 40 45, 10 and 25] bordering the Paleo-Tethys ocean (Fig. 7A). Wendt and his coworkers [56] divided Bahram Formation palaeogeography in three part, at the north of Kerman (Fig.9B). The recognized microfacies have allowed the differentiation of several carbonate-clastic marine system environments including shore (with mud flat), tidal flat, lagoon, shoal and shallow open marine environments. The following microfacies criteria, which are observed in microscopic examination of formation and investigation of lateral and vertical variation of facies show an idealized model summarizing the distribution of the encountered microfacies in a carbonate-siliciclastic mixed shelf that developed during the late Devonian in north Kerman is given in Fig. 7C.



Figs.6-Photomicrograph showing: (A,B and C) Dolostone, XPL. (D) Photomicrographs of the dolomite facies with bioclast dolomitization, XPL. (E) Bioclast grain stone microfacies, PPL. (F) Succession bioclast grain stone with abundance debris brachiopods. (G) Ooid grainstone with hematitized, XPL (H) Interclastic bioclast grainstone microfacies, PPL. (I) Bioclastic wackstone/packstone microfacies, PPL.



Figs. 7- Paleogeographic map of central Iran during the Late Devonian. (A) Paleo-tectonic, Paleogeographic and lithology map of the north Gondwana land and Central Iran plates during the Late Devonian (modified from [46]). The Central Iran is shown with chromatic line. (B) Paleogeographic map of north Kerman during the Upper Givetian to Famennian (modified form [56]). (D) Schematic block diagram for depositional model of the Bahram Formation in the study area with available facies belt.

Sequence stratigraphy

Sequences are defined as a conformable succession of genetically related strata, bounded at the bottom by angular unconformities and top by disconformities and/or their correlative conformities [49 and 50]. The angular unconformities are defined with Rizu Series overlain by Devonian-Carboniferous sequence and represent a significant time hiatus. The major control on deposition is relative sea-level change, determined by rates of eustatic sea level variation and tectonic subsidence. We constructed a sequence stratigraphy for the studied sections based on standard classification of Catuneanu et al. [3 and 4] that particular depositional system tracts are developed during specific phases of the sea-level change's curve: lowstand (LST) transgressive (TST), and highstand (HST) systems tracts. Third-order sequences are often seen as resulting from a combination of tectonic and glacioeustatic accommodation changes [47]. The studied formation is interpreted as having been deposited through a single 3rd order depositional sequence. The sequence stratigraphical study of the Bahram Formation led to recognition of three depositional sequences (Fig. 8).

• Sequence1

The depositional sequence 1 formed during the Frasnian-Famennian transgression (Figs. 8 and 9). At Shams Abad area, this sequence is 48 m thickness. The hiatus which comprises a time span of up to 200 Ma can be explained by a widespread emersion [56] thus the boundary between the Rizu Series and Bahram Formation is interpreted as a sequence boundary SBI. The upper boundary of the sequence 1 is composed of a thin to medium bedded sandstone with planar cross bedding thus it is interpreted as a sequence boundary SBI. It begins with 12 m thick sediments of the limestone and dolomite, tidal flat facies. These are interpreted as the lowstand systems tract (LST) of this sequence. The change from tidal flat belt to-wards shallowing (lagoon

and shoal) is interpreted as the transgressive surface (ts). The TST of sequence 1 shows a retrogradational stacking pattern and is made up of a range of depositional environments from tidal flat to lagoon, and shoal facies. This part of sequence starts with the deposition of silty mudstone and is continued with a lagoonal and shoal grain-supported facies. The mfs is marked by a thin, shallow open marine facies (Bioclastic wackestone/packstone) and separates transgressive systems tract (TST) deposits below from highstand systems tract (HST) deposits above. The HST is characterised by shore and tidal flat environmental conditions (Quartz arenite and diagenetic dolomite with quartz grain). The HST shows a trend to more protected sediments. Third-order accommodation space minimum (Sequence boundary) is characterised by sandstone (Quartz arenite).

