Sedimentary environment, sequence stratigraphy and paleogeography of Paleozoic Pre-Khuff succession in southern Iran (Zagros and Persian Gulf)

Afshin Asghari

National Iranian Oil Company

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ASGHARI Afshin

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Jury

J.F. DECONINCK, Professeur	Université de Bourgogne	Examinateur
J.F. BOUNCRISTIANI, Maitre de Conférence	Université de Bourgogne	Examinateur
E. VENNIN, Professeur	Université de Bourgogne	Directrice de thése
G. DESAUBLIAUX,	GDF SUEZ	Invité
M.G. H.GOODARZI, Chef de département de géologie	N.I.O.C.E.X.P.	Invité
F. BOULVAIN, Professeur	Université de Liège	Rapporteur
J.E. REYNAUD, Professeur	Université de Lille 1	Rapporteur

Laboratoire d'accueil: UMR/CNRS 6282

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RÉSUMÉ

Au cours du Précambrien et du Paléozoïque, la zone Zagros faisait partie de la plate-forme Arabe. La succession Paléozoïque du Zagros s'étend du Cambrien au Permien. La zone d'étude se situe entre le Lurestan et le Fars au sud et le Golfe Persique. Au Paléozoïque, dans le secteur du Zagros, la série stratigraphique comprend quatre séquences de second ordre (ou cycles tectonostratigraphiques) séparées par d'importantes discordances. L'eustatisme est le principal facteur déterminant les changements d'espace d'accommodation, même si localement dans l'Ouest du Haut Zagros, le rôle de la tectonique régionale et des mouvements diapririques est important.

Le premier cycle (Ordovicien) est composé des Fomrations Seyahou (Floien-Katien) et Dargaz (Hirnantien). Il enregistre une évolution depuis des milieux profonds à peu profonds de plate-forme siliciclastique. La Formation Seyahou est découpée en sept séquences de troisième ordre et la Formation Dargaz correspondant à des dépôts glaciogènes comprends deux séquences de troisième ordre.

Le deuxième cycle (Silurien inférieur) correspond à la Formation Sarchahan. Il est caractérisé des environnements marins peu profonds à profonds comprenant des marnes riches en matière organique. Il est composé par deux séquences de dépôt de troisième ordre. Localement à Kuh e Gahkum, la base de cette Formation enregistre des dépôts peu profonds de transition continental-marin dont la présence est attribuée à la mise en place d'un diapir dans le secteur.

Le troisième cycle (Dévonien) correspond à la Formation Zakeen. Les dépôts évoluent depuis des environnements continentaux à marins. La fin du Dévonien est marqué par des environnements marins carbonatés dans le sud de la région du Fars et dans le Golfe Persique. Il est divisé en trois séquence de troisième ordre. L'absence de la Formation Zakeen à Kuh e Surmeh et Kuh e Siah, et sa présence dans les régions voisines (Naura, West Agar, etc ...), suggèrent une activité diapirique, expliquant l'érosion locale des séries sédimentaires.

Le dernier cycle de la succession pré-khuff dans la zone d'étude correspond à la Formation Faraghan du Permien inférieur. Il surmonte une discontinuité attribué au jeu de l'orogenèse Hercynienne et est déposé dans toute la région du Zagros et dans le Golfe Persique. La Formation Faraghan correspond à des environnements de plaine côtière à marins et est divisé en trois séquences de troisième ordre.

La succession du Paléozoïque est marquée par plusieurs discordances majeures. Elles résultent de: (i) variations majeures du niveau marin en lien avec des variations glacioeustatiques comme pour le cas de la glaciation Hirnantien à la fin de l'Ordovicien et celle du Carbonifère; (ii) Un soulèvement du Moyen-Orient à la fin du Silurien associé aux mouvements épeirogéniques et à une baisse importante du niveau de la mer; et (iii) l'orogenèse Hercynienne allant de la fin du Dévonien à Carbonifère. Localement, les discordances peuvent aussi s'expliquer par le jeu de remontée diapirique induisant une érosion locale, comme c’est le cas dans les secteurs de Kuh e Surmeh et de Kuh e Gakhum pour des periodes de temps différentes.

Mots clés: Paléozoïque, pré-Khuff, la région de Zagros, Iran, plate Arabique, faciès sédimentaires, environnement de dépôt, stratigraphie séquentielle, paléogéographie, paléoclimats.

ABSTRACT

During the Precambrian and trough the Palaeozoic, the Zagros area was part of the Arabian platform (Beydon, 1993). The Palaeozoic succession of the Zagros extends from Cambrian to well-developed Permian deposits. The study area ranges from the Lurestan to Southern Fars onshore and to the Persian Gulf offshore wells. From Ordovician to Early Permian Palaeozoic succession of the Zagros area comprises four second-order tectonostratigraphic depositional cycles separated by major unconformities. Eustatic sea-level variation is the main controlling factor for accommodation space changes, whereas in West High Zagros and Kuh e Gahkum, the role of regional and salt tectonic activities may be also important.

The first cycle (Ordovician) is composed of the Seyahou (Floian-Katian) and Dargaz (Hirnantian) Formations. They are characterized by deep- to shallow-water (offshore to shoreface) siliciclastic deposits. The Seyahou Formation contains seven 3rd-order depositional sequences. The glaciogenic Dargaz Formation consists of one 3rd- order sequence.

The second cycle (Early Silurian) corresponds to the Sarchahan Formation is composed of two 3rd-order depositional sequences. They are characterized by deep-marine offshore to upper offshore environments. Locally in Kuh e Gahkum the base of the Formation presented continental fan delta deposits due to the salt tectonic activity.

The third cycle (Devonian) corresponds to the Zakeen Formation and divided in three 3rd-order depositional sequences. It started with the deposition of continental to near-shore marine clastic deposits. In Late Devonian, it evolved to carbonate marine deposits in the south of Fars area and the Persian Gulf. The lack of Zakeen Formation in Kuh e Surmeh and Kuh e Siah, and is presence in neighboring areas (Naura, Aghar, etc…), suggests structural salt plug activities (Jahani, 2008). This megasequence is capped by a major unconformity related to the Hercynian orogeny.

The last deepening-upward cycle of the Pre-khuff succession in the study area is the Early Permian Faraghan Formation. It capped the Hercynian orogeny and deposited throughout the Zagros area from Lurestan (west) to Bandar Abbas (East) areas as well as in Persian Gulf. The Faraghan Formation divided into three 3rd-order depositional sequences and deposited in coastal plain to shallow-marin near-shore environment. Basinward, in the deeper part (e.g. Kuh e Faraghan), they are replaced by marine upper offshore deposits.

The Palaeozoic succession is marked by several major unconformities associated with hiatus. They resulted from: (i) major sea level drops at the end of the Ordovician related to the Hirnantian glaciation (Ghavidel Syooki et al., 2011) and of during the Carboniferous related to the southern Hemisphere glaciation (Golonka, 2000); (ii) An uplift of the Middle East area at the end of the Silurian associated with epeirogenic movements (Ala et al., 1980; Berberian and King, 1981; Al-Sharhan and Nairn, 1997) and a major sea level drop at the end of Silurian (Al-

Husseini, 1991,1992; Sharland et al., 2001; Konert et al., 2001; Haq and Al-Qahtani, 2005); and (iii) impact of the Hercynian orogeny spanning from the Late Devonian up to the Carboniferous (Al-Hosseini, 1992; Sharland et al., 2001; Konert et al., 2001, Faqira et al., 2009).

Key words: Palaeozoic, Pre-Khuff, Zagros area, Iran, Arabian Plate, Sedimentary facies, Depositional environment, Sequence stratigraphy, Palaeogeography, Palaeoclimate.

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GENERAL INTRODUCTION

Main objectives

The Zagros area is one of the most important hydrocarbon systems in the world containing 8.6% of the oil and 15% of the gas proven world reserves and its tremendous hydrocarbon potential has always been an attractive topic for geologists. Geological investigation in the Zagros goes back to the first oil discovery, approximately one century ago. The study area ranges from the Lurestan to Southern Fars onshore and to the Persian Gulf offshore wells related to Cambrian to Early Permian succession. During the Precambrian and trough the Palaeozoic, the Zagros area was part of the Arabian platform (Beydon, 1993). The Arabian platform was an eastern extension of Gondwana. The Neoproterozoic recording the Panafrican tectonic phase was composed mainly of granites and organized in several basins (Stöcklin, 1968; Becker et al., 1973; Berberian and King, 1981; Davoudzadeh, 1997; Horton et al., 2008) infilled at the end of Neoproterozoic by a thick evaporitic succession named “Hormuz salt”. The Zagros area and its sedimentary succession are clearly impacted by the deformation of ductile evaporites (Jahani, 2008). The Early Cambrian is characterized by massive post rift clastic continental sediments covered by marine carbonate deposits that expends throughout the Middle to Late Cambrian (Mila Formation). The Ordovician time is characterized by a siliciclastic succession deposited on a gently dipping, wide and stable marine shelf bordering the Paleo-Tethysan Ocean (Senalp et al., 2001). It is capped by “Hot- shales” deposits that expended throughout the Silurian. At the end of the Silurian, an uplift in the Middle East area was related to epeirogenic movements (Ala et al., 1980; Berberian and King, 1981; Al-Sharhan and Nairn, 1997) and associated with a major sea level drop (Al-Husseini, 1991, 1992; Sharland et al., 2001; Konert et al., 2001; Haq and Al-Qahtani, 2005). The resulting hiatus is recorded in Southeast Turkey, Syria, Iraq and Oman and probably corresponds to the “Pre Tawil Unconformity” in Saudi Arabia. The Late Silurian hiatus was followed by a Devonian transgression caused by a global sea level rise (Vail et al., 1977). During the Middle and Late Devonian, a major hiatus resulted from epeirogenic tectonic movements in many parts of the Arabian plate (Al-Husseini, 1991). The latest Silurian and Devonian periods are poorly recorded due to erosion associated with Hercynian tectonism (Konert et al., 2001).The Hercynian tectonic period corresponds to a hiatus induced coinciding with a huge sea-level drop (Konert et al., 2001; Sharland et al., 2001). During the Mississipian (Lower Carboniferous), a horst and graben system is observed displaying a N-S orientation (Sepehr & Cosgrove, 2004). Dercourt et al. (1986), Kazmin (1991), Stampfli et al. (1991), Golonka (2000), and Heydari (2008) proposed a Permian age for the Neo-Tethyan rifting resulting in the separation of the Arabian platform from Cimmerian Plate (Central Iran, Afghanistan, Tibet, Sanandaj-Sirjan). However, Berberian & King (1981), Glennie (2000), Sepehr & Cosgrove (2004) and Bordenave (2005) attribute an Upper Trias age to this structuration.

The Palaeozoic succession also records two periods of glacial events in Gondwana: Late Ordovician and Carboniferous. During the Late Ordovician, Gondwana was covered by an extended ice-cap (Vaslet, 1990; Scotese, 1999). This glaciation developed during the Hirnantian (Brenchley et al., 2003; Sutcliff et al., 2000). In the Zagros, Hirnantian glaciation is recorded at Kuh-e Faraghan in Bandar Abbas area (Ghavidel Syooki et al., 2011). During the Late Carboniferous and Early Permian the southern regions of Pangea (southern South America and southern Africa, Antarctica, India, southern India, and Australia) were covered by ice. Alternating cool and warm periods during the ensuing Carboniferous Ice Age coincided with cycles of glacier expansion and retreat.

The first objective of this study was to present the main facies evolution of the Palaeozoic, to discuss the depositional environment and will tend to propose new palaeogeographic maps of the Palaeozoic succession.

The second objective will focus on the hiatuses observed all along the Palaeozoic succession and the inducing factors.

Industrial interests

Since 1990's, the oil and gas exploration are evolving towards deeper and more complex objectives. In the Middle-East, this evolution was declined by shifting from the conventional carbonate oil bearing Mesozoic and gas bearing Upper Permian towards deeper, relatively tighter and stratigraphically more complex clastic Palaeozoic section.

This exploration began in Oman and Saudi Arabia, where these Formations are shallower, and resulted in the discovery followed by production of several fields. The reserves discovered are situated mainly in the Devonian and Early Permian sections (Konert et al., 2001). The remaining potential is considered to be high as the exploration remained marginal in the other countries of the Persian Gulf.

As other international companies, NIOC are considering the exploration of these deeper targets, and the knowledge of the Palaeozoic succession and its depositional environment has a direct interest for the Groups. The Companies are involved in several licences in Middle East, in which the Devonian and Early Permian levels present a high potential. Moreover, the deeper levels of the Ordovician and Silurian, although they are not a direct target for today's exploration in the area, have a major importance as they are lateral analogues of the "Hot Shale" source rock and of the reservoirs of fields situated in Algeria and Libya.

The goal of this Ph.D is to answer to several uncertainties concerning Palaeozoic succession. The Lower Permian succession (called Unayzah/Haushi in Arabian Countries, Al Khlata/Gharif in Oman and Faraghan in Zagros) are a complex stacked pattern of continental clastics, varying from braided stream, flood plain, lacustrine deposits and Aeolian deposits that can fill paleoglacial valleys. The depositional sequence evolves while going further east, passing into more distal succession. However, the lateral evolution and the palaeogeography of this succession are badly understood. This weak knowledge is even truer for the older levels of Carboniferous or Devonian, Silurian and Ordovician.

The stratigraphical study of this succession in Iran will allow obtaining distal control points to fit the palaeogeographical interpretation of the area. This will help to better prognoses and assess the prospectively of the area. In addition, identifying hiatuses and regional markers will allow understanding the tectonic and sedimentary phases of this area.

The Ph.D is in coordination with NIOC that will assume the logistic for the outcrop observations.

The first objective will tend to determine the stratigraphic architecture throughout the pre-Khuff deposits. This approach will be based on facies and palaeolog datas.

The second is to constrain and compare at a reservoir scale the dimension and distribution of sand deposits during different geologic periods.

Methodology and scientific organization

The approaches applied in this study are listed below:

1- Identification of the regional stratigraphic framework of the Paleozoic Pre-Khuff series in Zagros area based on outcrops data and subsurface data (well logs, cores, cuttings, and paleologs).

2- Identification and dating of the major sequences and markers based on palynologic studies

3- Sedimentary facies analysis and depositional environments

4-Correlations of the depositional sequences and stratigraphic distribution through time in order to approach correlation at the Iranian platform scale and Arabian plate.

5- Reconstruction of palaeogeographic maps

All these initial objectives will be addressed in this Ph.D thesis. This study focused on the Palaeozoic deposits cropping out in the Bandar Abbas and Fars area (Eastern Zagros). Surface data collected during the Ph.D have been complemented and compared with numerous sub-surface sections. The study of sub-surface sections has been carried out in an earlier stage and now is available from the NIOC archive.

Main topics

This Ph.D thesis is arranged in six Chapters.

Chapter 1, as a general part, introduced the geology and geography of the study area based on previous carried out investigations.

Chapter 2 shows the different methods used for facies analysis, X-ray diffraction, gamma ray, sequence stratigraphy, lithostratigraphy and palynology in the Zagros area. At the end of this chapter some of the outcrop sections are described based on the stratigraphic studies such as lithostratigraphy and biostratigraphy.

Chapter 3 focused on litho-stratigraphy of Palaeozoic succession in the Zagros area including litho-stratigraphic sections, overview photos and geological maps.

Chapter 4 concentrates on depositional environments, regional sequence stratigraphy and paleogeography of the Pre-Khuff succession (Ordovician, Silurian, Devonian and Permian) in Fars, Bandar Abbas and Persian Gulf.

Chapter 5 described unconformities and major erosional surfaces, depositional environments, sequence stratigraphy and palaeogeographic distribution through time in order to approach correlation at the Zagros scale and Arabian plate. Various paleogeographic maps for the area are presented and discussed in detail through time.

Chapter 6 summarizes the conclusions.

States of the art

The limited Palaeozoic outcrops in the Zagros are insufficient to enable the geological evolution of this part of the Arabian Plate during this period to be determined. Many studies have been carried out in the Zagros area since 1929, and all proposed different structural classifications for this area. Several numbers of stratigraphical and palynological studies have been published, although many other unpublished reports are still available in the NIOC archives.

A summary of the main publications of the Zagros area is given below:

Boeck, Lees and Richardson (1929) addressed the entire Zagros area, extending from Iraq in the north to the Strait of Hormuz in the south, bounded by Makran zone located east of the Strait of Hormuz. These authors have mentioned different tectonic zones between the Mesopotamian depression (foreland) and the northeastern part of the Arabian Plate (Zagros allochthon): 1- Foreland autochthon and parautochthonous zone which is simply folded. 2- Fold and thrust units involving the Palaeozoic and Mesozoic platfonn senes of the fonner Arabian passive margin. 3- Far traveled radiolaritic and ophiolitic units. 4- Allochthonous Cretaceous carbonates units. 5- Allochthonous Palaeozoic metamorphic units.

Schroeder (1944) described the tectonics and architecture of the Zagros (Iran), and presented from the southwest to the northeast the following zones: 1- The Arabian foreland 2- The folded Zagros 3- The far travelled Palaeozoic thrust sheets 4- The radiolarite and ophiolite zones (basinal and paleo-oceanic units). He evidenced the similarities between the sedimentary contents of the Arabian plate and the more distal portions of the passive margin, which are currently thrusted in the Zagros Mountains.

Falcon (1958) published a paper called "oil fields in Iranian Zagros" focusing on stratigraphy. This paper dealed mainly with the gently folded parautochthonous successions of the outer Zagros (Sananndai-Sirjan ranges) (Fig. I.1), which thickness ranges from 6 to 12 km.

Stocklin (1968) has carried out a structural analysis in Iran. He considered that the main Zagros Thrust was a fundamental limit separating the Inner Zagros (Zagros area) from the Outer Zagros (Sanandai-Sirjan ranges) (Fig. I.1). He distinguished a folded parautochthonous sector in the Outer Zagros and a thrust zone in its inner part with Palaeozoic thrust units, including radiolarites and ophiolite units.

Setudehnia (1975) carried out the earliest work on the Palaeozoic strata in the High Zagros and indicated that the sequence comprised Cambrian clastics and carbonates deposits overlain disconforrnably by Early Permian sandstones which in turn were overlain by Middle- Late Permian carbonates. Late Ordovician to Devonian rocks was not recorded. Three sections have been re-measured and re-sampled at Kuh e Dena and one at Zard Kuh. As a result of this work a 1050 m-thick Middle and Upper Cambrian and Ordovician succession has been identified at Zard Kuh whilst a 900 m-thick Early Cambrian is obsereved at Kuh e Dena. The Ordovician deposits are absent at Kuh e Dena.

Berberian and king (1981) reviewed the geological evolution of the Iranian region since late Precambrian time. The large Silurian-Carboniferous sedimentary gap in the Zagros (following the Ordovician and (or) Early Silurian deposits) is correlated to epeirogenic movements, which led to a regional regression and general emergence of the region. Most of the Zagros basin, which emerged during Late Ordovician- Early Silurian, remained above sea level and underwent erosion until the end of the late Palaeozoic (Hercynian) movements. Following this large middle Palaeozoic (Silurian-Carboniferous) sedimentary gap, the regional shallow marine transgression of Permian sea with basal coastal clastics (Faraghan Formation), overlies with a low-angle unconformity the Ordovician and (or) Silurian rocks. The unconformity observed in the High Zagros indicated the earliest known activity of the High Zagros belt along its northern (Main Zagros) and the southern (High Zagros) fault.

Ghavidel Syooki (1996) worked on acritarch biostratigraphy of the Palaeozoic units in the Zagros basin. He proposed eleven acritarch assemblage zones for the Palaeozoic succession (zone C1 for the Middle - Late Cambrian, zone C2 for the Cambrian- Ordovician, zones O1 to O6 for the Early- Late Ordovician, zones S1 to S2 for the Early Silurian, zone D1 for late Devonian (Frasnian) and zone P1 the Early Permian.

Ghavidel Syooki (2003) introduced the Zakeen Formation (Devonian) by palynological study in Kuh e Faraghan (Zagros basin). The 65 palynomorphs have been arranged into 7 spore and pollen assemblage zones. Zones I-VI are presented in Zakeen Formation suggesting an Early Devonian (Lochklovian) to Late Devonian (Frasnian) age whereas zone VII suggests an Early Permian age (Faraghan Formation). As main result of this study, the Devonian Zakeen Formation is recorded for the first time in the Zagros basin.

Alavi (2004) has studied regional stratigraphy and its proforeland evolution of the Zagros area. He proposed for the Latest Neoproterozoic through Phanerozoic strata (7 – 12 km thick) four groups of rocks in different tectonosedimentary environments of the Zagros area: *(i)* Neoproterozoic to Devonian Pull-apart and Epicontinental Platform, *(ii)* Permian to Triassic Epi-Pangean Platform, *(iii)* Jurassic to Upper Cretaceous Neo-Tethyan Continental Shelf, and *(iv)* Latest Turonian to Recent foreland Basin. These groups include 11 megasequences. The lowest megasequence (I) represented deposits of pull-apart basins genetically related to Najd strike-slip tectonism of latest Neoproterozoic to Early Cambrian time. This megasequence is overlain by megasequence (II), which comprised the transgressive deposits of a shallow epicontinental platform that covered the region during tectonic quiescence in Middle and Late Cambrian time. Overlying the second megasequence, megasequences (III and IV) contains Ordovician, Silurian, and Devonian siliciclastic strata deposited in a warm shallow sea transgressiv over a platform along the margin of Gondwanan landmass during Permian and Triassic time.

Heydari (2008) worked on tectonics versus eustatic controls on 12 supersequences of the Zagros. They are: (1) Late Precambrian- Cambrian, (2) Ordovician, (3) Silurian, (4) Devonian, (5) Mississippian- Pennsylvanian, (6) Permian- Triassic, (7) Jurassic, (8) Early Cretaceous, (9) Late Cretaceous, (10) Paleocene- Oligocene, (11) Oligocene- Miocene, and (12) Miocene- Pleistocene supersequences. This study reconstructed the relative sea-level history of the Zagros region based on lithofacies characteristics and depositional environments. He confirmed that, the relative sea-level curve for the Zagros Mountains mimicted perfectly the second-order eustatic sea-level curve of Vail et al. (1977).

Zamanzadeh (2008 and 2009a,b) studied the petrography, sedimentary environment, diagenetic alterations and sequence stratigraphy of the Zakeen (Devonian) and Faraghan (Permian) Formations in Kuh e Faraghan and Kuh e Gahkum. Kuh e Gahkum comprises different conglomerates, sandstones, siltstones, shales, dolomites and limestones, meanwhile in Kuh-e Faraghan the main lithologies corresponded to sandstones, siltstones and shales for clastics and some dolomite layers and limestones. The Zakeen Formation presented a progradational (shallowing upward) stacking pattern, indicating a fall in relative sea-level during Middle to Late Devonian and the Faraghan Formation represented a retrogradational (deepening upward) stacking pattern which resulted from the rise in relative sea-level that continued up to late Permian.

Jahani (2008) mainly worked on the halokinesis in the eastern Fars Arc and adjacent area. He studied the activation of Late pre-Cambrian to Early Cambrian Hormuz salt Formation during and before Zagros Orogeny and showed that pre-existing diapirs controlled the localization of Late Cenozoic folding.

Ghavidel Syooki (2011) has studied the stratigraphic evidence for the Hirnantian (latest Ordovician) glaciation in the Zagros Mountains. He noticed that the effects of the Hirnantian glaciation has been recognised in Kuh e Faraghan and Kuh e Gahkum sections of the Zagros Mountains. The glaciogenic strata have been grouped in the Dargaz Formation, a new lithostratigraphic unit that comprises three progradational/retrogradational sedimentary cycles (bounded by two glacial erosive surfaces), each potentially controlled by the regional advance and retreat of the Hirnantian ice sheet.

Tavakoli (2012) focused on tectonic and thermal evolution during the Palaeozoic in the High Zagros. The most significant geological elements corresponded to large scale faulted detachment folds, associated with a complex system of thrust faults segmented by strike-slip faults. His work suggested that the existence of active Ordovician and/or Silurian “décollements” led to the development of duplex structures which are confined in the core of the anticlines. He also suggested an important heat flow during the Devonian and the erosion of ~3900m of the sedimentary pile prior to the deposition of Permian sequence. This outcome reinforced interpretation of a thermal uplift scenario responsible for pre-Permian vertical movements.

CHAPTER I:

GEOGRAPHICAL AND GEOLOGICAL PRESENTATION

I.1. Geographical Locations

The Zagros area is part of Alpian-Himalayan orogenic belt (Berberian and King, 1981) and located in the northeastern margin of the Arabian Plate (Fig. I.1). This margin, which accommodates more than half the world's hydrocarbon reserves, includes the Zagros and Persian Gulf basins (Sepehr et al., 2004). The Zagros area is about 1800 km long and 200–300 km wide. It ranges from eastern Turkey to the Strait of Hormuz, where it terminated against the Makran zone (Sepehr et al., 2004). It is also bounded by Main Zagros fold trust belt in north and Persian Gulf in south (Motiei, 2003). The Zagros area is divided into three tectonic zones from northeast to southwest: (1) the High Zagros (zone of tectonic activity), (2) the Zagros simply folded belt and (3) the Zagros foredeep zone (Stocklin, 1968). The Zagros simply folded belt is subdivided according to its tectonic and sedimentary evolution into three domains: Lurestan, Izeh and Fars areas (Motiei, 2003). The Fars area is separated into four parts: coastal, subcoastal, interior Fars and Bandar Abbas Hinterland (Fig. I.2).

In the Fars area, field investigations were carried out in Kuh e Surmeh outcrop and neighbouring subsurfaces drilled wells (Fig. I.2). Kuh e Surmeh is located approwimately in longitude 52° 29' E and Latitude 28° 30' N in south of Shiraz city. It is the highest structure in the area with about 2240 m elevation (Soleymani, 1997).

In Bandar Abbas area, the Pre-Khuff series are exposed in Kuh e Gahkum and Kuh e Faraghan outcrops. The anticlines are located in SE margin of the orogen, north of Bandar-Abbas city (Fig. I.2). These structures represented major topographic features and present the highest elevations in the SE Zagros (Tavakoli et al., 2013), exposing rocks as old as Ordovician and Cambrian in their cores.

The western High Zagros is located in the northwestern part of the Zagros within the Zone of activity between main Zagros Fault and High Zagros Fault, and is 30°00' - 33°30' N latitude and 49° 00' - 53° 00' E longitude (Fig. I.2). It is approximately 450 km long and 40 to 80 km wide, the width increasing to the southeastern part (Tavakoli, 2012).

In order to investigate lateral variations in sedimentary deposition and palaeogeography characterization, three subsurface sections in Persian Gulf (Kish, Golshan and Salman) were studied (Fig. I.2).

Fig. I.1: The Zagros area located in the northeastern part of the Arabian Plate. The Arabian plate comprises the Arabian Peninsula together with Jordan, Syria and Iraq. A Zagros crush zones bound the plate to the northeast, and is bounded by Arabian Sea and Gulf of Aden to the southeast, and by the Red sea to southwest (Sharland et al., 2001).

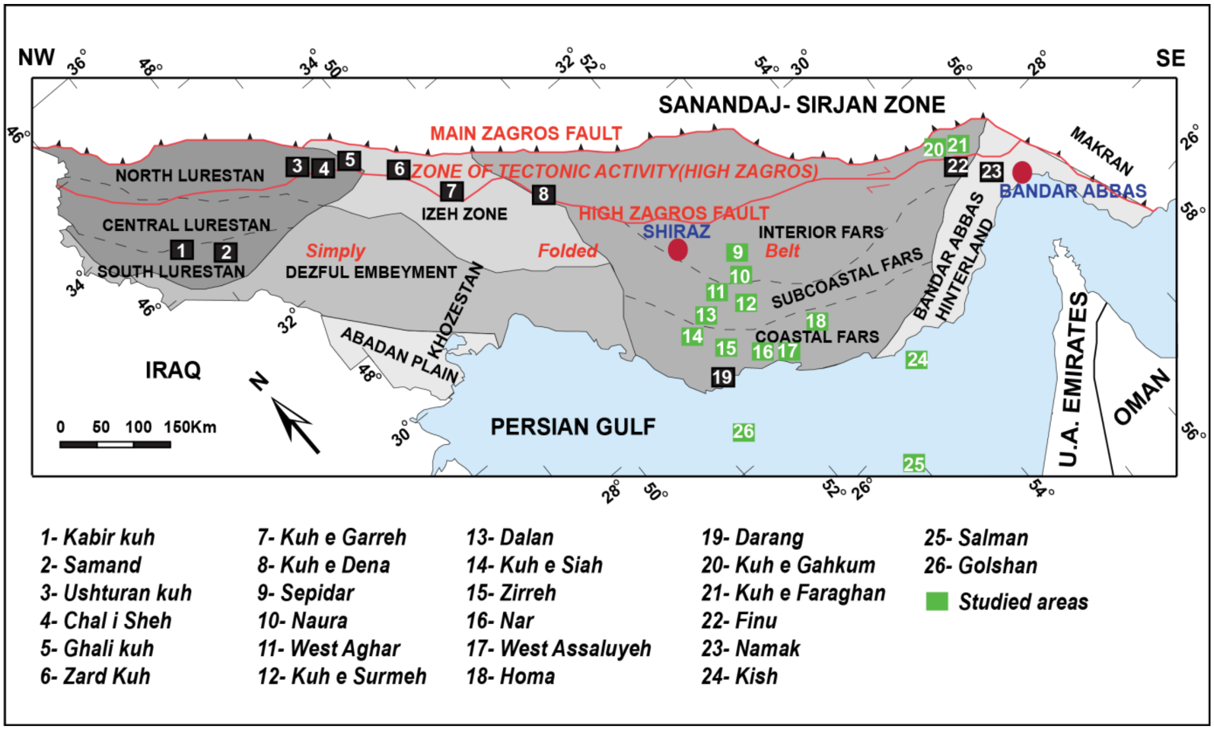

Fig. I.2: Tectonic zones of the Zagros area (Modified after Motiei, 2003) and locations of the surface and subsurface sections. The Zagros area is divided into three tectonic zones from northeast to southwest: the High Zagros (Zone of tectonic activity), the Zagros simply folded belt and the Zagros foredeep zone (Stocklin, 1968). The Zagros simply folded belt is subdivided according to its tectonic and sedimentary evolution into three domains: Lurestan, Izeh and Fars areas (Motiei, 2003). The Fars area is separated into four sectors: coastal, subcoastal, interior Fars and Bandar Abbas Hinterland.

Eleven sections of Palaeozoic deposits are exposed along the north side of the High Zagros Fault, from the west (north of Izeh zone) to the Bandar Abbas area. These sections, consisted of Ushtoran Kuh, Chal i Sheh, Ghali Kuh, Zard Kuh , Kuh e Garreh (Fig. I.2), Kuh e Lajin, Kuh e Sabzu and Kuh e Dena (Fig. III.8) in the West High Zagros area, Kuh e Surmeh in the Fars area, and Kuh e Gahkum and Kuh e Faraghan in the Bandar Abbas area (Fig. I.2). These sections exhibited uncomplete succession of Late Cambrian to Permian deposits. The main Palaeozoic litho-stratigraphic surface and subsurface sections in the Zagros are listed in the Table I.1.

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Table I.1 (Next page): The main Palaeozoic litho-stratigraphic surface and subsurface sections coordinates in the study area.

Well&Surface Section	Longitude	Latitude	Pre Khuff Paleozoic time range
Well Kabir Kuh#1	46° 43' 46.16"	33° 25' 27.22"	Ordovician-Early Permian
Well Samand#2	47° 13' 16"	32° 59' 09"	Ordovician
Ushtoran Kuh	49° 26' 13"	32° 11' 13"	Cambrian- Early Permian
Chal-I sheh	Base: 49° 30' 42" Top: 49° 31' 12"	Base: 32° 55' 06" Top: 32° 55' 14"	Cambrian- Early Permian
Ghali Kuh	49° 35' 37"	33° 00' 14"	Cambrian-Early Permian
Zard Kuh	Base: 49° 56' 10" Top: 49° 56' 55"	Base: 32° 27' 34" Top: 32° 27' 52"	Cambrian- Early Permian
Kuh-e- Garreh	50° 16' 37"	31° 55' 00"	Cambrian- Early Permian
Kuh-e- Dena	Base: 51° 21' 20" Top: 51° 22' 06"	Base: 30° 58' 38" Top: 30° 59' 15"	Cambrian- Early Permian
Well Naura#1	52° 51' 50.12"	28° 40' 38.30"	Devonian- Early Permian
Well West.Aghar#1	52° 29' 53"	28° 43' 40"	Devonian- Early Permian
Well Kuh e Siah#1	51° 42' 34.22"	28° 39' 19"	Ordovician- Early Permian
Well Dalan#1	52° 01' 33.22"	28° 39' 8.13"	Devonian-Early Permian
Well Zirreh#1	51° 56' 55"	28° 10' 22"	Ordovician- Early Permian
Kuh-e- Surmeh	Base: 52° 30' 25" Top: 52° 30' 23"	Base: 28° 31' 27" top: 28° 31' 24"	Ordovician-Early Permian
Kuh-e- Gahkum	Base: 55° 56' 40" Top: 55° 56' 57"	Base: 28° 05' 08" top: 28° 05' 18"	Cambrian- Early Permian
Kuh-e- Faraghan	Base: 56° 19' 34" Top: 56° 18' 42"	Base: 27° 51' 44" Top: 27° 51' 59"	Ordovician- Early Permian
Well Finu#1	56° 04' 27"	27° 51' 23"	Devonian- Early Permian
Well Namak#1	56° 19' 49"	27° 33' 38"	Devonian- Early Permian
Well Golshan#3	51° 21' 30"	27° 20' 41.04"	Silurian- Early Permian
Well Kish#2	53° 56' 07.05"	26° 31' 48.07"	Devonian- Early Permian
Well Salman 2SKD#1	53° 08' 44.10"	25° 32' 59.10"	Devonian- Early Permian
Well Sepidar#1	52° 41' 17.64"	29°04' 21.86"	Ordovician-Early Permian
Well Darang#1	51° 37' 11"	28° 07' 04"	Cambrian-Early Permian

I.2. Regional tectonic and geological setting

The Palaeogeographical evolution of the Zagros can be returned to the late Proterozoic-Cambrian when a series of island arcs and micro-continental fragments accreted against the northeastern margin of the African craton to form the Gondwanaland (Beydoun, 1991). According to Stocklin (1968) and Berberian and King (1981), the Central Iran Plates and Arabian Plate remained attached together during the Precambrian and Palaeozoic and formed the northern passive margin of Gondwana, bordering the Paleo- Tethys Ocean (Beydoun, 1993; Stampfli & Borel, 2004). The Precambrian basement exposed in the western part of the Arabian shield is comparable to the basement known from Central Iran (Al-Husseini, 1988; Alavi, 1994; Konert et al., 2001). This similarity is documented by the granite, gabbro, basalt, amphibolite and schist fragments, which have surfaced via salt diapers (Harrison, 1930; Kent, 1970; Haynes & Mc Quillan, 1974).

A thick succession of Palaeozoic to mid-Cretaceous sediment was deposited over the upper Proterozoic igneous and metamorphic rocks of the basement (James and Wynd, 1965). This significant amount of sedimentation results from rifting and subsidence of the Afro-Arabian plate margin (Stocklin, 1968; Setudehnia, 1975; Berberian and King, 1981). After a long period of tectonic quiescence during the uppermost Precambrian to Carboniferous, which was associated with uniform continental to epicontinental conditions, the geodynamic evolution of the Zagros domain was interrupted by a process of major plate reconfiguration in Permian-Triassic time (Stocklin, 1968; Kashfi, 1976; Setudehnia, 1975). This event was related to the closure of the Paleo-Tethys north of the Iranian Plate and coeval rifting between the Arabian and Iranian plates, resulting in the opening of the Neo-Tethys Ocean. This period was accompanied by a Late Palaeozoic Hercynian orogen between the Carboniferous and Triassic (Stocklin, 1968).

Following the Late Precambrian (Katangan) orogeny and the consolidation of the basement, the Precambrian craton of Iran, Pakistan, central Afghanistan, southeastern Turkey, and Arabia became a relatively stable continental platform with epicontinental shelf deposits (mainly clastics) and lack of major magmatism or folding. This regime presumably lasted until late Palaeozoic time, although there were some epeirogenic movements in the Late Silurian - Early Devonian time (Berberian and King, 1981). During the Precambrian–Cambrian the Zagros area was located at 5°-20° S latitude (Fig. I.3). The latest Precambrian Hormoz Salt was deposited (Fig. I.5) in several intrashelf basins during the first incursion of marine water (Konert et al., 2001; Heydari, 2008). Strata older than the Hormoz Salt have not yet been discovered from the Zagros region but were reported from adjacent areas such as the central Iran microcontinent (Berberian and King, 1981; Beydoun, 1991). The Hormoz Salt was deposited in basins on the peneplaned Arabian shield. The distribution of these sedimentary facies suggests that during the Late Precambrian, Central Iran and Zagros together with the Salt Ranges of Pakistan and Arabia were all part of the same landmass and were partly covered by a common shallow sea. The present Main Zagros reverse fault probably marks the site of a normal fault controlling the sedimentation and was associated with the formation of a passive continental margin to the north, recognizable by the Cambrian (Berberian and King, 1981). After deposition of the Upper Precambrian Hormoz Salt-dolomite, shallow-water red arkosic sandstones and shales of Cambrian age were deposited over a wide area from Arabia in the south to the Alborz Mountains in the north. These deposits also occur in Pakistan, Afghanistan, and Turkey. In this period, Iran, southeastern Turkey, Iraq, Syria, and parts of Afghanistan and Pakistan were connected (via Arabia) to Africa. This stratigraphic evidence is consistent with the palaeomagnetic data (Berberian and King, 1981). The clastic deposits were mainly provided by the Precambrian uplifted granitic and metamorphic highlands in Arabia, Iran, and other nearby continental areas (Berberian and King, 1981).

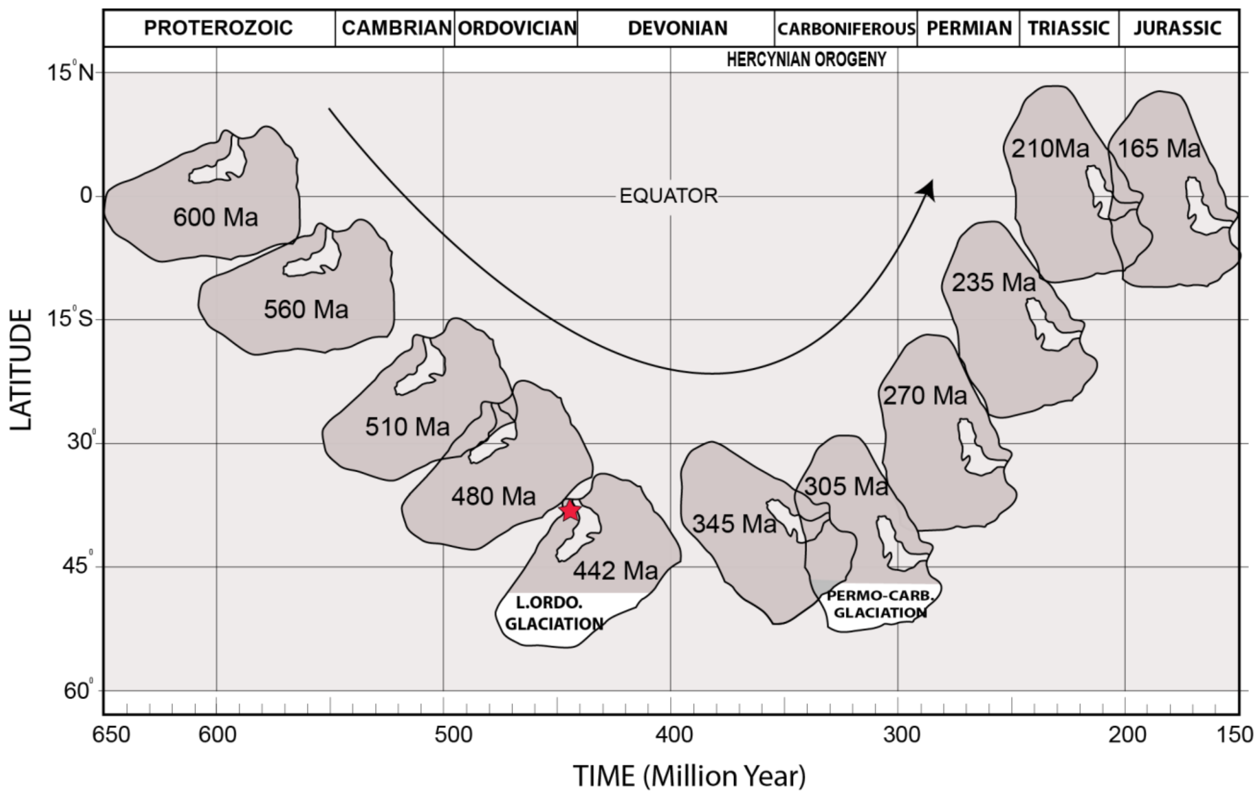

Fig. I.3: Palaeolatitude positions of the Arabian Plate during the Palaeozoic (Modified after Konert et al., 2001). The Arabian Plate rotated about 180° in Devonian time. A major polar glacial pulse covered western Arabia (McClure, 1978; Vaslet, 1990) and affected Bandar Abbas area in the Zagros region in Iran (Ghavidel Syooki et al., 2011)★.

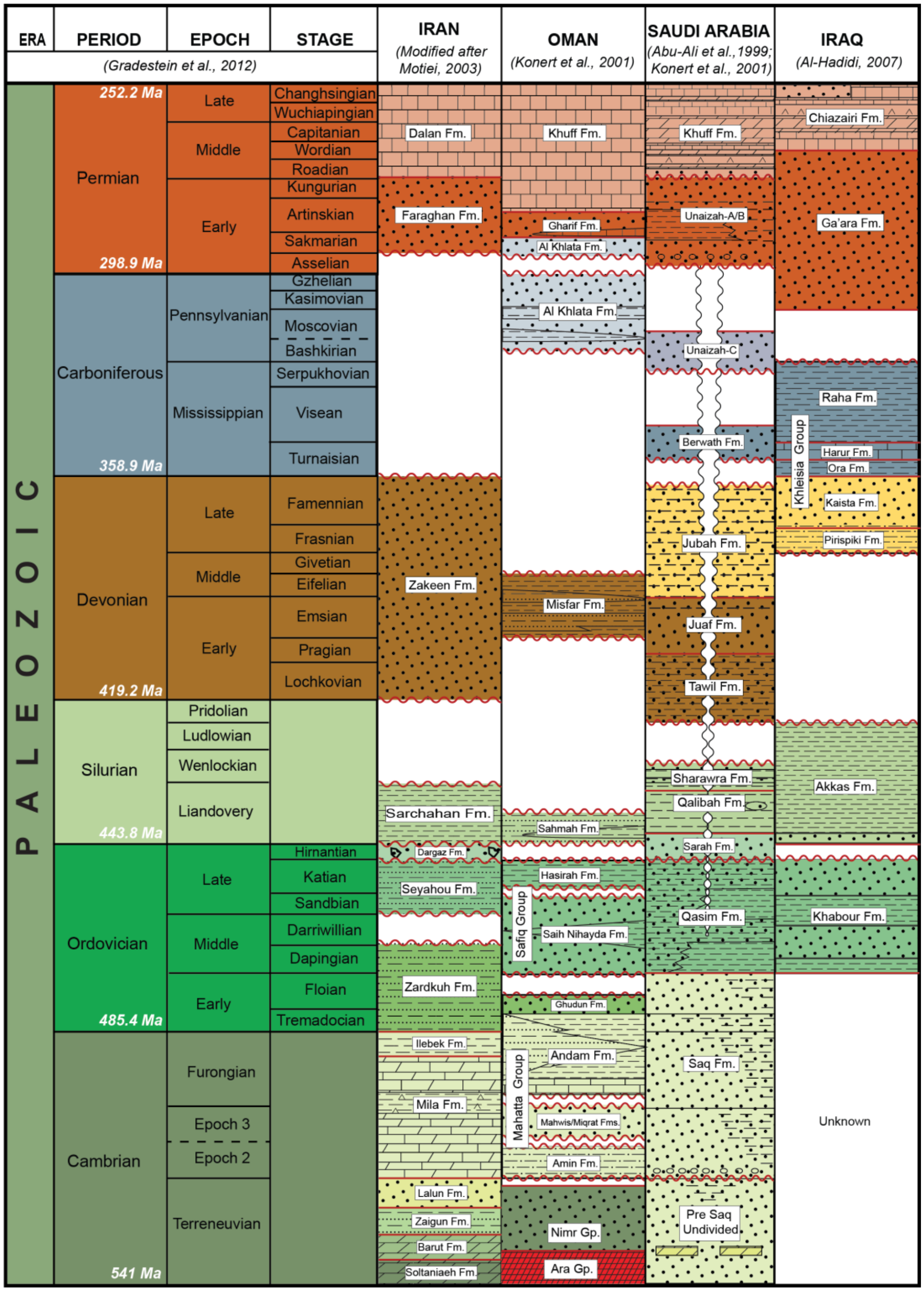

Fig. I.4: Litho-stratigraphic correlation chart in Arabian Plate showing different levels of erosion and discontinuous record of the Palaeozoic succession throughout the Zagros and Arabian Plate.

In late Early Cambrian time, widespread dolomites, marls, and shales with salt pseudomorphs were deposited in a shallow, shelf-sea (Member A of the Mila Formation) in the Zagros Mountains area (Fig. I.5) (Setudehnia, 1975). By the beginning of the Late Cambrian, a fully marine environment with fossiliferous limestones prevailed (Members C of the Mila Formation, middle to late Cambrian).

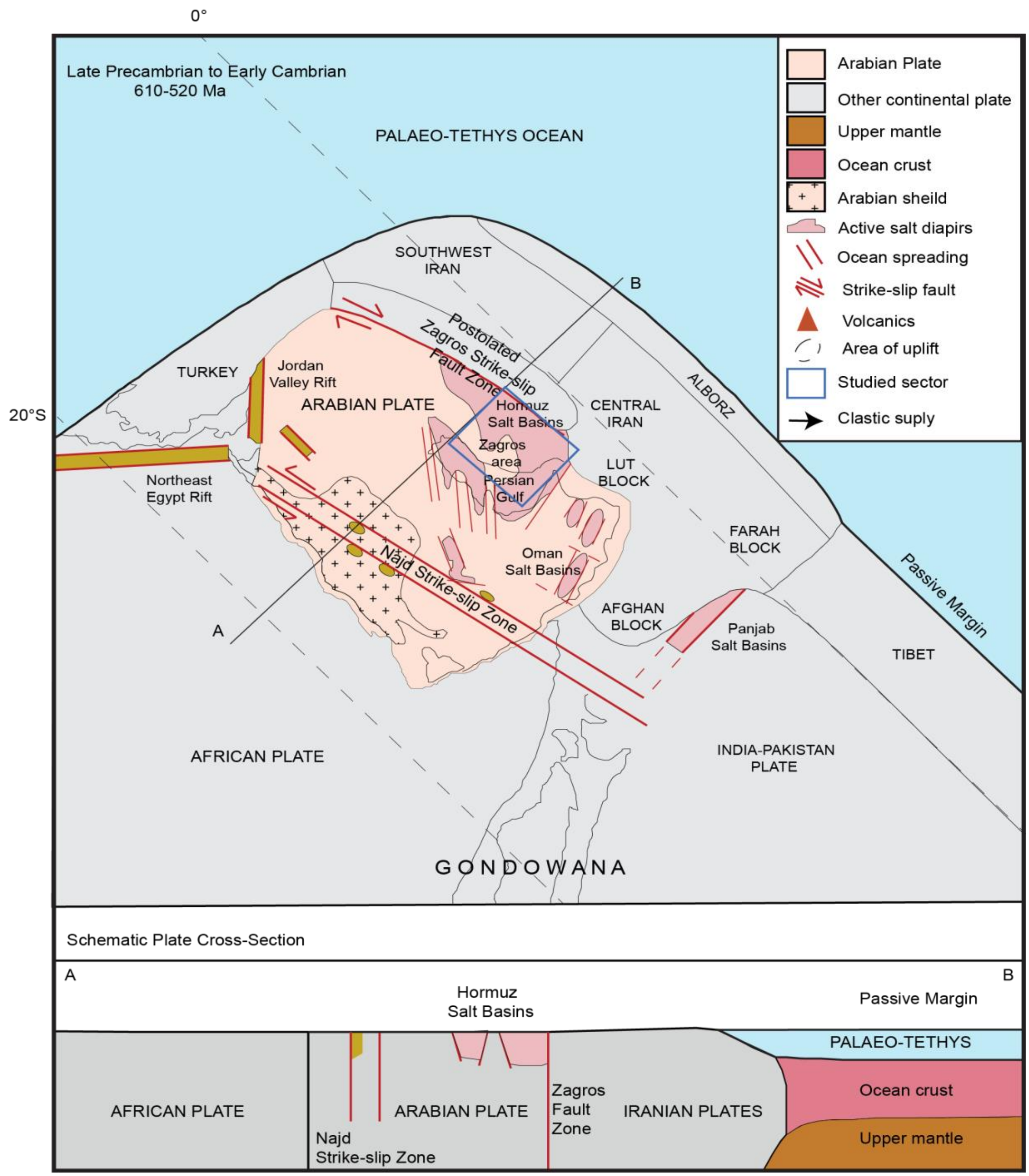

Fig. I.5: Schematic plate reconstruction and cross-section for Late Pre-Cambrian to Early Cambrian (Sharland et al., 2001). Hormuz Salt basins in Zagros activated since Palaeozoic age (Jahani et al., 2009).

During the Ordovician, the Zagros region was part of Arabian plate which occupied an intra-cratonic setting, and drifted towards higher southern latitudes (Beydoun, 1993). A passive margin is interpreted between this part of Gondwanaland and Paleo-Tethys (Sengor, 1990). The Zagros area was located around 30°-35°S latitude (Fig. I.3) (Konert et al., 2001; Heydari, 2008). By Cambrian times, as sea level rose to highstand, Arabian plate was lanketed by about 350 to 1000 m terrestrial and shallow marine sediments (Al-Husseini, 1989). In Early Ordovician as sea level peaked to a highstand, the western part of the Arabian plate was mostly peneplained and almost uniformly blanketed with several hundreds of meters of fluviatile and marginal marine clastics (Al-Husseini, 1989). By the latest Ordovician (about 445 Ma) the plate reached its low-latitude position (Fig. I.3) and a major polar glacial pulse covered western Arabia (McClure, 1978; Vaslet, 1990) and affected Bandar Abbas area in the Zagros region in Iran (Ghavidel Syooki et al., 2011). The deposition of this megasequence (Ordovician) initiated a period of stability in a passive margin setting which lasted until the Permian Period (Golonka, 2000).