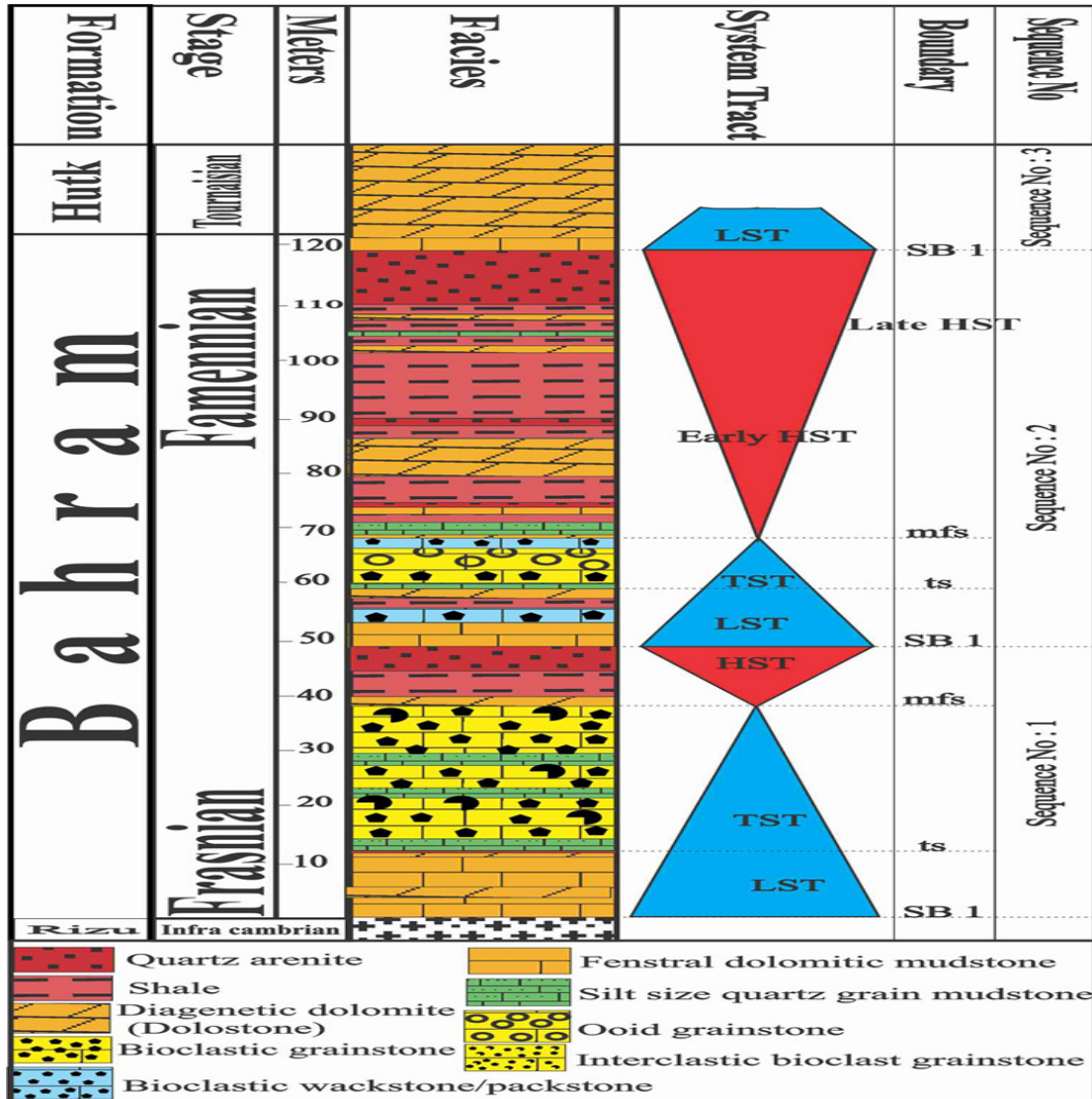


Fig. 8- Facies and sequence stratigraphy correlation chart of Shams Abad section. The recorded four sequence boundaries and depositional sequences are illustrated.

• **Sequence2**

The sediments of sequence 2 are Famennian in age. This sequence is 66m thick and its microfacies association can be grouped into Lowstand, Transgressive and Highstand Systems tracts (Fig. 8, 9). The upper sequence boundary is characterized by thickness sandstone with ripple mark and cross bedding with and is interpreted as a SBI type. The lower part of sequence 2 (LST) is characterized by an alternation of shale, dolomite and limestone with Brachiopod, debris fossil and fenestral fabric. The ts of this sequence is marked

by mudstone with sand grain. Deepening-upward microfacies trends (TST) of sequence 2 is indicated by change from shoal, restricted lagoonal microfacies to open lagoon and open marine facies. The mfs is marked by an open marine microfacies (brachiopod and crinoid wackestone/packstone) and separates TST from HST. HST of sequence 3 shows a shallowing upward trend with passing of a restricted to near-shore lagoonal and tidal flat environment. The 'shaley and sandstone unit' constitutes the late transgressive and the main part of the highstand systems tract of a depositional sequence and grades upward to platform margin facies as a result of late highstand basin ward progradation. The early highstand systems tract in sequence 2 is characterized by a proliferation of silty grain-supported tidal flat, lagoon and mud flat facies. The upper part of sequence 2 (late HST) indicates upward shallowing trend. This part mainly comprises the tidal flat and shale facies association. Progradation of strata into late HST is inferred by dolomite and mudstone facies (Figs. 8 and 9). The shallowing-upward trend from tidal flat/lagoonal to supratidal is indicative of a progradational stacking pattern during the highstand systems tract [31]. Dolomitized supratidal deposits with microbial mats, dis-solution features, birdseyes, which appear in the late HST indicate subaerial exposure [4].