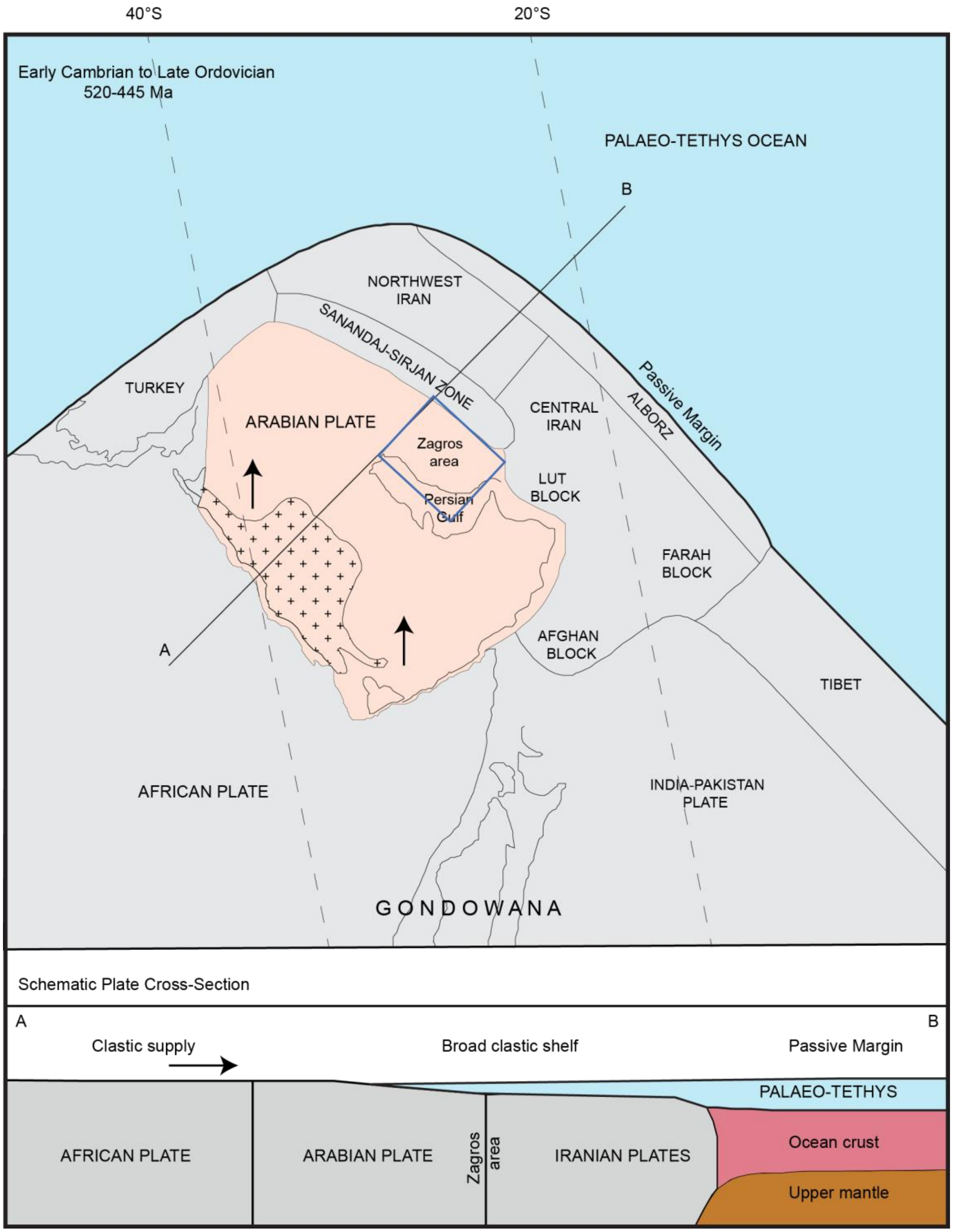

Fig. I.6: Schematic plate reconstruction and cross-section for Early Cambrian to Late Ordovician (Sharland et al., 2001). Transition from continental deposits of Early Cambrian to marine carbonates deposits of Middle-Late Cambrian. *For a key to the symbols used in the map, see Figure I.5.*

During the Silurian the Zagros region drifted southwestward reaching near 30°-35°S latitude (Fig. I.3) (Konert et al., 2001; Heydari, 2008). The post-glacial Silurian transgression is obsereved everywhere in the Arabian plate and characterized by thick, organic-rich shales and fine-marine clastics. The large Silurian-Carboniferous sedimentary gap in the Zagros (Fig. I.4) is apparently the effect of epeirogenic movement, which led to a regional regression and general emergence of the region by Silurian time (Berberian and King, 1981).

During the Devonian the platform started its northerly drift, reaching nearly 35°S latitude (Fig. I.3). Fluvial to deltaic deposits of the Zakeen Formation in the Zagros records transgression. Marginal marine equivalent strata in central Arabia and Central Iran support this interpretation (Konert et al., 2001; Heydari, 2008).

During the Carboniferous the Zagros region was located at around 35°–45°S latitude (Fig. I. 3) but was rotated in an N–S orientation by the Mississippian time (Heydari, 2008). Carboniferous deposits are absent from this area. This hiatus in the Zagros Mountains has frequently been related to the “Hercynian” event (Sharland et al., 2001). However, this time interval coincides with a major glacial episode of the southern Hemisphere (Golonka, 2000).

During the Permian the Zagros region continued drifting northward reaching approximately 10° - 15°S latitude during the Permian–Triassic interval (Konert et al., 2001; Heydari, 2008) (Fig. I.3).

During Late Permian, increasing accommodation space related to stretching of the crust accompanied the Formation of the Neo-Tethys Ocean along the Oman-Zagros suture (Fig. I.8). The break-up unconformity (pre-Khuff unconformity) marked the birth of this new ocean. The base of the resulting megasequence [base of AP6 dated at 255 Ma; (Sharland et al., 2001)] consists of continental to marine sandstones and shales [basal Khuff clastics; (Senalp and Al-Duaiji, 1995)]. These were followed by the deposition of extensive carbonates and anhydrites [Khuff Formation in Saudi Arabia and Oman; Dalan and Kangan Formations in Iran; (Al-Jallal, 1995)] over the entire Arabian shelf in shallow marine to tidal flat environments.

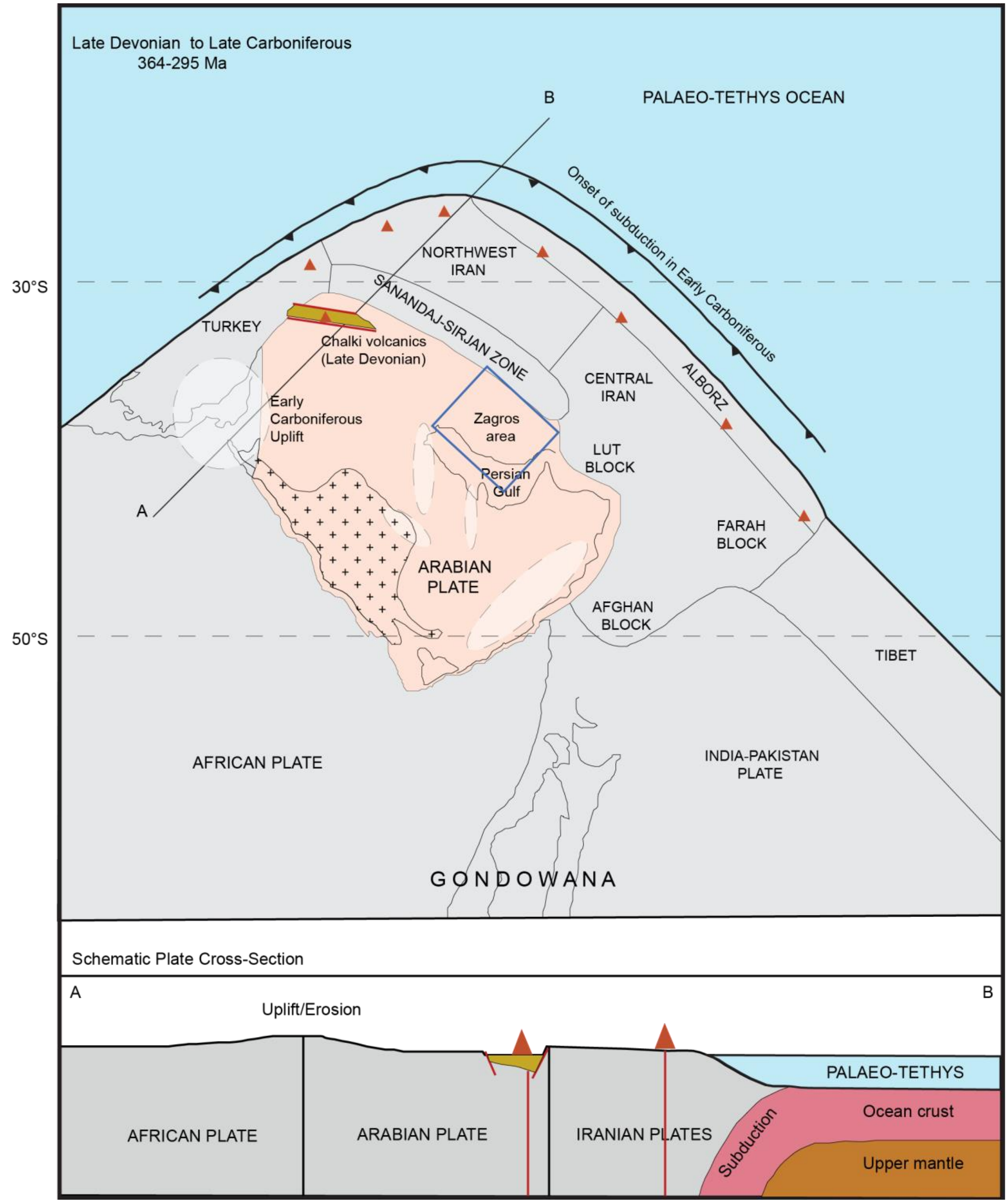

Fig. I.7: Schematic plate reconstruction and cross-section for Late Devonian to Late Carboniferous (Sharland et al., 2001). Hercynian Orogeny affects Zagros area and there is no Carboniferous deposits in Zagros area. *For a key to the symbols used in the map, see Figure I.5.*

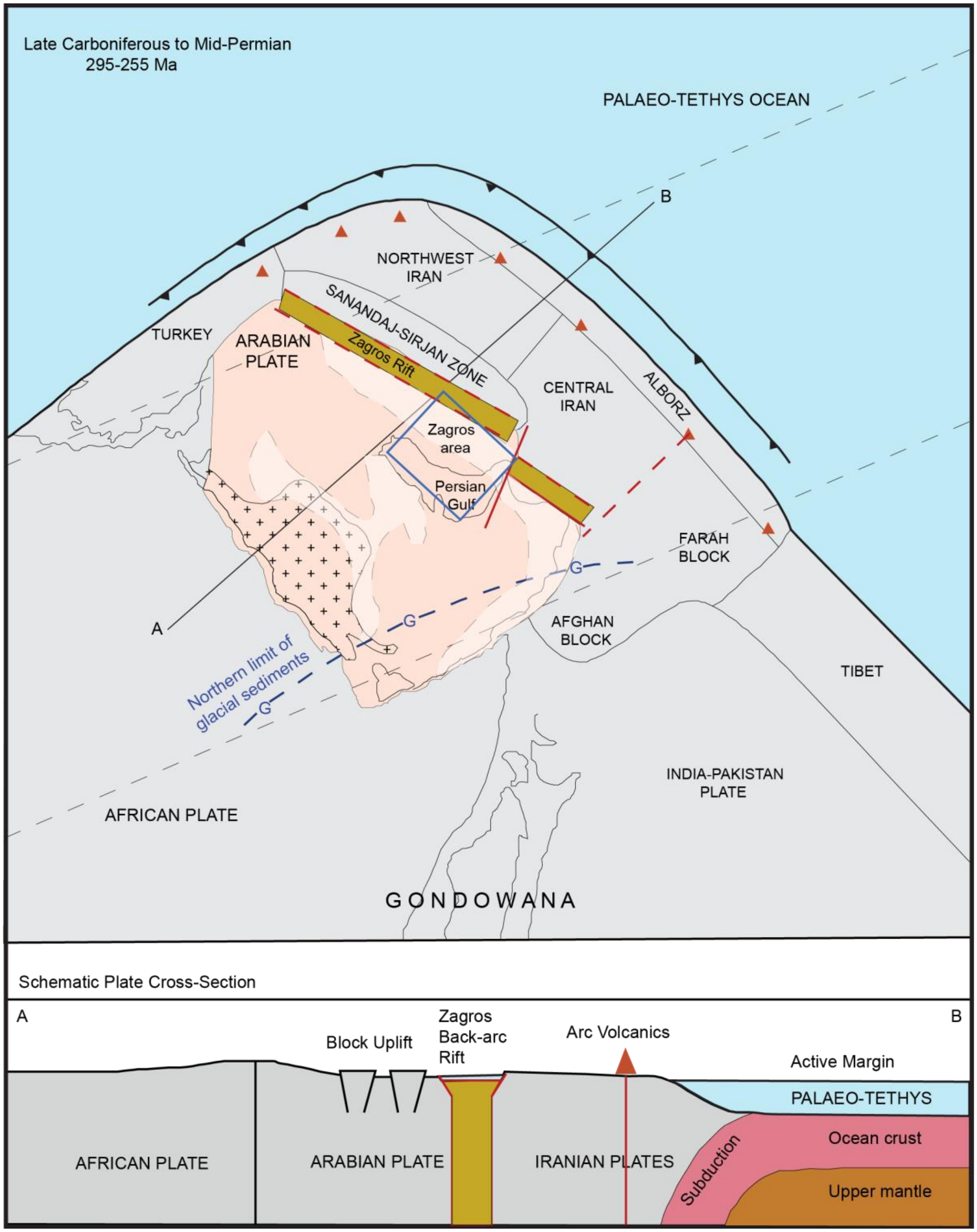

Fig. I.8: Schematic plate reconstruction and cross-section for late Carboniferous to Mid Permian (Sharland et al., 2001). Zagros Back-arc Rift and widespread Permo-Triasic Khuff (Dalan- Kangan Formations) carbonates in entire Zagros area. *For a key to the symbols used in the map, see Figure I.5.*

CHAPTER II:

MATERIALS AND METHODS

II.1. Tools

At the beginning of this study a regional synthesis was compiled, using all available information from the literature, including published and property surface and sub-surface sections, geological and structural maps for Fars, Bandar Abbas and West High Zagros.

II.1.1. Existing data:

A total of 6 outcrop sections and 15 subsurface wells from the zagros area, containing paleontological, Gamma Ray and Sonic/Density logs, were available in the NIOC archives. Data were used to prepare a series of regional transects. The former surface sections and logs employed in transects were redrawn. The main Palaeozoic litho-stratigraphic surface and subsurface sections in the Zagros are listed in the Table I. 1.

II.1.2. Field trips:

In total two field surveys were carried out in the Bandar Abbas (Kuh e Faraghan and Kuh e Gahkum) and in the Fars (Kuh-e- Surmeh) areas. During the fieldwork, the sedimentary structures, lateral variations and depositional geometries were studied in detail. In addition special emphasis was placed on detecting sequence stratigraphic parameters such as stacking patterns and characteristic surfaces. The average sampling interval is less than 3 m.

II.1.3. Thin sections:

A total of 270 samples were collected from Kuh e Gahkum, Kuh e Faraghan and Kuh e Surmeh and 5000 core drilled thin sections, have been studied, for petrofacies analysis.

II.1.4. X-ray diffraction:

Clay minerals are useful tools for studying provenance of the sediments and paleoclimatic conditions in the source area and of the sediments. They can also give information about the burial history of sediments (Moore & Reynolds, 1997). A total 200 samples were collected for X- ray Diffraction analysis to distinguish of clay minerals. This contribution concentrates on the distribution of clay mineral assemblages in the Palaeozoic succession at the Kuh e Faraghan, Kuh e Gahkum and kuh e Surmeh.

All samples are first cleaned and crushed in order to retain the unaltered portions. Products crushing are dried in an oven at low temperature (<40° C) and ground to a fine powder manually with a mortar and pestle. The particle size fraction of clay samples (<2 microns) is then isolated and prepared blades oriented in the detailed Protocol Holtzapffel (1985). A decarbonation is first performed by etching with hydrochloric acid N/5, stirring magnetic. Five to ten cycles of decanting / rinsing allow removal of excess acid and deflocculation of clay minerals. Samples were transferred to measuring cylinders and the clay fraction (less than 2 microns) was isolated from the coarser fraction by the Atterberg method (settling time based on Stoke's Law).

After micro- homogenisation, the sample settles to rest for 1h35min. Fraction of clays less than 2 microns, focused on the top two centimeters of suspension is imposed syringe. Centrifugation at 3500 rpm for 40 min to allow the solution collected obtain a concentrated clay pellet. Each preparation led to the making of two oriented slides.

DRX is applied to the thin slides having undergone three types of processing (Moore & Reynolds, 1997):

- Treatment (Natural drying of the sample at room temperature)

- Saturation in ethylene glycol for 6 hours, so as to vary the thickness of the field interlayer swelling clays

- Heating the oven to 490° C for 2h after 1h temperature rise to disrupt kaolinite, whose characteristic peaks disappear above this temperature , which allows the differentiate correctly chlorite, some of which are common peaks with kaolinite .

The slides are then analyzed by a diffractometer Bruker D4 Endeavor ®, using an anode Type - Kα1 Cu, a filter of Ni, and a detector LynxEye generator operating at a voltage of 40 kV at an intensity of 25 mA. The goniometer of the diffractometer allows a rotation of 2.5 to 28.5 ° with a step of 0.0399 ° for 11 min 34 s and a speed of 15 rotations per minute, for three tests. The result is the production of three diffractograms per sample (Fig. II.1).

The diffractograms are in the form of a series of localized peaks at angles specific to each mineral species reflection. These reflection angles are converted to thicknesses by Bragg's law. Each mineral species has a basal reflection peak, denoted (001) matching the interlayer space. The following peaks, denoted (002), (003), etc. Correspond to harmonics and reflection are located on integer multiples of the basal reflection. For example illite has a peak (001) located at 10 Å. Harmonics (002) and (003) illite are then localized 5 respectively and 3.33 Å.

The diffractograms are analyzed under MacDiff software (version 4.2.5; Petschick, 2000). The semi-quantification of minerals in the presence is checked by measurement of area, rather than by measures peak intensity on glycolated samples where the reflections are more widely spaced (Holtzapffel, 1985; Moore & Reynolds, 1997).

We could identify the four main clay mineral groups: illite, chlorite, illite/smectite, and kaolinite in the sediments of the Productive Series.

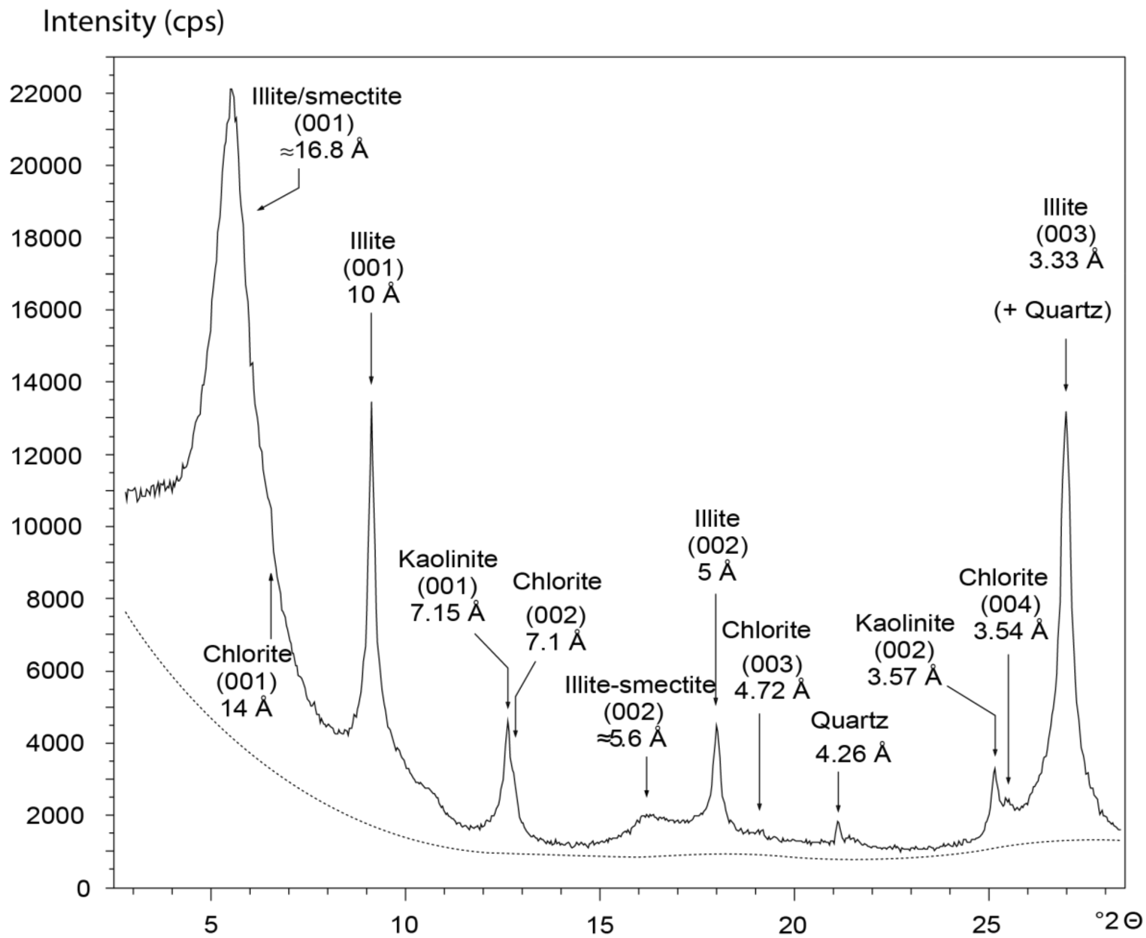

Fig. II.1: Example of diffraction of a glycol blade with location of the reflection peaks of the main species clay minerals (Moiroud et al., 2012).

II.1.5. Gamma-ray:

The measurements are performed in situ spectral gamma-ray with a spectrometer cell SatisGeo ® GS -512 (Fig. II.2). It consists of a probe with a diameter of 12 cm connected by a cable to a unit station that records the measurements. The probe is equipped with a scintillation detector GSP- 3 provided a crystal of NaI (Tl). During a constant acquisition time of one minute, the scintillator captures each gamma radiation and amplifies its signal. The latter is then converted into an electrical signal and counted by the CPU, which can measure the surrounding radioactivity. Each source radioactivity emits its own energy band. The device is designed to separate each band energy, which helps to distinguish the source of energy emitted by the rock (^{40}K, ^{238}U and ^{232}Th) noise background caused by cosmic interaction / atmosphere radiation or by anthropogenic pollution. In from these measurements, the CPU calculates the concentration of these three elements, expressed in % for ppm potassium and uranium and thorium. The amount of total radiation is expressed as ppm equivalent uranium (eU ppm, 1 ppm = 1µg / g; SatisGeo ®, instruction manual)

Fig. II.2: Measurement of gamma-ray with GS-512.

The camera captures 90% of its signal over a radius of about 20 cm (Vacek et al., 2010). Of biases effects to the measured surface flatness exist. If the measured surface is located in a cavity, the " overflow " of material around the probe leads to an overestimation of the value of spectral gamma-ray. Conversely, if the measurement is done on a projection (eg, on a very resistant limestone bed erosion compared marls that frame), the lack of material around the projection leads to an underestimation of the value of spectral gamma-ray. The measurements are taken at the most possible planar surfaces. The marl is routinely updated so as to measure the marl interbanc targeted and no alteration products. Precautions are taken to obtain flat surfaces after refresh cutting. Measuring 30 times the same sample of sandstones and shales tested the reproducibility of the measurements.

In this study, we used different scales for gamma-ray and amount of uranium, potassium and thorium (Table II.1).

Logs	GR(API)	U(ppm)	TR(ppm)	K(ppm)
Scales	0 150	0 40	40 0	0 10

Table II.1: The scales of spectral gamma-ray logs. We used different scales for gamma-ray and amount of uranium, potassium and thorium.

The gamma-ray log is an useful tool for discrimination of different lithologies. Its main use is the discrimination of shales and organig rich shales by their high radioactivity. By contrast, clean sandstones, dolomites and limestones have low gamma ray values.

The principle gamma-ray log shapes are frequently used for interpreting sedimentary cycles or depositional facies. The five log trends (Table II.2) are bell shape (upwards increasing in gamma counts), funnel shape (upward decrease in gamma counts), box-car or cylindrical (relatively consistent gamma readings), bow shape (systematic increase and decrease of gamma counts) and irregular trend (no systematic change in gamma values) (Cant, 1992; Reader, 1993). The shape of the curves can also assist in determining the depositional environment. For example, boxcar-, funnel- and bell-shaped patterns of gamma logs can be correlated with beach sands, prograding barrier islands and intertidal point bars, respectively (Table II.2).

Shapes	Boxcar	Funnel	Bell	Symmetric	Irregular
Gomma-Ray logs					
Gomma counts	Relatively consisting gamma ray reading	Upward decreasing	Upward increasing	systematic increasing and decreasing	no systematic changes
Sequences	Uniform	Finning upward	Coarsening upward	Coarsening and finning upward	Intercalation
Depositional environments	Beach sand Aeolian sand Evaporite	Barrier island Crevasse splay Mouth bar	Point bar Marine channel Tidal creek	Offshore shoal Trangressive-sands	Flood plain Tidal flat Marsh

Table II.2: The gamma ray log and depositional environments (after Cant 1992; Reader, 1993). These informations used to interpretation of lithology, facies, depositional environments and depositional sequences

In this study, the gamma ray of 1200 m thick of the Palaeozoic succession were measured for the first time in three outcrop sections (Kuh e Gahkum, Kuh e Faraghan and Kuh e Surmeh). These data is used to correlation with 11 subsurfaces sections in studied area containing of gamma ray and sonic/density logs. These informations used to interpretation of lithology, facies, depositional environments and depositional sequences.

II.1.6. Biostratigraphy:

Since 1984, more than 1000 surface and subsurface samples from the Palaeozoic succession were examined for palynomorph entites, in order to determine the stratigraphical age of these rock units by Pr. Ghavidel Syooki .The objectives of those studies are to summarized the known stratigraphic range of acritarch assemblages and species from Cambrian up to Permian. These studies confirm that despite of aboundant brachiopod, trilobite and graptolite fauna in the Barut, Zaigun and Lalun Formations (Setudehnia, 1975), these are barren in palynomorph entites (Gahvidel Syooki, 1996). The rest of Palaeozoic (Ordovician to Permian) succession of the Zagros Basin contains rich and well-preserved acritarchs (Gahvidel Syooki, 1996).

Nevertheless, detailed palynological studies in recent three decades by Pr. Ghavidel Syooki, carried out in surface sections (Kuh e Faraghan, Kuh e Gahkum, Kuh e Surmeh, Zard kuh, Chali sheh) as well as subsurface sections (well Dalan#1, well Kuh e Siah#1, well Golshan#3, well Kabir Kuh#1; well Finu#1, well Namak#1, well Zirreh#1, well Naura#1, well Darang#1), have resulted in precise biozonation and age determination of the Palaeozoic rock units in the Zagros area (Fig. II.3).

In this study, we used the Palynological informations of the surface and subsurface sections, to datation and estabilishing the age relationships and correlation of Palaeozoic succession and its depositional sequences.

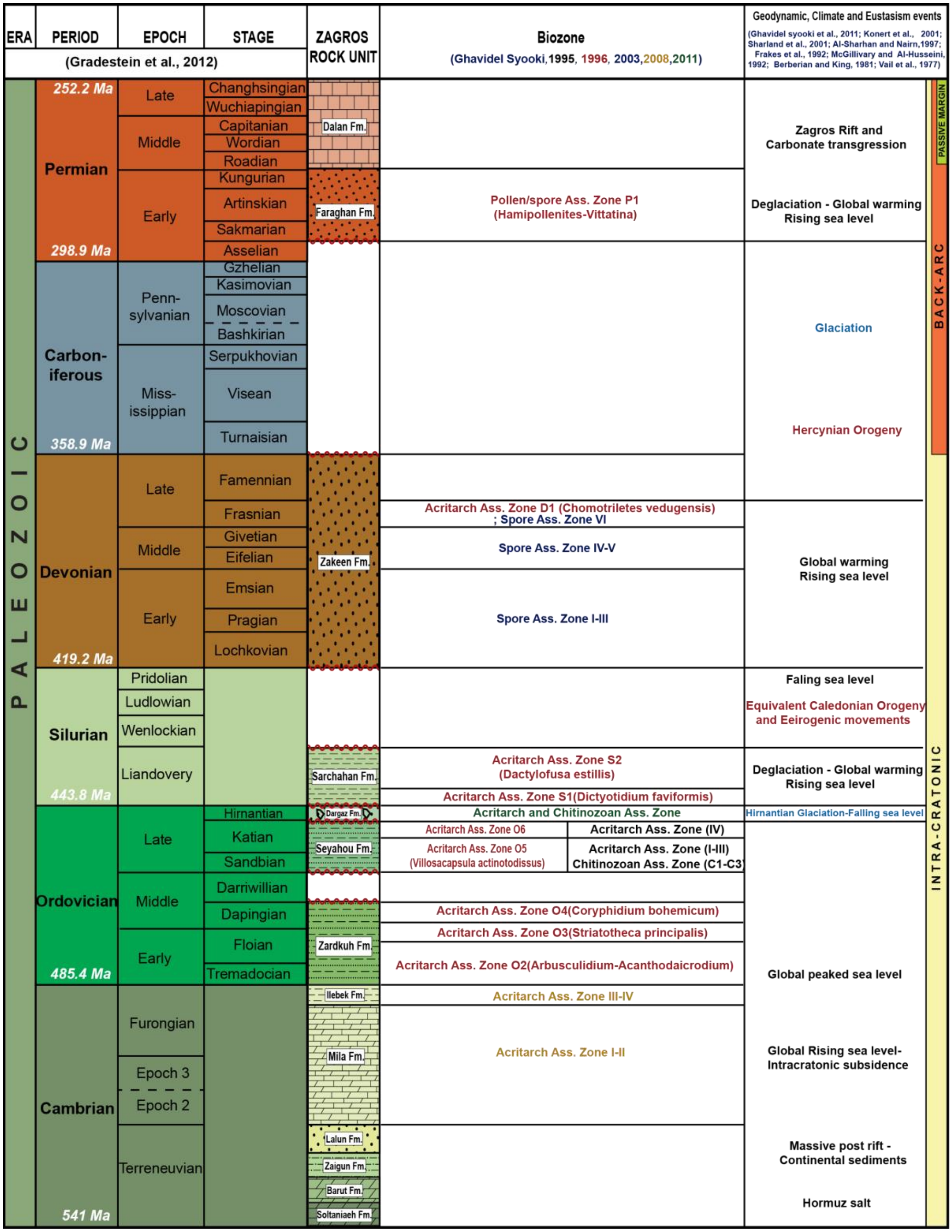

Fig. II.3: Biozonation and tectonic events in Palaeozoic succession in the Zagros area. Showing summarized the known stratigraphic range of acritarch assemblages and species from Cambrian up to Permian deposits and synthesis of the main proposed controlling factors at the origin of the sedimentation and unconformities for the Palaeozoic of Zagros area.

II.2. Conceptual methods

II.2.1. Facies interpretation

Detailed sedimentological analysis of the lithology (texture and composition), geometry, sedimentary structures, gamma-ray log interpretation, clay minerals withusing of X-Ray diffraction, palaeocurrent pattern, stratal stacking relationship and major surfaces in the field, resulted in the identification of several facies. The major controls of sediment architecture are discussed on the basis of the lithofacies and petrofacies characteristics and the nature of sedimentary cycles (Miall, 1996) as well as some facies classification and coding system. Folk's (1974) classification is used for sandstones and Dunham (1962) classification for carbonate rocks.

Five facies tables for Palaeozoic Formations (Seyahou, Dargaz, Sarchahan, Zakeen and Faraghan) are defined based on the combination of field observations and laboratory studies. The facies are grouped to facies association considering being genetically or environmentally related (Reading, 1996). The depositional profiles for each Formation illustrate the idealized distribution of the facies.

II.2.2. Sequence stratigraphy

Sequence stratigraphy is a main and widely used method of stratigraphic analysis that can be applied to build frameworks of sequences, systems tracts and bounding surfaces at different scales of observation, depending on the purpose of the study and on the data available (Catuneanu et al., 2013).

Although in the model of Catuneanu et al. (2002), five systems tract are defined by the relative sea level changes, two are adapted to the depositional system of the study areas. The transgressive systems tract (TST) is bounded by the maximum regressive surface and sequence boundary at the base, and by the maximum flooding surface at the top. This systems tract forms when base level rise, and the rates of rise is more from the sedimentation rates. The highstand systems tract (HST) is bounded by the maximum flooding surface at the base, and by a composite surface at the top that includes the subaerial unconformity, the regressive surface of marine erosion, and the basal surface of forced regression. It corresponds to the late stage of base level rise during which the rates of rise drop below the sedimentation rates, generating a normal regression of the shoreline.

The maximum flooding surface (MFS) separates retrograding strata below from prograding strata above. The change from retrogradational to overlying progradational stacking patterns takes place during continued base level rise at the shoreline, when the sedimentation rates start to outpace the rates of base level rise (Catuneanu et al., 2006). Development of bioturbation, deep marine deposits and high gamma ray peak are indicators used for determination of transgressive surface and maximum flooding surface.

Based on depositional environments, stratigraphic position and results from previous palynological study, the Palaeozoic succesions are described in depositional sequences.

In addition to the sedimentological characteristics of the facies, distinct erosional surface and gamma ray peaks used to determination of main sequence boundaries (SB).

Gamma-ray (GR), Uranium (U), Potassium (K) and Thorium (T) logs were used to trace sequence boundaries and maximum flooding surfaces for the surface sections. The most common petrophysical log types that are routinely used in this study for wells are gamma ray, sonic and neutron logs. Gamma ray logs are much more utilized in this study than the others, thus characterizing the lithology mostly within siliciclastic domains. The Gamma ray curve reflects the degree of radioactivity in response to the shaliness of the rocks or their organic content (Reader, 1993).

In comparison between my work and result with the chart proposed by Sharland et al., (2001), the sequence stratigraphic and chronostratigraphic interpretation is supported by a tectonostratigraphic review of the Arabian plate, and the identification, dating and correlation of Maximum Flooding Surfaces (MFS) (Fig II.4). However, the small difference between Zagros and Arabian Plate will be discussed in chapter 5. In the Zagros area, as a part of the Arabian Plate, sedimentary record developed through a series of major tectonic phases. The sedimentary cover was deposited during a late Precambrian to mid-Permian intra-cratonic phase, its tectonostratigraphic megasequences (TMS) and Maximum Flooding Surfaces (MFS) show in Fig II.4 (Sharland et al., 2001).

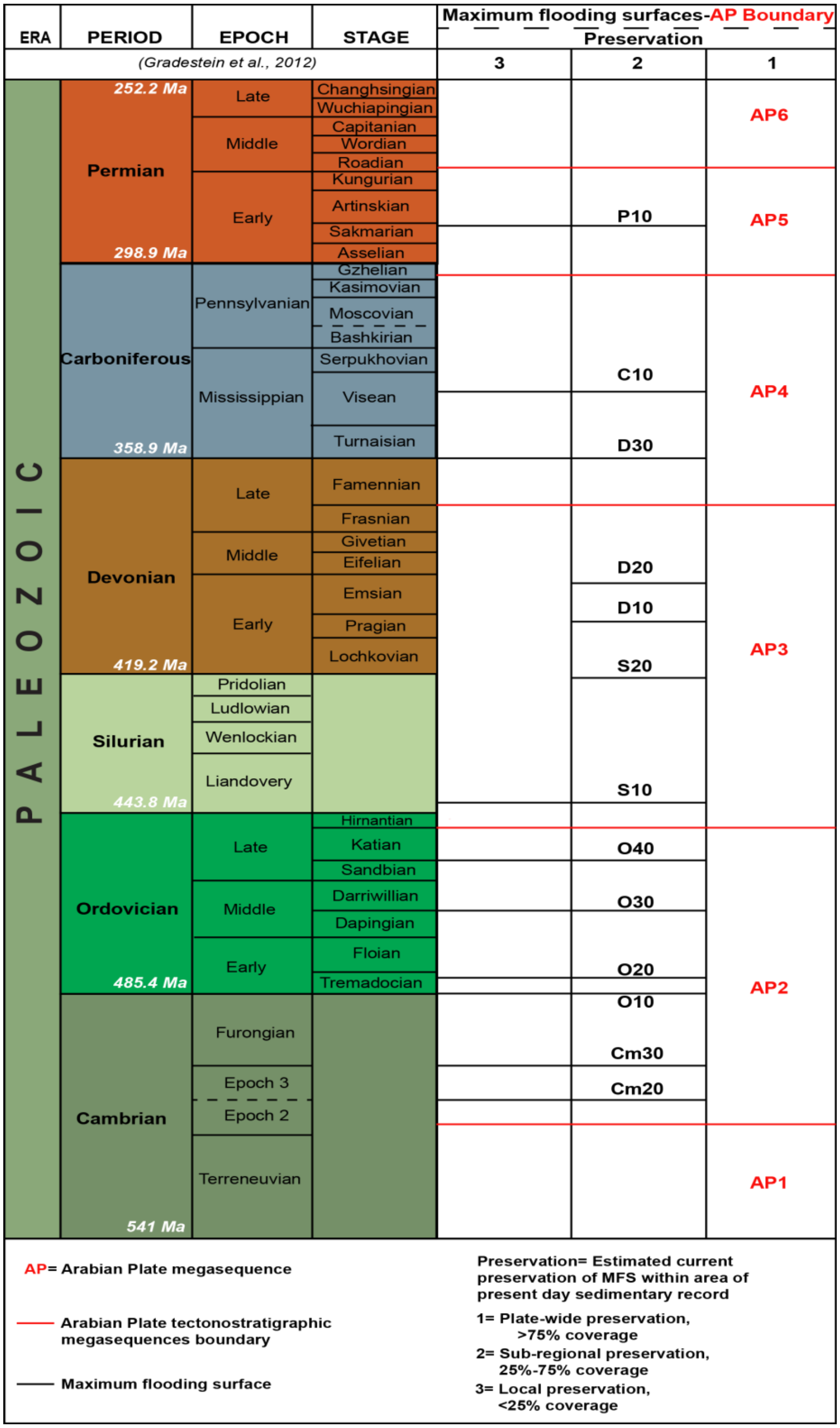

Fig. II.4: Chrono-sequence stratigraphy of the Palaeozoic succession of the Arabian Plate (Sharland et al., 2001). In Zagros, the sequence stratigraphic and chronostratigraphic interpretation is supported by a tectonostratigraphic review of the Arabian plate, and the identification, dating and correlation of Maximum Flooding Surfaces (MFS).

CHAPTER III:

LITHOSTRATIGRAPHY AND BIOSTRATIGRAPHY

In Zagros area, the Palaeozoic succession is incomplete due to various significant hiatuses. Moreover, the known Palaeozoic succession is not continuously exposed in any particular outcrop region, and subsurface sections. Accordingly, the Palaeozoic succession of Zagros has been reconstructed from outcrops in the northern region of the Zagros (High Zagros, Bandar Abbas and Kuh e Surmeh). This chapter presents general Overviewes of the different studied areas in term of Stratigraphy. Furthermore, at the end of this chapter, the known Palaeozoic Formations of the Zagros area have been present in stratigraphic order from oldest to youngest.

III.1. General Overviewes of the different studied areas in term of Stratigraphy

The stratigraphic sections in this study are located in three parts of Zagros zone: *(i)* Fars area, *(ii)* Bandar Abbas area and *(iii)* West High Zagros area.

III.1.1. Fars area

Kuh e Surmeh: is the only locality within the Zagros area where Palaeozoic successions are exposed (Fig. III.1). It is approximately located 120 km southern Shiraz city in Fars province (Fig. I.2). The sedimentary record of this area presents two main Formations corresponding respectively to the Ordovician Seyahou and Permian Faraghan deposits. The Silurian Sarchahan and Devonian Zakeen Formations are not recorded in Kuh e Surmeh. Nevertheless, detailed palynological studies have resulted in precise biozonation and age determination of the Late Ordovician Seyahou Formation and Early Permian Faraghan Formation and identification of a significant hiatus between the Seyahou Formation and overlying Faraghan Formation (Ghavidel Syooki, 1994e). Locally, drilled wells located in the surrounding areas (e.g; West Aghar, Naura, Zirreh, Dalan) (Fig.I.2), Devonian Zakeen Formation as indicated by the palynological studies (Ghavidel Syooki, 1996) recorded.

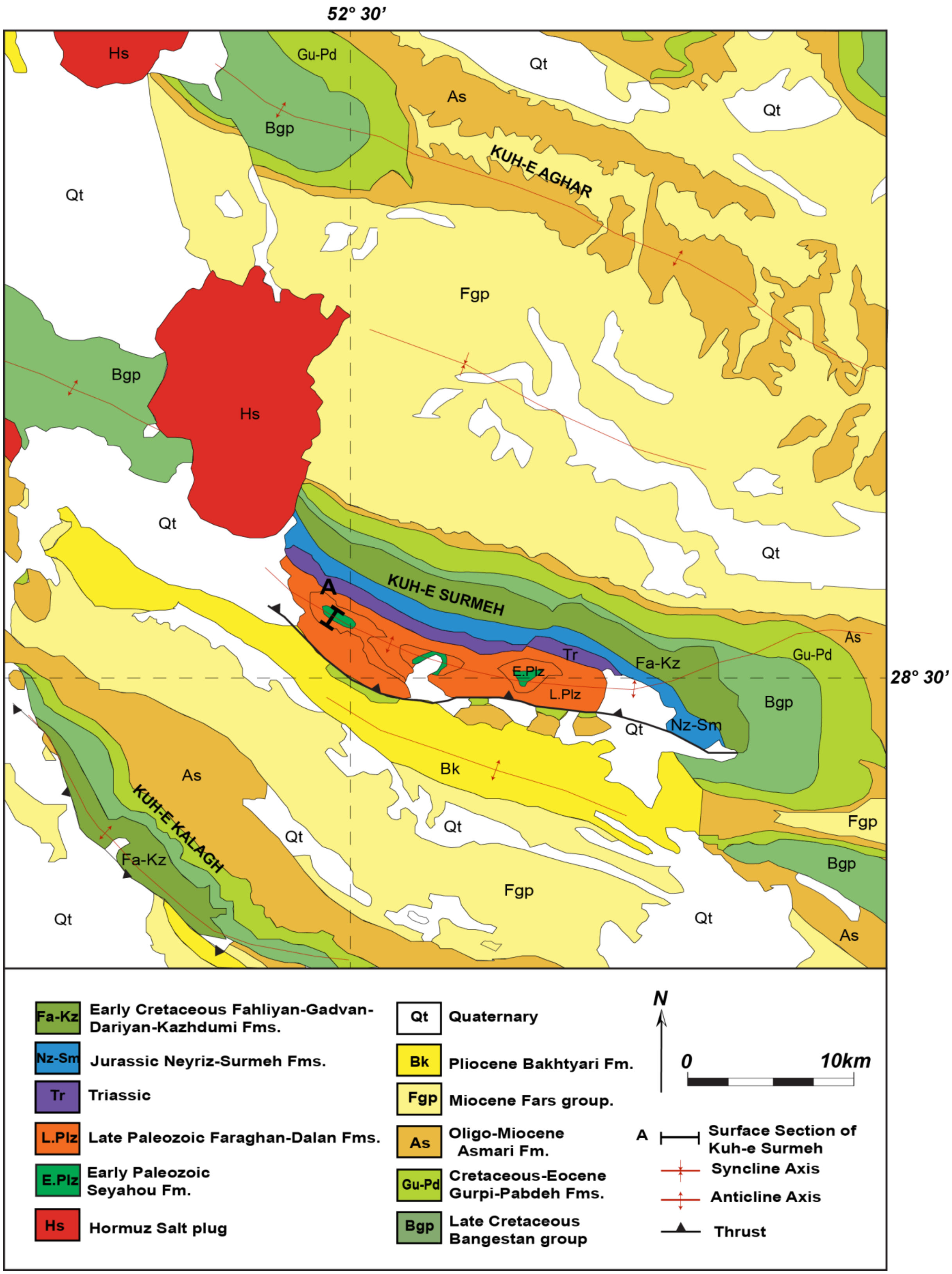

Fig. III.1: Geological map of Kuh e Surmeh and surrounding area. **(A):** Location of Kuh e Surmeh surface section (modified after Perry et al., 1965). *Fms=Formations*.

III.1.2. Bandar Abbas area

Kuh e Faraghan: is located approximately 103 Km north of Bandar Abbas city (Fig. III.2). A thick Palaeozoic sequence is well developed in Tang e Zakeen and comprises in ascending stratigraphic order: the Zard Kuh, Seyahou, Dargaz, Sarchahan, Zakeen, Faraghan and Dalan Formations. The Zard Kuh Early Ordovician Formation is the lowest Palaeozoic unit in this section and consists of conglomerates, sandstones and shales. The Erly-Late Ordovician Seyahou Formation consists of alternating shales, siltstones and sandstones. It contains well-preserved graptolites, brachiopods, acritarchs and chitinozoans (Ghavidel Syooki & Khosravi, 1995; Ghavidel Syooki et al., 2014). The Hirnantian Dargaz Formation consists of whitish sandstones and structureless to diffusely laminated diamictites (Ghavidel Syooki et al., 2011). The Early Silurian Sarchahan Formation is disconformably overlain by the Devonian Zakeen Formation and comprises mainly black shales with abundant graptolites. The Zakeen Formation is composed of white sandstones with intercalated shales and overlain by the Early Permian Faraghan Formation. The Faraghan Formation mainly consists of alternating shales, sandstones and limeslones. The uppermost Palaeozoic unit of Kuh e Faraghan is the Middle-Late Permian Dalan Formation, which is comprosed of fossiliferous limestones and dolomites.

Kuh e Gahkum is located 120 Km north of Bandar Abbas city (Fig. III.2). A thick Palaeozoic sequence is well developed in Tang e Abzagh and comprises in ascending stratigraphic order: the Cambrian?, Sarchahan, Zakeen, Faraghan and Dalan Formations. The Ordovician Seyahou and Dargaz Formations are not obsereved in this area. The Early Silurian Sarchahan Formation rest on Pre-Floian un-named conglomerates (Ghavidel Syooki et al., 2011) and is disconformably overlain by the Devonian Zakeen Formation and comprises calcareous conglomerates evolving vertically to olive-gray and black shales and sandstones with subordinate limestones beds. The Zakeen Formation comprises mainly white sandstones with intercalated shales and overlain by the Early Permian Faraghan Formation. The Faraghan Formation mainly consists of stromatolitic dolomite and sandstones with intercalated shales. The uppermost Palaeozoic unit of Kuh e Gahkum is the Middle- Late Permian Dalan Formation composed of shales and limestones.

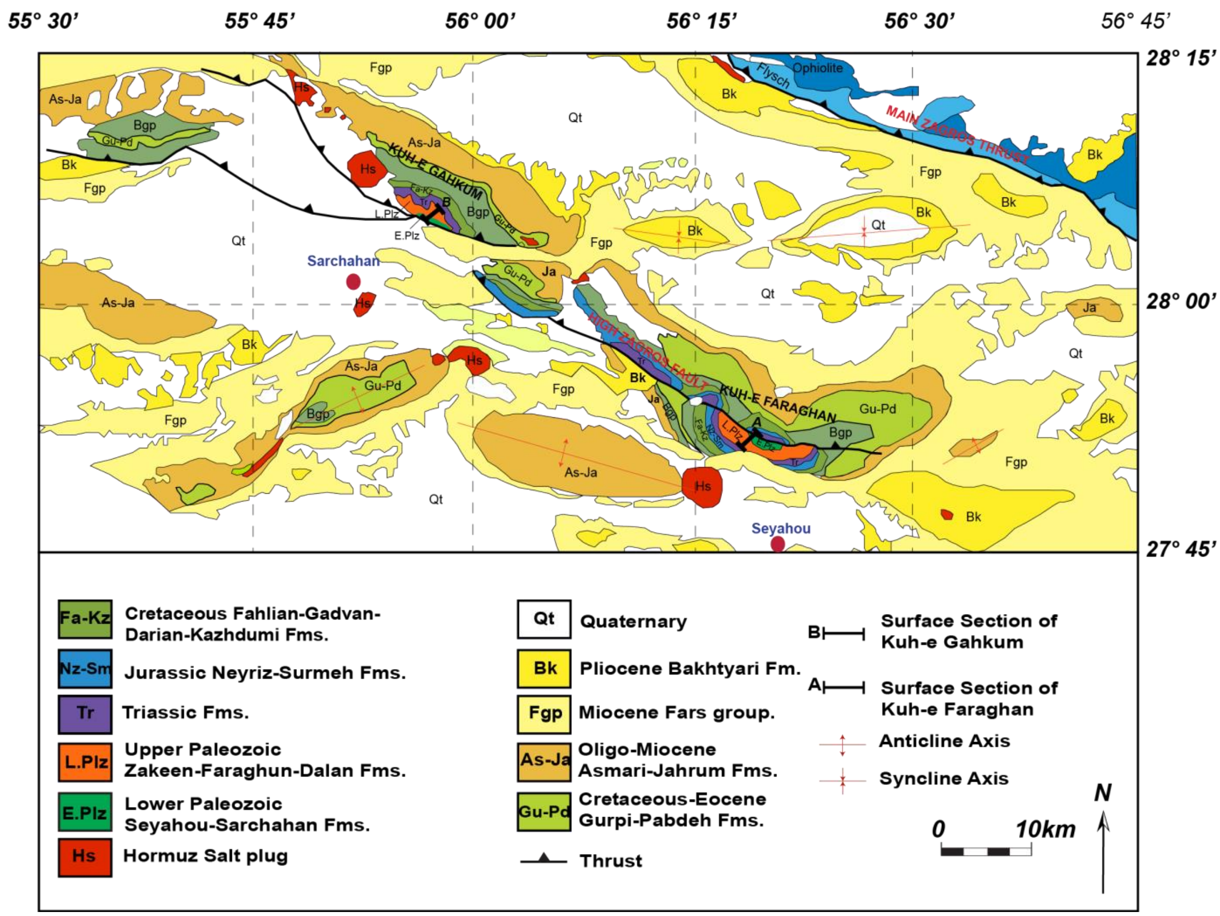

Fig. III.2: Geological map of Bandar Abbas area. **(A)** and **(B):** Locations of Kuh e Faraghan and Kuh e Gahkum surface sections, respectively (modified after Tavakoli et al., 2013). *Fms=Formations*.

III.1.3. West High Zagros

This region includes several mountains such as the Chal i Sheh, Zard Kuh, Kuh e Dena, Ushtoran Kuh, Ghali Kuh and Kuh e Garreh Mountains (Fig. I.2). This area is bounded by the Main Zagros fault in the north and High Zagros fault in the south.

Chal i Sheh: The Chal i Sheh section is located in 70 km southwest of Fereydoon shar city (Fig. III.3).The 1700 m-thick Palaeozoic Pre-khuff section in Chah i Sheh area is composed of the Mid to Late Cambrian Mila Formation (B and C Members), Late Cambrian Ilebek Formation and Early Permian Faraghan Formation (Fig. III.4 & III.5). Palynological zonation has been estabilished by Ghavidel Syooki (1993a) and Ghavidel Syooki and Vecoli (2008) and confirmed a hiatus within the Palaeozoic sequence of this area extending from Early Ordovician to Early Permian.