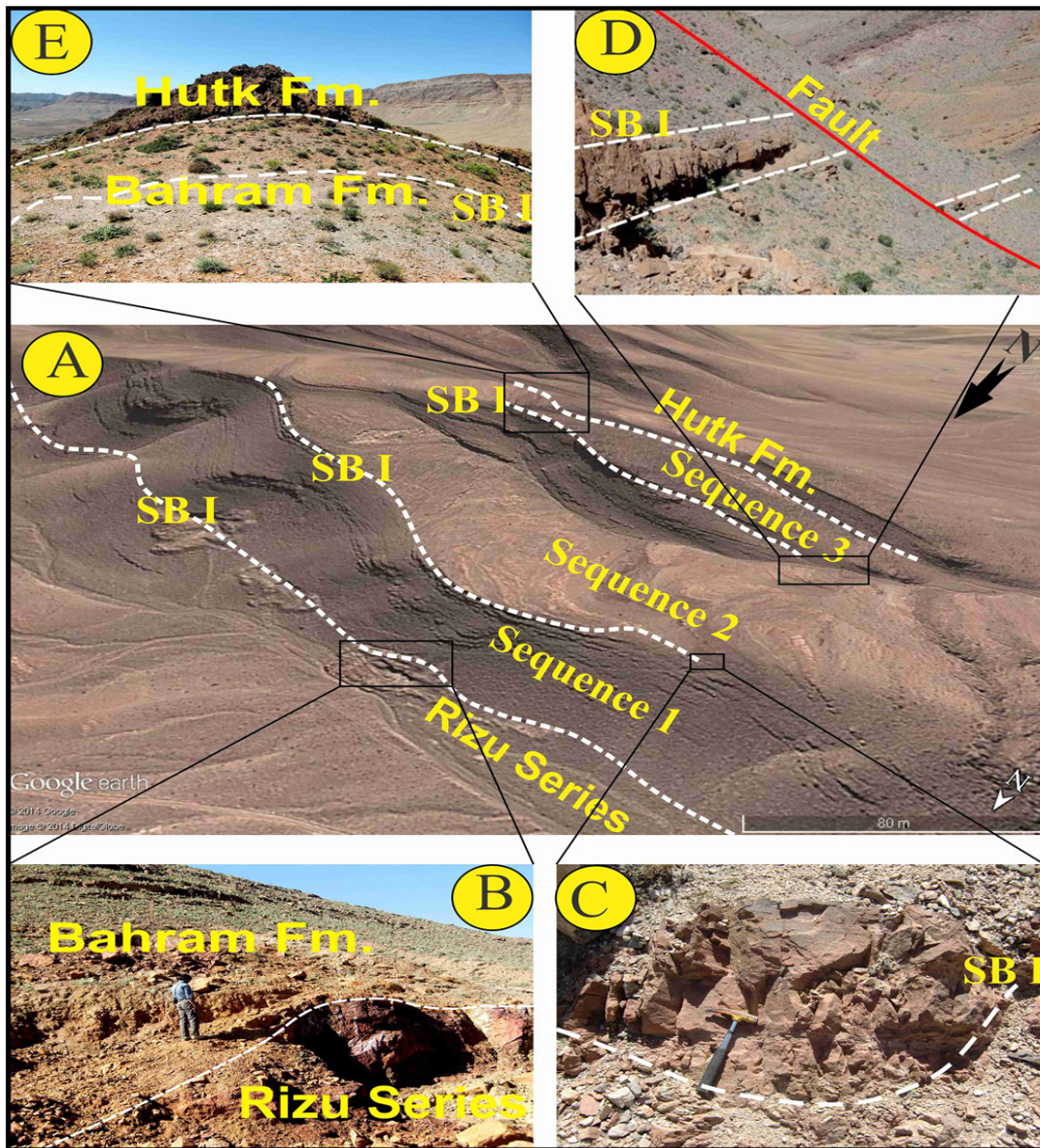


Fig. 9- (A) Panoramic photo of the Sams Abad section and depositional sequences. (B) Close-up view of sequence 1. (Bahram Formation is rested on Rizu Series disconformably) (C) Close-up view of sequence boundary between sequence1 and sequence2. (D) Close-up view of sequence boundary between sequence2 and sequence3. (D) Close-up view of top Bahram Formation is overlain by Hutk Formation paraconformably.

• Sequence3

Increasing accommodation space, resulting from shore transgression, is recorded by the deposition of shore sediments. The lower part of sequence 1 (LST) is characterized by a dolomite alternation of limestone and with interaction of limestone (mudstone). The end of the LST sediments is placed on the Hutk Formation, which is overlain by the TST carbonate deposits of the Hutk Formations (Fig. 8, 9).

Conclusions

Due to tectonic activity and hiatus in north of Kerman area, the upper and lower boundary of the Bahram Formation is doubtful. In parts of Kerman area, this hiatus is marked by metamorphic, volcanic, [2, 56]. The basal part of Bahram Formation of the Frasnian age in the section transgressively overlies the top of Rizu Series and continues to the Famennian. It perconformably underlies the gray limestones and massive dolomites of Early Carboniferous Hutk Formation. Bahram Formation, in the north of Kerman basin mainly consists of carbonate/clastic (lime-stone, dololimestone, dolomite sandstone, shales). Nine micro/petrofacies types dominated. The late Devonian part of the succession is the most different in the north of Kerman city (south Tabas block) [56] with a dominance of siliciclastic deposits of shelf to shoreline environments. The sedimentation of the Bahram Formation took place on a shallow carbonate-siliciclastic mixed shelf setting, in a facies belt consisting of a shore, tidal flat, lagoon, barrier shoal and shallow open marine. The regional differentiation most likely reflects their position on separate tectonic blocks on which different facies conditions developed due to different tectonic movements. In accordance with the global trend, the Middle Devonian to Upper Devonian is uniformly dominated by the production of massive carbonates, mostly of reefoidal origin, although a thick intercalation of biolaminated carbonates in the study area records a long period of restricted extremely shallow water conditions. The three upward-shallowing cycles have been recognized from the Bahram Formations and are related to sea level variations. Two 3rd-order depositional sequences complete in shallowing patterns were recognized in the studied formations. Sequences 3 joint with Hutk Formation in shallowing patterns were recognized in the studied formations. The predominant facies associations developed in Formation demonstrated an overall transgression-regression cycle in the middle to late Devonian in chapter south Tabas block.

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