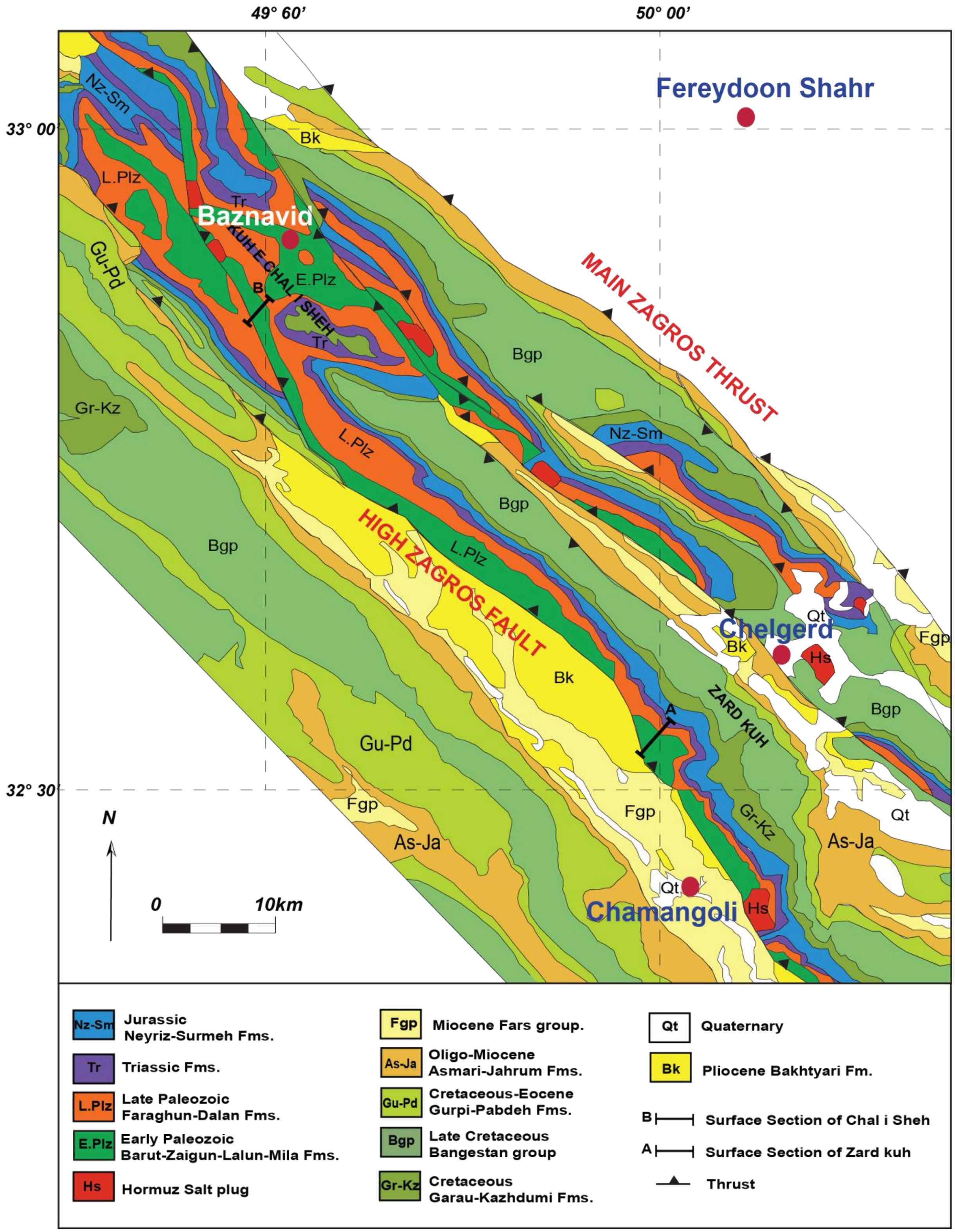

Fig. III.3: Geological map of Zard Kuh and Chal i Sheh area (modified after Tavakoli et al., 2013). **(A)** and **(B):** locations of the Zard Kuh and Chal i Sheh surface sections, respectively. *Fms=Formations.*

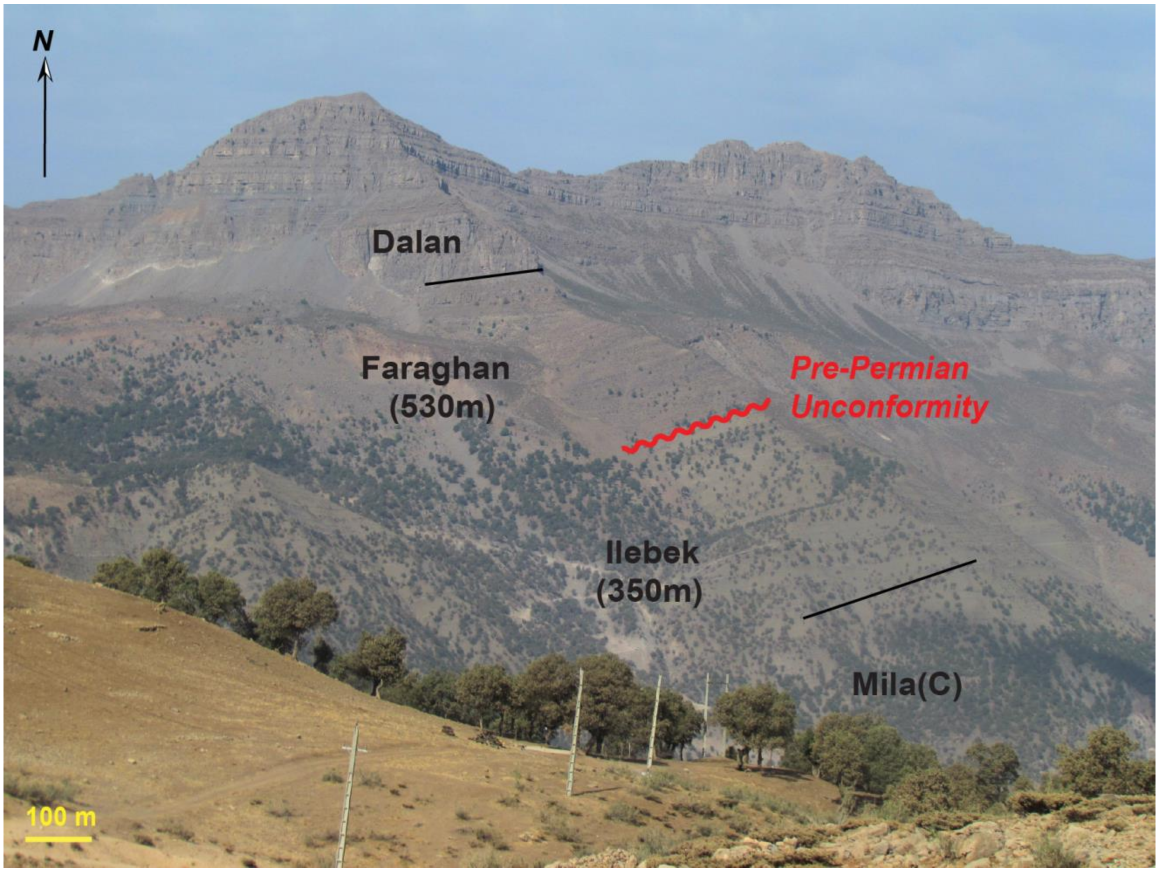

Fig. III.4: Overview Photo of the Chal i Sheh surface section, showing Early Permian Faraghan Formation resting on Late Combrian Ilebek deposits.

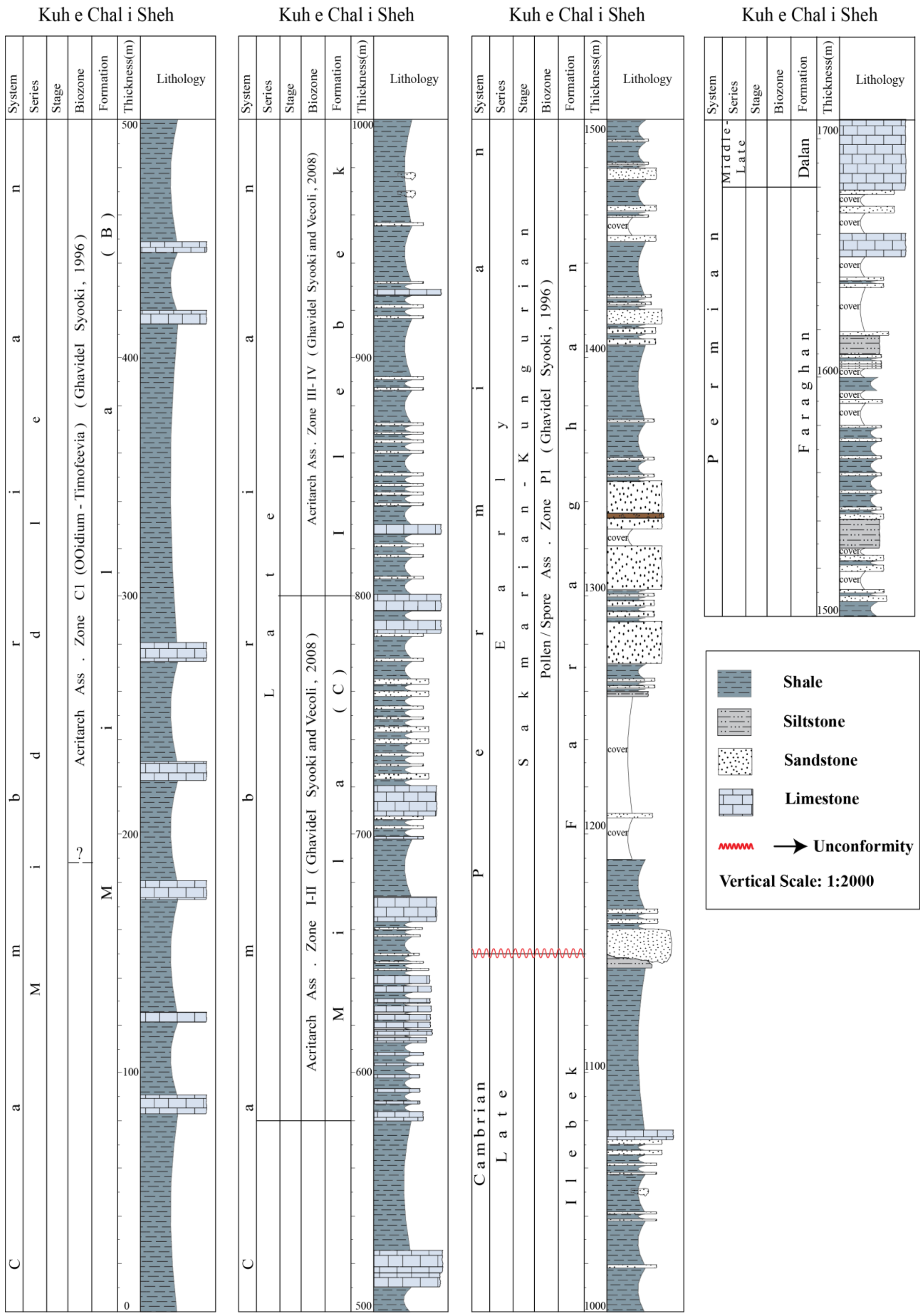

Fig. III.5: Litho-stratigraphic log of Chal i Sheh (modified after JOGMEC & NIOC, 2005).

Zard Kuh: is the only locality within the Zagros area where the Ordovician Zard Kuh Formation is exposed. It is located about 30 km south of Chelgard city (Fig. III.3). The Prekhuff succession in this area includes about 1000 meters thick of Late Cambrian to Early Permian deposits and consists of the Mila (C Member), Ilebek, Zard Kuh, an unnamed zone, and Faraghan Formations (Fig. III.6 & III.7). Based on marine fauna, such as, trilobites, brachiopods and graptolites (Setudehnia, 1975), and palynology (Ghavidel Syooki, 1990a,b; Ghavidel Syooki and Vecoli, 2008), the Mila and Ilebek Formations corresponded to the Middle to Late Cambrian, and Zard Kuh Formation to the Early-Middle Ordovician. Undifferenciated Palaeozoic sediments are topped by Early Permian Faraghan Formation.

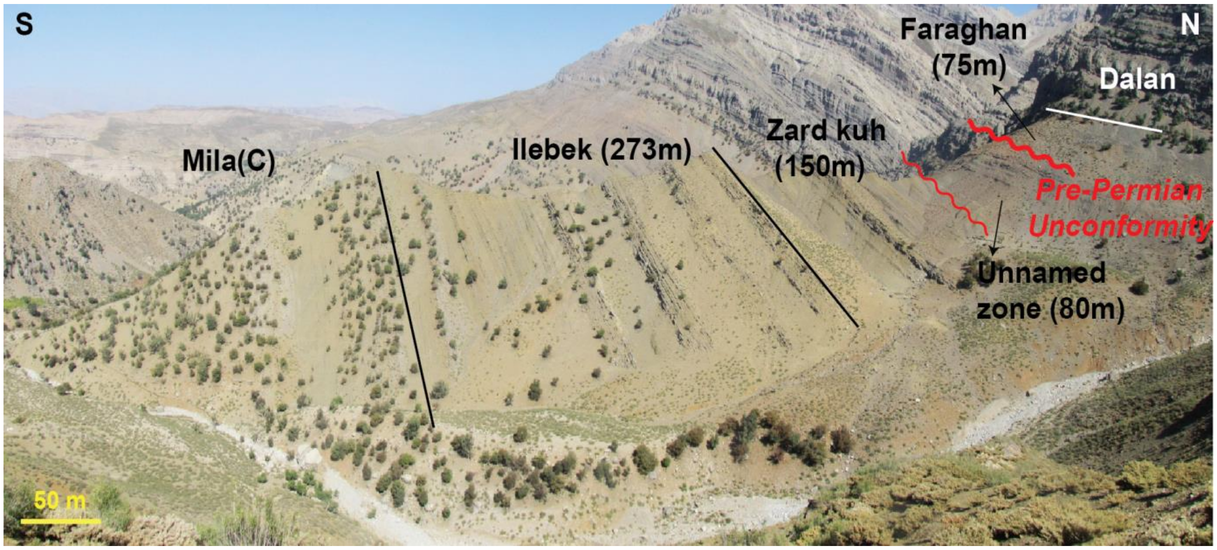

Fig. III.6: Overview Photo of the Zard Kuh surface section.

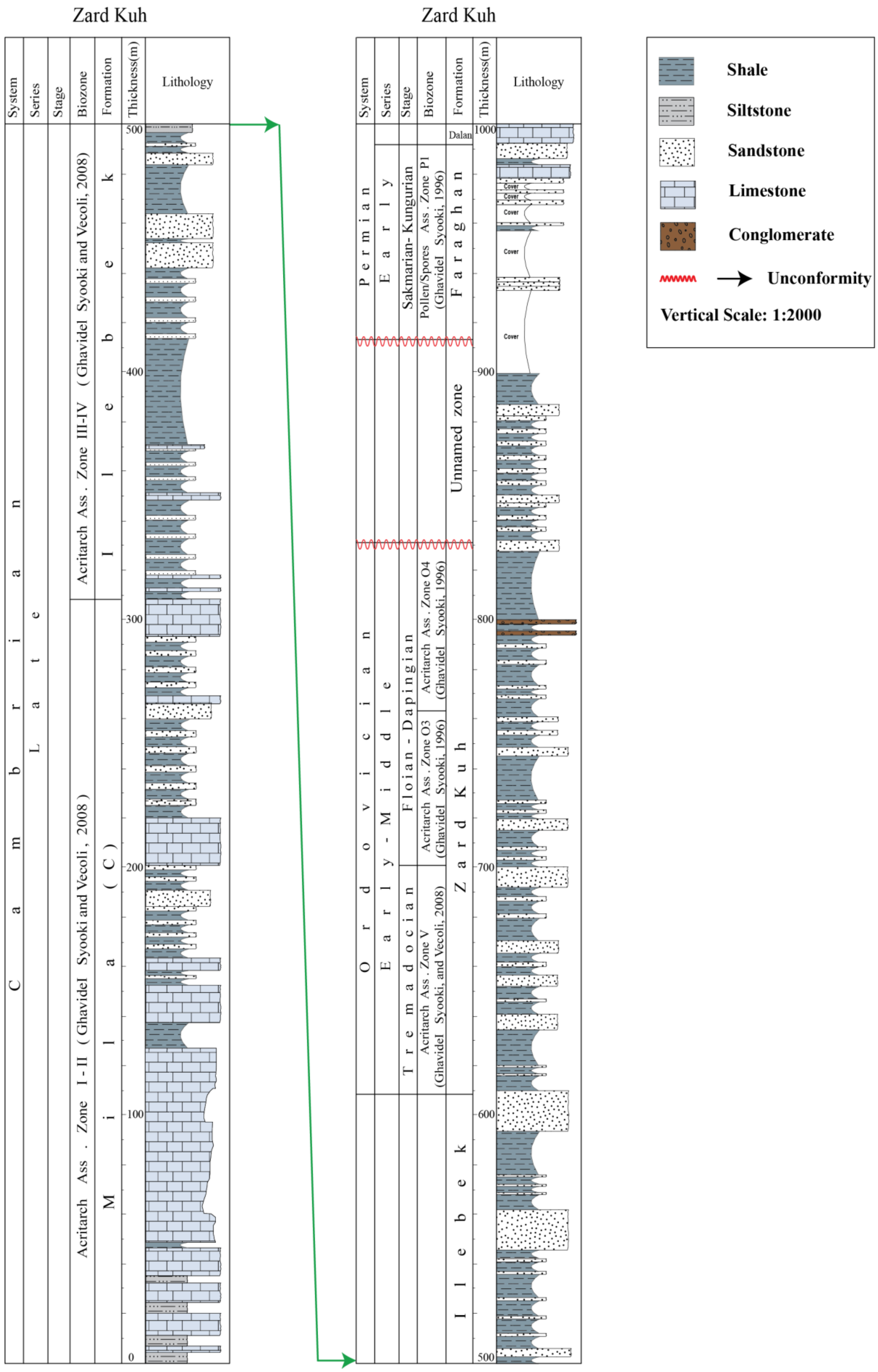

Fig. III.7: Litho-stratigraphic log of Zard Kuh (modified after Setudehnia, 1975).

Kuh e Dena: This section is located 30 km northwest of Sisakht city (Fig. III.8). The Pre-Khuff Palaeozoic succession consists of the Zaigun, Lalun, Mila (A, B, and C Members), and Faraghan Formations (Fig. III.9). It consists of 1120 m thick sandstones, shales, limestones and dolomites (Fig. III.10). In Kuh e Dena, the basal Faraghan unconformity capped Cambrian Mila Formation (Setudehnia, 1975). An extended hiatus ranged from Cambrian to Early Permian.

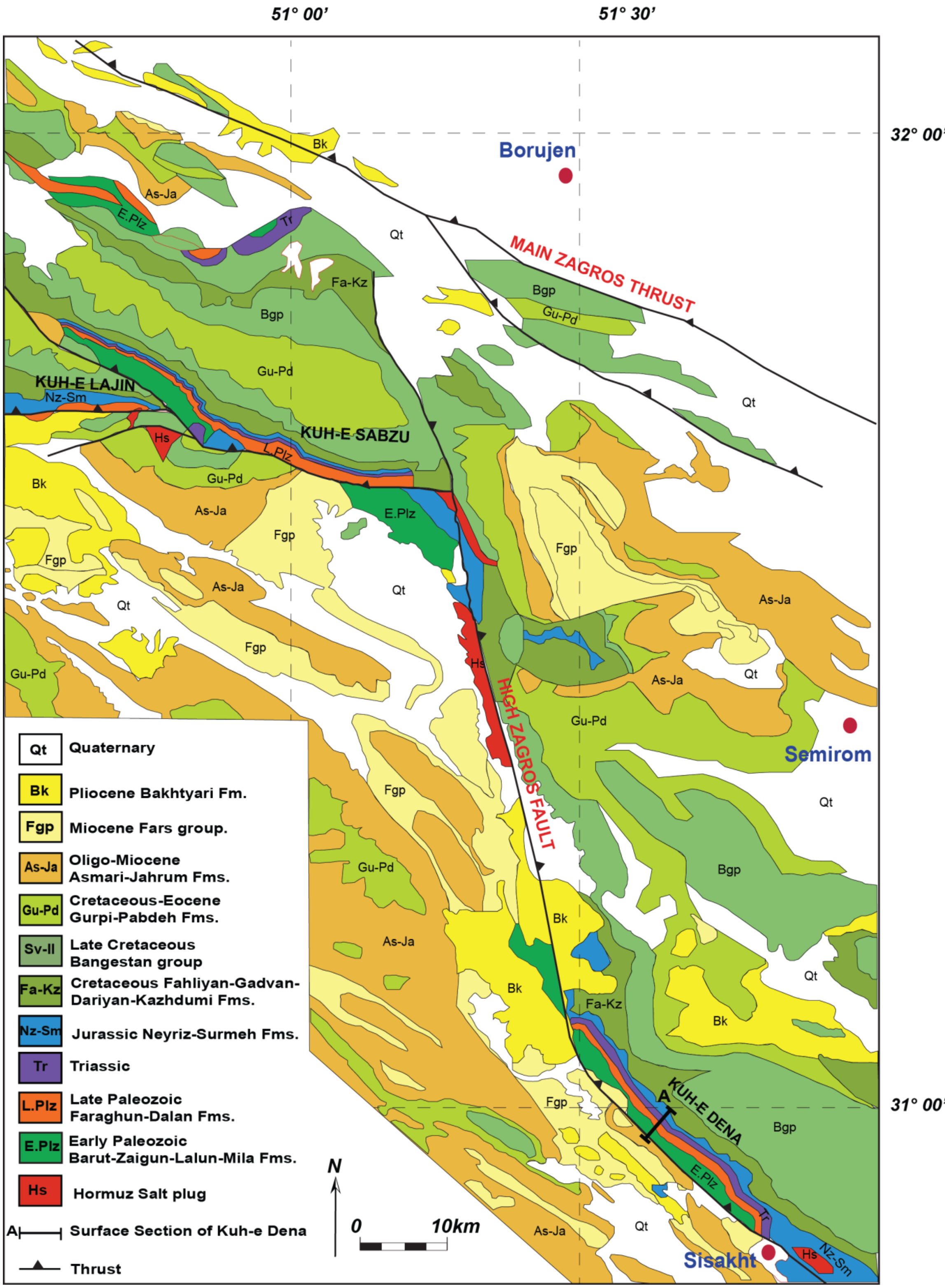

Fig. III.8: Geological map of Kuh e Dena, Kuh e Sabzu and Kuh e Lajin (modified after Tavakoli et al., 2011). **(A)**: Location of Kuh e Dena surface section. *Fms=Formations*.

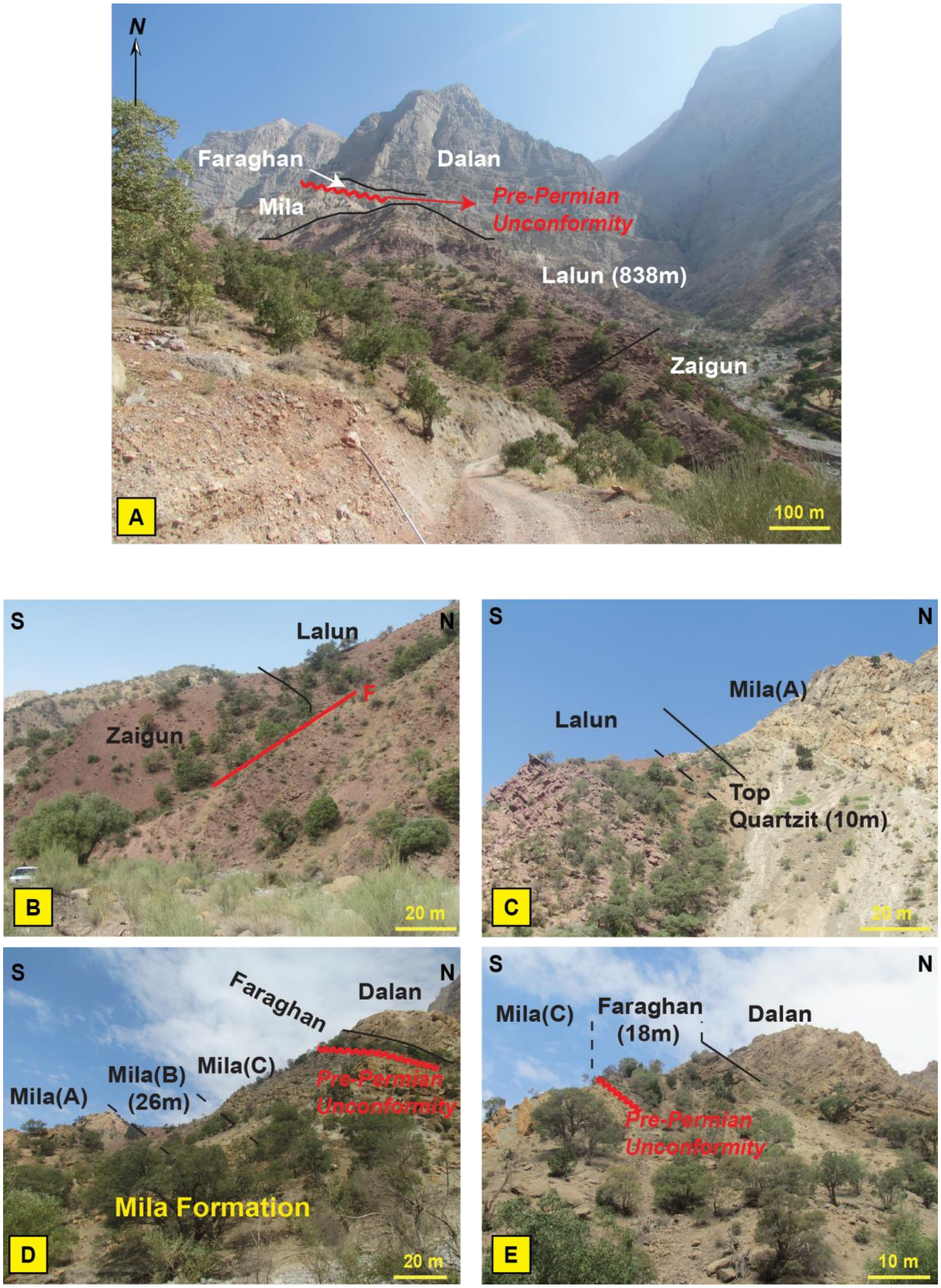

Fig. III.9: (A) Overview of the Kuh e Dena surface section; (B) The boundary between Zaigun and Lalun Formations; (C) The boundary between Cambrian Mila Formation (Member A) and the top quartzite deposits of the Early Cambrian Lalun Formation; (D) Three Members (A, B and C) of the Mila Formation; (E) Showing Pre-Permian unconformity where the Early Permian Faraghan Formation capped the Late Cambrian Mila Formation (Member C). *F= Fault*.

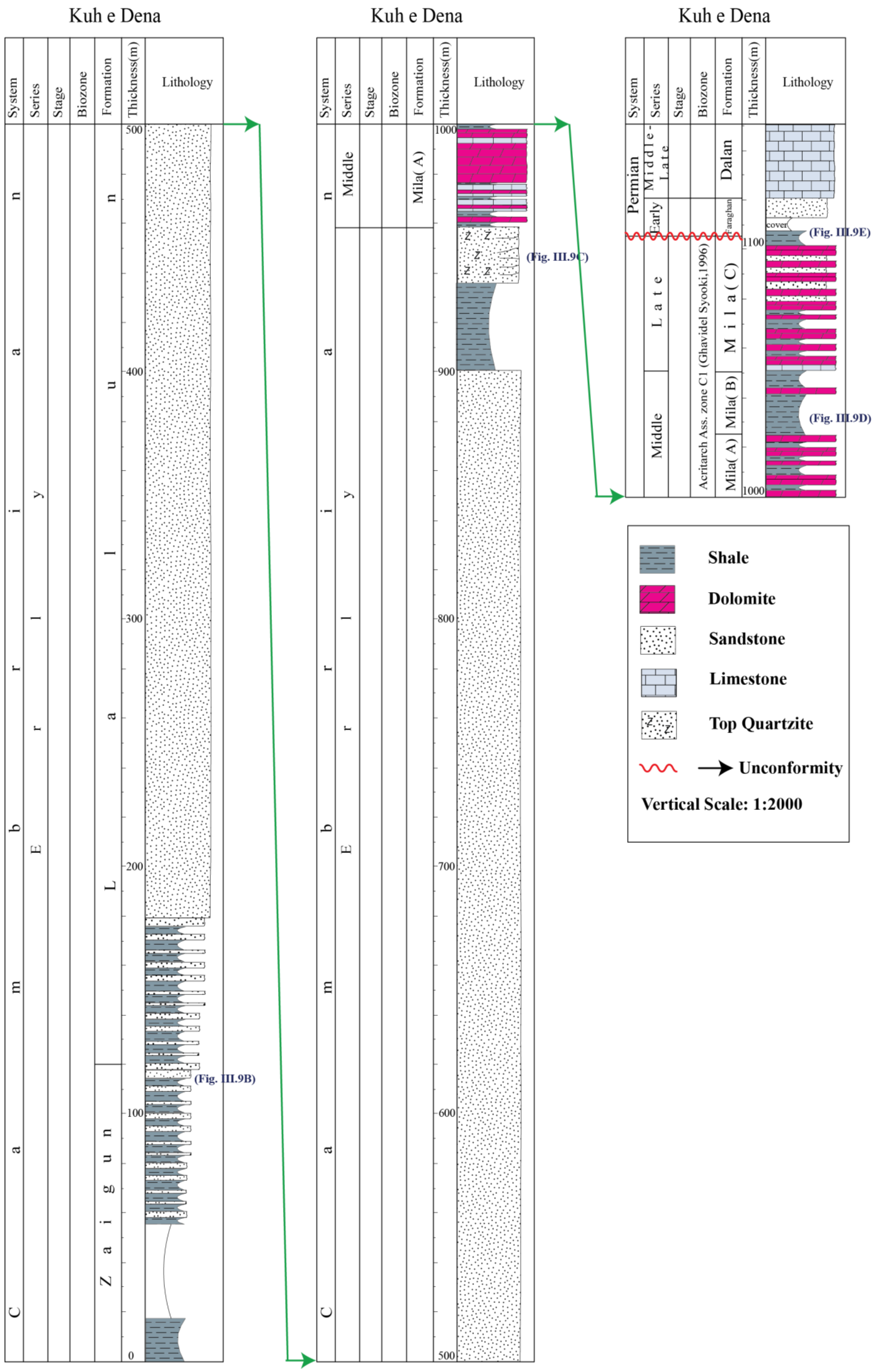

Fig. III.10: Litho-stratigraphic log of Kuh e Dena (modified after Setudehnia, 1975).

The litho-stratigraphy of Palaeozoic succession has been established in the Zagros area by James and Wynd (1965) and subsequently revised by Setudehnia (1975); Koop and Stoneley (1982); Motiei (2003); Ghavidel Syooki (2003); Alavi (2004) and Ghavidel Syooki et al. (2011) (Fig. III.11).

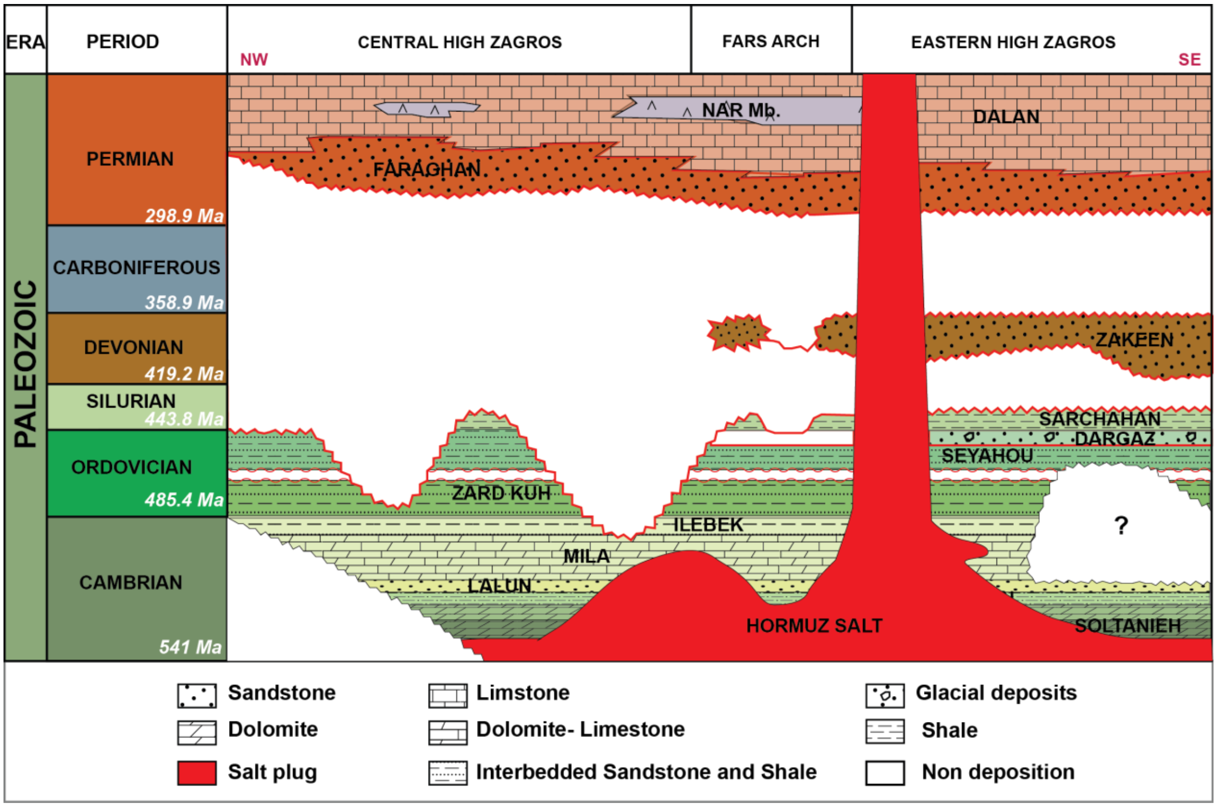

Fig. III.11: Palaeozoic litho-stratigraohic chart of the Zagros area (after Motiei, 2003). Palaeozoic stratigraphic succession in Zagros reveals different levels of erosion (and likely differential vertical movements) for the Pre-Permian rocks. In central High Zagros the basal Faraghan unconformity seals Cambrian and Ordovician deposits. In Fars and Bandar Abbas areas as well as the Persian Gulf, the Faraghan Formation unconformably rest on the Devonian Zakeen Formation.

At the bottom of the sedimentary pile, the Hormuz salt of Late Precambrian-Early Cambrian age was deposited in an evaporitic basin located mainly on the site of the present Fars Arc (Jahani et al., 2009). From a structural point of view, this salt layer and its lateral equivalents form the main décollement in the area decoupling the overlying sedimentary pile from probable pre-Hormuz sediments of unknown age and from the Panafrican basement (Alavi, 2004; Sherkati et al., 2006; Jahani et al., 2009; Vergès et al., 2011). This was followed by the development of epi-continental basins from Early Cambrian up to Late Devonian (Setudehnia, 1975). In the High Zagros , because of widespread uplift and erosion, which is generally interpreted as a far effect of the

Hercynian orogeny or locally as result of Hormuz salt movement (Sherkati et al., 2004), only Cambrian and Ordovician sequences are out cropping (Setudehnia, 1975). More precisely, Setudehnia (1975) recognized and dated the sandstone of the Lalun Formation as well as the Mila trilogy, both of Cambrian age, in the Kuh e Dena and the olive shale of the Ilebek Formation (Late Cambrian) at Zard Kuh. Silurian and Devonian strata have not been reported and are likely absent in West High Zagros. By contrast, they are out cropping in the Bandar Abbas area at Kuh e Faraghan and Kuh e Gahkum anticlines (Ghavidel Syooki, 2003; Ghavidel Syooki and Winchester-Seeto, 2004; Ghavidel Syooki et al., 2011). Examination of preserved Palaeozoic stratigraphic succession in Zagros reveals different levels of erosion (and likely differential vertical movements) for the Pre-Permian rocks (Fig. III.12). In Kuh e Dena the basal Faraghan unconformity seals Cambrian, Lalun and Mila Formations (Setudehnia, 1975) whereas, towards the northwest (Zard kuh area), the stratigraphic pile is more complete with presence of Cambrian Ilbek and Ordovician Zardkuh Formations (Setudehnia, 1975). In adition, in Fars and Bandar abbas areas as well as the Persian Gulf, the Faraghan Formation unconformably rest on the Devonian Zakeen Formation. Exceptionally, this Formation rest on Ordovician deposits at Kuh e Surmeh and Kuh e Siah in Fars area which marked the major hiatus from Late Ordvician to Early Permian (Ghavidel Syooki, 1994e) (Fig. III.12).

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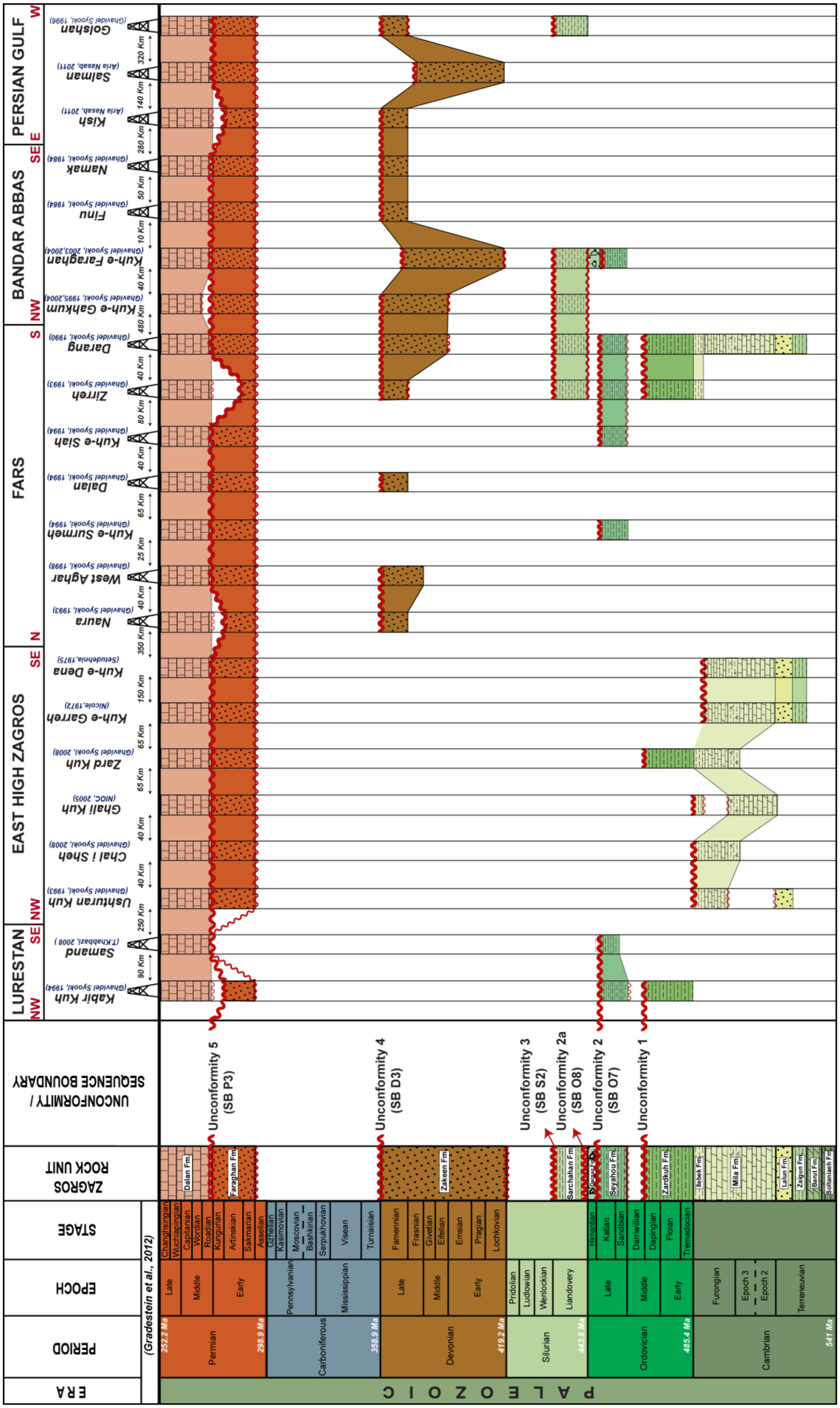
Fig. III.12 (Next page): Lithostratigraphic correlation chart of the Zagros area showing discontinuous record of the Palaeozoic succession throughout the Zagros and High Zagros areas. The palaeozoic stratigraphic of the Zagros area is marked by numerous hiatus bounded by major unconformities consists of Middle Ordovician, Pre Silurian and Pre Devonian unconformities: Heterogeneities unconformities; and Pre Permian and Pre-Khuff unconformities: Homogeneties unconformities.


ERA
PERIOD
EPOCH
STAGE
ZAGROS ROCK UNIT
UNCONFORMITY / SEQUENCE BOUNDARY
(Gradestein et al., 2012)
P A L E O Z O I C
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
Dalan Fm
Faraghan Fm
Zakeen Fm
Sarchahan Fm
Seyahou Fm
Zardkuh Fm
Ilebek Fm
Mila Fm
Lalun Fm
Zaigun Fm
Barut Fm
Soltanieh Fm
Unconformity 5 (SB P3)
Unconformity 4 (SB D3)
Unconformity 3 (SB S2)
Unconformity 2a (SB O8)
Unconformity 2 (SB O7)
Unconformity 1
LURESTAN
EAST HIGH ZAGROS
FARS
BANDAR ABBAS
PERSIAN GULF
Kabir Kuh
Samand
Ushturan Kuh
Chal i Shah
Ghali Kuh
Zard Kuh
Kuh-e Garreh
Kuh-e Dena
Naura
West Aghar
Kuh-e Surmeh
Dalan
Kuh-e Siah
Zireh
Darang
Kuh-e Gahkum
Kuh-e Faraghan
Finu
Namak
Kish
Salman
Golshan

III.2. Additionnal information on litho-stratigraphy and stratigraphy

The Cambrian, Early Ordovician and Late Permian detailled in this chapter are mainly focused on litterature. However, Late Ordovician, Early Silurian, Devonian and Early Permian are beyond the scop of the manuscript and will be described in detail in the following Chapter IV.

III.2.1. Cambrian and Early Ordovician

III.2.1.1. Barut Formation

The type section of this Formation is located at Barut Aghaji village in the Soltanieh Mountains, approximately 17 km west of Zanjan City. It is 741 m thick and composed of dolomites, limestones and shales (Stocklin et al. 1964).

In the Zagros area, 152 m of Barut Formation is exposed at Kuh e Subzu (Fig. III.8) and consists of thin bedded stromatolitic crystalline dolomite interbedded with red and purple shales. It is divided into three units.Two main dolomite units are in the lowermost and uppermost of the Barut Formation intercalated with a shale unit. The lower contact of the Barut Formation is not exposed in the Zagros Basin while the upper contact is gradual with Cambrian Zaigun Formation. The uppermost portion of the Barut Formation is exposed at Kuh e Dena, and consists of dolomite with interbedded red and purple shales (Setudehnia, 1975). In west of Kuh e Sabzu in Bazun pir section (Fig. III.8), the Barut Formation consists of 190 m of purple shales interbedded with dark color dolomites and thin bedded sandstones (Joulapour et al., 2001). At Tang e Chal pivary in Kuh e Dena (Fig. III.8), 500 m of red and green shales interbedded with some dark yellow dolomite and thin bedded sandstones of Barut Formation have been measured by Joulapour et al., (2001). The Formation is compared with the sections obsereved in northern Iran and an Early Cambrian age is proposed (Motiei, 2003).

III.2.1.2. Zaigun Formation

The type section of Zaigun Formation is measured at Zaigun village in the central Alborz (Assereto, 1963; Stocklin et al. 1964). At the type section, the Zaigun Formation is mainly composed of of a 453 m thick red-purple and green-blue shales. The shales are generally micaceous and fissile, and become sandier towards the top of the section.

In the Zagros area, the Zaigun Formation conformably capped by the Barut Formation, and is exposed at Kuh e Dena, Kuh e Garreh (Fig. I.2), Kuh e Sabzu and Kuh e Lajin (Fig. III.8) (Setudehnia, 1975). In Kuh e Dena at Tang e Rag e bavi (Fig. III.10), the thickness of the Zaigun Formation is 122 m thick without reaching the base and consists of red-purple shales with intercalation of red sandstones (Setudehnia, 1975) whereas in Tang e Chal pivari the thickness increases to 280 m (Joulapour et al., 2001). In west of Kuh e Sabzu in Bazoun pir section (Fig. III.8), 170 m of red sandstones and shales are exposed (Joulapour et al., 2001).

III.2.1.3. Lalun Formation

The Lalun Formation occurs throughout northern and central Iran. The type section is located in the Lalun Village in central Alborz (Assereto, 1963; Stocklin et al. 1964), where it consists of 582 m sandstones and shales.

In the Zagros region, this Formation is well exposed throughout the West High Zagros mountain ranges, except for the Zard Kuh (Fig. III.3). A composite section of this Formation at Tang e Rag e Bavi and Tang e Putak in Kuh e Dena (Fig. III.8) has been measured by Setudehnia (1975). It is 838.2 m thick (Fig. III.10) and consists mainly of sandstones and shales. The sandstones are well-sorted, medium- to coarse-grained (pinkish, red-purple, greenish-blue). They recorded cross-beddings, ripple marks and *Cruziana* trace fossils (Setudehnia, 1975). A thick red to purple shale unit occurs near the top of the Kuh e Dena section (Setudehnia, 1975). Likewise throughout in Iran, the uppermost unit of the Lalun Sandstones in Zagros area is characterized by white sandstone marker known as the 'top quartzite'. In Kuh e Garreh (Fig. I.2), Lalun Formation occurs and consists of 685 m (JOGMEC & NIOC, 2005) of red-cross-bedded sandstones with intercalation of shales.

In the West High Zagros, the Lalun Sandstone gradationally and conformably overlies the Zaigun Formation. It is overlain in turn by the Mila Formation at sharp, possibly unconformably, contact. Late Early Cambrian age assigned based on the presence of of *Redlichia trilobites* (Wolfart, 1983). Based on Middle Cambrian fossils found in the overlying Mila Formation, the Lalun Formation is considered to be Early Cambrian (Motiei, 2003).

III.2.1.4. Mila Formation

The Mila Formation represents the first marine phase of carbonate deposits. The type section is defined close to Mila Kuh in the eastern Alborz, where the Formation has a thickness of 585 m and consists of dolomites, shales and limestones with trillobite (Stocklin et al. 1964; Ghaviled Syooki, 1990a.b, Ghavidel Syooki and Vecoli, 2008).

In the Zagros area, the Mila Formation is exposed along the southwest flanks of several thrust - faulted structures between Zard Kuh and Kuh e Dena, along the High Zagros Thrust in Ushtoran Kuh, Zard Kuh, Chal i Sheh, Kuh e Garreh (Fig. I.2), Kuh e Dena, Kuh e Lajin and Kuh e Sabzu (Fig. III.8) where its thickness is greatly reduced and the upper portion is missing (Setudehnia, 1975). In the study area, the Mila Formation has been divided into Members A, B, and C.

Member A:

Member A has been measured by Setudehnia (1975), in Tang e Putak in Kuh e Dena (Fig. III.8). The thickness of this member is 67 m (Fig. III.10) and is composed of red silty shales, dolomites and limestones resting conformably on the top quartzite of the Lalun Sandstone. Member A exposed in Kuh e Garreh (Fig. I.2) is 70 m thick, but is absent in the Zard Kuh and Chal i Sheh areas (Setudehnia, 1975).

The thickness is 190 m in Ghali Kuh (Fig. I.2) and it consists of brownish limestones with dolomites and minor green-gray shales (JOGMEC & NIOC, 2005).

Member B:

Member B conformably rests on Member A and is exposed in the Zard Kuh, Kuh e Garreh, Kuh e Dena, Ushtoran Kuh, Ghali kuh, and Chal i Sheh areas (Fig. I.2). At Kuh e Dena, consists of 26 m thick (Fig. III.10) soft red silty and fractured shales with greenish shales bands that contain salt pseudomorphs (Setudehnia, 1975). In Zard Kuh at Tang e Ilebek (Fig. III.7), 137 m thick sucession comprises weakly weathered red and green shales, siltstones and dolomites.The upper part of this member is covered and the lower part is faulted (Setudehnia, 1975). In the Chal i Sheh area (Fig. III.5), it consists of 580 m olive-gray shales, siltstones and intercalated fossiliferous Limestones (JOGMEC & NIOC, 2005).

Member C:

The Member C of Mila Formation, is exposed in the Kuh e Dena, Zard Kuh, Ushtoran Kuh, Kuh e Garreh, Ghali Kuh and Chal i Sheh areas (Fig. I.2) (GOJMEC & NIOC, 2005). The lower contact with Member B is conformable in the Zagros region, while the upper contact with the Ilebek Formation is conformable only in the Zard Kuh area (Setudehnia, 1975). Member C is a 322 m thick in Zard Kuh at Tang e Ilebek (Fig. III.7), and shows alternating limestones, dolomites and gray shales. The upper part of Member C consists of alternating dark gray shale and light gray limestone layers. They contain brachiopodes and trilobites.

In Kuh e Dena (Fig. III.10), the Member C is 56 m and composes mostly of alternating gray limestones and dark gray shales. The lower part consists of alternating dark gray to black shales and limestones. The middle part is characterized by alternating limestones and shales layers of less than 5 cm in thickness. Thickly bedded fine sandstone layers are dominant in the upper part. The uppermost part of Member C was removed by Carboniferous erosion (Setudehnia, 1975).

Member C is considered as Middle to Late Cambrian, based on abundant brachiopodes and trilobites (Setudehnia, 1975). The Lower part of this member contains *Doripigelle, Solenoparia, Nisusia sp., Circotheca, Paradoxides sp., Obolus sp., Ligulella sp.*.

The upper is characterized by *Billingsella sp., Billingsella cf. rhomba, Circotheca sp., aff. Jamesella, Eurudagnostus, Agnostus, Coosina, Loganellus, Labiostria* (Setudehnia, 1975).

According to palynological studies (Ghavidel Syooki, 1990a,b; Ghavidel Syooki and Vecoli, 2008), the age of Member C is Middle –Late Cambrian based on occurrence and disappearance of following acritarchs:

Ooidium rossicum, Cristallinium combriense, Timofeevia phosphoritica, Timofeevia lancarac and *Zonosphaeridium ovillensis, Cristallinium ovillense, Vulcanisphaera Africana, Vulcanisphaera cirritta.*

This acritarch assemblage is considered to belong to *Acritarch assemblage zone C1 (Ooidium-Timofeevia)* and *Acritarch assemblage zone C2 (Timofeevia- Vulcanisphaera)* (Ghavidel Syooki, 1996).

III.2.1.5. Ilebek Formation

The type section of the Ilebek Formation is exposed at Tang e Ilebek within the Zard Kuh area (Fig. III.3), where it consists of 273 m (Fig. III.7) alternating greenish-gray shales and yellowish-white sandstones. The lower part of the Formation is mainly composed of thin interbedded silt to fine sandstone layers and greenish-gray shales, while the upper part is characterized by four sandstone units. The sandstones are characterized by trough cross bedding and parallel laminations. The basal section contains brachiopod-bearing fossiliferous carbonate layers (Setudehnia, 1975).

In Chal i Sheh area, Ilebek Formation consists of 350 m (Fig. III.5) of alternating greenish-gray calcareous shales and white sandstones. The sandstones are generally fine to very fine, with parallel laminations. Sandstone layers are thin (5-15 cm), but laterally continuous. Carbonate layers in the upper and lower parts of the Formation contain abundant brachiopods (JOGMEC & NIOC, 2005).

In Ghali Kuh (Fig. I.2), Ilebek Formation consists of 500 m alternating greenish-gray shales and silty micaceous sandstones. The thin sandstone layers (5-15 cm) are generally laterally continuous, with parallel laminations. Thick limestone layers (1.5-2 cm) occur in the upper and lower parts of Formation; the lower limestone layers contains brachiopods. (JOGMEC & NIOC, 2005).

In core drilled in Fars area of Zagros, Ilebek Formation is identified in well Kabir kuh#1 (Lurestan area) (Fig. I.2) and consist of 44 m shales and sandstones (Ghavidel Syooki, 1994a) and 115 m of shales and sandstones in well Zirreh#1 (Fars area) (Ghavidel Syooki, 1993c) (Fig. I.2).

Both upper and lower contacts of the Ilebek Formation are apparently conformable (Setudehnia, 1975). However the regional Permo-Carboniferous disconformity truncates this Formation southeastward. This Formation disappeared toward the southeast and is not present in Kuh e Dena and Kuh e Garreh (Setudehnia, 1975). The Ilebek Formation is considered to be Late Cambrian to Early Ordovician, based on fossil assemblages (Setudehnia, 1975) and Late Combrian, based on the actitarchs (Ghavidel Syooki and Vecoli, 2008).

In detailed, based on the presence of *Saucia iranicus, Plectotrophia sp., Saratogia laterfrons, Idahoia sp., Calvinella sp., Billingsella aff. tonkiniana, Baltagnostus sp., Coosia sp., Meeria sp., Circotheca sp., Hyolithes sp., Lotagnostus, Pseudoagnostus sp., Chuangia sp., Labiostria sp.*, a Late Cambrian age is defined for the lower part of the Ilebek Formation (Setudehnia, 1975).

Palynological studies by Ghavidel Syooki and Vecoli (2008) in Tang e Ilebek in Zard Kuh, Chal i Sheh and Kuh e Dena considered the age of this Formation as Late Cambrian based on occurrence of the following acritarch assemblage:

Timofeevia? sp., Leiofusa stoumonensis, Cristallinium cambriense, Acanthodiacrodium achrasii, Cristallinium randomense, Cymatiogalea aspergillum, Cymatiogalea bellicosa, Cymatiogalea membranispina, Dasydiacrodium caudatum, Dasydiacrodium obsonum, Impluviculus multiangularis, Impluviculussp., Veryhachium dumontii, Trunculumarium revinium, Vulcanisphaera africana, and Lusatia dendroidea.

III.2.1.6. Zard Kuh Formation

The Early-Middle? Ordovician Zard Kuh Formation was defined in the Zagros Basin by Setudehnia (1975). The type section is in Tang e Ilebek in the Zard Kuh area (Fig. III.3), 150 m in thick (Fig. III.7). It is divided to two members: *(1)* the lower member consists of interbedded green to gray fissile micaceous shales and green to yellow micaceous sandstones and covered by 10-20 cm sandstone layers. The sandstone beds are laterally continuous and contain trough cross bedding ; *(2)* The upper member is composed of green, dark gray and purple fissile graptolitic shales intercalated with shelly greenish-gray sandstones. The lower and upper contacts of the Formation are conformable.

In core drilled in Zagros area, the Zard Kuh Formation has been identified in well Kabir kuh#1 in Lurestan area (Fig. I.2) and consists of 49 m of shales, sandstones, dolomites and siltstones (Ghavidel Syooki, 1994a) and well Zirreh#1 in Fars area (Fig. I.2) which consists of 516 m shales and sandstones (Ghavidel Syooki, 1993c).

The Zard Kuh Formation is considered as Early-Middle? Ordovician based on fossil assemblages (Setudehnia, 1975) and actitarchs (Ghavidel Syooki, 1990).

The fossil markers identified in this member corresponds to *Dikelokephalina cf. asiatica,* and *Hysterolenus sp.* trilobites indicating a Lower Ordovician (Setudehnia, 1975). The Graptolites found in the siltstones about 82.3 meters above the base were dated as Ordovician. They include: *Didymograptus cf. extensus, Temnograptus sp., and Schizograptus sp.*.

Palynological studies carried out by Ghavidel Syooki (1990a) show that the Lower part of Zard Kuh Formation belongs to assemblage zone III *(Coryphidium bohemicum, Arbusculidium filamentosum, Arbusculidium mamillosum, Coryphidium persica, Piera dubia, Striatotheca principalis, Arbusculidium iranica, Acanthodaicrodium tasselii, Acanthodaicrodium* *complanata, Striatotheca triangula, Solisphaeridium solidispinosum, Veryhachium lairdii, Dactylofusa crossii)* and is considered as Late Tremadocian- Early Floian age.

The rest of Zard kuh Formation is related to assemblage zone IV *(Striatotheca triangularis, Striatotheca frequencies, Striatotheca trapeziformis, Diacrodiacrodium normale, Estiastra sp., Marrocanium simplex, Pirea sp., Aureostesta Sp., Peteinosphaeridium sp., Mltiplicisphaerisium ramusculosum)* is considered to Upper Floian- Dapingian? age.

These acritarch assemblages is considered to belong to *Acritarch assemblage zone O2 (Arbusculidium- Acanthodaicrodium), Acritarch assemblage zone O3 (Striatotheca principalis)* and *Acritarch assemblage zone O4 (Coryphidium bohemicum)* (Ghavidel Syooki, 1996).

Ghavidel Syooki et al. (2014) focused on Zard Kuh Formation in Kuh e Faraghan (Fig. III.2), and proposed Tremadocian-Floian age for this Formation.

III.2.1.7. Unnamed Zone

The unnamed zone (Setudehnia, 1975), in Zard Kuh (Fig. III.3) consists of about 80 m (Fig. III.7) shales alternating with minor thin sandstone layers. It is divided into two subzones. The lower unnamed zone consists mainly of thin-bedded alternating brownish-gray shales and gray sandstones. Reddish-white sandstones occur at the boundary between the upper and lower zones. The contact between the Faraghan Formation and the unnamed zone is covered (JOGMEC & NIOC, 2005).

The age of this zone considered as Silurian- Devonian based on palynologic studies by Ghavidel Syooki (1990a), which identified in assemblage zone V (*Tyligmasoma sp., Tunisphaeridium flaccidium, Veryhachium spp., Unellium piriferum, Stellinium micropolygonale, Navifusa exilis, Dunvernayshaera sp.*).

In this assemblage zone, recycled Silurian and Ordovician acritarchs are associated with the Devonian taxa. The reworked Silurian and Ordovician are:

Deunffia sp., domasia sp., Neoveryhachium carmina, Multiplicisphaeridium deticulatum, Dactylofuse neaghae, Eupoikilofusa striatifera, Multiplicisphaeridium romusculosum, Multiplicisphaeridium asturiae, Dactylofuse estillis.

III.2.2. Middle-Late Permian: Dalan Formation

The type section of the Dalan Formation is located at the Dalan Anticline, approximately 110 km SSW of Shiraz (Fig. I.2), (Motiei, 2003). The Formation is widely distributed in the Zagros Basin, with a thickness of 994 m at Zard Kuh, 377-324 m at Kuh e Dena, 774 m at Kuh e Garreh, 638 m at Kuh e Surmeh, 1600 m at Kuh e Faraghan, 739 m within the Kuh e Siah well#1, 767 m within the Dalan well#1 and 750 m in Kuh e Gahkum (Motiei, 2003). The Dalan Formation is subdivided into Lower carbonates, the Nar evaporate and Upper carbonates Members (Szabo and Kheradpir, 1978). The Lower and Upper carbonates Members consist mainly of massive bedded limestones and dolomites, while the Nar Member consists of evaporites including massive bedded anhydrites and anhydritic dolomites. The Dalan Formation rest on Faraghan Formation and the upper contact is unconformable with Triassic sediments of the Kangan Formation (Szabo and Kheradpir, 1978). In Kuh e Gahkum the Dalan Formation unconformably overlies the Faraghan Formation (Kolodka et al., 2011).

The Dalan Formation contains abundant *corals*, *crinoids*, *brachiopods*, *algae* and *fusulinids* that indicate a Mid-Late Permian age. Two Fusulinids biozones hav been identified for this Formation as follow (Motiei, 2003): (1) Biozone A: *Schwagerina sp.*, *Afghanella*, *Pachiphloia sp.*, *Endothyra sp.*, *Glubivalvulina sp.*, *Archeodiscus sp.*, *Tuberitina sp.*, *Cribrogenerina sp.*, *Lunucammina sp.*, *climacammina sp.*, *staffellids*, *Pseudovermiporella sp.,*, *Permucaculus sp.*, and (2) Biozone B: *Codonofusiella sp.*, *Reichelina sp.*, *Pachiphloia sp.*, *Glubivalvulina sp.*, *Tuberitina sp.*, *staffellids*, *Cribogenerina sp.*, *Palaeotextularia sp.*, *Pachiphloia iranica*, *Mizzia sp.*, *Paraglobivalvulina sp.*, *Dagmartia chanackchiensis*, *Ichthyolaria sp.*

More recently, five foraminifer's zones have been identified and one of algae for the Dalan Formation and give Wordian to the Changhsingian ages (Kolodka et al., 2011).

CHAPTER IV:

DEPOSITIONAL ENVIRONMENT AND SEQUENCE STRATIGRAPHY

IV.1. Introduction

The studied Palaeozoic succession is organized in four sedimentary intracratonic cycles. They are dominated mainly by siliciclastic and mixed sedimens, and are separated by unconformity surfaces. These cycles are: (1) Ordovician and represented by the Zard Kuh, Seyahou and Dargaz Formations; (2) Early Silurian and represented by the Sarchahan Formation; (3) Devonian and represented by the Zakeen Formation; and (4) Early Permian and represented by the Faraghan Formation.

This chapter examines the Palaeozoic Formations in three surface sections (Kuh e Faraghan, Kuh e Gahkum in Bandar abbas area and Kuh e Surmeh in Fars area) localized in the Zagros area and eleven subsurface sections in order to present and discuss their depositional environments, sequence stratigraphy pattern and palaeogeography.

IV.2. Cycle 1 (Ordovician)

During the Ordovician the Zagros area was part of the intra-cratonic Gondowanian Arabian plate, and drifted towards higher south latitudes (Beydoun, 1993). At this time, the Zagros area was located around 30°–35° latitude South (Heydari, 2008) (Fig. I.3). A passive margin is interpreted between this part of Gondwana (Zagros area) and the Paleo-Tethys (Sengor, 1990).

The Ordovician siliciclastic deposits are exposed in the Zagros area of southeastern Iran and are also recognized from core-drills. It consists of Floian-Katian Near-shore to deep-shore marine sandstones and shales of the Seyahou Formations (Ghavidel Syooki and Khosravi, 1995). Recently, Ghavidel Syooki et al. (2014) proposed Zard kuh Formation for 20 m thick of conglomerates in the base of Seyahou Formation. The uppermost Ordovician corresponds to the Hirnantian glaciogenic Dargaz Formation (Ghavidel Syooki et al., 2011). Two major erosional surfaces mark the top of the Seyahou and the Dargaz Formations, respectively.

IV.2.1. Seyahou Formation

IV.2.1.1. Introduction of the Seyahou Formation

The Seyahou name originates from the Seyahou village situated approximately 80 km north of Bandar Abbas city (Fig. III.2) (Ghavidel Syooki and Khosravi, 1995). The type section is located at Tang e Pashagh of Kuh e Faraghan, and consists of 731 m conglomerates, shales, siltstones, sandstones and fossiliferous limestones. Three members can be distinguished: (1) a lower conglomeratic Member (Fig. IV.5B), 20m thick, composed of polymictic conglomerate beds with thin sand and shale intercalations, this unit is newly defined as the Zard Kuh Fm. (Ghavidel-Syooki et al., 2014); (2) a mid heterolithic Member, composed of shale and sandstone alternations bearing interbedded phosphatic and bioclastic carbonate siltstones (Fig. IV.6A, 7A & 8A). These layers, have yielded a rich and diversified fauna, composed of trilobites, bryozoans, linguliform calcitic brachiopods, mollusks, and conodonts (Motiei, 2003); and (3) an upper Member, recognizable by thin-bedded, rhythmic claystone and sandstone couplets rich in ichnofossils (Fig. IV.9A & 10A) (Ghavidel Syooki et al., 2011). The lower contact of the Seyahou Formation is conformable with the underlying Zard Kuh Formation (Floian) in the type section (Ghavidel Syooki et al., 2014). White and brown sandstones of the Dargaz Formation interpreted as Hirnantian glacial deposits at Kuh e Faraghan mark the upper contact (Fig. IV. 11A) (Ghavidel Syooki et al., 2011).

The Seyahou Formation is also exposed at Kuh e Surmeh in Fars area (Fig. III.1 & IV.1). In comparison to the Kuh e Faraghan section, only the intermediate Member is preserved (Ghavidel Syooki, 1994e). The top is characterized by a 10° angular unconformity of the Early Permian Faraghan Formation (Fig. IV.1G).

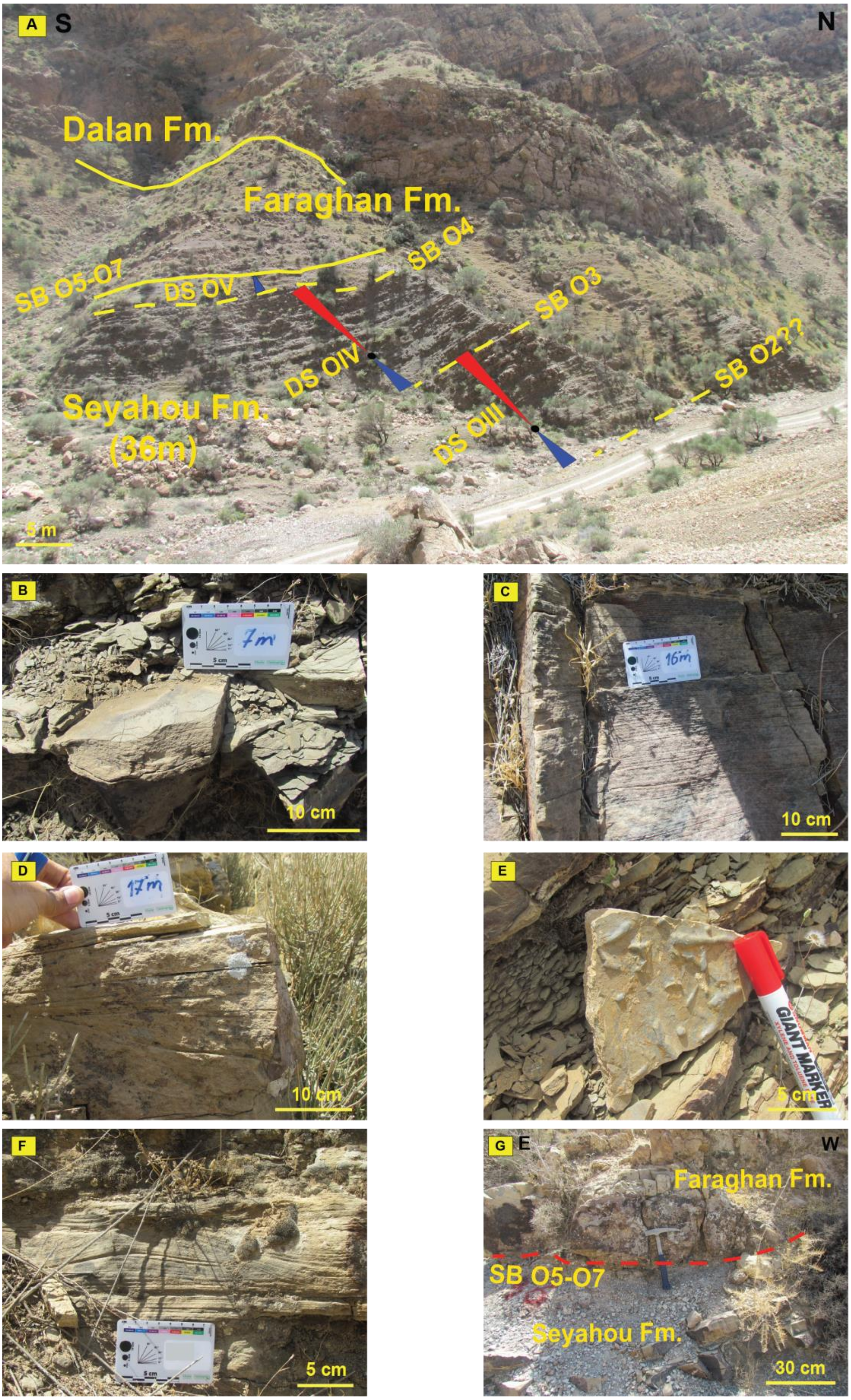

A
S
N
Dalan Fm.
Faraghan Fm.
SB O4
SB O5-O7
DS OV
SB O3
DS OIV
SB O2??
Seyahou Fm.
(36m)
DS OIII
5 m
B
7m
10 cm
C
16m
10 cm
D
17m
10 cm
E
GIANT MARKER
5 cm
F
5 cm
G
E
W
Faraghan Fm.
SB O5-O7
Seyahou Fm.
30 cm

Fig. IV.1 (Previous page): (A) Overview of the Kuh e Surmeh surface section, sequences and sedimentary structures, Early Permian Faraghan Formation resting on Late Ordovician Seyahou Formation; (B) Hummocky cross lamination in upper offshore sandstones from sequence OIII at 7 m level of section; (C) Horizontal lamination in shoreface sandstones from top of sequence OIII at 16 m level of section; (D) Tabular cross lamination in shoreface sandstones from top of sequence OIII at 17 m level of section; (E) Bioturbation in upper offshore sandstones of sequence OIV at 25 m level of the section; (F) Trough-cross lamination in shoreface sandstones from top of sequence OIII; and (G) Ungular unconformity between Seyahou Formation and Early Permian Faraghan Formation. *Fm.= Formation; SB= Sequence Boundary; DS= Depositional Sequence; O= Ordovician.*

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In core drilled of the Zagros area, the Seyahou Formation has been identified in the Lurestan (Fig. I.2) in two wells corresponding respectively to: (1) Kabir kuh#1 well, 91 m of shales, sandstones and siltstones (Ghavidel Syooki, 1994a) and (2) well Samand#2, 382 m shales, sandstones and dolomites (Tayefeh Khabbazi, 2010); It has also been evidenced in Fars area (Fig. I.2) in two wells: (1) Zirreh#1 well composed of a 117 m succession of shales, sandstones (Ghavidel Syooki, 1993c) and (2) Kuh e Siah#1 well with 154 m of shales, sandstones and limestones (Ghavidel Syooki, 1994b).

The Formation has been assigned to Floian- Katian (Gradestein et al., 2012) based on the occurrence of acritarchs and chitinozoans (Ghavidel Syooki, 1995, 2000). These have been arranged in four biozones, indicated on the log (Fig. II.3). Biozone are characterized by presence of: (1) biozone I: **Acritarchs:** *Veryhachium subglobosum, Veryhachium reductum, Villosacapsula setosapellicula, Orthosphaeridium ternatum, Orthosphaeridium octospinosum, Orthosphaeridium chondrododora, Evittia sanpetrensis, Leiosphaeridia ketchenata, Veryhachium tripinosum.* **Chitinozoan:** *Demonchitina minor, Calpichitina lenticularis, Conochitina senta, Desmochitina minor forma typica, Rhabdochitina usilata, Belonchitina micracantha typical.;* (2) biozone II: **Acritarchs:** *Batisphaeridium regnellii, Batisphaeridium hamatum, Multiplicisphaeridium raspa.* **Chitinozoan:** *Cathochitina fistulosa.;* (3) biozone III: **Acritarchs:** *Multiplicisphaeridium irregular, Evittia denticulata denticulate, Navifusa ancepsipuncta, Veryhachium valiente*. **Chitinozoan:** *Legenochitina baltica, Armoricochitina nigerica.;* and (4) biozone IV: **Acritarchs:** *Orthophaeridium inflatum, Actinotodissus crassus, Baltisphaeridium latiradiatum, Peteinosphaeridium nudum, Eupoikilofusa sp., Eupoikilofusa parvuligranosa.*

These acritarch assemblages (biozones I to IV) are considered to belong to *Acritarch assemblage zone O5 (Villosacapsula actionotodissus)* (Fig. II.3) composed of *Villosacapsula actionotodissus, Veryhachium reductum, Orthosphaeridium ternatum, Baltisphaeridium perclarum, Orthophaeridium quadrinatum, Leiosphaeridia endenense, Zonosphaeridium ovillensis, Actinotodissus crassus, Orthophaeridium inflatum, Orthophaeridium insculptum, Armoricochitina nigericais* and *Acritarch assemblage zone O6 (Orthophaeridium inflatum/ insculptum)* (Ghavidel Syooki, 1996).

The Seyahou Formation is time equivalent of the Kahfah, Ra'an and Quwarah Members of the Qasim Formation in Saudi Arabia, Dubeidib Formation in southwest of Jordan which are the most important oil and gas field, Bedinan Formation in southeast Turkey and the Hasirah Formation in Oman (Fig. I.4) (Konert et al., 2001).

IV.2.1.2. Precision on the sedimentology and stratigraphy

The Seyahou Formation was deposited on a gently dipping, wide and stable marine shelf bordering the Palaeo-Tethyan Ocean. The shelf was tilted toward the present-day north-east to provide accommodation space for the deposition of a siliciclastic succession (Senalp et al., 2001).

Outcrops of Ordovician Seyahou Formation in Zagros provide excellent opportunities for a detail facies analysis. In this study, two sections located in Kuh e Faraghan in Bandar Abbas area and Kuh e Surmeh in Fars area are presented with two associated wells (Kuh e Siah and Zirreh, respectively). The depositional environments evolve from foreshore, shoreface to offshore.

IV.2.1.2.1. Studied outcrops and well localisations

Kuh e Faraghan: is a 731 m thick succession composed of conglomerates, shales, siltstones, sandstones and fossiliferous limestones (Fig. IV.2). The lower boundary of Seyahou Formation is not exposed and was attributed to a basal conglomerate (Ghavidel Syooki and Khosravi, 1995). Ghavidel Syooki et al. (2014) proposed this basal conglomerates (20 m thick) belonging to the Floian Zard Kuh Formation. Its upper boundary is an erosional surface below the Dargaz Formation. The sand-shale ratio, grain size and bed thicknesses of the sandstones gradually increase upward.

Kuh e Surmeh: is characterized by a 36 m shales, micaceous sandstones and siltstones succession. (Fig. IV.2). The age Formation is Katian based on palynological study by Ghavidel Syooki (1994e).

Well Zirreh#1: 117 m thick (Ghavidel Syooki, 1993c) shales and siltstones interbeded with sandstones (Annexe I). The sandstones are moderately-sorted, sub-mature and sub-angular to sub-rounded. Sandstones are fine to medium grains size (150-300µm). The Silurian Sarchahan Formation covers the Formation.

Well Kuh e Siah#1: 154 m thick (Ghavidel Syooki, 1994b) shales, sandstones and limestones (Annexe I). The sandstones are very fine to fine grains (70-200 µm) and characterized by moderately-sorted, sub-mature, and sub-angular to sub-rounded grains.

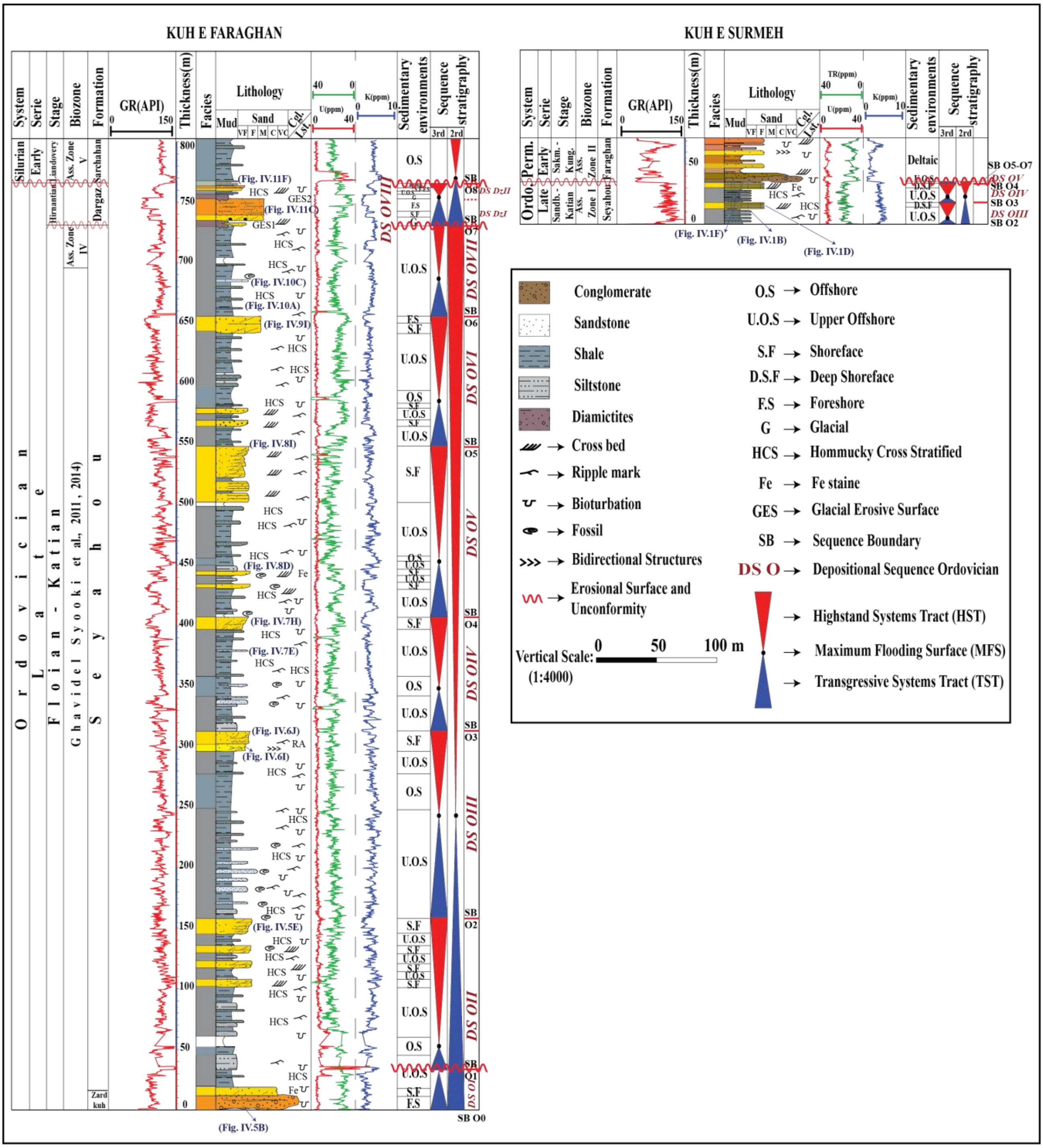

Fig. IV.2: Facies, depositional environments and sequence stratigraphy of the Zard Kuh, Seyahou and Dargaz Formations in Kuh e Faraghan and Seyahou Fomation in Kuh e Surmeh. *For the facies color codes see table IV.1&2.*

IV.2.1.2.2. Facies and depositional environments

This study shows the facies of Zard Kuh Formation corresponds to 20 m thick finning-upward conglomerates, and sandstones (Fig. IV.5B). It is characterized by Cruziana trace fossils. Crudly-stratified conglomerates are polymictite and poorly sorted grains. In upper part it It upgrades to pebbly, very coarse- to medium-grained litharenite sandstones. the sandstones characterized by trough and tabular cross-lamnatin. Illite is the most abundant clay mineral identified by XRD measurements (Fig. IV.3). Strong current activity is exoressed by erosive conglomerates channels and bars. The extensive burrows (Skolithus) suggest deposition under foreshore to shoreface condition (Nio and Yang, 1991). Comparing with San Sebastien Sandstone, Oregon, USA, the succession show the same basal lag conglomerate deposits interpreted as storm-wave dominated transgressive cycle of the foreshore environment (Bourgeois, 1980). The planar to trough cross-bed, the mature and well-sorted arrangement of grains indicate upper flow regime and high energy conditions (Collinson and Thompson, 1989).

For the Seyahou Formation, facies are summarized in (Table. IV.1) and their association allowed determining three main depositional environments that corresponds to inner to outer platform: (1) Shoreface; (2) Offshore (Fig. IV.4).

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Table. IV.1 (Next page): Facies table of the Seyahou Formation.It consists of 8 facies are deposited in two main depositional environments corresponding to inner to outer platform: (1) Shoreface; (2) Offshore.

Facies	Diagnostic features	Other components	Sedimentary structures and bioturbation	Stratal pattern	Energy and depositional environment	Environmental interpretation
O1 Planar laminated sandstones (Sp)	Very fine to medium grains, moderately sorted, sub mature, quartzarenite (Qz~90), arkose (Qz~60-70%, Fld~20-30%)	Heavy minerals, muscovite, calcite, iron oxides and pyrites	Low bioturbation, planar cross lamination structures, ripple marks, normally graded at top of each sandstone units	10 to 70 cm thick beds, sheet like geometry and coarsening upward	High flow regime	Inner platform domain -shoreface
O2 Trough-cross lamination sandstones (St)	Fine to coarse grains, moderately sorted, sub mature, quartz arenite (Qz~90), arkose (Qz~60-70%, Fld~20-30%)	Heavy and opaque minerals, muscovite, calcite, iron oxides and pyrites	Low bioturbation, trough cross lamination structures, ripple mark, occasional storm induced deposits (hummocky cross stratification)	10 to 70 cm thick beds, lenticular and sheet like geometry	High flow regime; Moderate to high-energy, wave-dominated	
O3 Bidirectional lamination sandstones	Fine to medium grains, moderately to well sorted, mature (Qz. ~80-85%, Fld. ~15-20%)	Opaque and heavy minerals, calcite, iron oxides and pyrites	Low bioturbation, Bidirectional cross-bedding, asymmetric and interference ripples	20 to 70 cm thick beds, lenticular and sheet like geometry	High-energy, tide-dominated subtidal	
O4 Amalgamated hummocky cross lamination sandstones (HCS)	Alternations of fine- to medium grains, sub mature, sub arkose (Qz~80%, Fld~10%)	Siliceous cements, clay minerals	HCS, SCS (swaley-cross stratifications) and clayey silty beds, cogenetic wave ripple	2-10 m coarsening upward unit	Low to moderate energy (storm-induced), upper offshore	Mid platform - Upper offshore
O5 Siltstones (SZ)	Medium to coarse silts	Muscovite and chlorite	HCS, unidirectional flaser bedding and fine lamination, high bioturbation	3 to 10 cm thick beds	Low to moderate energy (storm-induced), upper offshore	
O6 Clay mud-dominated heterolithic	Poor to medium sorted - immature to sub mature grains, shales, silts and very fine sandstones	Muscovite, chlorite, heavy minerals	Flaser bedding, unidirectional cross laminated and laminated siltstones to sandstones, rare HCS at a cm scale wave lengths	3 to 10 cm sandy to silty beds	Low to moderate energy (storm-induced), upper offshore	
O7 Storm induced (HCS and rare SCS) bioclastic accumulation	Poor to well sorted - immature to mature - angular to subrounded - very fine to medium grains - arkose (Qz~60-70%, Fld~20-30%), sub arkose (Qz. ~80-85% , Fld. ~15-20%), quartz arenite; brachiopods, trilobites, bivalves, echinoderms	Gastropods	Inversely graded planar laminated centimetre to decimetre accumulations (tempestites?), erosive basal surface, HCS and swaley-cross stratifications (SCS)	10 to 70 cm beds, lenticular and sheet like geometry	Low to moderate energy (storm-induced), upper offshore	
O8 Dark silty clay	Clay-mud dominated	Bioturbation (*Planolites*)			Lower offshore	Outer Platform - Lower offshore

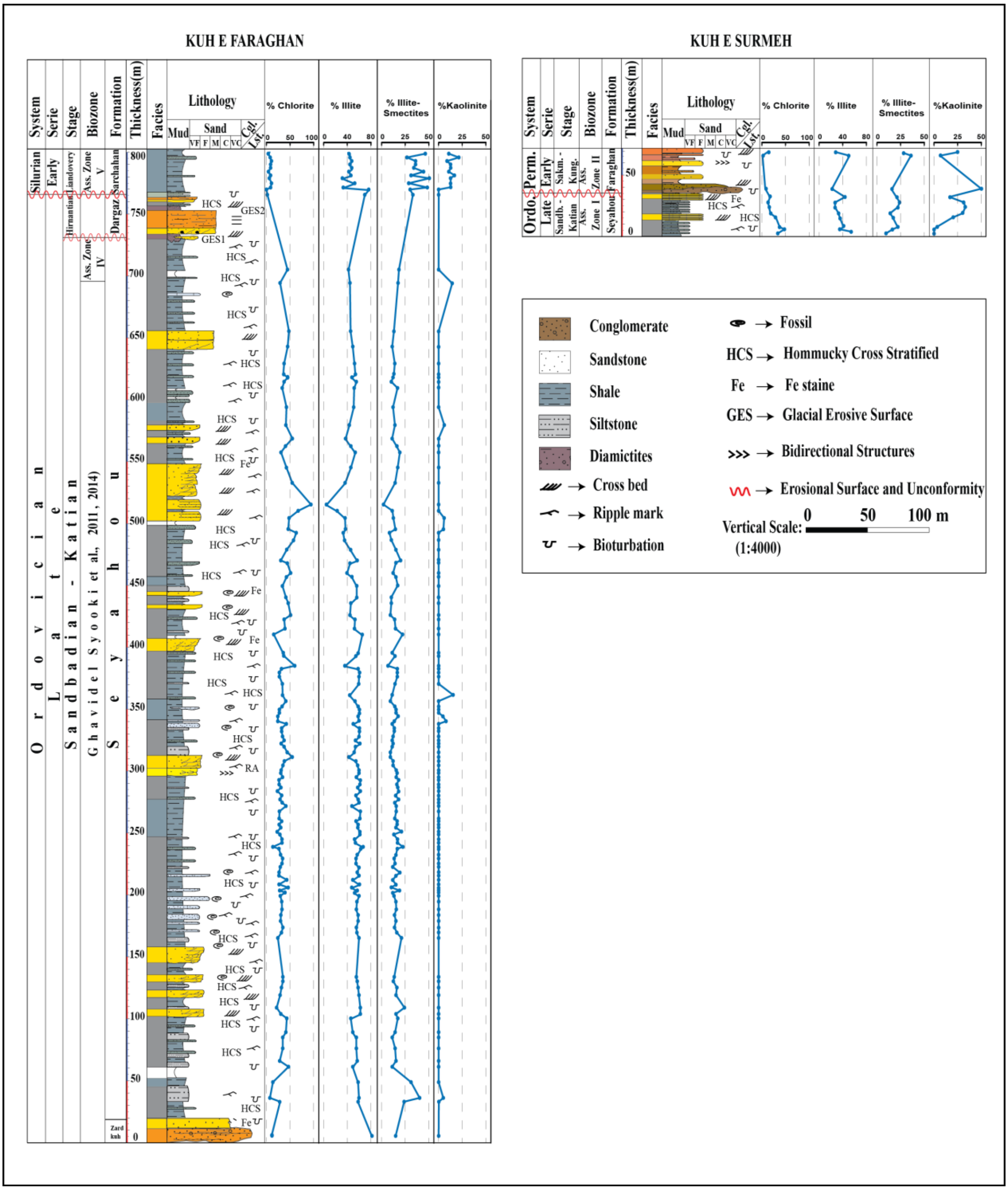

Fig. IV.3: Lithology vs. Chlorite, Illite, Illite/ Smectites and Kaolinite for the Zard Kuh, Seyahou and Dargaz Formations in Kuh e Faraghan and Seyahou Fomation in Kuh e Surmeh. *For the facies color codes see table IV.1&2*

Shoreface environment

Facies O1 to O3 (Table IV.1) consist in massive sandstones classified as quartzarenite to arkose. Subordinate components consist of heavy minerals and muscovite. XRD analysis of the samples reveals that chlorite is the most abundant clay mineral (Fig. IV.3).

The bases are bounded by flat to erosive base and wavy tops. Based on the sedimentary structures and grain size contents, three facies have been characterized. Facies O1 shows planar cross-lamination sandstones (Fig. IV.1D & 5F). O1 consists of fine to medium-grains, quartzarenites and arkoses organized in horizontal beds. It is commonly interstratified with trough cross-bedded sandstones (facies O2) (Fig. IV.1F). The planar-bedded sandstones are suggested to record deposition upon flat sediment surface under high-energy (upper flow regime) conditions (Ashley, 1990). Wave ripple lamination occurs at the top of the sandstone beds. Hummocky cross stratification and bioclastic accumulations are common. Skolithos is abundant in the coarsening upward sandstone layers. Facies O1and O2 are frequently interbedded. O3 consists of bidirectional trough cross-bedded (Fig. IV.6I) sediments affected by erosion surfaces and mud-drape layers. The stacked occurrence of trough cross-bedded sandstones is interpreted to record the migration of 3D megaripples. When both facies O1 and O2 are interstratified, it is further to suggest intervals of current acceleration, in which the formation of bedforms on the sediment surface was suppressed. The low degree of bioturbation indicates a high sedimentation rate (Aigner and Reineck, 1982). Skolithos indicates a shallow-marine subtidal setting, generally associated with a mobile substrate (Frey and Pemberton, 1984). The presence of bidirectional cross-laminations, argillaceous draps and erosive surfaces indicate tide-induced processes. Reactivation surfaces are related to fluctuating flow velocities currents under tidal conditions (Reading, 1996).

Offshore environment

Facies O4 to O7 (Table. IV.1) involve centimetre to decimetre-thick alternations of sandstones and siltstones-claystones, which are developed in the basal and middle part of the Seyahou Formation. Sandstones are framework-supported and moderately sorted. They are classified as subarenite to subarkose. Average quartz content is 55 to 85%. Feldspar and muscovite are minor components with a range of 20-30%. On the base of the relative abundance of sandstones and siltstones-claystones and the sedimentary structures, four facies types can be distinguished. Illite is the most abundant clay mineral (>50%) identified by XRD measurements (Fig. IV.3). The amount of chlorite is less than 40% and the Smectite-Illite is about 20% (Fig. IV.3).

Facies O4 is heterolithic with alternations of sandstones and siltstones, characterized by 2-10 m thick coarsening upward sequences and therefore predominance of sandstones. Basal surface is planar to irregular wavy beddings. Hummocky cross stratifications (HCS) and cogenetic wave ripples rework some top surfaces. Bioturbation, mainly represented by Planolites and Skolithos, occurs occasionally. Facies O5 and O6 are two silty-clay-rich facies containing hummocky cross stratifications, wavy bedded layers, unidirectional cross laminations and common flaser-lenticular stratifications. It also characterized by lenticular shell layers (O7). The clay-mud dominated heterolithic facies (O6) contains layers of laminated siltstones and rare sandstones.

O8 (Table. IV.1) is composed of dark grey to dark micaceous bioturbated *(Planolites)* shales with silty laminae and very fine beds sandstones intercalation (Fig. IV.5G).

Among the sedimentary structures observed, HCS, cogenetic wave ripples, silty laminae and bioclastic accumulations are related to storm wave action (Aigner, 1985; Einsele, 1992). Their occurrence in the sedimentary record is controlled by the position of the deposits along a shelf profile. According to facies models based on the sedimentary structures and on the sand/clay ratio, the facies O4 to O7 describe in Table IV.1 range from the proximal (O4 to O5), to the distal part (O6 to O7) of the upper offshore. The distribution and taphonomic grades of the shell layers are related to storm wave accumulations on upper offshore environments. The decrease in sand thickness, the fine grain size and the increase in bioturbation are associated with the deposition of distal tempestites (Aigner, 1985; Seilacher and Aigner, 1991). Based on bioturbation and predominantly fine-grained deposits with interbedded very thin, sharp-based sandstones and siltstones in facies (O8) indicate a calm depositional condition, in an open marine lower offshore environment (Kreisa, 1981).

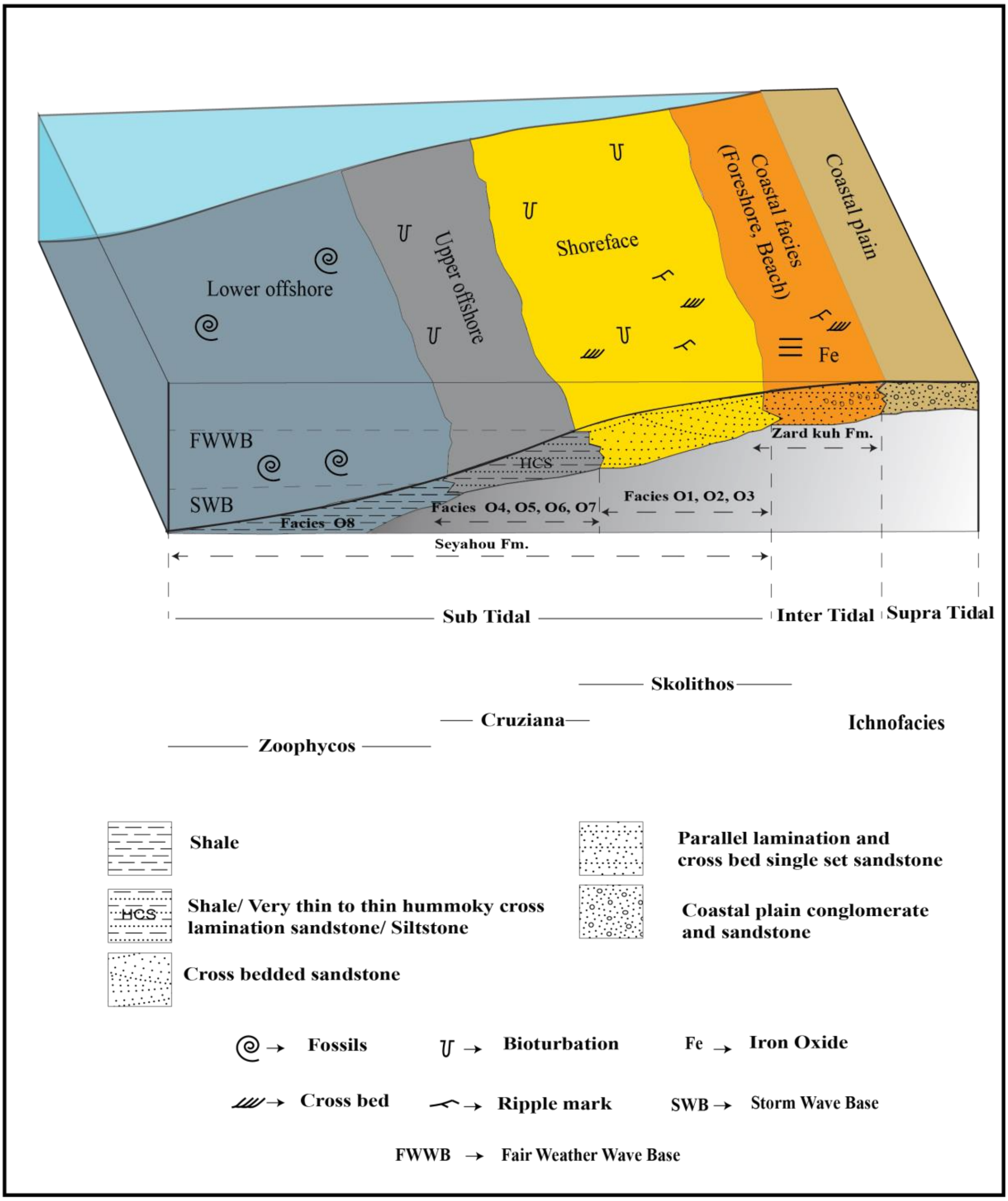

Fig. IV.4: Schematic depositional scheme for the Seyahou Formation in proximal to distal platform evolving from shoreface to lower offshore. *For the facies color codes see table IV.1&2.*

IV.2.1.3. Sequence Stratigraphy

Sequence stratigraphy has been used as the preferred approach for the stratigraphic analysis of sedimentary systems and basins. The workflow described below led to a comprehensive model of the sequence stratigraphy, depositional framework and paleogeography of the Late Ordovician Seyahou Formation.

Within the Arabian sequence stratigraphy framework of Sharland et al. (2001), the Seyahou Formation is located in the upper part of tectonostratigraphic megasequence AP2. Maximum flooding surface (MFS) designated as Ordovician 40 (MFS O40), occurs in the Katian.

The thickness and organisation of the Ordovician succession varies considerably throughout the different areas, ranging from non-deposition (West High Zagros area) and in Kuh e Gahkum (Bandar abbas area), 36 m at Kuh e Surmeh in Fars area and several hundred meters (731 m) in Kuh e Faraghan. In subsurface (Kuh e Siah and Zirreh), its identification is more difficult (Annexe I).

The Seyahou Formation exhibits a complete cycle in Kuh e Faraghan and records a coarsening-upward progradational tectono-sedimentary cycle (15 Ma). It is subdivided in seven 3rd-order depositional sequences. The facies, sequences and bounding surfaces are shown in the detailed surface log cross-sections (Fig. IV.2) and are described below:

<u>Sequence OI- DS OI:</u>

DS OI is an incomplete sequence recognized in lower most part of the succession (Fig. IV.5A). This DS is 33 m and its basal sequence boundary (SB O0) is not exposed. The upper boundary (SB O1) characterized by unconformity marked the hiatus spanning from Dapingian to Early Darriwillian (Ghavidel Syooki et al., 2014).

The TST of the sequence characterized by gradual transistion from Near-shore conglomerates to sandstones of the Zard Kuh Formation and followed by upper offshore deposits (O4 to O6) of the Seyahou Formation.

MFS is located in phosphoarenitic bed in the Seyahou Formation. It characterized by concentration of hardground-derived clasts and microfossils, mainly brachiopods and linguliformean brachiopods (Ghavidel Syooki et al., 2014).

This layer is the last sediments deposited in this sequence and marks the unconformity below the Dapingian to Early Darriwillian hiatus. As a result the HST of the DS OI is not preserved.

<u>Sequence OII- DS OII:</u>

DS OII is recognized in Kuh e Faraghan and consists of 122 m thick of the Seyahou Formation. The lower boundary (SB O1) characterized by an unconformity atop of Dapingian to Early Darriwilian (Ghavidel Syooki et al., 2014). The upper boundary (SB O2) marks transition from thick unit sandstones of shorface environment to upper offshore sediments of DS OIII.

The TST is about 17 m thick and evolves from Upper offshore (O4 to O7) to lower offshore (O8) environments.

The MFS is placed within an offshore bioturbated black shales (O8) with high gamma ray response and Uranium content (Fig. IV.2).

The HST is 107 m thick, and consists of an overall upward-shallowing succession composed of several parasequences, which show an upward transition from offshore dark shales (O8) to HCS sandstones and siltstones corresponding to an upper offshore, and evolve into Planar and trough cross-bed sandstones (O1 and O2) interpreted as shorface environment. Several gamma-ray cylinder shapes occur in the HST and are a medium to thick beds of shoreface sandstones.

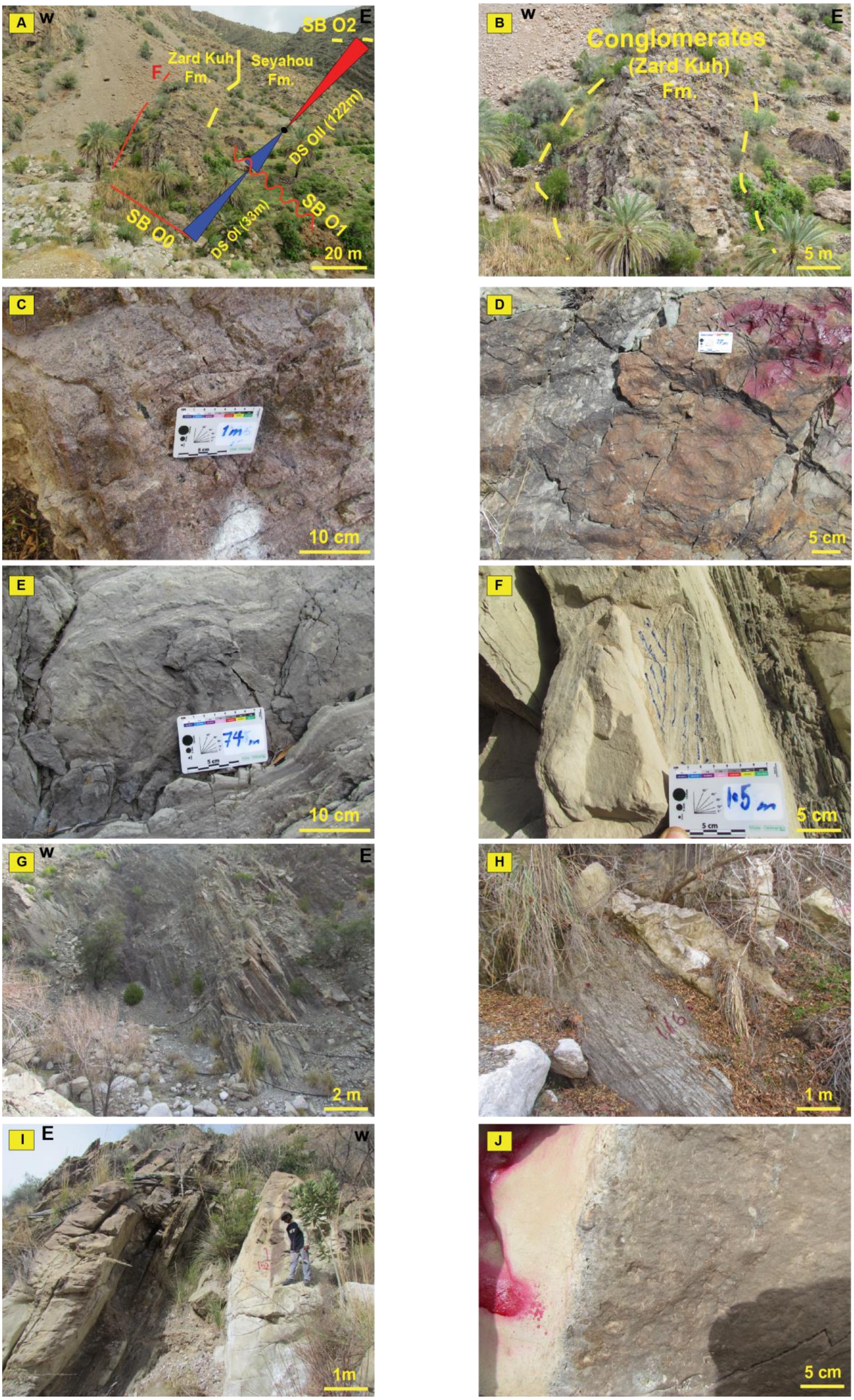
A
W
E
SB O2
Zard Kuh Fm.
Seyahou Fm.
F
DS OII (122m)
DS OI (33m)
SB O0
SB O1
20 m
B
W
E
Conglomerates (Zard Kuh) Fm.
5 m
C
10 cm
D
5 cm
E
10 cm
F
5 cm
G
W
E
2 m
H
1 m
I
E
W
1m
J
5 cm

Fig. IV.5 (Previous page): (A) Sequences and sedimentary structures of the DS OI and OII for the Seyahou Formation exposed in Kuh e Faraghan; (B) View of Zard Kuh Formation at base of Seyahou Formation in Kuh e Faraghan;(C) lower conglomeratic unit belonging to Zard Kuh Formation; (D) Ripple marks in the lower conglomeratic unit of the Zard Kuh Formation; (E) Bioturbation in thin-bed upper offshore sandstones at 74 m level of section; (F) Planar cross-lamination in shoreface sandstone from the top of parasequence in 105 m level of section; (G) Shallowing and thickening-upward Parasequence passing from bioturbated offshore shales and sandstones to shoreface sandstones in DS OII (H) Channelized sandstones in upperoffshore environment at 116 m level of section; and (I,J) Bioclastic accumulation sandstones placed in shoreface environments at top of DS OII. *Fm.= Formation; SB= Sequence Boundary; DS= Depositional Sequence; O= Ordovician.*

Sequence OIII- DS OIII:

DS OIII present in the Bandar Abbas area in Kuh e Faraghan and in the Fars area in Kuh e Surmeh (Fig. IV.6A). The total thickness of sequence OIII is 155 m in Kuh e Faraghan while its measured only 18 m in Kuh e Surmeh. However because of the non-outcrops of the basal part of succession, the total thickness and the lower sequence boundary of the sequence OIII in Kuh e Surmeh is unspecified. The lower boundary of this sequence is the correlative conformity at the abrupt change in facies from shorface cross-bed sandstones (O1 and O2) of sequence OII, to very thin to thin bed HCS sandstones and siltstones (O4-O6) of DS OIII. In both areas, sequence OIII shows a shallowing- and thickening -upward trend.

The TST is a thick 90 m in Kuh e Faraghan and evolves from very thin to thin bed HCS sandstones and siltstones (O4) to storm induced bioclastic accumulations in sandstones (O7).

The MFS was placed in the deepest part of Seyahou Formation characterized by very high gamma-ray response.

The HST is up to 65 m thick and consists of up to 3 parasequences containing successively shallower facies, from dark shales (O8) to HCS sandstones (O6) and bidirectional structures in tide environments (O3).

In Kuh e Surmeh the sequence OIII may be correlated with the lower part of the Seyahou Formation with uncertain lower boundary (Fig. IV.1A). It is 18 m thick consists of bioturbated shales interbed with thin bed HCS sandstones (O4) and Planar and trough cross-bed sandstones (O1 and O2) deposited in shoreface environment.

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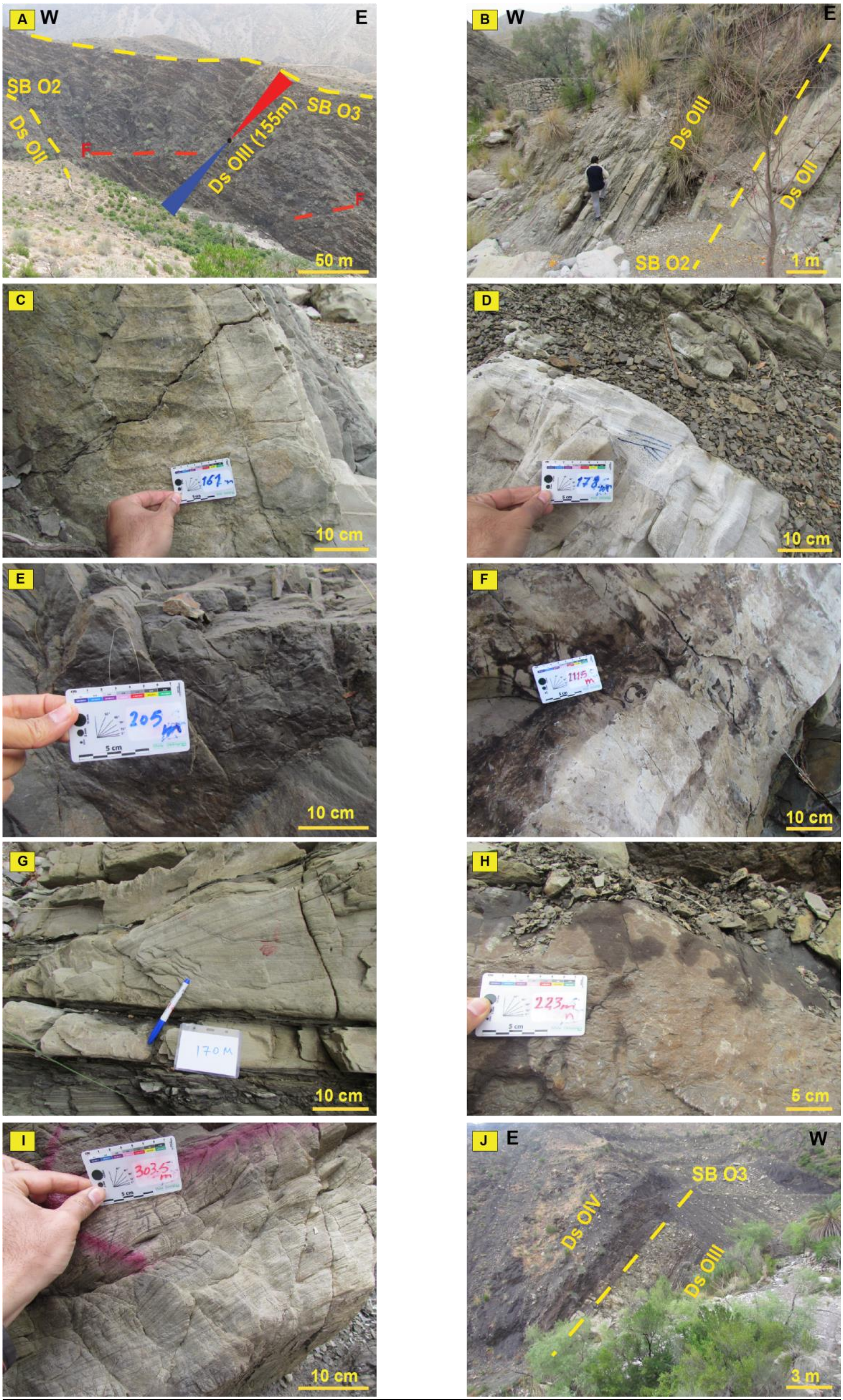
Fig. IV.6 (Next page): (A) Sequences and sedimentary structures of the DS OIII for the Seyahou Formation exposed in Kuh e Faraghan; (B) Sequence boundary between DS OII and DS OIII; (C) Ripple mark in upper offshore sandstones at 167 m level of section; (D) Tabular cross lamination in shoreface sandstones at upper part of parasequences ; (E) Bioturbation in very thin sandstones in upper offshore environment; (F) Fossils in the Storm induced bioclastic accumulation sandstones in upper offshore sandstones; (G) Tabular cross-lamination in shoreface sandstones; (H) Storm induced bioclastic accumulation sandstones in upper offshore sandstones; (I) Bidirectional lamination in the tide dominated deposits; and (J) Sequence boundary SB O3 at top of DS OIII. *Fm.= Formation; SB= Sequence Boundary; DS= Depositional Sequence; O= Ordovician.*


A
W
E
SB O2
Ds OII
F
Ds OIII (155m)
SB O3
F
50 m
B
W
E
Ds OIII
Ds OII
SB O2
1 m
C
167 m
10 cm
D
178 m
10 cm
E
205 m
10 cm
F
1115 m
10 cm
G
170 M
10 cm
H
223 m
5 cm
I
303.5 m
10 cm
J
E
W
SB O3
Ds OIV
Ds OIII
3 m

Sequence OIV- DS OIV:

DS OIV occurs in the middle part of the Seyahou Formation in both Bandar Abbas area (Kuh e Faraghan) and Fars areas (Kuh e Surmeh) (Fig. IV.7A). The thickness of this sequence is about 96 m in Kuh e Faraghan and 16 m in Kuh e Surmeh. The basal sequence boundary was placed at sharp contact between bidirectional cross-bed sandstones (O3) in Kuh e Faraghan and with the Planar and trough cross-bed sandstones (O1 and O2) in Kuh e Surmeh. In both areas it overlying by upper offshore siltstones and sandstones (O4-O7).

The TST is about 30 m thick in Kuh e Faraghan, and show a deepening-upward trend from HCS sandstones (O4) to storm induced bioclastic accumulation sandstones (O7) and to bioturbated dark shales (O8).

The MFS is placed in the offshore dark shales (O8) corresponding with the positive gamma-ray peak.

The (HST) is an upward-shallowing succession, of 66 m thick in Kuh e Faraghan and shows a transition from offshore to Upper offshore of HCS sandstones and siltstones interbeds (O4-O7), to planar and trough cross-bed sandstones (O1 and O2) deposited in shoreface environment.

In Kuh e Surmeh the sequence OIV is in the middle part of the Seyahou Formation and rest on sequence OIII (Fig. IV.1A). It is 16 m thick consists of bioturbated shales interbed with thin bed HCS sandstones (O4-O6) and planar and trough cross-bed sandstones (O1 and O2) deposited in shoreface environment.

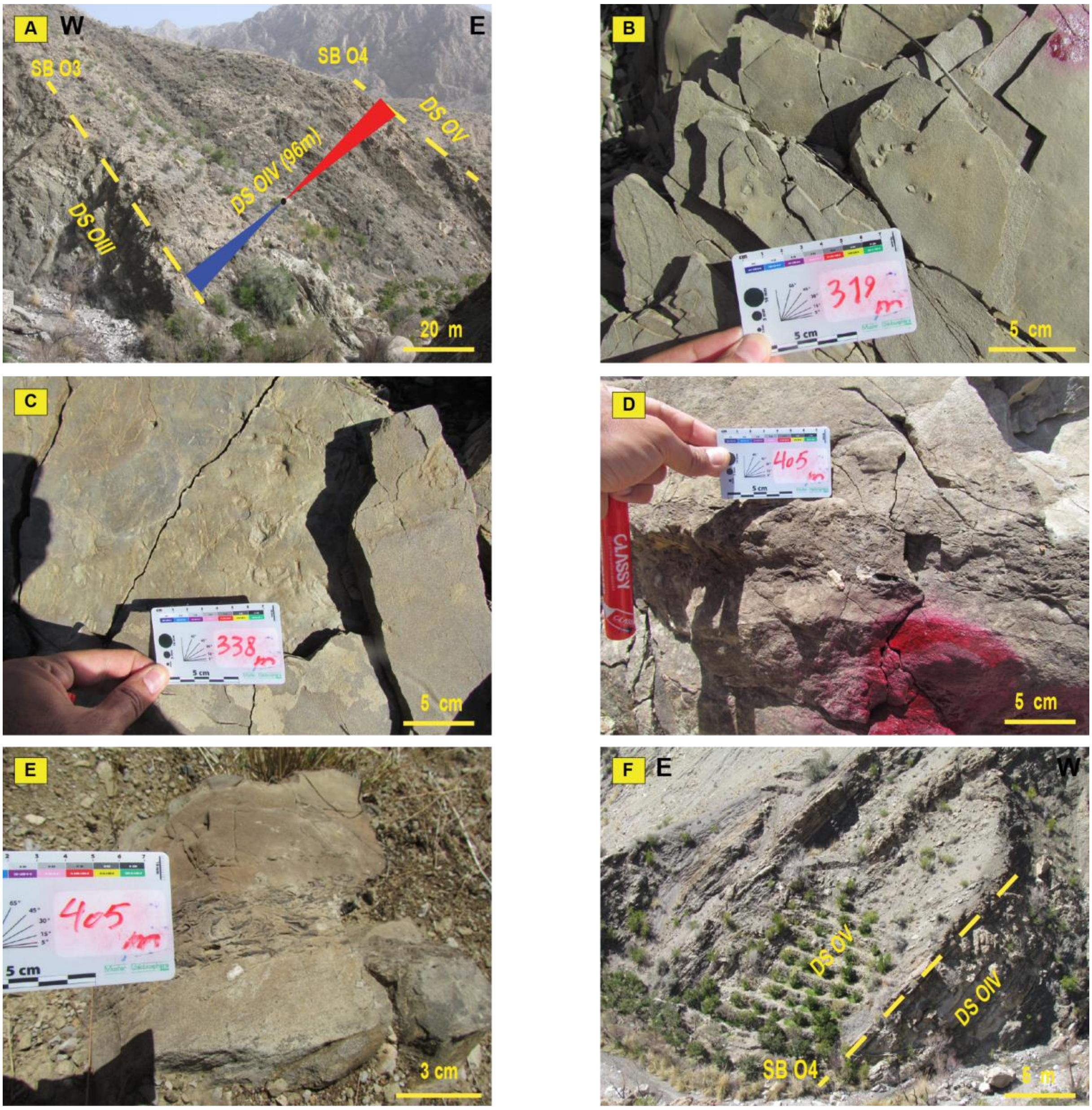


Fig. IV.7: (A) Sequences and sedimentary structures of the DS OIV for the Seyahou Formation exposed in Kuh e Faraghan; (B) Bioturbation in very thin sandstones in upper offshore environment; (C) Bioturbation in very thin sandstones in upper offshore environment in 338 m level of seyahou Fm.; (D) Fossils in the Storm induced bioclastic accumulation sandstones upper offshore environment; (E) Storm induced bioclastic accumulation sandstones upper offshore environment; (F) Sequence boundary SB O4 between DS OIV and DS OV. *Fm.= Formation; SB= Sequence Boundary; DS= Depositional Sequence; O= Ordovician.*

<u>Sequence OV- DS OV:</u>

DS OV has been identified in both areas in the Bandar Abbas area in Kuh e Faraghan and in the Fars area in Kuh e Surmeh (Fig. IV.8A). has a thickness about 140 m in Kuh e Faraghan. The basal sequence boundary is a sharp contact with an abrupt upward change of facies from cross-bedded (O1 and o2) to HCS sandstones (O4). DS OV has four coarsening and shallowing-upward parasequences.

The TST, is about 50 m thick in kuh e Faraghan deepening upward-fining units. It consists of very fine HCS sandstones and siltstones facies (O4-O6).

The MFS is placed within deeper water bioturbated dark shale (O8) with the highest in gamma-ray and Uraniuom peaks.

The HST is a thick 90 m unit in Kuh e Faraghan where where evolve from open marine and storm induced facies (O7) to planar and trough cross-beds sandstones (O1 and O2) of shoreface.

In Kuh e Surmeh the sequence OV is in the uppermost part of the Seyahou Formation and rest on sequence OIV (Fig. IV.1A). The measured thickness of this sequence is only 2 m consists of bioturbated mudstones interbed with thin bed HCS sandstones (O4) as a part of TST. In this area, the sequence OV is an incomplete sequence due to major erosion between Upper Ordovician and Lower Permian succession (Ghavidel syooki, 1994e).

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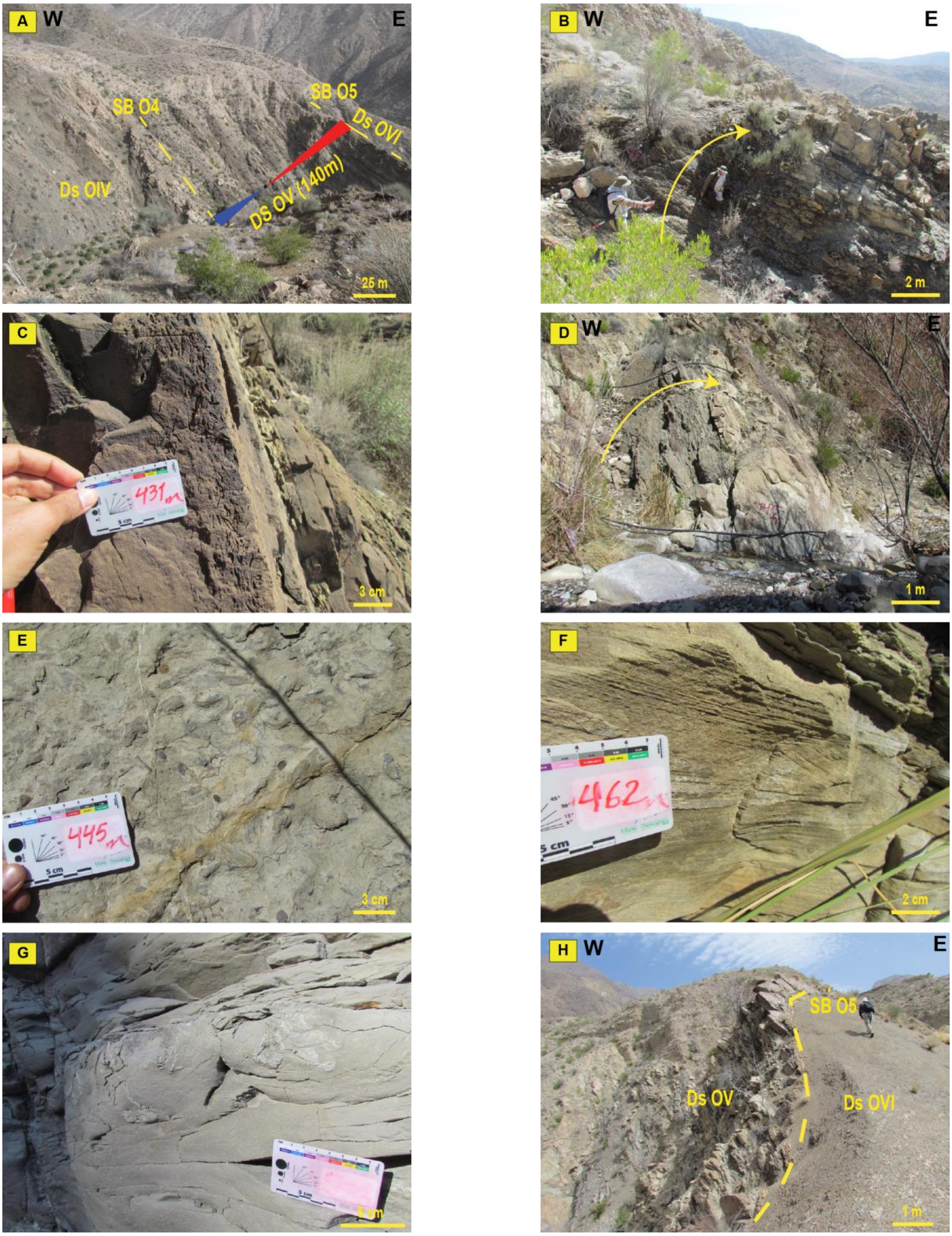
Fig. IV.8 (Next page): (A) Sequences and sedimentary structures of the DS OV for the Seyahou Formation exposed in Kuh e Faraghan; (B) Shallowing and thickening-upward parasequence show facies change from upper offshore to shorface; (C) Storm induced bioclastic accumulation sandstones in upper offshore environment; (D) Shallowing and thickening-upward parasequence show facies change from upper offshore to shorface; (E) Bioturbation in HCS sandstones; (F) Planar cross-Lamination in shoreface sandstones; (G) Convolute structures in shoreface sandstones of upper part of DS OV; and (H) Sequence boundary SB5 between DS OV and DS OVI. *Fm.= Formation; SB= Sequence Boundary; DS= Depositional Sequence; O= Ordovician.*


A
W
E
SB O4
SB O5
Ds OVI
Ds OIV
DS OV (140m)
25 m
B
W
E
2 m
C
431m
5 cm
3 cm
D
W
E
1 m
E
445m
5 cm
3 cm
F
462m
5 cm
2 cm
G
H
W
E
SB O5
Ds OV
Ds OVI
1 m

Sequence OVI- DS OVI:

DS OVI (Fig. IV.9A) has been recognized in the Bandar Abbas area in Kuh e Faraghan. It rests conformably on sequence OV and has about 108 m thick in Kuh e Faraghan. Its basal boundary is place at top of the cross-bed sandstones (O1 and O2) interpreted as shallowest-water facies of sequence OV.

The TST is about 35 m thick and evolve from upper offshore very fine HCS sandstones and siltstones (O4-O6) to lower offshore dark shales (O8).

The MFS is marked by high gamma-ray response within deep-marine facies (O8).

The HST is 70 m of coarsening-upward succession evolving from lower offshore (O8) to upper offshore (O4-O6) and into shoreface (O1 and O2) sandstones.

Sequence OVII- DS OVII:

DS OVII is the uppermost sequence in the Seyahou Formation at Kuh e Faraghan (Fig. IV.10A). It is capped by the Hirnantian glacial deposits of the Dargaz Formation and consists of 75 m of upper offshore very fine HCS sandstones and siltstones (O4-O6). The SB O6 is a sharp contact at top of the shallowest facies of DS OVI.

The TST is a 30 m thick in Kuh e Faraghan and evolves into upper offshore HCS sandstones and siltstones (O4-O6).

The MFS is localized in the bryozoan limestones indicate open marine environment.

The HST is a 45 m thick consists of very fine HCS sandstones and siltstones facies (O4-O6). It is overlain by the Hirnantian glacial Dargaz Formation.

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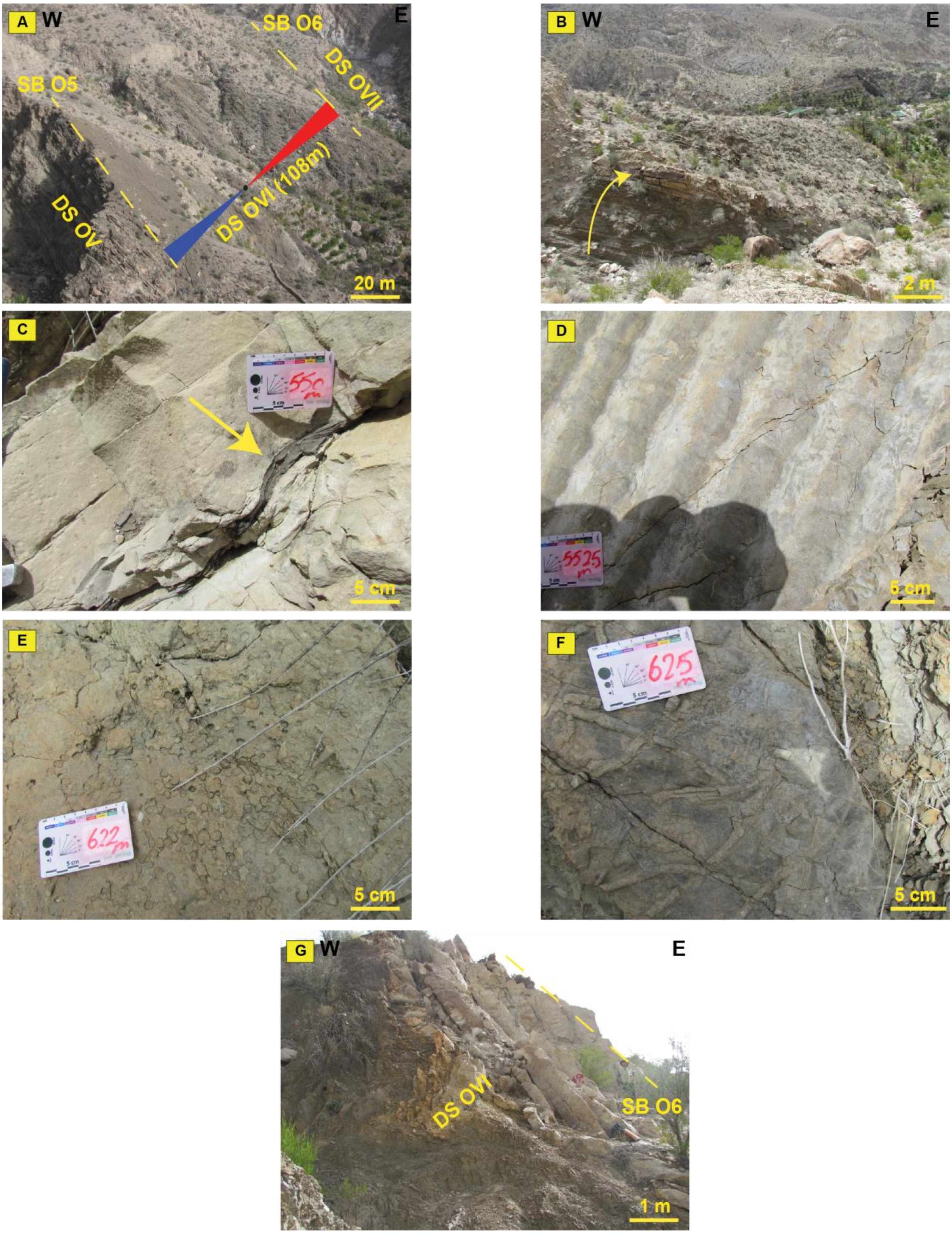
Fig. IV.9 (Next page): (A) Sequences and sedimentary structures of DS OVI for the Seyahou Formation exposed in Kuh e Faraghan; (B) Shallowing and thickening-upward parasequence in DS OVI show facies change from upper offshore to shoreface; (C) Mud clast in shoreface sandstones; (D) Ripple mark in upper offshore sandstones in DS OVI; (E) Vertical bioturbation in thin bed HCS sandstones (O4); (F) Horizontal bioturbation in thin bed HCS sandstones (O4); (G) Sequence boundary SB5 between DS OVI and DS OVII. *Fm.= Formation; SB= Sequence Boundary; DS= Depositional Sequence; O= Ordovician.*


A
W
E
SB O6
DS OVII
SB O5
DS OV
DS OVI (108m)
20 m
B
W
E
2 m
C
5 cm
D
5 cm
E
5 cm
F
5 cm
G
W
E
DS OVI
SB O6
1 m

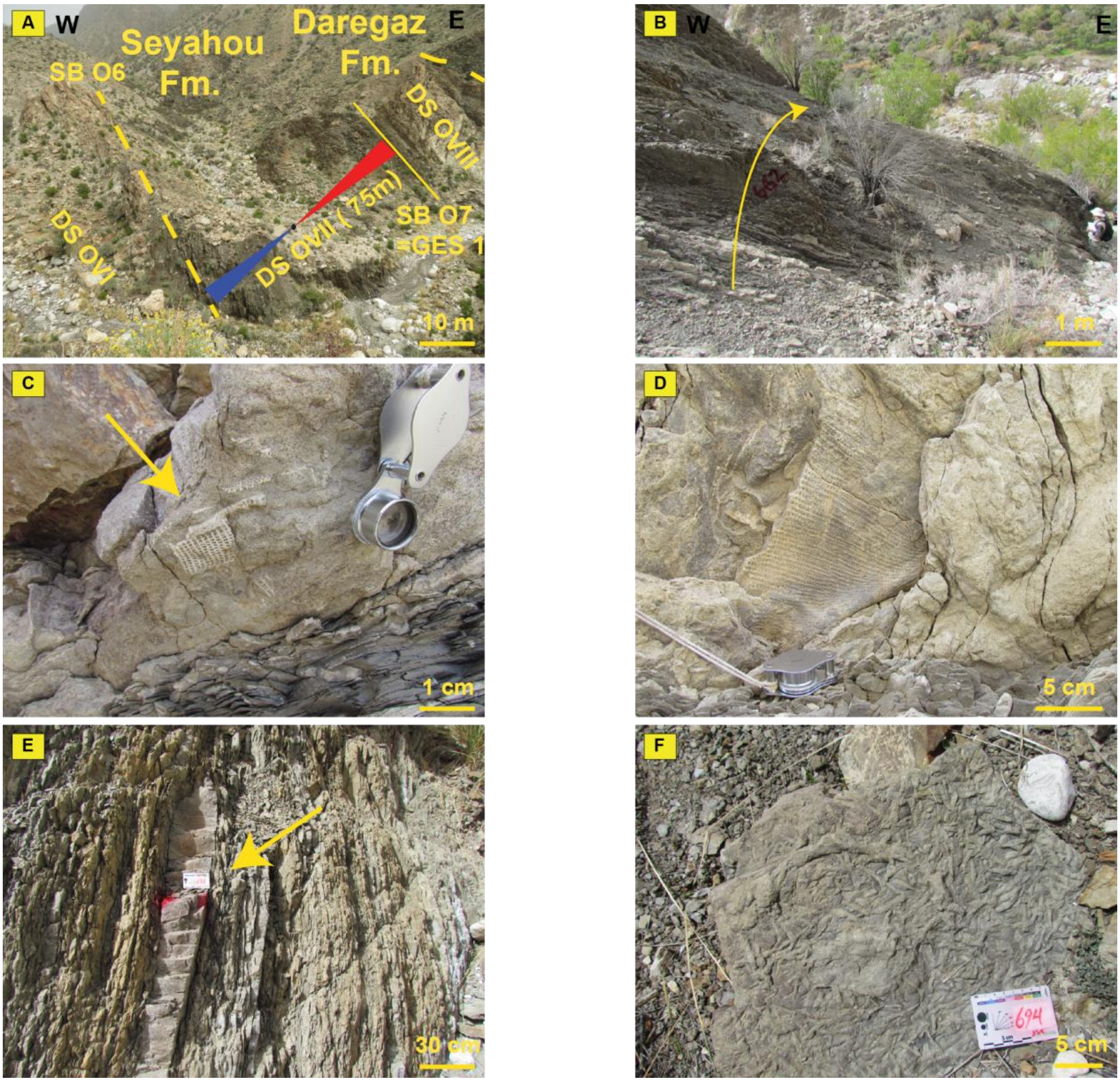


Fig. IV.10: (A) Sequences and sedimentary structures of DS OVII for the Seyahou Formation exposed in Kuh e Faraghan; (B) Shallowing and thickening-upward parasequence in DS OVII; (C, D) Bryozoa in limestone in open marine environment; (E) Channelized sandstones in upper offshore environment; and (F) Bioturbation in very fine HCS sandstones and siltstones facies (O4). *Fm.= Formation; SB= Sequence Boundary; DS= Depositional Sequence; O= Ordovician.*

IV.2.2. Dargaz Formation

IV.2.2.1. Introduction of the Dargaz Formation

The evidence of a Late Ordovician glacial event was first recognised in the Kuh e Faraghan outcrop in Bandar Abbas area (East of Zagros) by Ghavidel Syooki et al. (2011). Glacial deposits have been identified across Africa, South America and Arabian Plate (Beuf et al., 1971; Vaslet, 1990; Powell et al., 1994; Ghienne and Deynoux, 1998; Le Heron et al., 2004, Eschard et al., 2005; Moreau et al., 2005; Turner et al., 2005; Melvin and Sprague, 2006; Denis et al., 2007; Le Heron et al., 2007). The glaciation occurred during the Hirnantian stage (Sutcliffe et al., 2000; Brenchley et al., 2003). Glacial valleys gained economic importance over the past two decades because they host significant hydrocarbons (Hirst et al., 2002).

The Dargaz Formation has been defined by Ghavidel Syooki et al. (2011) at Tang e Zakeen in Kuh e Faraghan in Bandar Abbas area. Glaciogenic strata related to hirnantian glaciation have been grouped in the Dargaz Formation. Based on stratigraphic relationships, this Formation was assigned originally to the Upper Ordovician Seyahou Formation (Ghavidel Syooki and Khosravi, 1995). Since then, a detailed palynologigal study has been carried out by Ghavidel Syooki et al. (2011), in Kuh e Faraghan, which has resulted in the identification of palynomorph taxa. Dargaz Formation is correlated with Sarah Formation in Saudi Arabia (Fig. I.4) (Ghavidel Syooki et al., 2011).

The Dargaz Formation shown lateral thickness variation from has 10 to70 m (and 35 m in this study) thick in the Kuh e Faraghan, consists of white sandstones and structureless to diffusely laminated diamictites. Both the lower and upper contacts are erosive unconformities (Fig. IV.11A). The Formation is poorly exposed but easily distinguishable and mappable at the southeast corner of the Kuh e Faraghan (Ghavidel Syooki et al., 2011).

The Formation has been assigned to the Hirnantian based on the occurrence of the chitinozoans and acritarchs (Ghavidel-syooki et al., 2011).

Chitinozoans:

In Kuh e Faraghan, some taxa of Hirnantian chitinozoan assemblage zones are present, including *Armoricochitina nigerica (Bouché), Spinachitina oulebsiri Paris, Bourahrouh and Le Hérissé, Belonechitina pseudarabiensis Butcher, Calpichitina lenticularis Bouché, Desmochitina minor Eisenack, Bourahrouh and LeHérissé, and Tanuchitina cf. elongata Bouché*. The associated assemblage includes *Armoricochitina nigerica, Calpichitina lenticularis, Euconochitina sp., and Lagenochitina baltica Eisenack*. The upper Dargaz diamictite contains an oligotaxic association that includes *Tanuchitina cf. elongata, A. nigerica, Belonechitina pseudarabiensis, and C. lenticularis*.

Acritarchs:

In the lower Dargaz diamicts, there are a few recycled acritarch taxa including *Coryphidium sp., Aureotesta sp., Pirea sp., and Striatotheca sp*. These recycled taxa derived most probably from the underlying Seyahou strata. The phytoplankton recovered from the Dargaz diamictites contains some common taxa *(e.g., Villosacapsula irrorata (Loebich and Tappan), Dactylofusa spinata (Staplin, Jansonious and Pocock), Dorsennidium hamii (Wright and Meyers), Multiplicisphaeridium spp., and Villosacapsula setosapellicula (Loeblich and Tappan).*

IV.2.2.2. Precision on the sedimentology and stratigraphy

The Zagros region was located around 30°–35° S latitude and drifted to 40°-45° S by the end of the Ordovician time (Fig. I.3). An abrupt sea-level fall, linked to Late Ordovician Hirnantian glaciations, terminated the deposition of Ordovician (Heydari, 2008; Konert, 2001). In outcrop sections (McClure, 1978) and subsurface (McGillivray and Al-Husseini, 1992) in the Arabian plate there are widespread evidence of the latest Ordovician Hirnantian Glaciation. The position of channels and tunnel valleys at the surface and from the subsurface in Arabia suggest that the glaciated area was to the west in the region of the Nubian and Arabian shield and that sediment transport was toward the present-day east and northeast (Bell and Spaak, 2007).The abrupt end of glaciar episods is marked by an extensive marine flood that deposited organic-rich "hot shale" across large parts of the Arabian Plate (McGillivray and Al-Husseini, 1992).

II.2.2.2.1. Presentation of the studied succession

The Dargaz Formation in Kuh e Faraghan consists of 35 m thick (Fig. IV.11) sandstones and diamictites. The sandstones are characterized by cross beds and horizontal laminations, while, the diamictites are green to brown, structureless to crudely stratified. Its lower contact is an erosive unconformity topping the pre-glacial highly bioturbated, very thin-bedded, mudstone/sandstone of the Seyahou Formation. The upper contact is sharp and erosive and is capped by the post-glacial black shales of the Early Silurian Sarchahan Formation.

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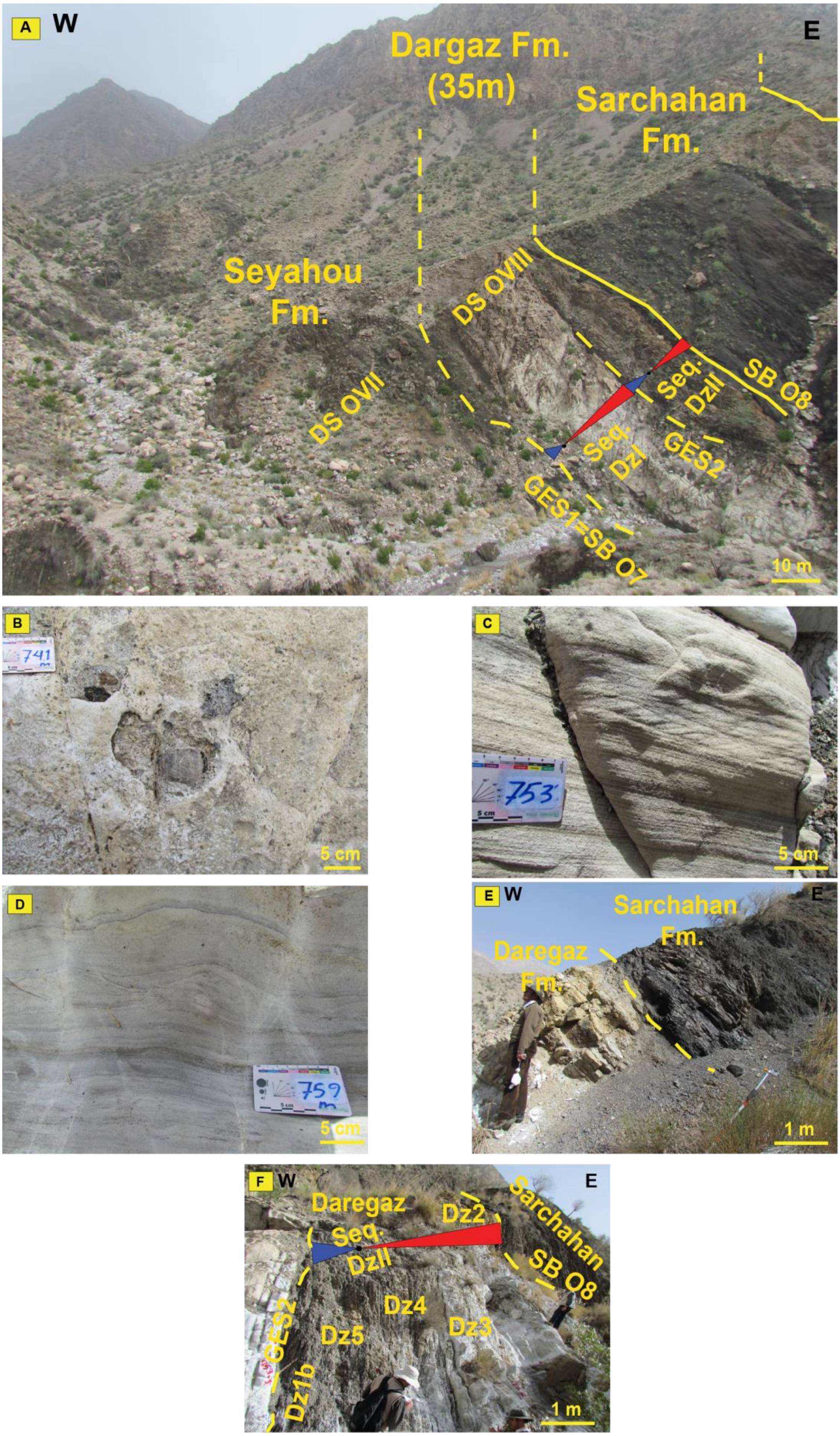
Fig. IV.11 (Next page): (A) Sequences and sedimentary structures of the DS for the Dargaz Formation exposed in Kuh e Faraghan; (B) Clast reworked at base of channelized sandstones in shoreface environment in Seq. DzI; (C) Horizontal lamination with lineation in foreshore sandstones in top of Seq. DzI; (D) Horizontal lamination with lineation in foreshore sandstones in Seq. DzII (E) Unconformity between Dargaz Formation and Early Silurian Sarchahan deposits; (F) Seq. DzII of the Dargaz Formation evolving from glacial diamicte to upper offshore thin bed sandstones and to shoreace sandstones which topped by shales and sandstones of lagoon environment at top the Dargaz Formation. *Fm.= Formation; SB= Sequence Boundary; DS= Depositional Sequence; O= Ordovician; Dz=Dargaz.*


A
W
E
Dargaz Fm.
(35m)
Sarchahan
Fm.
Seyahou
Fm.
DS OVIII
DS OVII
Seq.
DzII
SB O8
Seq.
DzI
GES2
GES1=SB O7
10 m
B
741
5 cm
C
753
5 cm
D
759
5 cm
E
W
E
Sarchahan
Fm.
Daregaz
Fm.
1 m
F
W
E
Daregaz
Seq.
DzII
Dz2
Sarchahan
SB O8
Dz4
Dz3
Dz5
GES2
Dz1b
1 m

IV.2.2.2.2. Facies and depositional environments

Facies are divided into five main depositional environments (Fig. IV.12): (1) diamictites; (2) lagoon (3) foreshore; (4) shoreface; and (5) upper offshore; which are summarized in Table (IV.2) for the Dargaz Formation. Environmental interpretations are described below:

Facies	Diagnostic features	Components	Sedimentary structures and bioturbation	stratal pattern	Energy and depositional environment	Environmental interpretation
Diamict (Dz1)	Scattered granule to pebble size,	Outsized clast	Lamination	Massive to crudly stratified, tabualr beds, up to 6 m thick,	Low energy - Glacial	Glacial
Shale/ Very fine lamination sandstone (Dz2)	poorly sorted - immature to sub mature- angular to subangular- shale and very fine sandstone (40-70 µ) -	Mica moscuvite- chlorite- heavy minerals	Lamination- high bioturbation	Very thin to thin bedded (3-10cm), sheet like geometry, dark gray to black		Lagoon
Horizental lamination Sandstone (Dz3)	Well sorted - mature - rounded - fine to medium (100-300 µ) - quartz arenite (Qz. ~97% , Fld. ~3%) -	Heavy minerals	Horizontal lamination	Thick bed to massive (0.7 to 2 m), white to green	High energy- Foreshore	Foreshore
Trough cross beds Sandstone (Dz4)	Moderately sorted - sub mature - sub angular - fine to coarse grain (100- 600 µ) - sub arkose (Qz. ~97% , Fld. ~3%) to arkosic graywack	Heavy minerals	Planar and trough cross lamination	Medium to thick bed (20 to 70 cm.), coarsening upward, channelized and lenticular bedding with some clast at the base of unit	High energy- Shoreface	Shoreface
Hummocky cross lamination sandstone (Dz5a)	Very fine to fine grains (70-150 µ), poorly sorted, immature to submature arkose, Qz~60%, Fld~35,Rf	Mica moscuvite- chlorite- heavy minerals	Hummocky cross stratification- high bioturbation		Low to moderate energy (storme induced) - upper offshore	Upper Offshore
Shale (Dz5b)				Dark gray to black		

Table. IV.2: Facies table of the Dargaz Formation. It consisits of 6 fies and sub-facies deposite in 5 main depositional environment corresponding to glacial, lagoon, foreshore, shoreface and upper offshore.

Diamictites

This facies association is composed of facies Dz1 (a and b) (Table. IV.2) and is presented by Ghavidel Syooki et al., (2011), for the first time. Confirming to their studies, there are two diamictites parts in the Dargaz Formation. Both lower and upper boundaries characterized by the glacial erosive surface (GES 1 and 2, sensu Le Heron et al., 2010). This part commonly cut by cross-lamination sandstone beds. The upper Dargaz diamictite (DZ1b) is homogeneous in lithology and is about 3 m in thick. It is topped by the second glacial erosive surface (GES2).

The channelized contacts of these facies testifies to their erosionally and channelized-based contacts. According to interpretation made by Ghavidel Syooki et al., (2011), the outsized clasts embedded in diamictites shows rainout processes formed by the deposition of suspended fine grains and release of coarser dropstones from icebergs. The channels from the lower Dargaz diamictite represent high-energy episodes, most probably related to glaciomarine bars (Ghavidel Syooki et al., 2011).

Lagoon environment

Facies association Dz2 (Table. IV.2) present at the upper part of Dargaz Formation. It is characterized by 2m structurless very thin sandstones and shales. Facies Dz2 overlain facies Dz4 and topped by major erosional surface at the base of Silurian Sarchahan Formation. The presence of very thin sandstones and shales and the placement above thinning-upward shorface (Dz4) environments indicate low energy regime in the lagoon environment.

Foreshore environment

Facies Dz3 (Table. IV.2) is well represented and topped by GES 2. It characterized by about 15 m thick consists of thick to massive horizontal lamination sandstones. Plane- parallel beds may record upper flow regim. The out-size clasts suggest rip-up by extreame floods (Russel and Marren, 1999). The clasts were reworked from the sedimentary column immediately below the GES. This package is interpreted to record the high energy of bedload under upper plane bed conditions on a foreshore. The coarsening and progressive-upward of large bedforms of these sandstones (Fig. IV.11A) indicate retrogradation of beach complex.

Shoreface environment

This facies association (Dz4) present at the lower part and middle part of the Dargaz Formation (Table. IV.2). The first unit located at top of the first diamictite facies (Dz1a) and coverd by facies Dz3. It is characterized by 3m coarsening upward sandstones. The upper unit of facies Dz4 characterized by about 5 m thick thinning-upward cross-stratification sandstones. The thinning-up trend and trangressive upward appearance of thin bedforms of the upper sandstone packages (Fig. IV.11A) represent retrogradation of shallow marine deposits. The trough cross-bedded sandstones indicate deposition in the high energy shoreface environment above the fair-weather wave base (Reading, 1996).

Upper offshore environment

This facies association is composed of facies Dz5 (Table. IV.2). It is subdivided into two subfacies Dz5a and Dz5b. Facies Dz5 is about 5 m thick, thinning-upward package showing thin bed hummocky cross stratification sandstones (HCS). Presence of thin beds HCS sandstones and high bioturbation indicate deposition below the mean fair-weather wave base under storm-wave influences in an Upper offshore environment. The pinch-out style of sandstone beds also supports a storm-generated origin of these beds (Kreisa, 1981). The presence of ripple marks, biutorbation and shales (Dz5b) indicate the low energy regime below the fair-weather wave base (Kreisa, 1981; Reading, 1996).

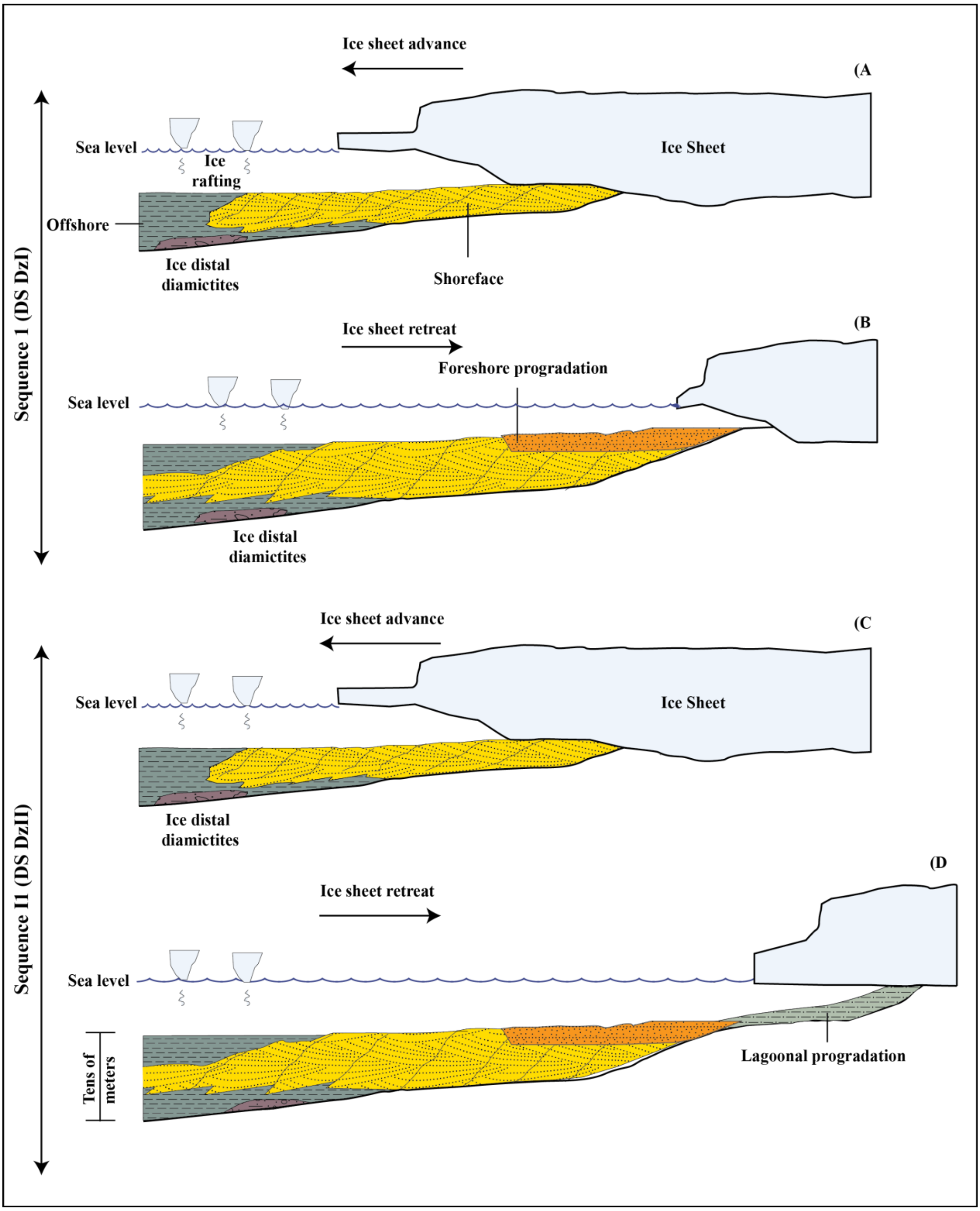


Fig. IV.12: Schematic depositional scheme for the Dargaz Formation evolving from: (1) diamictites; to (2) lagoon; (3) foreshore; (4) shoreface; and (5) upper offshore. *For the facies color codes see table IV.2.*

IV.2.2.3. Sequence Stratigraphy

Le Heron et al., (2010), introduced the glacial depositional sequences as packages of glacial or glacially-related strata that record separate cycles of glacial advance and retreat across a basin. The term glacially related is used to refer to successions deposited under the overall influence of an ice sheet in the hinterland, also encompassing a range of sediments deposited in paraglacial settings. In basins which have experienced multiple glaciations/glacial cycles, glacial depositional sequences may be stacked vertically, in which case they are bounded above and below by glacial erosion surfaces (GES: i.e. unconformities produced subglacially. In the process-based interpretation by (Ghavidel Syooki et al., 2011), two GES are recognised in the Dargaz Formation in Kuh e Faraghan (Fig. IV.11A).

The Dargaz Formation consists of one third order sequence (DS OVIII) divided to two small sequences (Seq. DzI and Seq. DzII). These sequences bounded by major erosive boundaries or unconformities. Its basal sequence boundary is erosional contact on the pre-glacial Late Ordovician Seyahou (GES 1) and upper sequence boundary is channelized contact beneath the post-glacial Early Silurian Sarchahan Formations.

Sequence DzI (Seq. DzI), marked by glaciogenic erosive surface (GES 1= SB O7) into a pre-glacial (Sandbian-Katian) sediments and deposition of first glaciomarine diacmictites (Dz1a). It is follow by coarsening-upward of large bedforms of parallel lamination sandstones (Dz3) indicate retrogradation of shoreface to foreshore complex. The upper contact shows another glaciogenic erosive surface (GES 2).

Sequence DzII (Seq. DzII), related to the advance of an ice front. As a result a marked erosive surface (GES 2) appears when outwash deposits (Dz1b) directly scoured deposits of previous sequence (Seq. DzI) (Ghavidel Syooki et al., 2011). This transgressive cycle followed by sedimentation of thin bed hummocky cross stratification sandstones (Dz5). Regressive cycle characterized by the deposition of a 5 m thick unit of shoreface sandstones (Dz4) and finally ended with 2 m lagoonal very thin sandstones and shales (Dz2). Sequence DzII is capped unconformably by the marine flooding Silurian shales (SB O8) (Fig. IV.11D).

IV.3. Cycle 2 (Early Silurian)

The Early Silurian is marked by an extensive marine flooding indicated by the deposition of organic-rich 'hot shales' covering large areas of the Arabian plate and northern Africa. This gives the distinctive 'hot' (positive shift) response of gamma ray logs. The Silurian base is a proven source for hydrocarbons throughout North Gondwana, from Morocco to the Zagros. This transgression marks the end of the Ordovician glaciation and corresponds to a diachronous flooding event that affected the African-Arabian margin of Gondwana (Bell and Spaak, 2006). In the Zagros, Early Silurian deposits (Ghavidel Syooki, 1995) and 'hot shales' correspond to the Sarchahan Formation.

IV.3.1. Introduction of the Sarchahan Formation

The Sarchahan name is from Sarchahan village located approximately 120 km north of Bandar Abbas city (Ghavidel Syooki, 1995). The 100 m thick type section of the Sarchahan Formation is located in Tang e Abzagh of Kuh e Gahkum. It consists of conglomerates, sandstones, siltstones, shales and fossiliferous limestones. This Formation unconformably overlies the Cambrian Barut Formation (?).

At Tang e Zakeen of Kuh e Faraghan, the Sarchahan Formation is 105 m thick and consists of dark gray to black silty shales with thin interbedded sandstones. Its lower contact is sharp and overlies the glaciogenic Dargaz Formation.

In both areas, its erosive tops are marked by occurrence of the channeled conglomerates of the Devonian Zakeen Formation.

In subsurfaces Zagros area, the Sarchahan Formation been identified in well Zirreh#1(Fars area) where it is characterized by 73 m of shales and sandstones (Ghavidel Syooki, 1993c) and in well Golshan#3 (Persian Gulf) where it is 66 m of shales, sandstones and limestones (Ghavidel Syooki, 1994c).

The Sarchahan Formation contains brachiopods, bryozoans, graptolites, acritarchs and chitinozoans.

Ghavidel Syooki (1995) has studied the palynomorph taxa of Sarchahan Formation in Kuh e Gahkum. These have been arranged in two biozones: (1) *Dicryotidium faviformis, Dicryotidium dictyotum, Leiosphaendia sp. Schimatosphaera perforatum , Evittia denticulate, Neoveryhachium carminae ;* and (2) *Dactylofusa estillis, Visbysphaera pinifera. Visbysphaera microspinosa, Dictyotidium favifomis. Visbysphaero oligofurcata, Dictyotidium perlucidum, Evittia denticulate denticulate, Helosphaeridium clavispinosum, Cymatiosphaera imperfecta, Onondagaella asymmetrica, Cnondagaella sp. Varyhachium valiente, Veryhachium scabratum, Veryhachium Irispinosum, Gorgonisphaeridium sp., Micrhystridium siellatum, Salopidium granuliterum, Eupoikilofusa striatifera, Multiplicisphaeridium arbusculum.*

These acritarchs assemblages are considered to belong to *Acritarch assemblage zone S1 (Dictyotidium faviformis)* and *Acritarch assemblage zone S2 (Dactylofusa estillis)* (Ghavidel Syooki, 1996).

Ancyrochitina longicollis, Ancyrochitina longicomis, Ancyrochitina ansarviensis, Clathrochitina sylvanica. Cyathochitina companulaeformis, Sphaerochitina sphaerocephala macrostomata, Sphaerochitina fragilis psaudcagglutinas.

The samples were also studied for chitinozoans (Ghavidel Syooki and Winchester-Seeto, 2004). At Kuh e Faraghan, the Sarchahan Formation is marked by the presence of 5 biozones: (1) *Spinachitina fragilis biozone;* (2) *Ancyrochitina udayanesis – Pterochitina deichai biozone;* (3) *Conochitina alargada– Ancyrochitina convexa biozone;* (4) *Angochitina macclurei biozone;* and (5) *Ancyrochitina vikiensis – Plectochitina kazhdumiensis biozon*

Based on palynology data, the Sarchahan Formation is Early to Late Liandovery (Rhuddanian-Telychian) in age (Ghavidel Syooki and Winchester-Seeto, 2004).

According to collected graptolites in Kuh e Faraghan by Rickards et al. (2000), the Sarchahan Formation contains two following biozones attributed to the Liandovery: (1) Biozone Lepotthcca: *Metaclimacograptus ? hughesi, Monograftus ? millipede, Monograptus Iriangulatus cf. separatus; and (2)* Biozone Convolutes: *Glyplograptus sp., P. (Pseudorthograptus) inopinatus, Clinoclimocograptus retroversus, Pristiograptus cf; regularis, Prisliograptus jacufum, P. cf. jaculum, Monograptus convolutes, Monograptus capis, Monograptus sp., Lagarograptus sp., Pribylograptus sp.*

In Kuh e Gahkum, Rickards et al. (2000), reported two biozones, one of them different, in the Sarchahan Formation attributed to the Liandovery. They correspond respectively to: (1) Biozone Sedgwicki: *Normalograptws sp., Glyptograptus sp., Neodiplograptus thuringiacus, Metaclimacograptus undulates, Clinoclimacograptus retroversus, Rhaphidograptus toernquisti, Pseudoretiolites perlatus, Pristiograptus cf. regularis, Monograptus lobiferus , Monograptus decipiens, Monograptus capis, Monograptus fragilis, Stimulograptus sedgwicki, Torquigraptus denticulatus , Torquigraptus sp., Coronograptus sp .;* and (2)Biozone Convolutes:_*Glyptograptus cf. serratus, Neodiplograptus thuringiacus, Metaclimacograptus hughesi, Petalulithus ovatoeingatus, Prisliograptus regularis, Monograptus lobiferus, Monograptus decipiens, Monograptus clingani, Rastrites cf. longispinus.*

IV.3.2. Precision on the sedimentology and stratigraphy

During the Silurian the Zagros region drifted southwestward reaching near 55° S latitude by the end of Silurian time (Fig. I.3) (Heydari, 2008). The post-glacial Silurian transgression is observed almost everywhere in Arabian plate and characterized by thick, organic-rich shales and fine-marine clastic sediments. The end of the Silurian, record an uplift in the Middle East area related to epeirogenic movements (Ala et al., 1980; King and Berberian, 1981; Al-Sharhan and Nairn, 1997) and a major sea level drop (Husseini, 1991, 1992; Sharland et al., 2001; Konert et al., 2001; Haq and Al-Qahtani, 2005) corresponds to a major hiatus recorded in Southeast Turkey, Syria, Iraq and Oman and probably corresponds to the “Pre Tawil Unconformity” in Saudi Arabia (Fig. I.4).

Three main facies association evolve from proximal fan delta to basin environments.

IV.3.2.1. Studied outcrops and well localisations

The Early Silurian Sarchahan Formation is exposed at Kuh e Faraghan and Kuh e Gahkum in the Bandar Abbas area (Fig. III.2) of Zagros. This Formation is also recognized in wells e.g. Golshan#3, Zirreh#1(Fig. I.2).

Kuh e Gahkum: 100 m thick (Fig. IV.13) overlies the Pre-Floian unnamed deposits (Ghavidel Syooki et al., 2011) and consists mainly of conglomerates, sandstones, siltstones, shales and fossiliferous limestones. The base of the Sarchahan Formation is marked by a 10 m thin bed conglomerates that contains up to 10 cm in diameter angular clasts. Clasts include cherts, shales, limestones and dolomites. The middle parts of the Sarchahan Formation comprises mainly alternating shale and siltstone and channelized 5-20 cm conglomerate layers. The upper part of the Sarchahan Formation comprises black to dark gray silty shales with thin interbedded silty sandstones and thin bedded fossiliferous limestones. The sandstones are dominant toward the upper part (Fig. IV.13). The upper contact of the Formation is characterized by an unconformity with the overlying Devonian Zakeen Formation.

***Kuh e Faraghan*:** 105 m thick (Fig. IV.13) overlies the Ordovician Dargaz Formation and consists of dark gray to black silty shales with thin interbedded siltstones and sandstones. The lower Sarchahan Formation consists mainly of dark gray to black graptolite-rich shales, interbedded with silty sandstones. The upper Sarchahan Formation is composed of dark gray to black shales interbedded with thin laminated (1-3 cm) silty sandstone layers. Sandstones are dominant in the upper part of the Formation. The uppermost Sarchahan Formation consists mainly of shales alternating with minor thin HCS sandstone layers. Greenish-reddish shales occur near the unconformable contact with the overlying Devonian Zakeen Formation (Fig. IV.13).

Well Zirreh#1: 73 m thick (Ghavidel Syooki, 1993c) overlies the Late Ordovician Seyahou Formation and is composed of shales and siltstones interbedded with sandstones (Annexe I). The sandstones are moderately-sorted, sub-mature and sub-angular. The Formation is topped by the Devonian Zakeen Formation.

Well Golshan#3: 66 m thick (Ghavidel Syooki, 1994c) with an unspecified total thickness due to the lack of the lower boundary. It consists of shales, sandstones and limestones (Annexe I). The sandstones are very fine to fine grains size (70-150 µm). It is overlied by Devonian Zakeen Formation

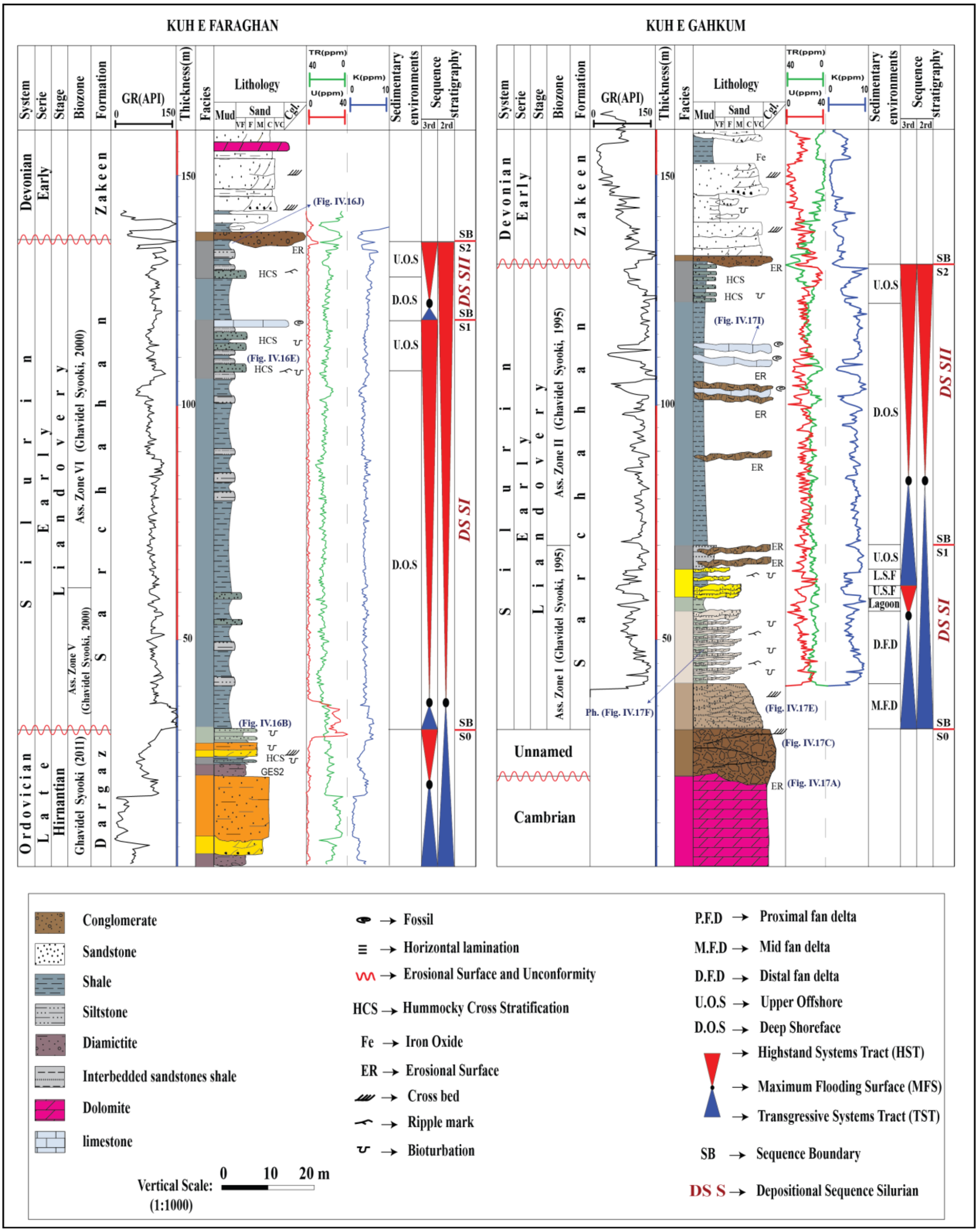


Fig. IV.13: Surface log of the Sarchahan Formation in Kuh e Faraghan and Kuh e Gahkum showing facies, depositional environments and sequence stratigraphy. *For the facies color codes see table IV.3.*

IV.3.2.2. Facies and depositional environments

Facies associations correspond to five main depositional environments evolving from proximal to distal platform: (1) Fan delta; (2) Lagoon; (3) Shoreface; (4) Upper offshore; and (5) Deep offshore environments (Fig. IV.15). They are detailed in (Table. IV.3) and interpreted below:

Facies	Diagnostic features	Components	Sedimentary structures and bioturbation	stratal pattern	Energy and depositional environment	Environmental interpretation	
Conglomerate (S1a)	Polymictic orthoconglomerate - grain suported - sandy matrix - poorly sorted - angular	Chert, shale lithic, carbonate and sandstone, mud clast, volcanic grains - 1 to 10 cm size -	Tabular Cross bedding Alluvial imbrication	Thick bed to massive (0.5 to 3 m.), channelized geometry and erosional base,	High energy- Fan delta	Fan delta	Proximal
Gravelly Sandstones (S1b)	Medium to coarse grain (300-600 μ), moderately sorted, sub angular to sub rouded sandstones	Chert, shale lithic, carbonate , mud clast, volcanic grains - 1 to 10 cm size	Tabular Cross bedding	Thin to medium bed (5 to 20 cm.), Lenticular geometry and erosional base, Thinning upward	High energy- Fan delta		Mid
Thin lamination gravelly sandstones/ mudstone (S1c)	Fine to very fine grain (80-200 μ), poorly sorted, sub angular, immature sandstones,	Chert, shale lithic, carbonate , mud clast, volcanic grains - 1 to 10 cm size	Low-angel lamination- Sole, flut and tool marks at base- ripple mark at top High bioturbation	Thin bed (5 to 10 cm.), Lenticular geometry and erosional base,	Low energy- Fan delta to lagoon		Distal
Lagoonal shales (S2)			High bioturbation	Dark to dark gray shale, up to 5 m thick	Low energy- lagoon	Lagoon	
Barrier gravelly sandstones/ conglomerates (S3)	Coarse grain (500-600 μ), moderately to well sorted, sub angular to rounded sandstones		Cross stratification Low bioturbation	Medium to thick bed, intercalation with conglomerates	High energy- Shoal or bar	Shorface	
Hummocky cross stratification Sandstone (S4)	Poor to moderatly sorted - immature - sub angular - very fine (60-100 μ)- arkose wack (Qz. ~90% , Fld. ~10%)	Mica moscuvite- chlorite	Hummocky cross stratification- high bioturbation	Thin bed (5 to 10 cm), brown to cream,	Low to moderate energy (storme induced) - upper offshore	Upper Offshore	
Shale (S5a)			High bioturbation	Dark , yellow, green and red shale physil thin bed (2 to10cm),	Low energy Lower offshore	Deep Offshore	
Siltstone (S5b)	Medium to coarse silt (20-50 μ)	Mica moscuvite- chlorite		Thin bed (5 to 10 cm.), sheet like geometry			
Limestone (S5c)	Dolomitized Limestone to Dolostone	Brachiopds	Ripple mark	Thin to medium bed (5 to 20 cm.), sheet like geometry			

Table. IV.3 (Previous page): Facies table of the Sarchahan Formation. It consists of 9 facies and sub-facies deposited in 5 depositional environments corresponding to proximal to distal platform: (1) Fan delta; (2) Lagoon; (3) Shoreface; (4) Upper offshore; and (5) Deep offshore environments.

……………………………………………………………………………………………………

Fan delta environment

This facies association (S1) (Table. IV.3) has been defined only in Kuh e Gahkum and consists of three subfacies (S1 a, b and c) that corresponds to 28 m thick bed conglomerates, gravelly sandstones and mudstones (Fig. IV.17). The lower contact is erosional and channelized. It capped the unnamed deposits, whereas the upper contact is gradational and change to facies (S2). Illite and Illite/smectite are the most abundant clay minerals identified by XRD measurements (Fig. IV.14).

A facies model has been constructed for shelf-type fan delta, which gradually fining-upward from proximal fan delta (subfacies S1a), braided stream mid fan delta (subfacies S1b) into gravelly sandstones and mudstones of distal fandelta (subfacies S1 c). Subfacies S1c is amalgamated with very thin sandstones and shales (S2) of low-energy lagoon environment.

Fan deltas (Holmes, 1965), subdivided into three types *(i)* Shelf-type; *(ii)* Slope-type; and *(iii)* Gilbert-type, according to the water depth and the gradient of the delta profile (Postma, 1990). Shelf type or shallow-water deltas exceed on to low-gradient shelves with very shallow water depth near the river mouth (Reading, 1996). Regarding the facies associations observed in Kuh e Gahkum and Kuh e Faraghan, Shelf-type fan deltaic proposed.

There is a gradual distal reduction of grain size (Colella and Prior, 1990) from poorly bedded, fluvial imbricated, poorly sorted coarse-grained gravels through fine-grained gravel and tabular cross-bedded sand to interbedded mud and rippled sand. It gives a well-developed coarsening- upward from distal to proximal fan delta sequence (Galloway, 1976). The erosive nature of the proximal fan delta conglomerates shows deposition during high-energy conditions. Conglomerate imbrication represents deposition under fluvial regime. Tabular cross-bed sandstones interbedded with gravels, inferred deposition in braided stream deposition environment. In addition, absence of bioturbation in facies (S1a and S1b) confirms non-marine depositional environments. Bioturbations and ripple mark and gravelly sandstones of facies (S1c) indicate deposition below sea level. Erosional structures and scoures at the base of sandstones show deposition of high-energy channels in a low-energy lagoon environments (S2).

Lagoon environment

Facies association S2 (Table. IV.3) is characterized by structurless very thin sandstones and shales. The upper part of this facies is homogeneous in lithology, whereas the lower part hosted sandstones and gravelly sandstones (S1c). The presence of very thin sandstones and shales and the position between both fluvial (S1a andS1b) and shoreface (S3) environments indicate low energy regime in the lagoon environment.

Shoreface environment

This facies association (S3) (Table. IV.3) rests on very thin sandstones and shales (S2). It is characterized by 9 m thick of cross-lamination sandstones and gravelly sandstones. Its lower part shows shallowing-upward trend whereas the upper part is thick bed channelized sandstones.

The low degree of bioturbation and cross-lamination indicate frequent reworking and a high sedimentation rate (Aigner & Reineck, 1982). The channelized and pinch-out style of sandstone beds supports a storm-generated origin of these beds (Kreisa, 1981). The lower part with cross-Lamination indicates upper shoreface deposition whereas, the upper part, with intercalated HCS (S4), indicates lower shoreface depositional environments (Brenchley, 1989).

Upper offshore environment

Facies association S4 (Table. IV.3) comprises thin bedded hummocky cross-stratification sandstones, in places amalgamated, but mostly separated by marine shales (S5).

The presence of very thin beds HCS indicate storm-dominated deposition (Reading, 1996). Upper contacts are broadly horizontal and often are characterized by wave ripples which reflect the late-stage waning of the storm event (Collinson and Thompson, 1989). The coarsening-up trend of hummocky cross stratified (HCS) sandstones of the upper part of Silurian Sarchahan Formation in both Kuh e Faraghan and Kuh e Gahkum sections allowed to consider position in an Upper offshore environment. XRD analysis of the samples reveals that Illite and Illite/smectite are the most abundant clay minerals in the lower part of the Formation, while Kaolinite is the most abundant in upper part near the boundary between Sarchahan and Zakeen Formations (Fig. IV.14).

Deep offshore environment

Facies association S5 (Table. IV.3) is composed of four sub-facies (S5a) shales; (S5b) very thin beds siltstones; (S5c) thin bedded full brachiopods limestones and clast supported conglomerates (S5d).

The shale and very thin beds siltstones sediments were deposited in a low energy offshore open-marine shelf environment below storm-wave base. Erosional bases, wedge-shape of conglomerates (S5d) and brachiopod limestones (S5c), suggest an event deposition under storm-wave current deposition (Kreisa, 1981).

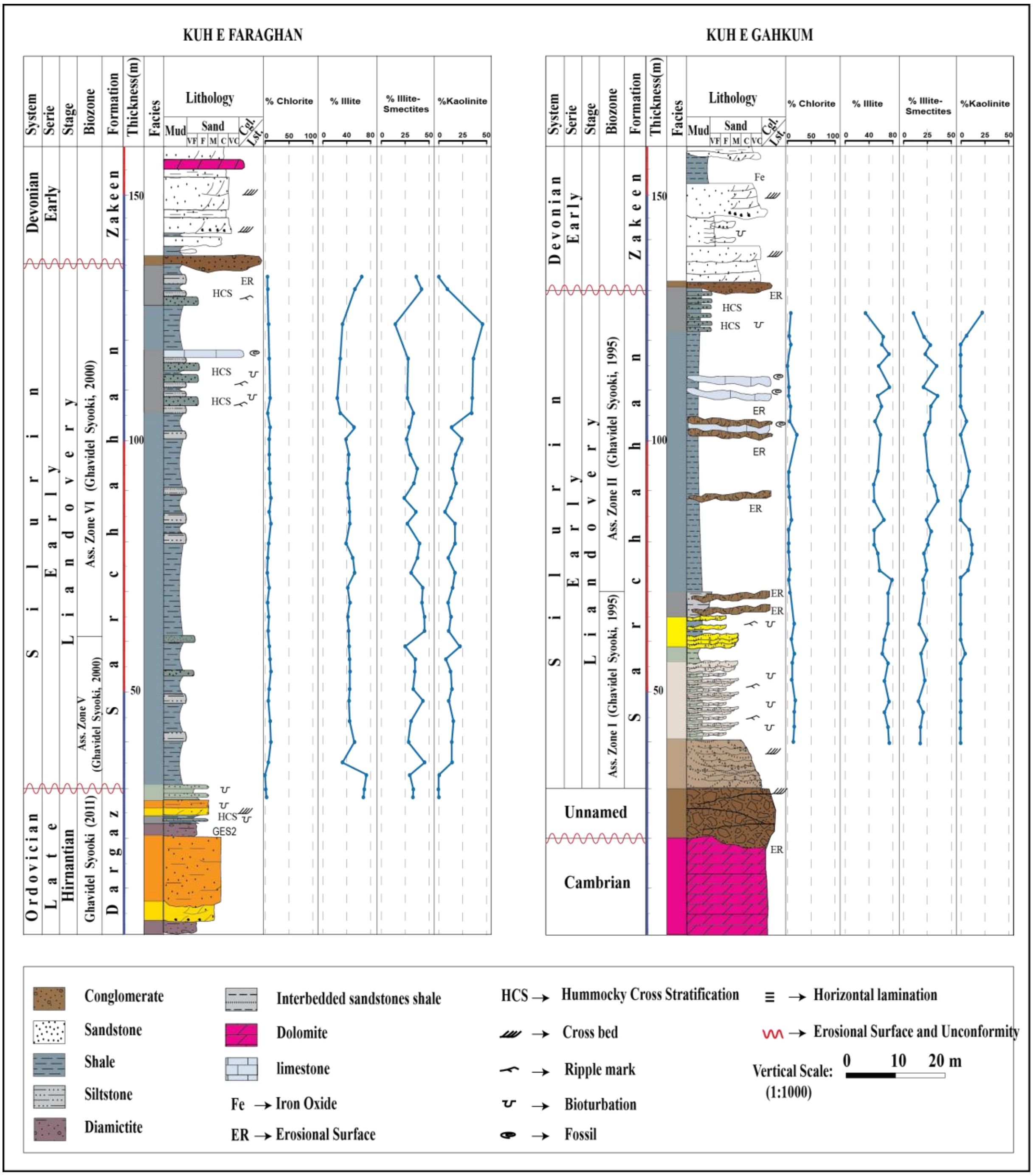


Fig. IV.14: Lithology vs. Chlorite, Illite, Illite/ Smectites and Kaolinite for the Sarchahan Formation in Kuh e Faraghan and Kuh e Gahkum outcrops. *For the facies color codes see table IV.3.*

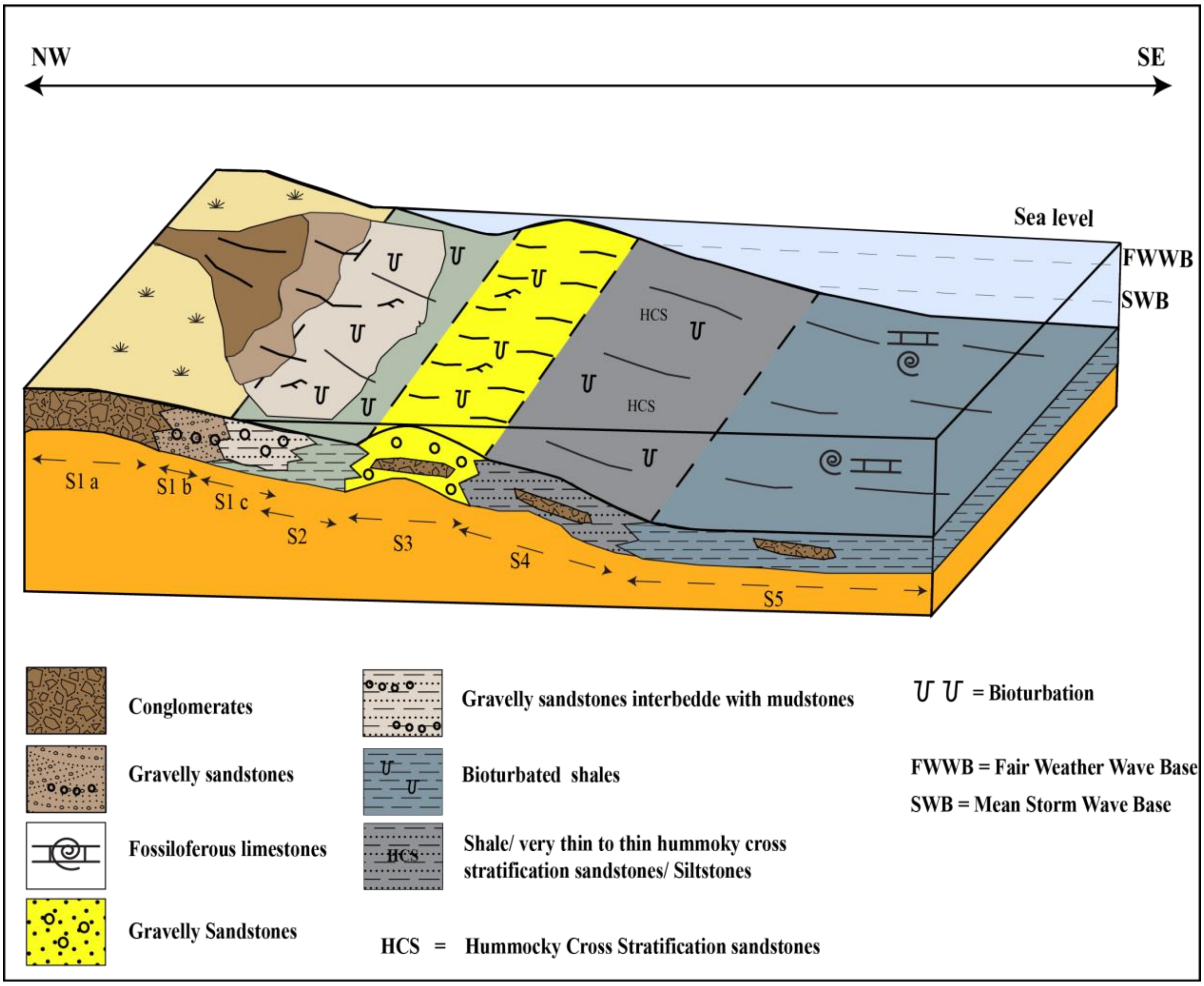


Fig. IV.15: Schematic depositional profile for the Sarchahan Formation showing proximal to distal platform evolving from (1) Fan delta; to (2) Lagoon; (3) Shoreface; (4) Upper offshore; and (5) Deep offshore environments. *For the facies color codes see table IV.3.*

IV.3.3. Sequence Stratigraphy

In this cycle, two 3rd order sequences have been defined in Kuh e Faraghan and Kuh e Gahkum. These sequences are illustrated in (Fig. IV.16A & IV.17B) and are described below:

<u>Sequence SI- DS SI:</u>

The Early Silurian DS SI has been recognized in the Bandar Abbas area in Kuh e Faraghan and Kuh e Gahkum. The thicknesses range from 87 m to 32 m respectively. This sequence is preserved in subsurface in the Fars area Well Zirreh#1and Persian Gulf in Well Golshan#3. It rests on glaciogenic Hirnantian Dargaz Formation in the Kuh e Faraghan while it topped the Cambrian dolomites in Kuh e Gahkum. It corresponds to a major erosional surface (SB S0) at the base of Sarchahan Formation. This DS is organized in a transgressive-regressive cycle.

The TST is characterized by a transition from proximal (S1a) to distal fan delta (S1c) which ends by lagoonal shales (S2) (Table. IV.3; Fig. IV.17E). The deltaic system is only preserved in the proximal Kuh e Gahkum area and passes distally to deep offshore environments (S5) in Kuh e Faraghan.

The MFS is placed in a positive gamma ray and corresponds to deep offshore environments (S5) (Fig. IV.13).

The HST is up to 80 m thick in both area and records a shallowing-upward trend. It corresponds to a transition, from deeper facies (S5) to gravelly sandstones and conglomerates deposited in shorface environments (S3) in Kuh e Gahkum; and HCS sandstones (S4) in Kuh e Faraghan.

<u>Sequence SII- DS SII:</u>

The Early Silurian DS SII has been identified in Kuh e Faraghan and Kuh e Gahkum. In subsurface, its identification is difficult. It shows lateral facies variations, from bioclastic-rich limestones in Kuh e Gahkum to sandy deposits in Kuh e Faraghan. The lower sequence boundary (SB S1) is placed at top of DS SI. The upper sequence boundary (SB S2) corresponds to an erosion surface and is covered by the Devonian Zakeen Formation.

The transgressive systems tract (TST) is up to 20 m thick and characterized by deep offshore shale (S5).

The MFS is placed within deep offshore bioturbated dark shales (S5) corresponding to the highest peak in gamma-ray (Fig. IV.13).

The HST consists of a coarsening-upward succession. It shows a transition from deep offshore shales (S5) storm-induced deposits.

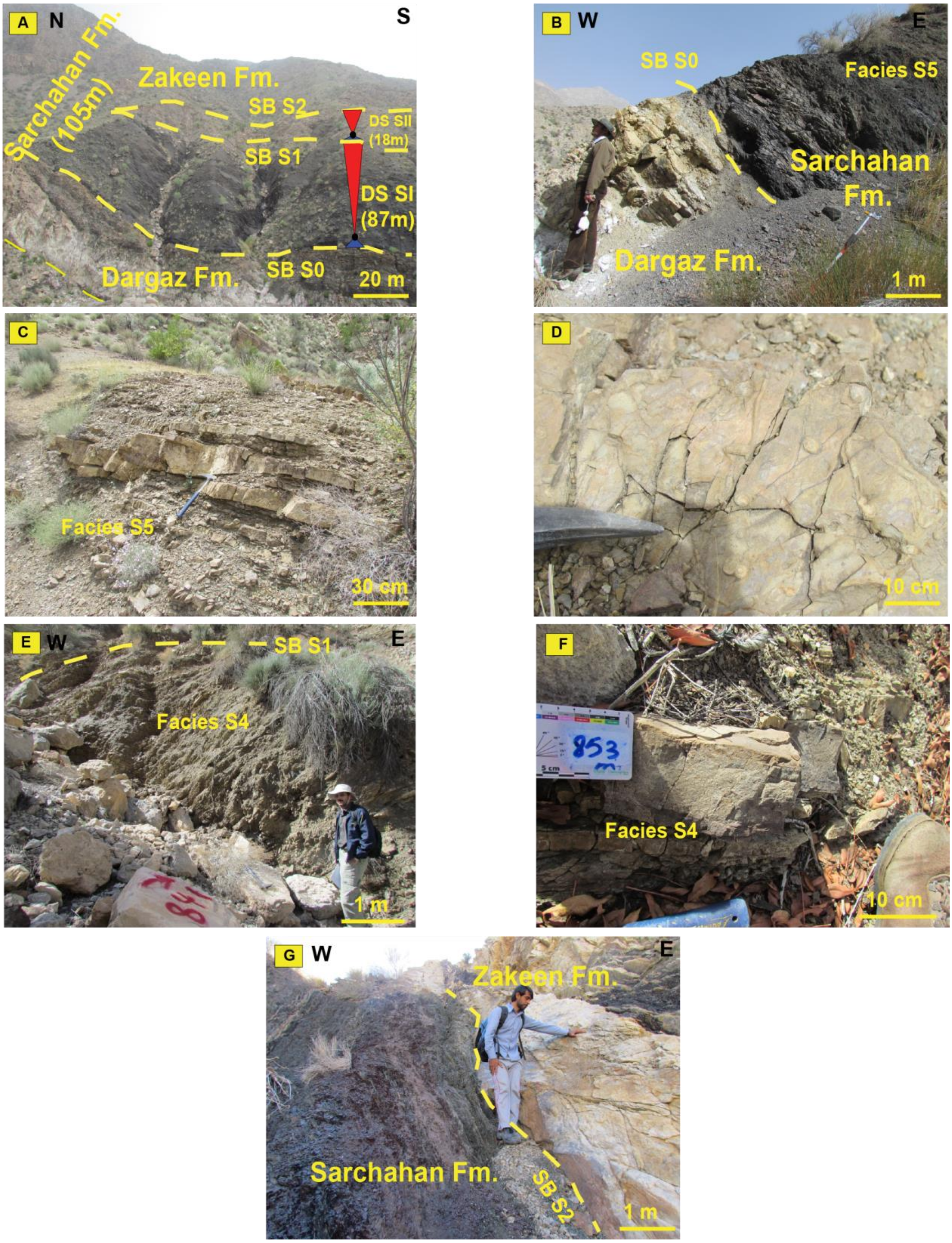

A
N
S
Sarchahan Fm. (105m)
Zakeen Fm.
SB S2
SB S1
DS SII (18m)
DS SI (87m)
Dargaz Fm.
SB S0
20 m
B
W
E
SB S0
Facies S5
Sarchahan Fm.
Dargaz Fm.
1 m
C
Facies S5
30 cm
D
10 cm
E
W
E
SB S1
Facies S4
1 m
F
853
Facies S4
10 cm
G
W
E
Zakeen Fm.
Sarchahan Fm.
SB S2
1 m

Fig. IV.16 (Previous page): (A) Sequences and sedimentary structures of the DS SI and DS SII for the Sarchahan Formation exposed in Kuh e Faraghan; (B) Boundary between Hirnantian Dargaz and Early Silurian Sarchahan Formations; (C) Channelized sandstones in Offshore depositional environment ; (D) Bioturbation in thin-bed sandstones in offshore environment; (E) Shallowing and thickening-upward HST of the DS SI in upper offshore environment ; (F) Hummocky cross stratification sandstones in upper offshore environment; (G) Boundary between Early Silurian Sarchahan and Devonian Zakeen Formations marked by erosional purple shales. *Fm.= Formation; SB= Sequence Boundary; DS= Depositional Sequence; S= Silurian.*

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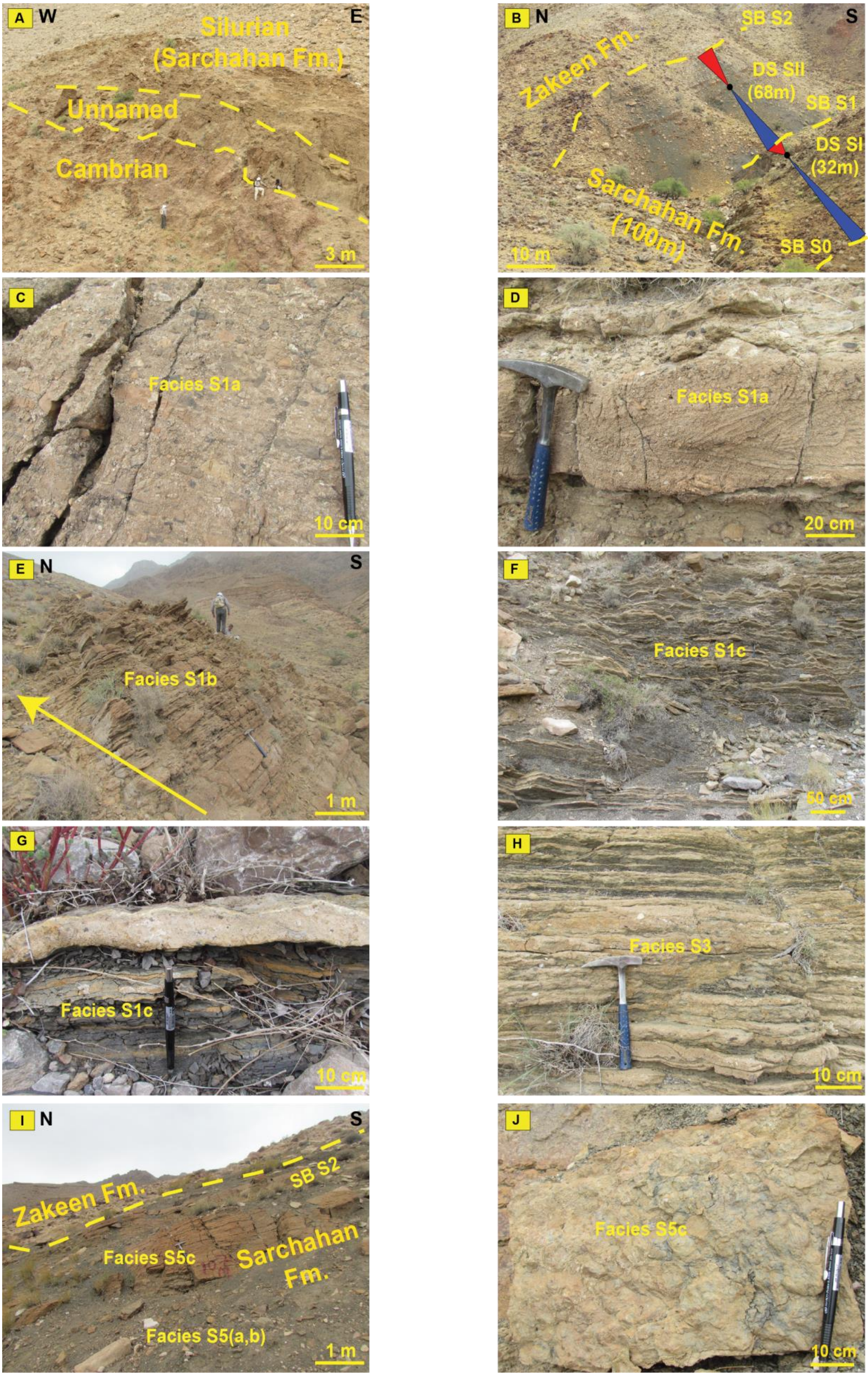
Fig. IV.17 (Next page): Sequences and sedimentary structures of DS SI and DS SII for the Sarchahan Formation exposed in Kuh e Gahkum. (A); Boundary between Cambrian dolomite deposits and Early Silurian Sarchahan Formation marked by erosional and channelized surface; (B) Overview Photo of sequences and sequence boundaries for the Sarchahan Formation; (C) Basal conglomerates in proximal fan delta; (D) Trough cross lamination in basal conglomerates in proximal fan delta; (E) Deepening and thinning-Upward mid fan delta conglomerates; (F) Intercalation of distal fan delta shales and conglomerates; (G) Ripple mark in conglomerates of distal fan delta; (H) Shoreface conglomerates at the top of DS SI; (I) Fossiliferrous limestones in the sequence DS SII; (J) brachipodes in meter-thick limestones in upper parts of DS SII . *Fm.= Formation; SB= Sequence Boundary; DS= Depositional Sequence; S= Silurian.*


A
W
E
Silurian
(Sarchahan Fm.)
Unnamed
Cambrian
3 m
B
N
S
SB S2
Zakeen Fm.
DS SII
(68m)
SB S1
DS SI
(32m)
Sarchahan Fm.
(100m)
SB S0
10 m
C
Facies S1a
10 cm
D
Facies S1a
20 cm
E
N
S
Facies S1b
1 m
F
Facies S1c
50 cm
G
Facies S1c
10 cm
H
Facies S3
10 cm
I
N
S
Zakeen Fm.
SB S2
Facies S5c
Sarchahan
Fm.
Facies S5(a,b)
1 m
J
Facies S5c
10 cm

IV.4. Cycle 3 (Devonian)

In Arabian Plate, the Devonian period is poorly represented in the rock record. It related to Hercynian tectonism associated with a tectonic uplifting and the resulting erosion (Konert et al., 2001). In the east Zagros region, the Devonian Zakeen Formation has excellent exposures in Bandar Abbas area. This Formation is one of the most important siliciclastic units in the area and is under investigation for its hydrocarbon reservoir capasity. It rests on the Early Silurian Sarchahan Formation, which has been considered as a major source rock in the area (Kamali and Rezaee, 2003). Despite of its importance in the Zagros stratigraphy, only minor information on the sedimentary facies, depositional environment, sequence stratigraphy and paleogeography of the Zakeen Formation is available. Detailed palynologic studies carried out by Ghavidel Syooki (1986, 1999 and 2003) have resulted in precise biozonation and age determination. A significant hiatus (of almost 80 million years has been identified) between the Zakeen and overlying Early Permian Faraghan Formations.

IV.4.1. Introduction of the Zakeen Formation

The Zakeen Formation has been identified in Kuh e Faraghan and Kuh e Gahkum in Bandar Abbas area (Fig. III.2) and consists of sandstones with interbedded shales and dolomitic limestones. It contains well-preserved and abundant palynomorphs (Acritarch, miospores). In Zagros area, it rests unconformably on the Early Silurian Sarchahan Formation and is overlain by the Early Permian Faraghan Formation.

In addition, the Zakeen Formation is also observed in subsurface core drills. In Fars area (Fig. I.2), it is characterized by 107m of sandstones and shales in well Naura#1 (Ghavidel Syooki, 1993b), 34m sandstones and shales in well Zirreh#1 (Ghavidel Syooki, 1993c), 121m of sandstones, shales, dolomites and limestones in well West Aghar #1 (Ghavidel Syooki, 1998), and 86m of sandstones, shales, dolomites and limestones in well Dalan #1 (Ghavidel Syooki, 1994d). In Bandar Abbas area (Fig. I.2) the Zakeen Formation is composed of 13 m sandstones and shales in well Finu #1 (Ghavidel Syooki, 1984b) and 51m sandstones and shales in well Namak #1 (Ghavidel Syooki, 1984c).

The Zakeen Formation in Persian Gulf (Fig. I.2) have been identified in wells Golshan#3 consists of 60m sandstones and shales (Ghavidel Syooki, 1996), in well Kish#2 with 102 m (Aria Nasab, 2011) and well Salman 2SKD#1 with 422 m (Aria Nasab, 2011) with the same lithology.

Based on stratigraphic, this Formation was assigned originally to the Early Permian (Szabo and Kheradpir, 1978). However, a detailed palynological studies, has been carried out on this Formation by Ghavidel Syooki (1986, 1999 and 2003) in Kuh e Faraghan and Kuh e Gahkum. The age of this Formation is attributed to the Early to Late Devonian (Lochkovian-Frasnian stages) (Ghavidel Syooki, 2003) based on the occurrence and disappearance of palynomorphs (Fig. II.3): (1) Biozone I: *Chelinospora retorrida, Clivosispora reticulata, Retusotriletes dittonensis, Ambitisporites avitus, Ambitisporites dilutes, amicosporites splendidus, Laeovancis devillomedium, Cymbosporites proteus, Cymbosporites dammamensis*.; (2) Biozone II: *Verrucosisporites polygonalis, Stenozonotriletes minus, Clivosispora verrucata*. ;

(3) Biozone III: *Dictyotriletes minor, Dibolisporites eifeliensis, Dibolisporites quebecnesis, Dibolisporites wetteldorfensis, Grandispora douglastownense, Grandispora macrotuberculata, Dibolisporites echinaceus, Acinosporites lindarensis*.; (4) Biozone IV: *Acinosporites acanthomammillatus, Apiculatisporis adavalensis, Verrucosisporites premnus, Acinosporites macrospinosus, Cyclogranisporites amplus, Rhabdosporites langii, Rhabdosporites parvulus, Emphanisporites rotatus, Calyptosporites velatus*. ; (5) Biozone V: *Grandispora incognita, Grandispora owensii, Grandispora zakeenensis, Grandispora mammillata, Cymbosporites catillus, Convolutispora mimerensis, Samarisporites concinnus, Geminospora lemurata*. ; and (6) Biozone VI: *Convolutispora subtilis, Geminospora punctate, Verrucosisporites confertus, Ancyrospora ampulla, Ancyrospora melvillensis, Ancyrospora carnarvonensis, Ancyrospora furcula, Auritolagenicula zagrosensis, Ancyrospora puchra, Hystricosporites furcatus, Hystricosporites reflexus.*

The acritarchs of biozone VI is composed of: *Saharidia iranica, Papulogabata persica, Chomotriletes vedugensis, Chomotriletes bistchoensis, Deltotosoma intonsum, Dictyotidium torosum, Histopalla capillosa, Helosphaeridium microclavatum, Gorgonisphaeridium abstrusum* and is considered to belong to *Acritarch assemblage zone D1 (Chomotriletes vedugensis)* (Ghavidel Syooki, 1996).

The Zakeen Formation is similar and time equivalent to the Devonian Tawil, Jauf and Jubah Formations of Saudi Arabia, Misfar Formation in Oman; and also Pirispiki and Kaista Formations of Iraq (Fig. I.4).

IV.4.2. Precision on the sedimentology and stratigraphy of the Devonian Formation

During Devonian, the studied area was part of the Arabian Platform (Beydoun, 1988) located at southern margins of the Neo-Tethys Ocean at latitudes of about 30° to 45° south (Fig. I.3) (Berberian and King 1981; Al-Husseini 1992; Konert et al., 2001). During the Devonian, the platform started its northerly drift, reaching nearly 30° S latitude by the end of Devonian. Continental to shallow marine deposits of the Zakeen Formation in the Zagros suggests the initial stages of a sea-level rise. Marginal marine equivalent strata in central Arabia and Central Iran support this interpretation (Konert et al., 2001; Heydari, 2008).

For interpretation of main facies of Devonian Zakeen Formation, two Outcrops (Kuh e Faraghan and Kuh e Gahkum in Bandar Abbas area) (Fig. III.2) and seven wells (Golshan#3, Zirreh#1, Kish#2, Salman 2SKD#1, Dalan#1, West Aghar#1 and Naura#1) (Fig. I.2) have been studied. The depositional environments based on facies analysis evolve from continental to estuarine environments.

IV.4.2.1. Presentation of the studied successions

Kuh e Faraghan: 158 m thick (Fig. IV.18 & 20) overlies the Silurian Sarchahan deposits and consists of white to brown sandstones, green siltstones, shales and green sandy shales layers, with some rusty dolomite bed. In ascending lithological order, it has been divided into two units. The first unit consists mainly of thick white sandstones, with dolomites and shale beds while the second unit is more shaly (Fig. IV.20). The age of this Formation is Lochkovian to Frasnian stages (Ghavidel Syooki, 2003). Therefore, the Famennian stage is not recorded. The Zakeen Formation is unconformably topped by early Permian Faraghan Formation.

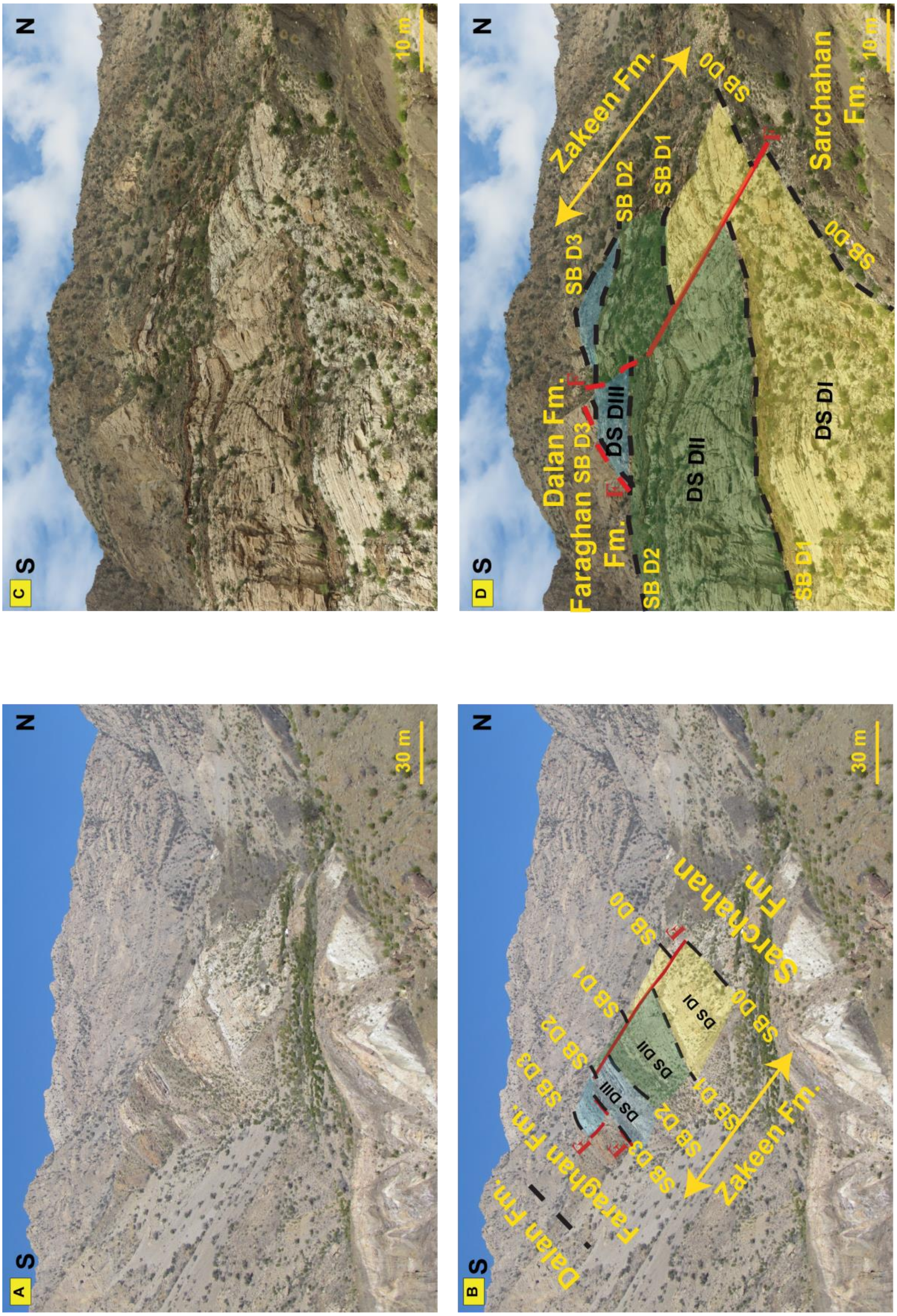


Fig. IV.18: Overview Photos of the Zakeen Formation exposed in Kuh e Faraghan showing faulting which affected the three Sequences. *Fm.= Formation; SB= Sequence Boundary; DS= Depositional Sequence; D= Devonian.*

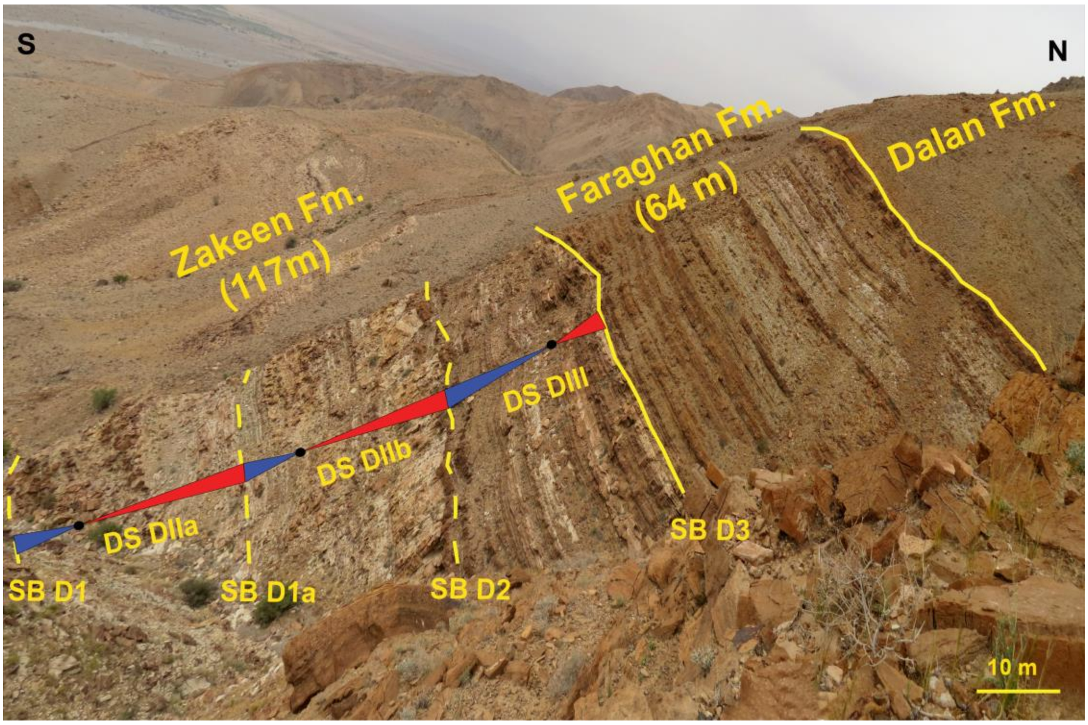


Fig. IV.19: Panorama of the Zakeen Formation exposed in Kuh e Gahkum showing three Sequences. *Fm.= Formation; SB= Sequence Boundary; DS= Depositional Sequence; D= Devonian.*

Kuh e Gahkum: 117 m thick (Fig. IV. 19 & 20) is resting unconformably on the Early Silurian Sarchahan Formation and is overlain by the Early Permian Faraghan Formation. It is composed of brown conglomerates, white, and brown to green sandstones, siltstones, shales, green sandy shale and rarely dolomitic beds. According to the palynological study by Ghavidel Syooki (1986), the Early Devonian (Lochkovian - Emsian) is not preserved at Kuh e Gahkum and it ranges from Eifelian to Famennian stages.

Well Zirreh#1: 34 m overlies the Early Silurian Sarchahan Formation and composed of sandstones and shales (Annexe I). The sandstones are moderately-sorted, submature and sub angular. They are fine to medium grains size (150-300µm). The Formation topped by Lower Permian Faraghan Formation. The age is Late Devonian (Famennian) based on the occurrence of *Acritarch ass. zone V* (Ghavidel Syooki, 1993c).

Well West Aghar#1: 121 m with an unknown lower boundary and is composed of limestones and dolomites with sandstones and shales (Annexe I). The limestones vary from mudstones to grainstones. The grain size of sandstones is fine to medium (150-250µm) and characterized by moderately to well sorting, sub angular to rounded and submature to mature. It is topped by Early Permian Faraghan Formation. Ghavidel Syooki (1998), proposed Late Devonian age (Frasnian- Famennian).

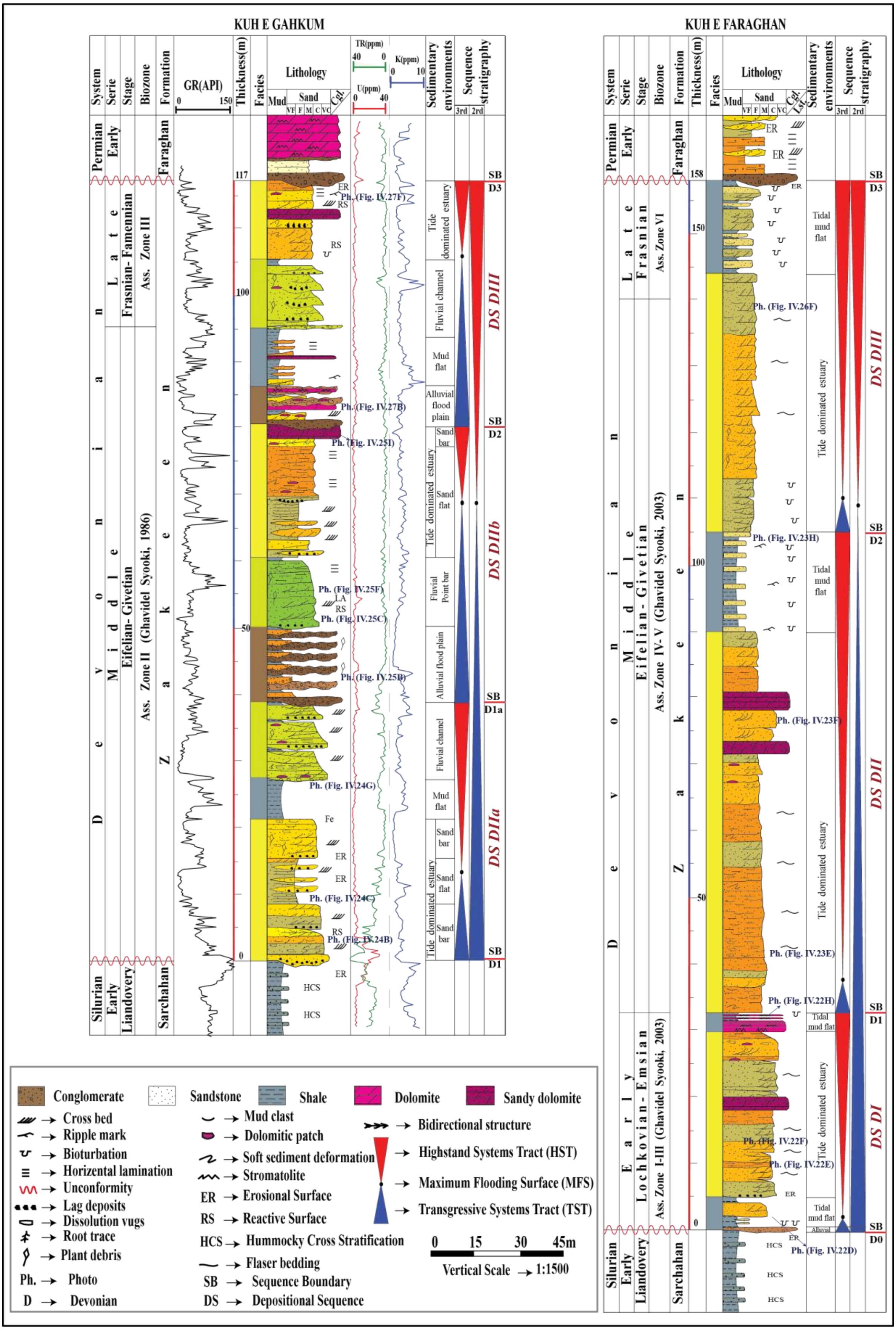


Fig. IV.20: Facies, depositional environments and sequence stratigraphy of the Zakeen Formation in Kuh e Faraghan and Kuh e Gahkum. *For the facies color codes see table IV.4.*

Well Naura#1: 107 m thick and composed mainly of shales, sandstones and limestones (Annexe I). The sandstones are moderately to well sorted, sub rounded to rounded and submature to mature. The grain size of sandstones is fine to coarse grain (200- 600 µm). It is overlain by Early Permian Faraghan Formation. The age is Late Devonian (Famennian) according to the occurrence of *Acritarch ass. zone I and II* (Ghavidel Syooki, 1993b).

Well Dalan#1: 86 m with uncertain lower boundary and is composed of sandstones, shales, dolomites and limestones (Annexe I). It is overlain by Early Permian Formation. Based on the occurrence of *Acritarch ass. zone I*, Ghavidel Syooki (1994d) proposed a Late Devonian age (Famennian).

Well Golshan#3: 60 m thick resting on Early Silurian Sarchahan Formation and is composed of sandstones, shales and limestones (Annexe I). The grain size of the sandstones is very fine to fine grain (70-150µm). It is overlain by Early Permian Faraghan Formation. According to the playnologic studies, Ghavidel Syooki (1994c) proposed a Late Devonian age (Frasnian- Famennian).

Well Kish#2: 102 m with uncertain lower boundary and is composed of sandstones and shales with limestones (Annexe I). The sandstones characterized by poorly to well sorted and subangular to rounded grains. The graine size is fine to coarse grain (150- 600µm). It is overlain by Early Permian Faraghan Formation. Based on the occurrence of *Acritarch ass. zone D1 (Chomotriletes vedugensis)*, Aria Nasab (2011a) proposed a Late Devonian age (Frasnian- Famennian)

Well Salman 2SKD#1: 422 m with an unknown lower boundary and is composed of sandstones, shales and limestones (Annexe I). It is overlain by Early Permian Faraghan Formation. According to the palynologic studies, Aria Nasab (2011b) proposed an Early to Mid Devonian age.

IV.4.2.2. Facies and depositional environments

Five main depositional environments have been identified, that evolve from proximal to distal platform (Fig. IV.21): (1) Alluvial flood plain; (2) Fluvial; (3) Tidal mud flat; (4) Tide-dominated estuarine; and (5) marine deposits (Table.IV.4).

Alluvial conglomeratic environment:

Facias association D1 (Table.IV.4) crops out as multiple channelized clasts supported (D1a) and mud supported (D1b) conglomerates. D1 is nearly completely enveloped within wedge- and lens-shaped cross bed pebbly sandstones, muds. Its basal contacts are channelized while the upper contacts are gradational.

Conglomerates are interpreted as part of braided alluvial flood plain systems are well documented in modern records (Mial, 2000). Clast imbrications and cross-bed pebbly sandstones interbedded with gravels, inferred deposition in braided stream deposition environment. Intercalation of sandstones within the conglomerates lead to believe that they developed as relatively thin, laterally discontinuous sheets modern gravelly streams described by Whiting (1988). The vertical stacking of subsequent pebble sheets over in-channel braid bars produced the intercalated sandstone lenses and stringers within conglomerates. The pebbly sandstones characterized by broad, wedge- and lens-shaped beds suggest sand deposition in narrow shallow channels (Mial, 1978). The lack of trace fossils is also consistent with an alluvial setting.

Fluvial environment:

Facies association (D2) is composed of two facies: *(i)* sandstone channel facies (D2a); and *(ii)* lateral-accretion clastic facies (D2b) (Table.IV.4). Thick discontinuous bed of sandy conglomerate and coarse to fine sandstones with a sharp erosive basal contacts occupy the scoured valley bottoms and is consistent with facies observed in the landward of incised valley systems . The thickness of this facies association is locally up to 10 m and rest on mud flat (D4) and alluvial conglomerates (D1). The fluvial channel systems across the palaeovalleys are indicated by fluvial channel structures (e.g. trough, planar, low angle cross bedded and flat lamination sandstones) (Reading, 1996), root debris, plant debris, fining-upward trend, and the lack of marine fauna and wave or current structures (Hou, 2001). The coarse grain size and poor sorting of the basal beds suggest deposition in a high-energy fluvial setting, and the fine sediments indicate a low energy overbank or flood plain setting.

Facies D2b (Table.IV.4) is dominated by package ranging from conglomerates and pebbly sandstones at base into mud at top. This fining-upward package is commonly 10m thick. It topped the alluvial conglomerates facies assocciation (D1), and is overly by low-angle cross-bedded sandstones (D4e). Facies D2b is characterized by lenticular geometry, fining-upward trend, lateral accretion deposits, lag deposits, plant debris and fluvial point-bar structures (trough and tabular cross beds sandstones at base and horizontal lamination sandstones and ripple mark at top changing to mud overbank) and corresponds to fluvial point-bar environment.

Facies association D2 is due to lateral accretion on point bar (Thomas et al., 1987), consistent with the low angle dipping, heterolithic beds. Mial (1978) and Walker (1992) considered that the point bars are good examples of the lateral-accretion architectural element. The literature provides many examples of point bars recorded by Clifton (1983), Walker (1992), Porebski (1995), Allen (1963) and visher (1965).

The origin of the reactivation surfaces in these deposits may record either seasonal fluctuations in fluvial influx or erosion due to long-term tidal oscillations (Rossetti et al., 2004). The dominance of cross-stratification, the overall upward-fining nature of major package, and the lenticular sandstone geometries in facies D2b indicate that stream flow processes were important during deposition (Mial, 1978). The amalgamated trough cross-stratified sandstone sets are the product of migration and scouring of three-dimential ripples in fluvial channels (Harmez et al., 1982; Munoz, 1992). The upward-fining package in point bar illustrated by the model of Allen (1963). The deposition of the fine-grained mud at top of channel shows suspended load sediments during submergence by major floods.

Mud flat environment:

Facies association D3 comprises three facies: *(i)* shales (D3a), and (ii) massive sandstones (D3b) and (iii) dolomitized stromatolites. The thickness of the D3 (Table.IV.4) is up to 10 m. Dalrymple, Zaitlin & Boyd, (1992) considered that the muddy sediments accumulates primarily in the low energy tidal flats and marshes along the side of the estuary.

The fine grain sandstones is mainly dominated by ripple cross-laminations and small-scale cross-bedding but these structures are commonly disturbed or destroyed by bioturbations (Singh, 1972). Bioturbation and predominantly fine-grained deposits with interbedded very thin, sharp-based sandstones in facies (D3) indicate a calm depositional condition in mud flat environments (Kreisa, 1981).

Tide-dominated estuarine environment:

This facies association (D4) (Table.IV.4) is the thickest and subdivided into six subfacies association (D1a, b, c, d, e and f).

The trough (D4a) and planar (D4b) cross-bedded sandstones indicate deposition in high energy conditions. Erosional bases, basal lag, and finning-upward trends provide evidence for channel deposition. The mud drapes (Shanley, 1992) and bidirectional structures such as herringbone cross bedding (D4c) and associated reactivation surfaces are indicative of tidal sedimentation (Allen, 1991). Elliott, (1968) considered that cross-bed sandstones with an erosional base, basal lag, and finning-upward trends in association with bidirectional structures sediments represent estuarine tidal channels and elongated tidal sand bars (Dalrymple, Zaitlin & Boyd, 1992). These bars lay seaward of the tidal-energy maximum, which coincides with the upper flow regime horizontal lamination (D4d) and low-angle cross-bedded (D4e) sandstones deposited in the upper flow regime sand flat (Dalrymple, Zaitlin & Boyd, 1992). Low-angle cross-bedded sandstones (D4e) probably record the migration of bed waves under transitional (lower to upper) flow regime condition. The geometry of the cross-strata and their lateral transition into flat and horizontal lamination sandstones (D4d) are described from modern and ancient fluvial successions (Fielding, 1999 and 2000).

Limestone marine environment:

Facies association D5 (Table.IV.4) is recognized in the subsurface sections (e.g. Golshan#3, Salman#2SKD1, Kish#2, Naura#1, West Aghar#1 and Dalan#1).

Very fine mudstones to wackstones facies formed in low energy, deep lagoonal environments and are composed of fine carbonates, divers foraminifer assemblages and sponge spicules, along with rare planktonic foraminifers. The skeletal peloidal and ooids wackestone to packstone with miliolids were formed in a shallow lagoonal environments in the water depth of 5-10 m (Hughes, 2000). The skeletal grainstone formed in very shallow, high-energy environments within shoal complex.

Facies	Diagnostic features	Components	Sedimentary structures and bioturbation	stratal pattern	Energy and depositional environment	Environmental interpretation
Clast suported Conglomerate (D1a)	Polymict- Clast supported - moderate to poorly sorted- sandy matrix	Sandstones, chert, volcanic, rip-up mud clast, 1 to 10 cm grain size	Planar cross stratified (crude) and massive or crudly stratified conglomerate- imbrication	Medium to thick bed (20 cm to 1 m) , finning- upward , Lenticular geometry - erusional based	High energy- Continental	Alluvial (D1)
Matrix supoted Conglomerate (D1b)	Polymict- matrix supported - poorly sorted- dolomite to dolomicrite matrix	1 to 10 cm grain size- sandstone, chert, volcanic, rip- up mud clast and dolomite grains		Medium to thick bed (20 cm to 60cm), massive or crudly stratified- Lenticular geometry - erusional based	High energy- Continental	
Sandstone channel (D2a)	Fine to coarse grains- Poorly to moderate sorted- immature to sub mature- sub arkose, sublitharenite and lithic arenite	Root traces- plante debris	Cross bedding	Medium to thick bed (20 cm to 80cm)- Lenticular geometry - erusional based- Lag deposits- thinning upward	High energy- Continental	Fluvial (D2)
Lateral accretion Sandstone (D2b)	Fine to medium grains- Poorly to moderate sorted- sub mature- sub arkose,	Plante debris	Lateral accretion cross beds reactive surfaces	Massive to thick bed (1m to 50cm)- Lenticular geometry- erusional based- Lag deposits- thinning upward-	Medium to High energy- Continental	
Shale (D3a)	Clay(illite) to fine silt grains- mica- quartz, felspar and carbonate grains		Finely lamination Mud cracks	Gray to dark gray and green	Low energy	Mud flat (D3)
Massive sandstone (D3b)	Fine to medium grains - moderate to poor sorted- sub mature - sub rounded to angular grains, sub arkose, sublitharenite sandstone	Mud clast- Heavy minerals- chert	Massive or faint lamination High bioturbated	Medium to thick bedded (20 to 90 cm), lenticular geometry, erosional base, ferroan dolomite bands locally	High energy	
Stramatolithic dolomite (D3c)	Stramatolithe- Carbonate grains (peloids and intraclasts)	Aboundant mica- Chert- phosphatic grains	Microbial stromatolitedolomite	Medium bedded to massive (20 to 90 cm), sheet like geometry, carbonate and sandy patches localy observed,	Low to medium energy	
Trough cross beds sandstone (D4a)	Fine to medium grains- moderately sorted- submature- sub rounded- sub arkose	Heavy minerals- Phosphatic grains	Trough cross lamination structures, Reactive surface	Thick bedded (90 cm), lenticular and sheet like geometry white to cream, sharp lower contact and upper contact is transitional	High energy- Tidal sand bar	Estuarine (D4)
Planar cross beds sandstone (D4b)	Fine to coarse grains- very coarse to pebbely observed rarely- moderate to well sorted- submature to mature- subrounded to well rounded- quartz arenite and sub arkosic sandstone	Heavy minerals- Phosphatic grains Plante debris Fe nodules	Planar cross lamination structures, Reactive surface	Medium to thick bedded (30 to 90 cm), lenticular to sheet like geometry, white to cream, with some dolomite patch	High energy- Tidal sand bar	

Continue

Facies	Diagnostic features	Components	Sedimentary structures and bioturbation	stratal pattern	Energy and depositional environment	Environmental interpretation
Bidirectional lamination (D4c)	Medium to coarse grains - moderate to well sorted- mature- sub arkose, quartzarenite	Heavy minerals- Phosphatic grains	Herringbon structures	Medium to thick bedded (30 to 90 cm), lenticular to sheet like geometry, white to cream	High energy- Tidal sand bar	Estuarine (D4)
Horizontal lamination sandstone (D4d)	Very fine to coarse grains - moderate to well sorted- mature- sub arkose, quartzarenite, sublitharenite and lithic arenite	Heavy minerals- Mud clast Root traces	Horizontal lamination or partind lineation, Flaser bedding,	Thin to masive bedded (10 cm to 1m), sheet like geometry, white to cream, ferroan dolomite bands locally	High to medium energy Sand flat	
Low-angle cross stratified sandstone (D4e)	Very fine to medium grains - well sorted- mature- sub arkose, quartzarenite, sublitharenite sandstone-	Mud clast- Heavy minerals- Phosphatic grains	Low angle <15° cross beds, Reactive surface, Flaser bedding	Medium to thick bedded (20 to 70 cm), lenticular to sheet like geometry, both erosional and sharp contacts, ferroan dolomite bands localy observed	High energy- Upper flow regime- Sand flat	
Sandy dolomite (D4f)	Dolomicrite- Sandy dolomite	Phosphatic grains		Thick bedded to massive (40cm to 1m), sheet like geometry, carbonate and sandy patches localy observed,	High energy- Tidal sand bar	
Mudstone to wackestone (D5a)	Sponge spicules, green algae, ooids, Peloids, Miliolids		It is observed in sub-surfacs sections intercalation with Sandstones and shales		Low energy- Lagoon	Marine (D5)
Packstone to grainstone (D5b)	Green algae, echinoderm, brachiopod, bryozoa, gastropode, oolite, ostracode				High energy- Shoal	

Table. IV.4 (Previous page): Facies table of the Zakeen Formation. It consists of 15 facies and sub-facies deposited in 6 main depositional environments corresponding to (1) Alluvial flood plain; (2) Fluvial; (3) Tidal mud flat; (4) Tide-dominated estuarine; and (5) marine deposits.

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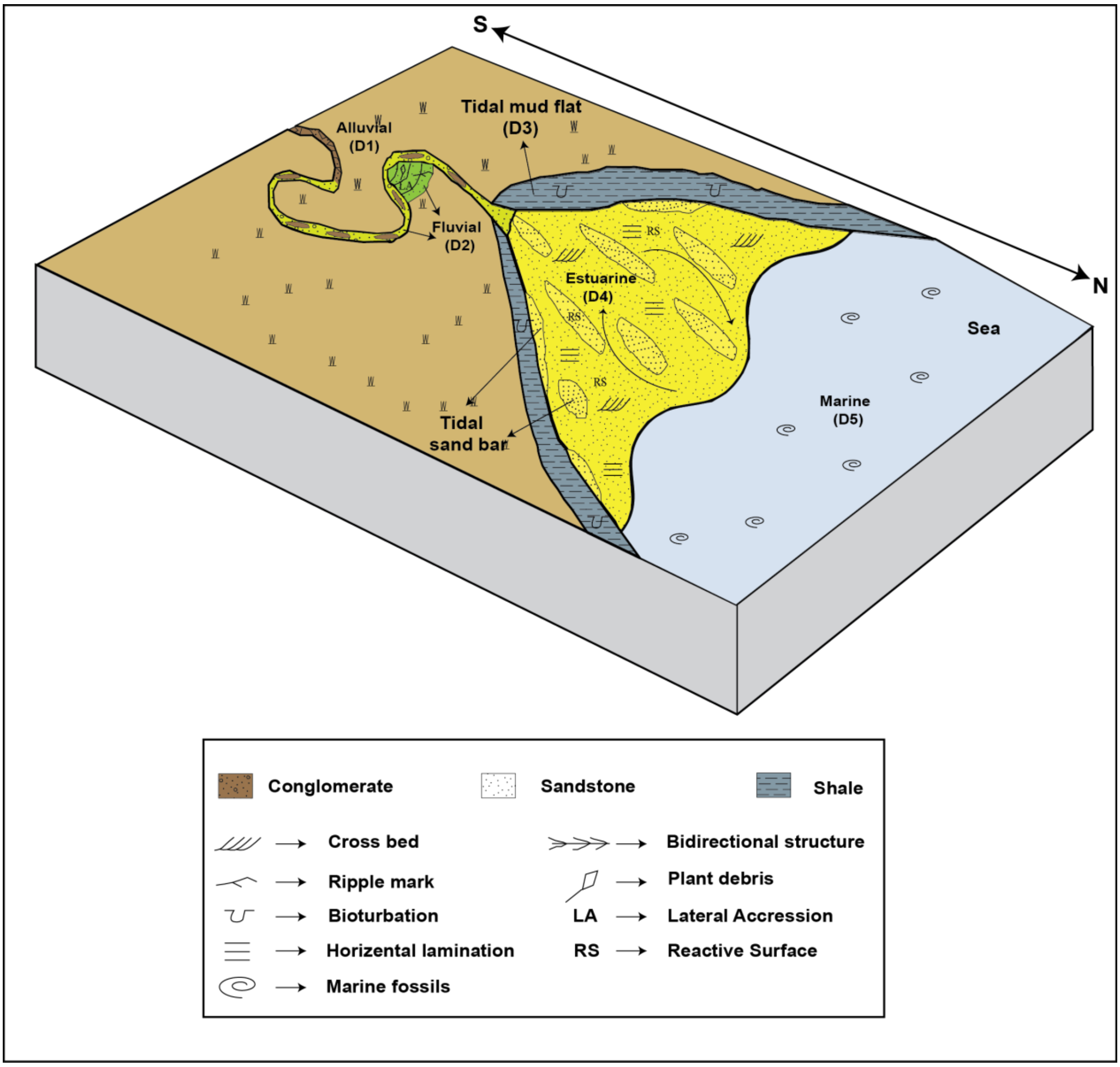

Fig. IV.21: Schematic depositional profile for the Zakeen Formation showing continental to marine environments evolving from alluvial flood plain and Fluvial to Tidal mud flat, Tide-dominated estuarine and marine deposits. *For the facies color codes see table IV.4.*

IV.4.3. Sequence Stratigraphy

The sequence-stratigraphic model indicates that the studied sections (Kuh e Gahkum and Kuh e Faraghan in Bandar Abbas area consists of three 3rd- order depositional sequence that includes transgressive and highstand systems tracts (TST and HST). The thickness of the Devonian succession varies considerably throughout the different areas, ranging from non-deposition (West High Zagros area), Kuh e Surmeh and Kuh e Siah (Fars area), 158 m at Kuh e Faraghan and 117 m in Kuh e Gahkum (Bandar Abbas area). The facies, sequences and bounding surfaces are shown in the detailed surface log cross-sections (Fig. IV.20) and are described below:

<u>Sequence DI- DS DI:</u>

Sequence DI has been identified only in Kuh e Faraghan (Fig. III.2) and well Salman (2SKD#1) drilled in the south Persian Gulf (Fig. I.2). The basal sequence is bounded by SB D0 and is placed on top of a reddish shale unit. SB D0 corresponds to Middle Silurian to Early Devonian hiatus (Ghavidel Syooki, 2003). SB D0 is an eroded channelized incised valley floor and is marked by scouring features. DS DI ended with SB D1 and is predominantly composed of 33 m thick of tide-dominated estuarine (facies D4) and mud flat (facies D3) (Fig. IV.22).

The TST is composed of tide-dominated estuarine sandstones and sandy dolomites (facies D4). The transition from TST to the overlying HST is represented by a downlap surface, indicating the MFS (Posamentier and Vail, 1988), but lithologically this contact is difficult to recognise. In the estuarine channels and further landward reaches, the MFS may be at the downlap surface between the highstand mudstones (facies D3) and the underlying transgressive sandy units (facies D4) (Hou et al., 2003).

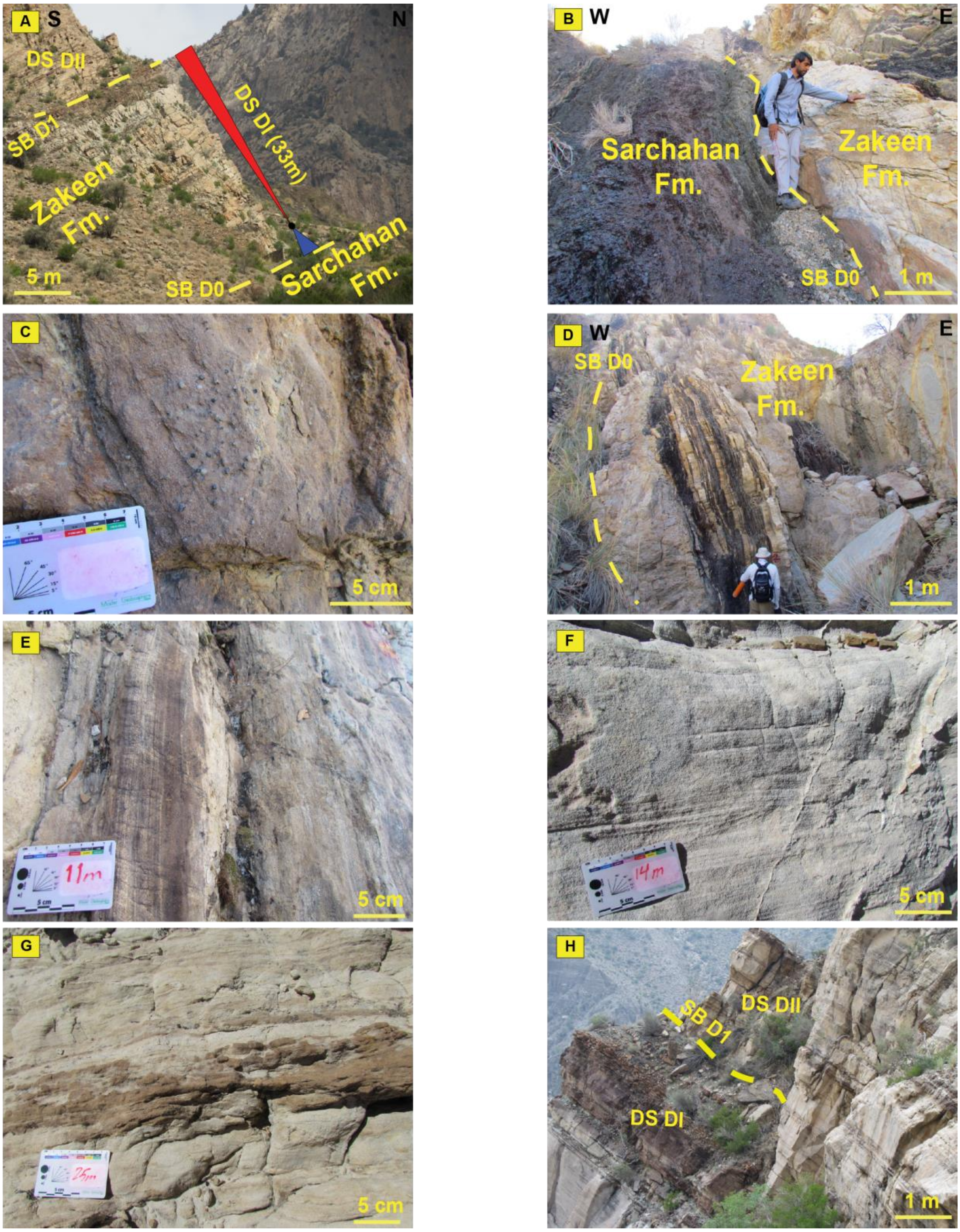

Fig. IV.22: (A) Sequences and sedimentary structures of DS DI for the Zakeen Formation exposed in Kuh e Faraghan; (B) Boundary between Silurian Sarchahan and Devonian Zakeen Formations; (C) Conglomerate at the base of Zakeen Formation; (D) Intercalation of bioturbated shale and sandstones in mud flat environment at the lower part of Zakeen Formation; (E) Tide-dominated estuarine horizontal lamination sandstones at 11 m level of section; (F) Tide-dominated estuarine tabular cross lamination sandstones at 14 m level of section; (G) Dolomitized sandstones in tide-dominated estuary; (H) Mud flat facies at the top of sequence of the Zakeen Formation topped by SB D1. *Fm.= Formation; SB= Sequence Boundary; DS= Depositional Sequence; D= Devonian.*

Sequence DII- DS DII:

This sequence has been recognised in the northern part of the Zagros area at Kuh e Faraghan and Kuh e Gahkum (Figs. III.2). In both areas, it is mainly composed of tide-dominated estuarine (facies D4) and mud flat (facies D3) depositional environments. It shows a lateral facies changes, from more estuarine sandstones at Kuh e Faraghan (Figs. IV.23) to more fluviatile sandy channels (facies D2) and alluvial conglomerates flood plain (facies D1) at Kuh e Gahkum (Figs. IV. 24 & 25). DS DII is also present in the southern part at well Salman (2SKD#1) (Aria Nasab, 2011b).

This sequence is bounded by SB D1 and is marked by a sharp facies change from mud flat (facies D3) to tide-dominated estuarine (facies D4) at Kuh e Faraghan (Figs. IV.23). In the Kuh e Gahkum outcrops, this boundary is placed toward the top of the Late Silurian shales (Fig. IV.24). The upper boundary is marked by SB2, that corresponds to facies changes into estuarine-dominated facies (D4) at Kuh e Faraghan (Figs. IV.23) and alluvial conglomerates flood plain (facies D1) at Kuh e Gahkum (Figs. IV.24 & 25).

DS DII is composed of transgressive estuarine channels and bars sediments (facies D4). Transition from transgression to highstand system tracts corresponds to a mud flat (facies D3).

According to the age determination (Ghavidel Syooki, 2003), DS DII may be correlated with two of the sequences (DS DIIa and DS DIIb) of Kuh e Gahkum (Fig. IV.24). In this area the first sequence (DS DIIa), shows a TST characterised by tide-dominated estuarine (facies D4) which passes to a highstand fluvial sandy channels (facies D2) system. The TST in the second sequence (DS DIIb), shows alluvial conglomerates flood plain (facies D1), that evoves to mud flat (facies D3) and is overlay by highstand tide-dominated estuarine (facies D4) (Figs. IV.24 & 25).

In both areas, the Maximum flooding surface (MFS) is placed locally within the trough (D4a) and planar (D4b) and low-angle cross-bedded (D4e) sandstones of the tide-dominated estuarine facies association (D4) as a deepest part of the sequence (Figs. IV.23, 24 & 25).

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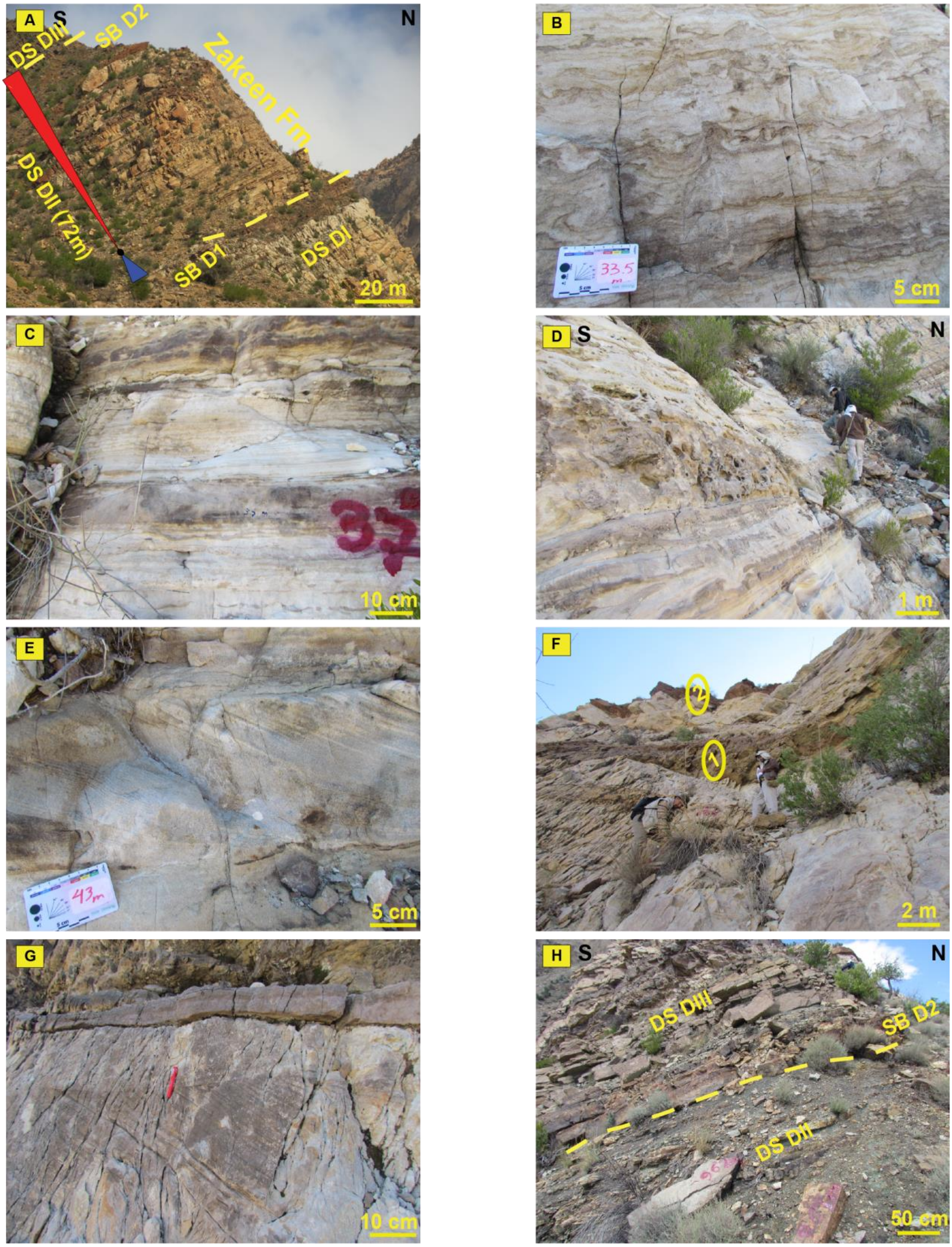
Fig. IV.23 (Next page): (A) Sequences and sedimentary structures of the DS DII for the Zakeen Formation exposed in Kuh e Faraghan; (B) Soft sediment deformation in horizontal lamination sandstones in tide- dominated estuary; (C) Tide-dominated esturine horizontal lamination sandstones; (D) Low-angle cross stratified sandstones related to tide-dominated estury ; (E) Planar cross lamination sandstones in tide-dominated estury; (F) View of the middle part of DS DII showing two brown color dolomithic beds in tide-dominated sand bars; (G) Planar cross lamination sandstones in tide-dominated estury; (H) Mud flat facies at the top of DS II of the Zakeen Formation capped by SB D2. *Fm.= Formation; SB= Sequence Boundary; DS= Depositional Sequence; D= Devonian.*


A
S
N
DS DIII
SB D2
Zakeen Fm.
DS DII (72m)
SB D1
DS DI
20 m
B
33.5
5 cm
C
10 cm
D
S
N
1 m
E
43m
5 cm
F
2
1
2 m
G
10 cm
H
S
N
DS DIII
SB D2
DS DII
50 cm

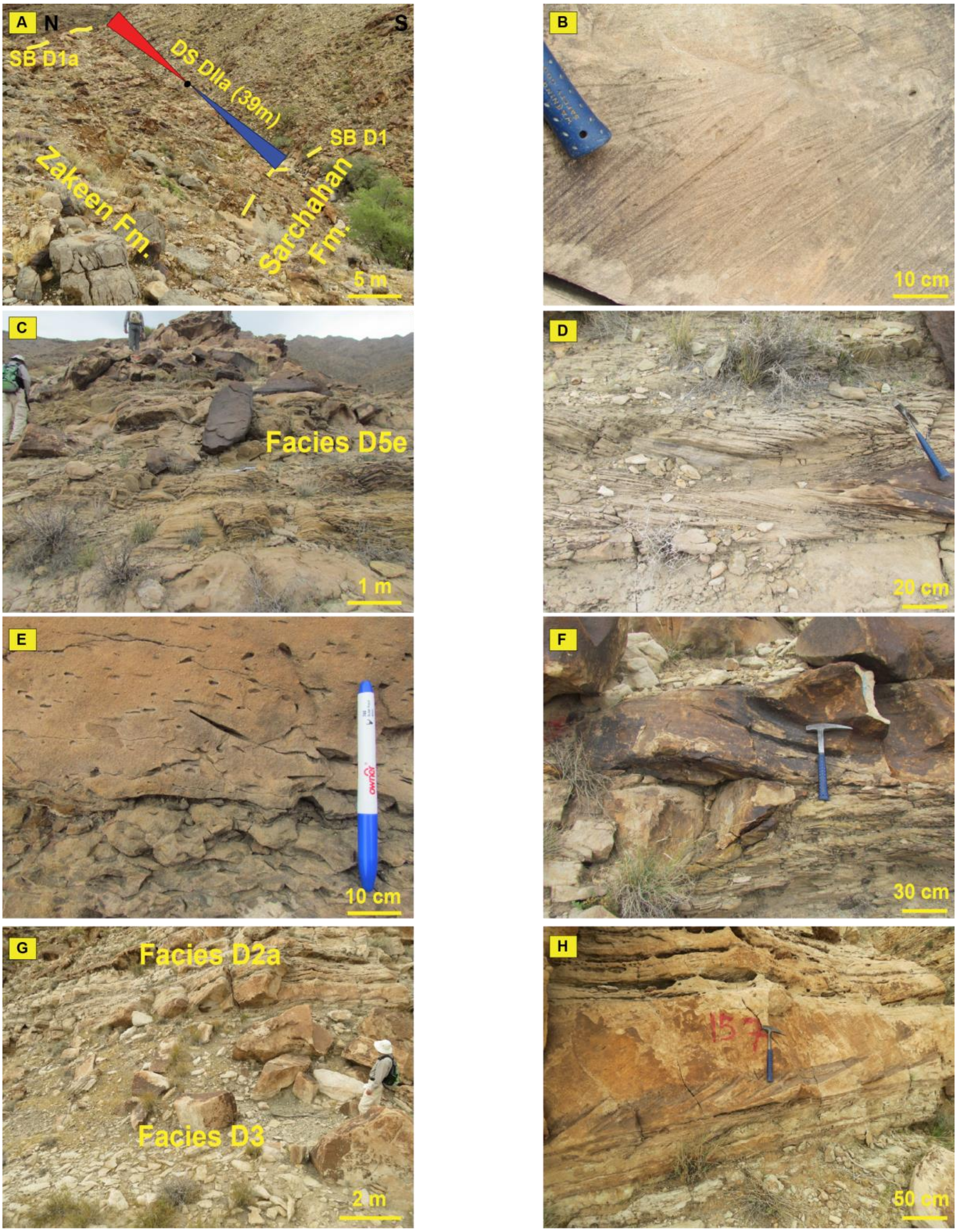


Fig. IV.24: (A) Sequences and sedimentary structures of the DS DIIa for the Zakeen Formation exposed in Kuh e Gahkum; (B) Heringbone cross lamination with reactive surfaces in tide-dominated sandy bars at level of 5 m of section; (C) low-angle cross lamination sandstones related to sandy flat in tide-dominted estuary; (D) Tide-dominted estuary low-angle cross lamination sandstones (E) Mud clasts in sandstones in tide dominated sandy bars; (F) Basal erosional channelized sandy bar sandstones topped the low-angle cross lamination sandstones ; (G) Mud flat facies covered by fluvial channel sandstones; (H) Fluvial channel sandstones at upper part of DS DIIa. *Fm.= Formation; SB= Sequence Boundary; DS= Depositional Sequence; D= Devonian.*

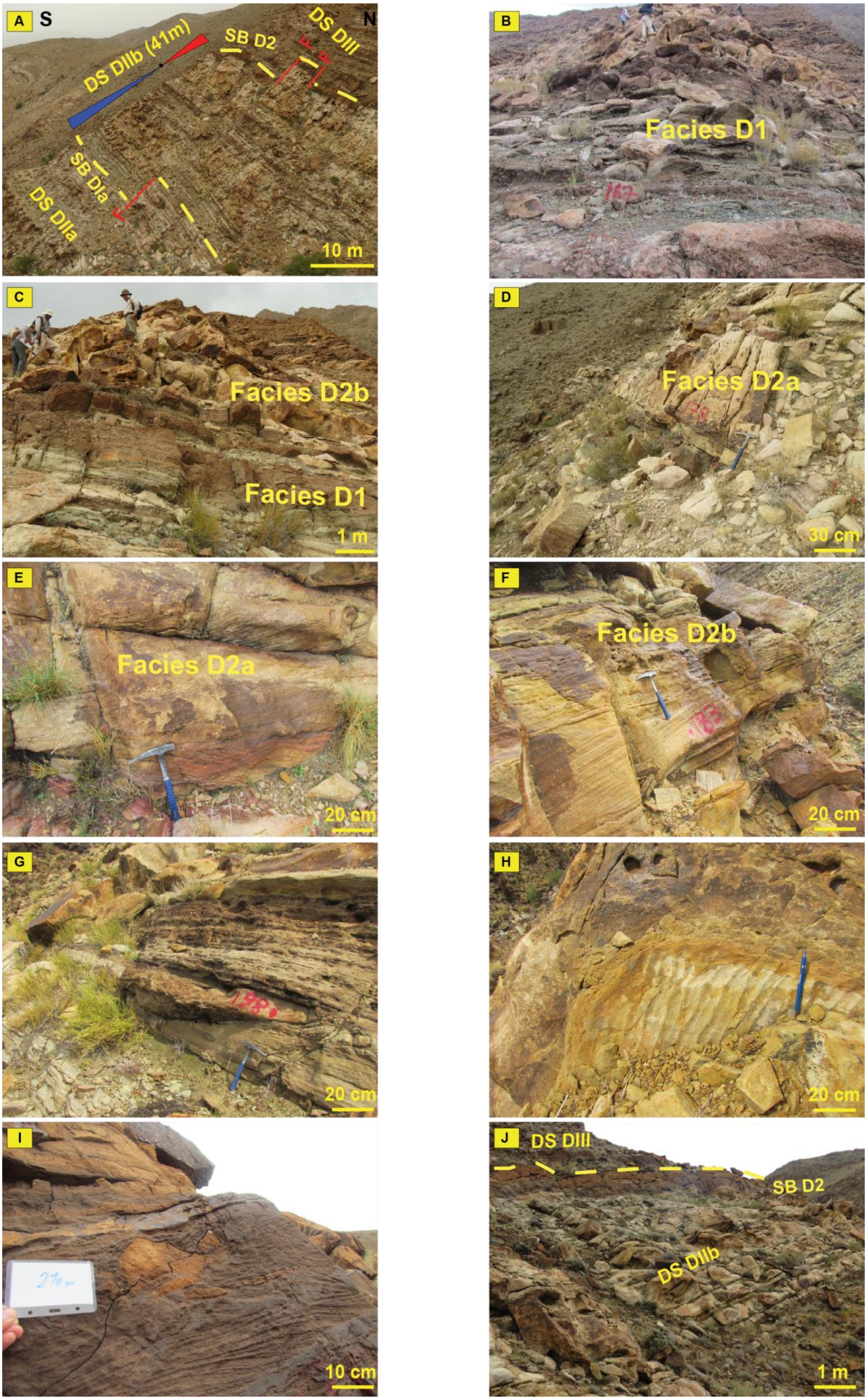

A
S
N
DS DIIb (41m)
SB D2
DS DIII
F
SB DIa
DS DIIa
10 m
B
Facies D1
C
Facies D2b
Facies D1
1 m
D
Facies D2a
30 cm
E
Facies D2a
20 cm
F
Facies D2b
20 cm
G
20 cm
H
20 cm
I
10 cm
J
DS DIII
SB D2
DS DIIb
1 m

Fig. IV.25 (Previous page): (A) Sequences and sedimentary structures of DS DIIb for the Zakeen Formation exposed in Kuh e Gahkum; (B) Intercalation of Conglomerates , sandstones and shales in alluvial facies at base of DS DIIb; (C) Changing from alluvial to fluvial facies; (D) Channelized sandstones in the fluvial facies at level of 50 m of section ; (G) Sandstones of fluvial facie corresponding to facies D2a; (F) Planar cross lamination sandstones in the fluvial facies; (G) Channelized sandstones topped the low-angle cross lamination sandstones in the estuarine facies; (H) Ripple mark in sandstones of sandy bars in tide-dominated estuary at level of 75 m of section; (I) Planar cross-bed dolomite at the top of DS IIb in tide-dominated estuarine sandy bars; (J) Estuarine sandstone facies at top of DS DIIb in the Zakeen Formation topped by SB D2. *Fm.= Formation; SB= Sequence Boundary; DS= Depositional Sequence; D= Devonian.*

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Sequence DIII- DS DIII:

Sequence DIII has been identified in studied area at outcrops and subsurfaces. Nevertheless, Hercynian tectonic event eroded and removed part of this sequence at Kuh e Faraghan (Ghavidel Syooki, 2003) in the north (Fig. IV.26), and all the sequence is removed at well Salman (2SKD#1) (Aria Nasab, 2011b). DS III shows a lateral facies change at the regional scale, from more sandstones-dominated to the north (in the Bandar Abbas area), to more carbonates-sandstones to the south (in the Fars and Persian Gulf). It is bounded by the SB D2 and SB D3 (Figs. IV.26 & 27). The SB3 is a major unconformity below Early Permian Faraghan sandstones due to the Hercynian tectonic event (Ghavidel Syooki, 2003). DS DIII consists of a transgressive estuarine sandstones (facies D4) and highstand mud flat (facies D3). The MFS is located at the surface between the highstand mudstones (Facies D3) and the underlying transgressive sandy units (facies D4).

Toward Kuh e Gahkum, a more complete sequence (from Givetian to Famennian) is exposed (Ghavidel Syooki, 2003) (Fig. IV.20). The TST is composed of alluvial conglomerates flood plain (facies D1) and mud flat (facies D3) and the HST is a tide-dominated stuarine (facies D4) (Fig. IV.27).

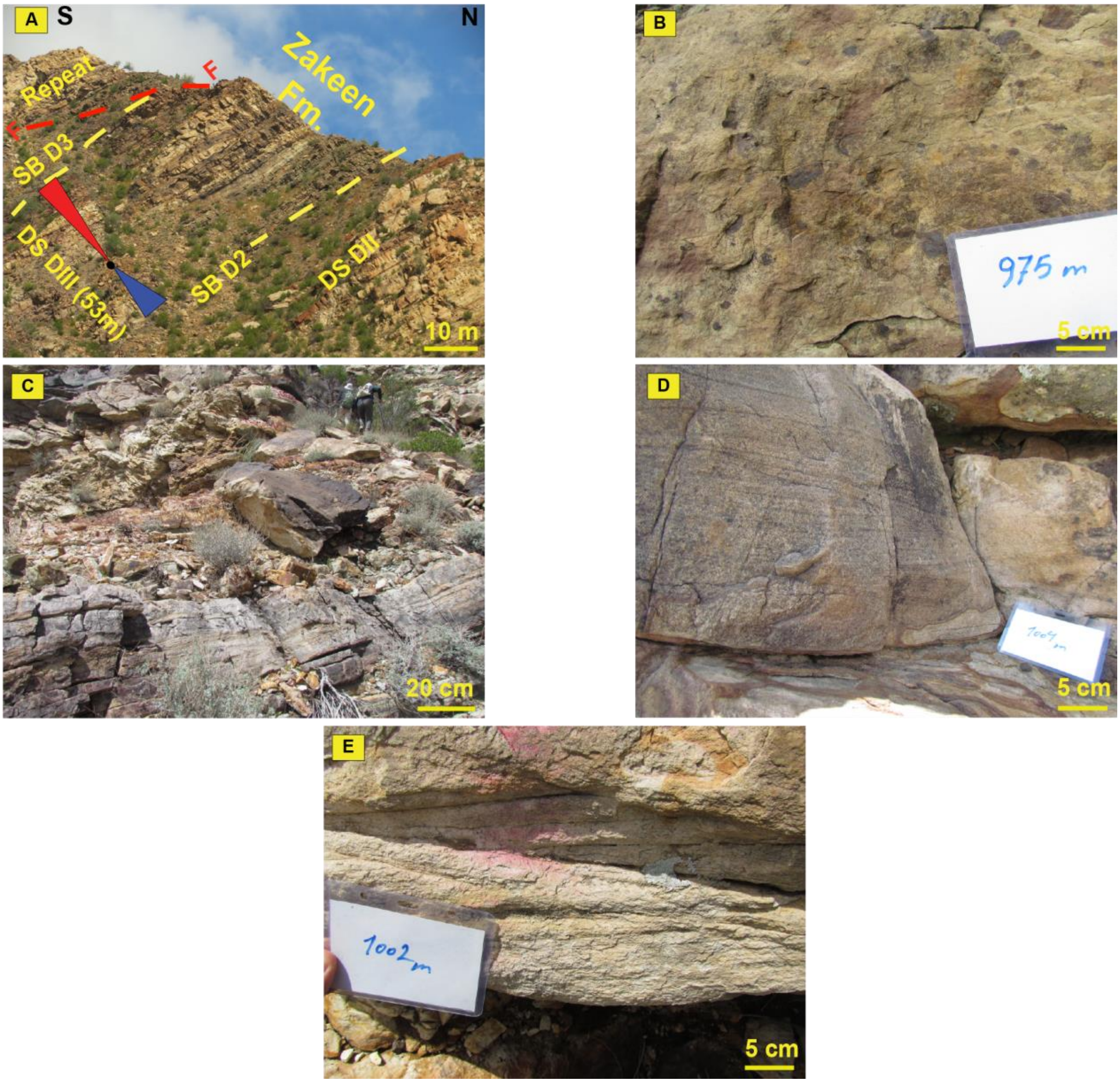

Fig. IV.26: (A) Sequences and sedimentary structures of DS DIII for the Zakeen Formation exposed in Kuh e Faraghan; (B) Bioturbated sandstones in lower part of DS DIII in tide-dominated estuary; (C) Channelized sandstones related to tide-dominated sandy bars; (D) Horizontal lamination sandstones in sandy flat within tide-dominated estuary; (E) Cross stratification sandstones in upper part of DS DIII in tide-dominated estuary. *Fm.= Formation; SB= Sequence Boundary; DS= Depositional Sequence; D= Devonian.*

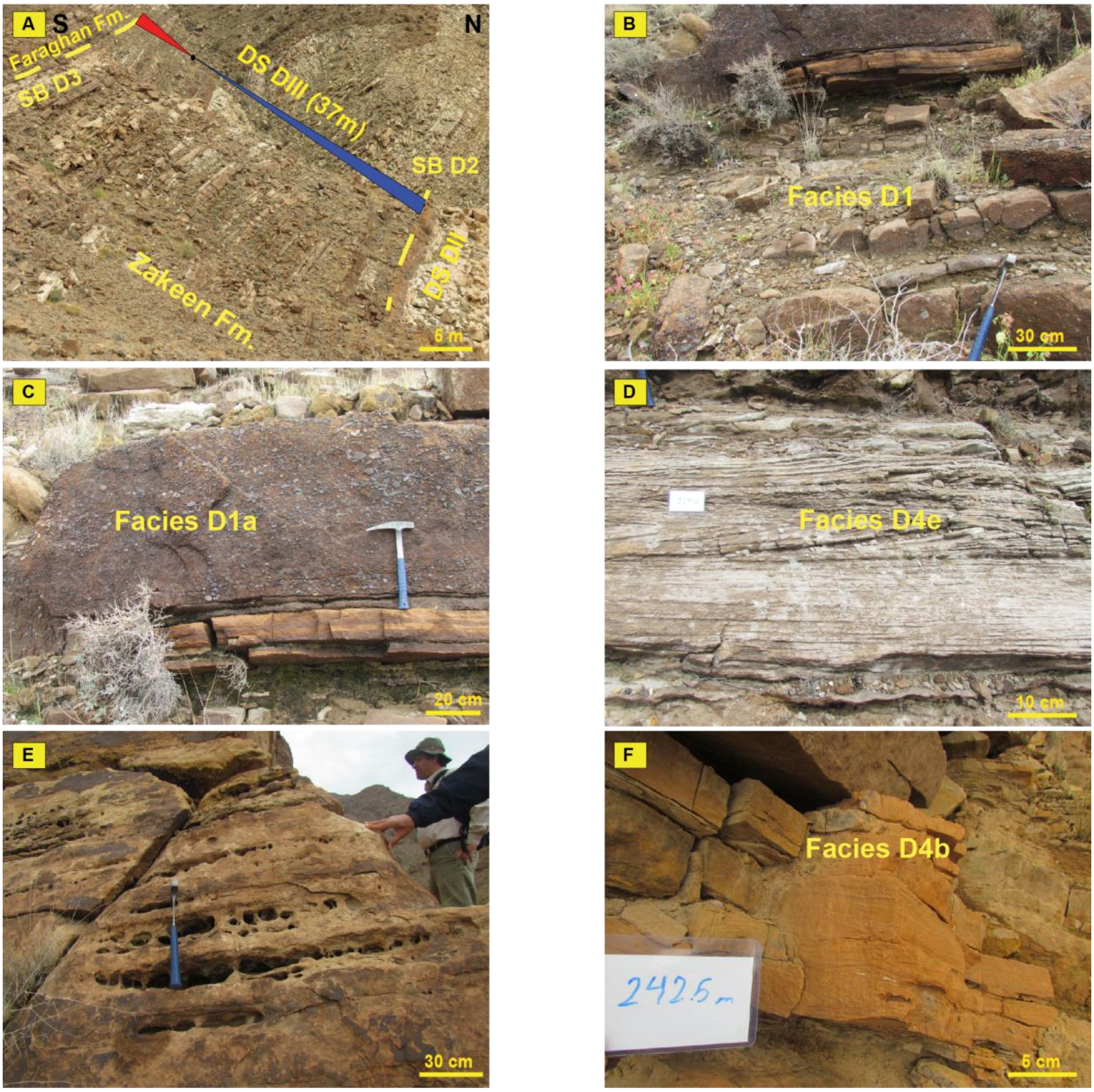

Fig. IV.27: (A) Sequences and sedimentary structures of DS DIII for the Zakeen Formation exposed in Kuh e Gahkum; (B) Intercalation of Conglomerates, sandstones and shales in alluvial facies at lower part of DS DIII; (C) Clast supported conglomerates in alluvial facies at lower part of DS DIII; (D) Low-angle cross lamination sandstones in the estuarine facies; (E) Estuarine sandstone facies at top of DS III in the Zakeen Formation; (F) Planar cross bed dolomite at the top of DS DIII in tide-dominated estuary. *Fm.= Formation; SB= Sequence Boundary; DS= Depositional Sequence; D= Devonian.*

IV.5. Cycle 4 (Early Permian)

The Early Permian Faraghan Formation is well exposed in the High Zagros zone (Berberian and King, 1981) from Lurestan to Bandar Abbas area and in the Fars area at Kuh e Surmeh and in numerous subsurfaces wells (Ghavidel Syooki 1996) (Fig. I.2). The Formation grades upward into the thick carbonates Dalan Formation considered as Middle to Late Permian. Both Faraghan and Dalan Formations are major hydrocarbon reservoirs of SW Iran and are time equivalents of the Unayzah and Khuff Formations in Saudi Arabia, respectively (Fig. I.4). As a result, identification of the depositional environment, sequence stratigraphy and palaeogeography of the Faraghan Formation is important. The palynological studies performed by Ghavidel Syooki (1986, 1994, 1997, 1999 and 2003), improve the biozonation and age definition of the Faraghan Formation (Fig. II.3). Consequently a significant hiatus between the Devonian Zakeen and Early Permian Faraghan Formations is refind.

IV.5.1. Introduction of the Faraghan Formation

The Faraghan Formation is widely distributed in the Zagros Basin (Szabo and Kheradpir, 1978). The type section is located at Kuh e Faraghan, approximately 103 km north of Bandar Abbas city (Ghavidel Syooki, 2003) (Fig. III.2). It is well obsereved in Kuh e Dinar, Zard Kuh, Chal i Sheh, Ghali Kuh, Kuh e Garreh, Ushtoran Kuh, Kuh e Surmeh and Kuh e Gahkum outcrops (Ghavidel Syooki 1997). The Faraghan Formation also reported in subsurface Finu#1, Namak#1, Kabir Kuh#1, Kuh e Siah#1, Dalan#1, Zirreh#1,West Agar#1, Naura#1, Darang#1, Golshan#3, Kish#2, Salman 2SKD#1, Homa#1, West Assaluyeh#1, Nar#2 and Sepidar#1 wells (Ghavidel Syooki, 1996) in the Zagros (Fig. I.2). The Faraghan Formation unconformably overlies Devonian (Fars and Bandar Abbas area), Cambrian to Ordovician deposits (West High Zagros).

In the Kuh e Dena at Tang e Putak, the Faraghan Formation is composed of 20 m of alternating gray shales and white to brown thick sandstones. The sandstone layers are 3-7 m in thickness, and contain trough cross-bedding stratification. In this section, The Faraghan Formation overlies Late Cambrian Mila(C) Formation (Setudehnia, 1975) (Fig. III.10).

In Zard Kuh, the Faraghan Formation consists mainly of 75 m of white sandstones and very thin dark gray shale layers (Fig. III.7). The sandstone layers are typically 1-2 m thick, and have well developed through cross-bedding stratification. The Faraghan Formation unconformably overlies Devonian- Silurian unnamed unit (JOGMEC & NIOC, 2005).

In Chal i Sheh, the Faraghan Formation consists mainly of 530 m of sandstones dominated alternating with black to dark gray shales (JOGMEC & NIOC, 2005) (Fig. III.5). The thickness of sandstone layers is 0.8-1 m, and they present trough cross-bedding stratification. Shales typically include fragments of plant fossils. The lower part of the Faraghan Formation consists mainly of white thick sandstones. The thickness of sandstone layers is 30-80 cm, and they are fine-grained with trough cross bedding. The sandstones includes plant fossils, especially *Sigillaria Persica*, which is an index fossil indicating Carboniferous to Early Permian age. Some sandstone layers contain 10-30 cm thick pisolite layers. The Faraghan

Formation unconformably overlies Early Ordovician Ilebek Formation (JOGMEC & NIOC, 2005).

In Ghali Kuh, the Faraghan Formation is poorly exposed, and the contact between the Faraghan and Dalan Formations is obscured by screen. The Faraghan Formation consists mainly of 200 m white sandstones alternating with minor gray shale. The sandstone layers contain trough cross-bedding stratification and abundant plant fossils, although Sigillaria Persica is not reported from this section. The upper part of the Faraghan Formation is exposed near the Ab-e Sefid area, and consists of alternating gray to dark gray shales and white sandstone layers of 30-50 cm in thickness that contain trough cross-bedding . The Faraghan Formation unconformably overlies Middle- Late Cambrian MilaFormation (JOGMEC & NIOC, 2005).

In Ushtoran Kuh and Kuh e Garreh, the Faraghan Formation unconformably overlies Middle-Late Cambrian Mila Formation (JOGMEC & NIOC, 2005).

Based on Pollen assemblage zone VII (Ghavidel Syooki, 1984a,2003), the age of the Faraghan Formation is considered to be Early Permian. This zone is characterized by the disappearance of the whole Devonian Palynomorph taxa and the appearance of following Early Permian index Pollen species:

Vittatina subsaccata, Caheniasaccites ellipticus, Mabuitasaccites ovatus, Corisaccites alutas, Fusacolpites fusus, Striomonosaccites triangulais, Boutakoffites elongates, Potonieisporites granulatus, Hamiapollenites perisporites, Hamiapollenites saccatus.

This pollen/spores assemblage (Assemblage zone VII) is considered to belong to *Pollen/Spores assemblage zone P1 (Hamiapollnites-Vittatina)* (Ghavidel Syooki, 1996) (Fig. II.3).

However, the Formation contains *Sigillaria persica* in the Chal-i Sheh area, which indicates a Carboniferous age (Szabo and A. Kheradpir, 1978).

IV.5.2. Precision on the sedimentology and stratigraphy

During the Late Palaeozoic, the Zagros Basin was situated in the northern part of the Arabian Plate (Beydoun 1988; Konert et al. 2001) which in turn was located at the southern margin of the Paleo-Tethys at about 30°– 45° southern latitudes (Berberian and King 1981; Smith et al. 1981; Al-Husseini 1992; Konert et al. 2001) (Fig. I.3). Following the Hercynian Orogeny late Carboniferous- Early Permian, clastic sediments were the first widely deposits in the Arabian Plate and rest in angular unconformity (Hercynian unconformity) with older Palaeozoic rocks (Al-Husseini, 1992). They were partly deposited coeval with rift tectonics along the eastern and northern margins of the Arabian Plate (Konert et al., 2001). Generally, braided plain, channel fill, and eolian sandstones and siltstones of Unayzah A and B members in Saudi Arabia were deposited in semi-arid conditions (Senalp and Al-Duaiji, 1995). Basinward in Zagros area, they are replaced by continental sediments to shallow marine deposits (Szabo and Kheradpir, 1978; Zamanzadeh, 2008) under warm climatic conditions (Frakes et al., 1992). In the Late Early Permian (Artinskian-Kungurian) the Arabian Plate is interpreted to have undergone a second major phase of crustal extension (rifting, stretching and thinning), which this time led to continental separation (Sharland et al., 2001). Progressive thermal uplift (the pre-cursor to continental rifling and spreading) is interpreted to have occurred during the Late Carboniferrous to Early Permian along the present day Zagros fold belt, culminating in the regional “pre Khuff unconformity” at the base of Middle Permian (Fig. I.4) (Sharland et al., 2001). This unconformity eroded much of the underlying Palaeozoic section in this region (Szabo and Kherndpir, 1978).

IV.5.2.1. Presentation of the studied successions

Kuh e Faraghan: 58 m thick (Fig. IV. 28) unconformably overlies the Devonian Zakeen deposits and consists of brown, pinkish to white sandstones with brown to greenish shales and dolomites (Fig. IV.31). The dolomite beds increased vertically all along the succession. The age is Sakmarian to Kungurian stages (Ghavidel Syooki, 2003).

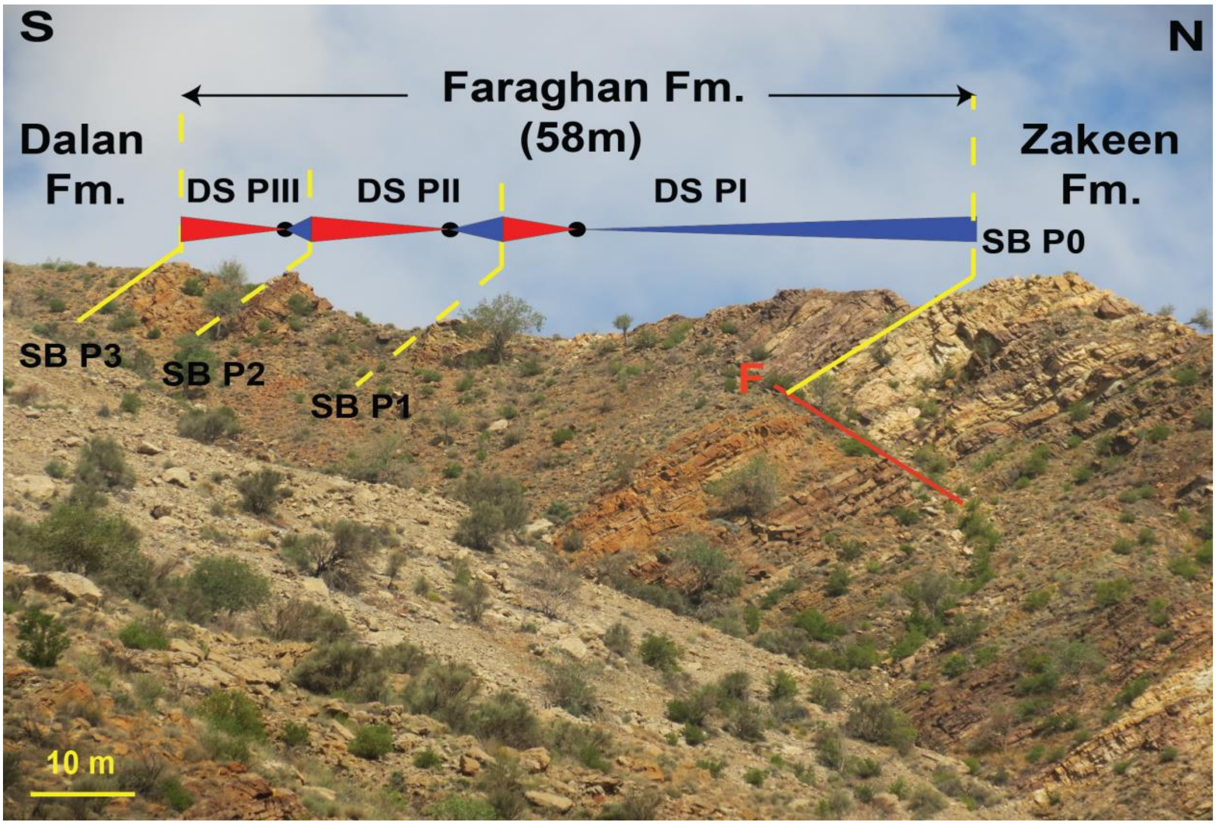

Fig. IV.28: Faraghan Formation exposed in Kuh e Faraghan showing three depositional sequences. *F=Fault.*

Kuh e Gahkum: 64 m thick (Fig. IV.29) topped unconformably the Devonian Zakeen Formation (Kolodka et al., 2011). It is composed of brown conglomerates, white to brown sandstones, brown siltstones and dark, gray to green shales with almost 15 m brown stromatolithic dolomites in lower part (Fig. IV.31). According to the palynological study by Ghavidel Syooki (1986), its age ranges from Sakmarian to Kungurian stages.

Kuh e Surmeh: 36 m thick (Fig. IV.30) resting on the Late Ordovician Seyahou Formation with a 10° angular unconformity. It is characterized by basal conglomerates, gravelly sandstones, brown to cream sandstones and black and red shaly beds. Palynologic studies carried out by Ghavidel Syooki (1994e), shows that the age of this Formation is from Sakmarian to Kungurian stages (Fig. IV.31).

Well Zirreh#1: 100 m overlain by Middle to late Permian Dalan Formation and consists mainly of shales, sandstones and siltstones (Annexe I). The sandstones are moderately to well-sorted, sub-rounded to rounded and sub-mature to mature. The grain size of sandstones is fine to coarse grain (150- 500 µm). The age of the Faraghan Formation is Early Permian (Sakmarian) based on the occurrence of the *Pollen/Spores assemblage zone P1 (Hamiapollnites-Vittatina)* (Ghavidel Syooki, 1996).

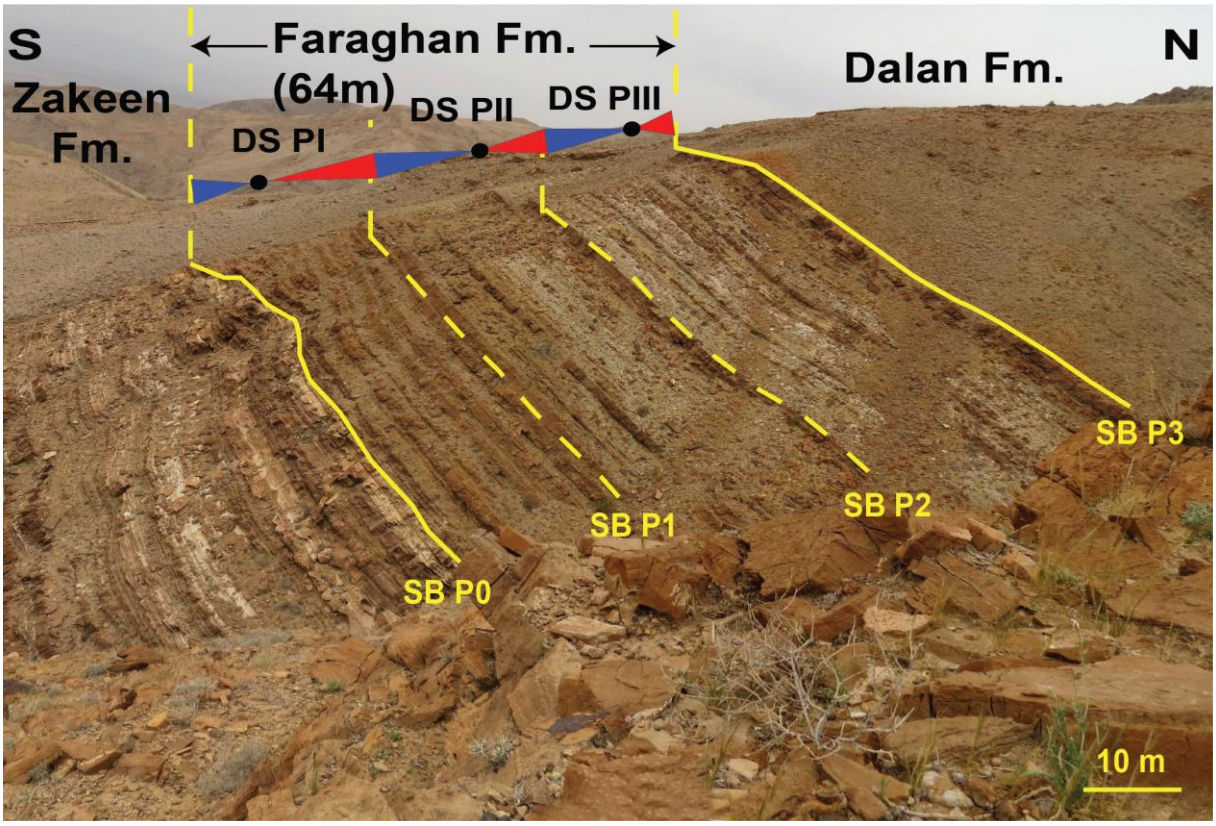

Fig. IV.29: Faraghan Formation exposed in Kuh e Gahkum showing three depositional sequences.

Well West Aghar#1: 68 m sandstones and sandy shale beds (Annexe I). The grain size of sandstones varies from fine to medium (125-200µm). These sandstones contain moderately to well sorting, sub angular to sub-rounded and sub-mature grains. The Faraghan formation overlies the Zakeen Formation. Based on the playnologic studies by Ghavidel Syooki (1998), the age of this Formation is Early Permian (Sakmarian- Kungurian).

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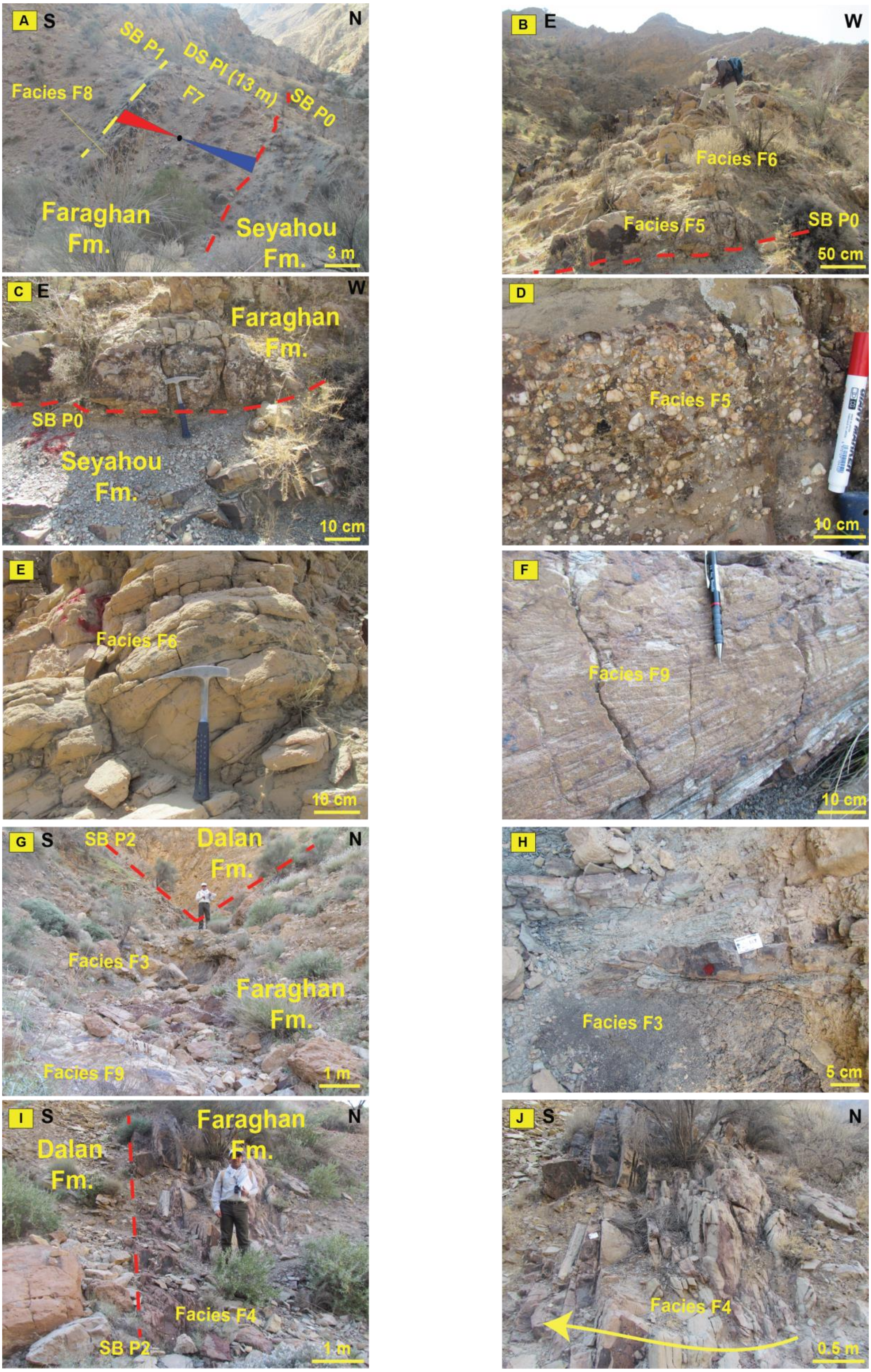
Fig. IV.30 (Next page): (A) DS PI for the Faraghan Formation exposed in Kuh e Surmeh; (B) Conglomerates and gravelly sandstones at the base of Faraghan Formation (C) Boundary between Late Ordovician Syahou Formation and Early Permian Faraghan Formation; (D) Clast supported conglomerates at base of Faraghan Formation in landward part of the esturine depositional environment; (E) Gravelly sandstones in bay-head delta of estuary rests on Clast supported conglomerates ; (F) Bidirectional lamination sandstones tidal flat; (G) View of HST in DS PII; (H) Black to reddish black shales in flood tide delta; (I&J) Wedge-shape sandstones in bay-head delta at uppermost part of Faraghan Formation, and sequence boundary (SB P2) between Faraghan Formation and Middle to Late Dalan Formation.


A
S
N
SB P1
DS Pl (13 m)
SB P0
Facies F8
F7
Faraghan Fm.
Seyahou Fm.
3 m
B
E
W
Facies F6
Facies F5
SB P0
50 cm
C
E
W
Faraghan Fm.
SB P0
Seyahou Fm.
10 cm
D
Facies F5
10 cm
E
Facies F6
10 cm
F
Facies F9
10 cm
G
S
N
SB P2
Dalan Fm.
Facies F3
Faraghan Fm.
Facies F9
1 m
H
Facies F3
5 cm
I
S
N
Dalan Fm.
Faraghan Fm.
Facies F4
SB P2
1 m
J
S
N
Facies F4
0.5 m

Well Naura#1: 51 m of sandy shales and sandstones (Annexe I). It caps the Devonian Zakeen Formation. The sandstones are moderately sorted, sub-rounded and sub-mature. The grain size of sandstones is coarse grain (500- 600 µm). The age of the Faraghan Formation is Early Permian (Sakmarian- Kungurian) according to the occurrence of *Pollen/Spores assemblage zone P1 (Hamiapollnites-Vittatina)* (Ghavidel Syooki, 1996).

Well Dalan#1: 63 m of sandstones and shales overlies the Zakeen Formation (Annexe I). Palynologic study carried out by Ghavidel Syooki, (1994d) give Early Permian age for the Faraghan Formation based on the occurrence of *Pollen/Spores assemblage zone P1 (Hamiapollnites-Vittatina)* (Ghavidel Syooki, 1996).

Well Kuh e Siah#1: 43 m topped the Late Ordovician Seyahou Formation. The Faraghan Formation consists mainly of sandstones, siltstones and subordinate shaly beds (Annexe I). The grain size of sandstones is very fine to coarse (70- 500 µm) and they are poorly to moderately sorted, sub-rouded and sub-mature. The age of the Faraghan Formation is attributed to the Early Permian (Sakmarian- Kungurian) based on the presence of the *Pollen/Spores assemblage zone P1 (Hamiapollnites-Vittatina)* (Ghavidel Syooki, 1996).

Well Golshan#3: 123 m of sandstones, shales and sandy limestones, overlies the Devonian Zakeen Formation (Annexe I). The grain size of the sandstones are medium to coarse grain (250-500µm) and composed mainly of mature, well-sorted and rounded grains. Based on the occurrence of *Pollen/Spores assemblage zone P1 (Hamiapollnites-Vittatina)*, the age of this Formation is considered as Sakmarian- Kungurian stages (Ghavidel Syooki, 1994c).

Well Kish#2: 72 m thick topped the Devonian Zakeen deposits. The Faraghan Formation consists mainly of sandstones, shales and shaly limestones (Annexe I). The sandstones are moderately to well-sorted, sub-rounded to rounded and sub-mature to mature, fine to coarse grain (125- 600µm). Palynological studies carried out by Aria Nasab (2011a) confirmed that the age of the Faraghan Formation is attributed to Early Permian (Sakmarian-Kungurian), based on the occurrence of *Pollen/Spores assemblage zone P1 (Hamiapollnites-Vittatina)* (Ghavidel Syooki, 1996).

Well Salman 2SKD#1: 99 m thick sandstones and shales which rest on Devonian deposits (Annexe I). The age of Faraghan Formation is Sakmarian- Kungurian (Aria Nasab, 2011b).

Well Sepidar#1: 102 m thick sandstones, shales, siltstones and limestones (Annexe I). The sandstones are fine to very coarse (200- 1000µm), immature to mature, angular to sub-rounded and poorly to well-sorted grains. The Faraghan Formation is attributed to Early Permian, whereas underneath deposits is related to Early Ordovician Tremadocian (Rosen, 1976).

Well Homa#1: 128 m thick with uncertaine lower boundary (Annexe I). It is composed of sandstones and shales. The grain size of the sandstones is medium to coarse (250-500 µm). According to the occurrence of *Pollen/Spores assemblage zone P1*

(Hamiapollnites-Vittatina), the age of the Faraghan Formation is considered as Sakmarian-Kungurian stages (Ghavidel Syooki, 1996; Bahrami, 2000).

Well West-Assaluyeh#1: 115 m thick of shales and sandstones with uncertaine lower boundary (Annexe I). The sandstones are characterized by rounded, well-sorted and mature grains. Based on the occurrence of *Pollen/Spores assemblage zone P1 (Hamiapollnites-Vittatina)*, the age of the Faraghan Formation considered to Sakmarian-Kungurian (Ghavidel Syooki, 1996).

Well Nar#2: 140 m thick of shales and sandstones in lower part that upgrade into limestones in upperpart (Annexe I). Its lower boundary is uncertain. The sandstones are characterized by sub-rounded, moderately-sorted and sub-mature grains. The limestones are bioclastic mudstones to grainstones. The age of the Formation is Sakmarian- Kungurian stages based on the occurrence of *Pollen/Spores assemblage zone P1 (Hamiapollnites-Vittatina)* (Ghavidel Syooki, 1996).

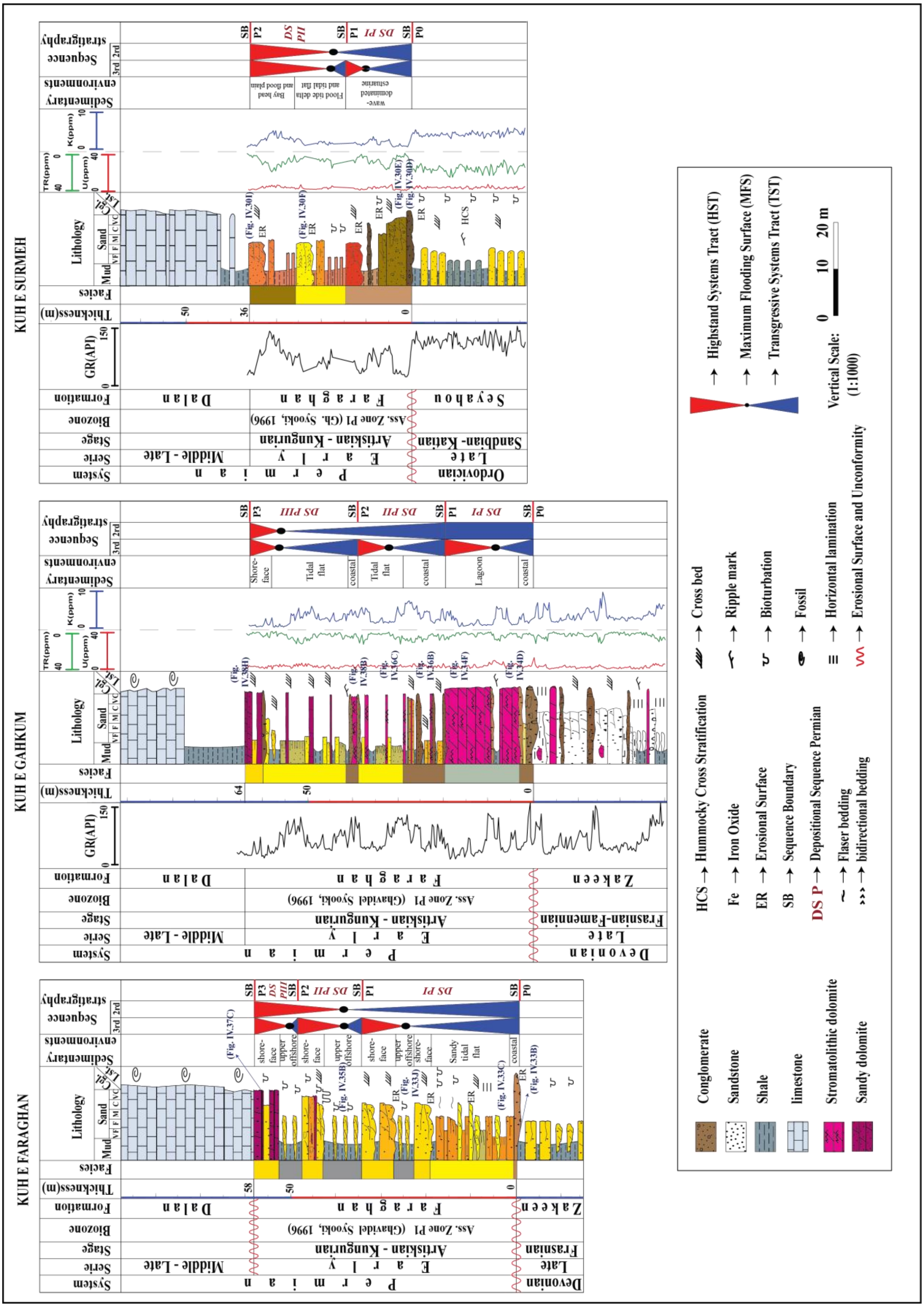


Fig. IV.31: Facies, depositional environments and sequence stratigraphy of the Faraghan Formation sections in Kuh e Faraghan, Kuh e Gahkum and Kuh e Surmeh. *For the facies color codes see table IV.5.*

IV.5.2.2. Facies and depositional environments

Seven main depositional environments have been identified, that evolve from continental coastal plain to shallow marine platform (Fig. IV.32): (1) Coastal plain; (2) Bay-head delta and alluvial plain; (3) Estuarine low energy central basin; (4) Wave dominated estuary; (5) tidal flat and flood tide delta; (6) Lagoon; (7) shoreface; and (8) Uper offshore environments (Table.IV.5).

Facies	Diagnostic features	Components	Sedimentary structures and bioturbation	stratal pattern	Energy and depositional environment	Environmental interpretation	
Clast suported Conglomerate (F1)	Polymict- Clast supported- 1 to 10 cm grain size - moderate to poorly sorted- sandy and dolomicritic matrix	Sandstone, chert, volcanic, rip- up mud clast and dolomite grains- anydrite and phosphatic grains, dolomite to ferroan dolomite cement	Massive to crudly stratified, mud cracks at top	Medium bed to massive (20 cm to 2 m), Lenticular geometry- erosional based- brown to dark brown- intercalation with shales and gravelly sandstones	High energy- Fluvial	Coastal plain	
Mudsupoted Conglomerate (F2)	Polymict- matrix supported- 1 to 10 cm grain size- poorly sorted- subangular to sub rouded grains	Sandstone, chert, volcanic, carbonate and stromatolithic dolomite grains- dolomite and dolomicrite matrix	Massive to crudly stratified	Medium to massive bed (20 cm to 2 m), Lenticular geometry- erosional based, intercalation with shales and gravelly sandstones	High energy- Fluvial		
Red shale dominated heterolithic (F3)	Shale reddish intercalated organic debris with fine sandstone beds	Organic debris	Poorly structured sandy layers in massive shales- rare flaser bedding	Thick and homogenous unit	Low energy- flood plain deposits	Bay-head delta and alluvial plain	Wave dominated estuarine
Small scale trough cross bedded sandstones (F4)	Medium to coarse grains- oxydes- organic debris- well sorted- mature- quartz arenite	Oxides- Organic debris	Trough cross-bedding in sets <0.25 m thick- erosive surface- symmetrical ripples- coarsenning upward	Pluri-m thick bedded unit lenticular	Medium to high energy- sandy bar in a progradational delta		
Lag Conglomerates (F5)	Monomict clasts of quartzits gravels- microconglomerate matrix-supported size- sub angular to sub rounded pebbels	Quartz ower growth and calcite	Erosional score bases- massive to crudely stratified- thinning-upward- imbrication- The conglomerates are clast-supported containing weak matrix proportion(<20%) made of sandstones and microconglomerates	Demi-m thick beds lenticular	Conglomeratic lag		
Gravelly sandstones (F6)	Coarse to very coarse grains- well sorted- mature- quartz arenite	Zircon- Chlorite	Planar cross-bedding toward top- trough cross-bedding- erosive surface- finning- upward succesion- rare flasser bedding	Thinning-upward, pluri-demi beds- channelized and lenticular	Upper flow regim- coarse grain lag on channel floors and bars		
Heterolithic siltstones and mudstones (F7)	Fine to very fine grains- sub angular- arkose	Zircon- mica	Inter- laminated and thinly interbedded mudstones and thin siltstones (1-5 cm)- flaser bedding- bioturbation (Skolitus and Planolithes)	Lenticular and wavy bedding of the siltstones and massive clay unit	Lower flow regim- undirectional current and suspention- central estuarine basin	Central part	
Sandstones (F8)	Fine to medium grains- sub litharenite	Zircon- mica	Thining-upward succession, smal scale bidirectional and planar, trough -cross bedding- planar lamination on top of the sandstone unit and rare ripple mark- bioturbation	Low-angle cross-bedded, 20 cm thick beds	Mouth sand barrier	Mouth bar	

Continue

Facies	Diagnostic features	Components	Sedimentary structures and bioturbation	stratal pattern	Energy and depositional environment	Environmental interpretation
Bidirectional Sandstones (F9)	Medium to coarse grains- sub mature to mature- quartz arenite	Associated with facies F7	Bidirectional cross-lamination- reactive surfaces- ripple mark at top	Metric to dm thick lenticular bedding- erosional base	High energy- tide dominated	Tidal flat and flood tide delta
Low-angle cross stratified sandstone (F10)	Very fine to medium grains- well sorted- mature- sub arkose, sublitharenite and sometimes calcarenite sandstone	Mud clast- Heavy minerals- phosphatic grains	low angle <15° cross beds- low bioturbation	Medium to thick bedded (20 to 80 cm), sheet like geometry, coarsening upward, green, brown, purple, sometimes intercalation with sandy dolomites	Medium to high energy- tidal flat	
Stromatolithic dolomite (F11)	Stromatolithic Dolomicrite	Carbonate grains (peloids and intraclasts)- chert- phodphatic grains, stylolithe, dolomite cement		Rusty dolomite, Medium bedded to massive (20 to 90 cm), sheet like geometry, carbonate and sandy patches localy observed, intercalation with sandstone beds and shales, anhydrithic dissolution vugs, both lower and upper contacts gradational	Low to Medium energy	Lagoon
Sandy Dolomite (F12)	Subhedral to anhedral neomorphorm dolomite	Fish debris, phosphatic grains, heavy minerals, dolomite and calcite cement	Cross-lamination- low to medium bioturbation	Rusty dolomite, thick bedded to massive (70 cm to 1m), sheet like geometry, carbonate and sandy patches localy observed, anhydrithic dissolution vugs, lower contact gradational and erosional in channels	High energy- shoreface	Shorface
Planar cross lamination sandstones (F13)	Medium to very coarse grains (250- 2000 μ) to gravelly graine size- well sorted- mature- quartzarenite, Qz >95%	Heavy minerals, Intergranular silice and overgrowth quartz, calcite, ferroan dolomite and clay (sericite) cement	Planar cross-beds- low to medium bioturbation	Medium to thick bedded (~20-40cm), white and limonitic in color, both lower and upper contact are gradational, thining upward, wedge shape, fe oxide at top of beds	High energy-shoreface	
Trough cross beds sandstone (F14)	Fine to medium grains (0.3-0.75mm), moderately sorted, sub mature, sub litharenite, Qz ~80% , Rf. ~15%,Fld. ~3%,	Heavy minerals, intergranular silice, Fe and clay mineral cement	Trough cross-beds- low to medium bioturbation	Medium bedded(~20cm), light green and limonitic in color,lower contact is gradational and upper is sharp,thinning upward, ripple mark at surface	High energy-shoreface	
Very thin bed sandstone/ shales (F15)	Very fine to fine grains- poor to moderatly sorted- submature to subarkose-	Mica moscuvite- chlorite Silice and clay (chlorite, sericite) cement	Massive to flint cross-lamination- High bioturbation	Thin to medium bedded (10-20 cm), interbedded with shale	Low energy- offshre	Upper offshore

Table. IV.5 (Previous page): Facies table of the Faraghan Formation. It consists of 15 facies and sub-facies deposited in 8 main depositional environments corresponding to (1) Coastal plain; (2) Bay- head delta and alluvial plain; (3) Estuarine low energy central basin; (4) Wave dominated estuary; (5) tidal flat and flood tide delta; (6) Lagoon; (7) shoreface; and (8) Uper offshore environments.

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Coastal plain environment:

It is subdivided to two facies (F1 and F2) (Table.IV.5) and only obsereved in Kuh e Gahkum. These facies correspond to coastal-plain depositional environment (Bluck, 1976; Rasmussen, 2000). The coastal plain deposits are represented mainly by red- and green-colored conglomerates of alluvial plain (Rasmussen, 2000) and pebbely-sandstones and shales of flood plain (Rasmussen, 2000) (Fig. IV.34B & 36B). Facies F1 and F2 (Table.IV.5) characterized by multiple channelized conglomerates. Conglomerates are amalgamated with wedge-shaped pebbely sandstones and shales. Its basal contacts are channelized while the upper contacts are gradational.

The geometry and erosional bases suggest deposition within fluvial channels. Textral charcteristics of the channel-fill suggest rapid deposition from highly concentrated flows. This interpretation is based on the disordered fabric with no clast imbrication, and the lack of sedimentary structures. The small size of the channel bodies and the sharp upper boundary marking a change into normal flood plain deposits suggest relatively short-lived channels (Bluck, 1976).

Estuarine bay head delta and alluvial plain:

This depositional environment obsereved in Kuh e surmeh and is determined by the presence of F3 and F4 facies observed at the top and by F5 to F6 at the base of the Faraghan succession. The red and green shales (F3) may be considered as inter-distribuary bay or prodelta as proposed by Reading (1996); the poor outcrop preservation makes difficult the interpretation. Structureless and unbioturbated mud-dominated facies are considered to be deposited rapidly by fluid enriched in muds (Dalrymple and Choi, 2007). Small-scale trough cross-bedded sandstones characterize F4 facies. The unidirectional nature of ripple cross laminations of Facies F4 suggests a current-dominated environment. The coarsening upward pattern are suggestive of a deltaic progradation. Facies F5 is organized in a pebbly sandstones with subangular to rounded pebbles (5-10 mm) of white quartz either randomly scattered throughout the bed or organized in discontinuous cm- thick layers embedded in a coarse micro-conglomerate matrix (50%). It overlies a 10° angular unconformity bounding the Seyahou and Faraghan Formations. F5 is interpreted as a transgressive lag at base of a river-dominated zone with a bedload transport in an alluvial domain. F6 is composed of gravel to sandy fining upward successions frequently reworked by waves (ripples and unidirectional laminations) and tides (presence of local flaser structures and symmetric ripples). This facies corresponds to a bay-head delta depositional environment (Dalrymple et al., 1992; Reading, 1996; Li et al., 2006). The bay head delta is formed almost exclusively of river-derived sediment, deposited at the point where the river currents decelerate and lose energy.

Estuarine low-energy central basin:

F7 is heterolithic facies with a high clay and mud contents. It corresponds to the fine-grained sediments with a symmetrical grain-size trend deposited in the central part of the estuarine system. Basal scoured surface overlain by conglomeratic lags and the overall fining upward trend of the sandstones package in F5 and F6 indicate channel scouring and filling (Bridge, 2006; Pontén and Plink-Björklund, 2007). The bioturbation, the channelized sandstones with trough-cross laminations, flaser beddings and discontinuous/continuous mud draps argue for an increase in tide influence (Dalrymple and Choi, 2007). The low diversity of ichnofossil assemblages indicates a mobile substrate consistent with a brackish depositional setting (Pemberton et al., 2001). Where trace fossils are limited to Planolites and vertical burrows, a non-marine setting cannot be excluded (e.g. Pemberton et al., 2001).

Estuarine mouth sand barrier:

The lenticular small-scale trough cross-bedded sandstones (F8) are 0,5 to 0,7 m thick. It is obsereved in Kuh e Surmeh and is composed of fine to medium grain, bidirectional though cross-bedding, are interrupted by finer centimetre shales (drapes?) layers and exhibit planar laminations locally reworked on top by wave-ripples. The sandstones are considered as the mouth bar system of the estuarine domain. The low angle cross-beddings, the planar cross-beddings and ripple-marks probably record successive progradational events of a sandy mouth bar (Rasmussen, 2000). Later reworking by waves, wave-induced-currents and bioturbation completely or partially obliterated original structures and suggest shallow marine setting (MacEarchen and Bann, 2008).

Tidal flat and flood tide delta environments:

This depositional environment is composed of two main facies of F7, F9 and F10. None of the bedding types are restricted to tidal flats only, but the presence of fine-grained usually mud (silt and clay) sediments and small-size channelized sandstones are frequently observed (Reineck and Singh, 1980). The ten-metre thick homogeneous mud-dominated accumulation observed in the middle part of the Kuh-e Surmeh area is interpreted as mud flats where thick mud layers deposited with thin sandy intercalations. The sandstones (F9) correspond to gullies or channels with bipolar tidal currents and bidirectional cross-bedded stratifications. Sandstones F10 mainly obsereved in Kuh e Gahkum and characterized by bidirectional low-angle cross beds sandstones.

Considering the erosive nature of basal contact, the unidirectional flow, the predominance of fining upward trends and the overall abundance of heterolithic facies with marine traces, this depositional environment observed at the base of the Faraghan Formation is considered as a wave-dominated estuarine system (Dalrymple et al., 1992; Dalrymple and Choi, 2007). Upward, it records a transition from wave-dominate estuary to delta. The wave-dominated estuary is arranged in tripartite facies zonation consisting of a bay-head delta and alluvial plain at the head, a low-energy central basin and a coast-parallel barrier. The evolution of the wave estuary is characterized by a seaward progradation of the bay-head delta and a landward expansion of the flood-tide delta, infilling the central basin (Nichol et al., 1997). The infilling of the central basin is also indicated by the progradation of the alluvial plain over intertidal and flood tide delta (tidal flat area; Lessa and Masselink, 1995). The system evolves to a delta but in the absence of detail information on channel morphologies, determining the point at which an estuary becomes a delta is not straightforward (Heap et al., 2004). Given sufficient time and under conditions of stable sea level and continuous sediment supply, all estuaries have the potential to infill their paleo-valleys and evolve to delta (Dalrymple et al., 1992).

Lagoon environment :

Facie association F11 characterized by 16 m thick of microbial stromatolites (Fig. IV.34). In both lower and upper boundaries, it limited between two coastal-plain deposits of facies F1.

Microbial communities on tidal flats produce flat mats, or ones with tufted, crinkled or pustular surface morphology (Kinsman and Park, 1976). Under suitable condition microbial mats can form domal structures or stromatolites; those with relief of more than a few centimetres generally appear to have formed in lower intertidal to shallow subtidal areas (Davies, 1970; Tucker and Wright, 1990). The lack of exposure horizons or dessication features suggests that the stromatolite was growing in shallow and subtidal restricted lagoon conditions (Rodríguez-Martínez et al., 2012). Lamination is a distinctive feature in intertidal deposits and reflects alternation of sediment input and microbial activity (Reading, 1996).

Shoreface environment:

Shorface environment is composed of three facies (F12, F13 and F14) (Table. IV.5) corresponding to cross-lamination sandstones (Fig. IV.33E) and sandy dolomite (Fig. IV.35F) respectively.

This facies association constitutes only about 15-20% of the studied succession. The low degree of bioturbation suggesting a high-energy depositional environment (Aigner & Reineck, 1982). The planar cross- lamination (F13) and trough cross-lamination (F14) sandstones indicate deposition above the fair-weather wave base in the high energy shoreface environment (Reading, 1996). This facies scheme follows the convention of Elliott (1986) and Walker and Plint (1992), in which shoreface facies associations are related to sedimentary structures generated by storm and fair-weather wave processes.

Upper offshore environment:

Facies association F15 (Table. IV.5) is identified by very thin bed bioturbated sandstones alternating with shales intervals (Fig. IV.33J).

The presence of facies sediments of shoreface environments at top of this facies indicates facies F15 deposits in an Upper offshore environment below the mean fair-weather wave base. Based on bioturbation and predominantly fine-grained deposits with interbedded very thin, sharp-based sandstones indicate a calm depositional condition, in an open marine upper offshore environment (Kreisa, 1981).

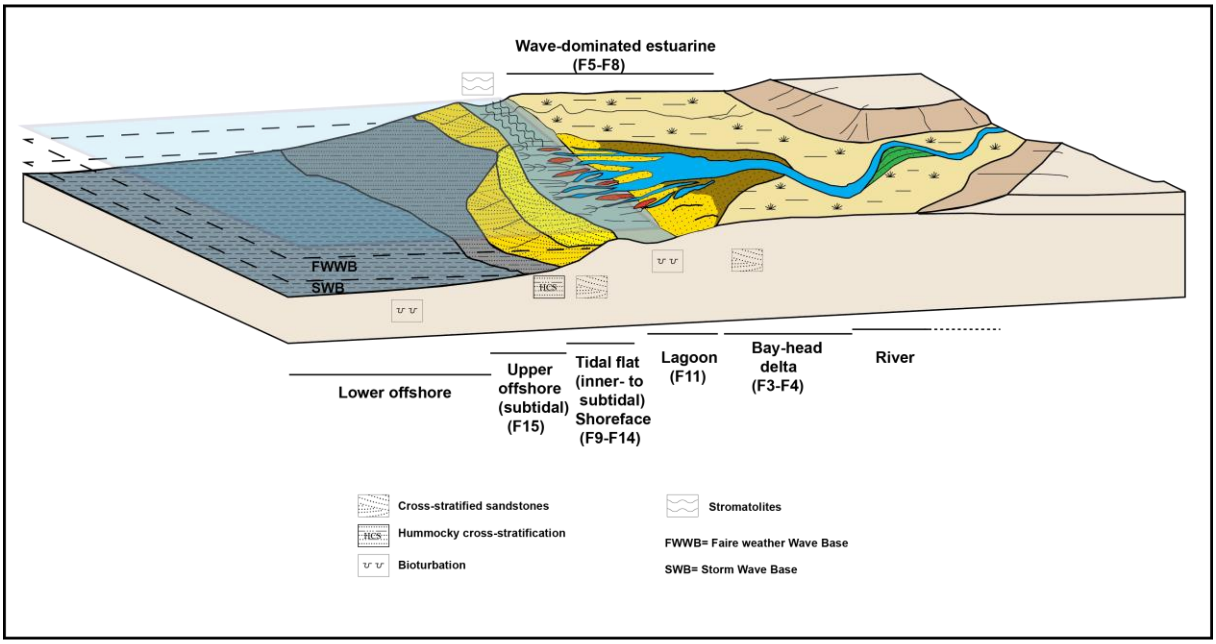

Fig. IV.32: Schematic depositional profile for the Faraghan Formation showing continental to marine environments evolving from Coastal plain, Bay- head delta and alluvial plain to Wave dominated estuary to tidal flat and flood tide delta; and Lagoon to shoreface and Uper offshore environments. *For the facies color codes see table IV.5.*

IV.5.3. Sequence Stratigraphy

Four unconformities and disconformities have been recognized. These correlable surfaces define three 3rd-order depositinal sequences, each consisting of transgressive and high stand systems tracts (TST and HST respectively) (Fig. IV.31). Depositional sequences are compelete in Kuh e Faraghan in Bandar Abbas area.

<u>Sequence I- DS I:</u>

DS PI comprises the lower part of the Faraghan Formation in the area. SB P0 is an unconformity surface characterized between Zakeen Formation (corresponds to the area) and coastal plain deposits of the Faraghan Formation (Fig. IV. 33B & 34B). In Kuh e Surmeh and Kuh e Siah, this sequence boundary (SB P0) is an ungular unconformity topping the Seyahou Formation (Fig. IV.30).

The lower part of the TST consists of conglomerates of the coastal plain environment (F1 and F2) (Fig. IV. 33B & 34B). It grades into sandy tidal flat (F9-F10) (Fig. IV.33J). In Kuh e Gahkum, facies are dominated by stromatolites corresponding to lagoon environment (F11)

(Fig. IV.34D). Toward the Fars area in Kuh e Surmeh, the SB P0 is overlain by a thin transgressive conglomerate (facies F5), which evolves to a fining upward bay-head (facies F4), system in a wave estuarine domain and passes to central part of the estuarine system (facies F7) (Fig. IV.30).

In Kuh e Faraghan, the maximum flooding surface (MFS) corresponds to deeper environment characterized by bioturbated shales deposited in an upper offshore environment (F7) (Fig. IV.33J). whereas in Kuh e Surmeh, it is located in sentral part of estuarine (facies F7).

The HST is characterized by high-energy shoreface facies association (F13-F14) (Fig. IV.33I). The thickness of the HST increases toward the Kuh e Gahkum area with high carbonate content. In Kuh e Surmeh, The sequence ended with the progradation of the estuarine mouth sand bar system (facies F8).

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Fig. IV.33 (Next page): (A) Sequences and sedimentary structures of DS PI for the Faraghan Formation exposed in Kuh e Faraghan; (B) Boundary between Devonian Zakeen and Early Permian Faraghan Formations; (C) Thin bed horizontal lamination sandstones in sandy tidal flat environment; (D, G) Channelized horizontal lamination sandstones in sandy tidal flat environment; (E) Bidirectional structures channelized sandstones sandy tidal flat environment topped facies F10; (F) View of bidirectional sandstones in sandy tidal flat environment (H) Bioturbated sandstones in uppermost part of TST in DS PI in sandy tidal flat environment; (I) White channelized sandstones of shorface environment; (J) Shally deposits in upper offshore environment.


A
S
N
SB P1
Faraghan Fm.
SB P0
DS PI (34m)
Zakeen Fm.
5 m
B
Faraghan Fm.
SB P0
Zakeen Fm.
1 m
C
Facies F10
50 cm
D
20 cm
E
Facies F9
50 cm
F
Facies F9
30 cm
G
10 cm
H
17m Fr.
10 cm
I
Facies F13-F14
20 cm
J
Facies F15
1 m

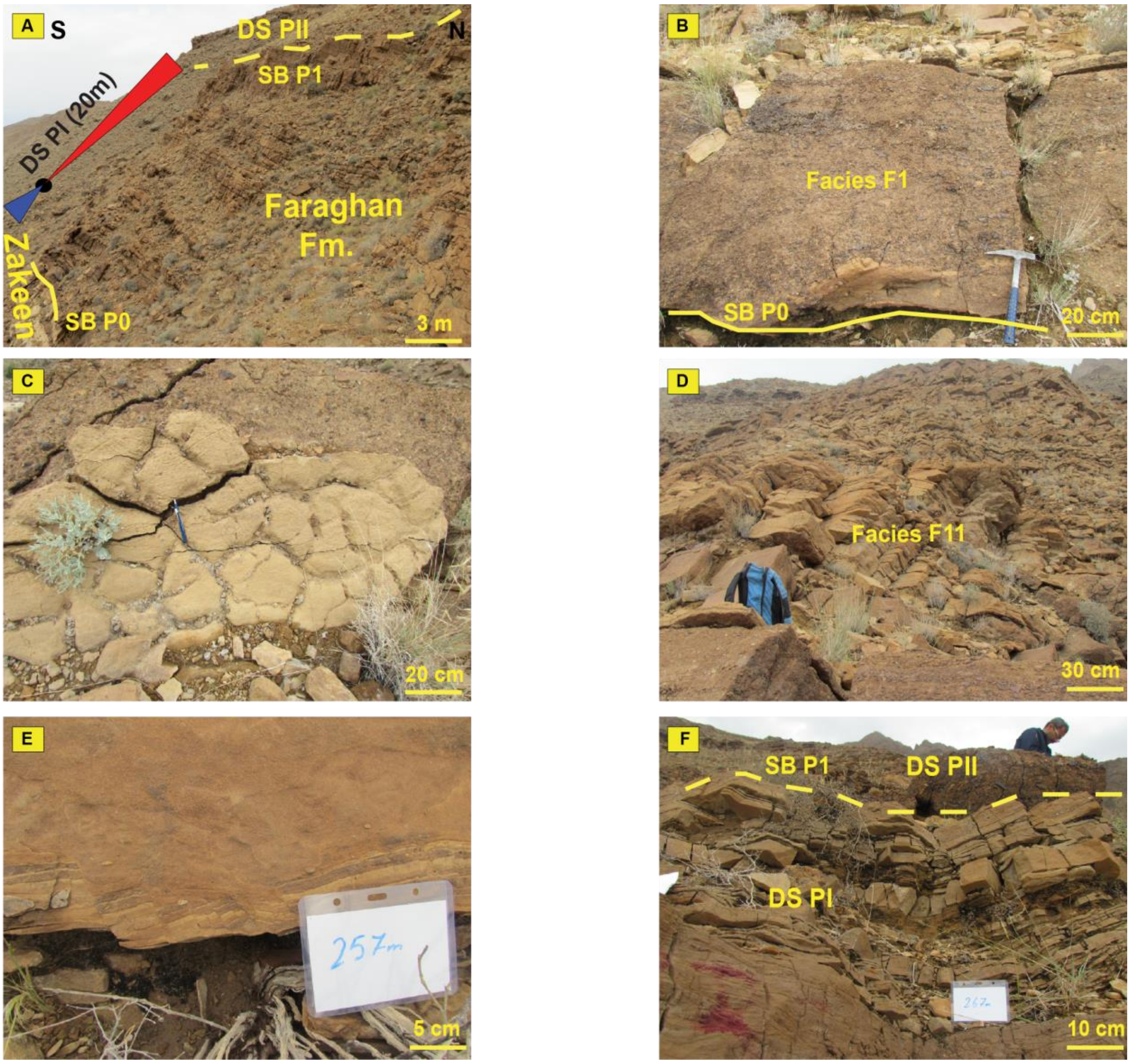

Fig. IV.34: (A) Sequences and sedimentary structures of DS PI for the Faraghan Formation exposed in Kuh e Gahkum; (B) Sequence boundary SB P0 at base of Faraghan Formation; (C) Mud cracks at top of alluvial conglomerate; (D) Stromatolithic beds in lagoon environment (F5); (E) Syn-tectonic sedimentary structure; (F) Sequence boundary SB P1 at top of DS PI shows coastal plain deposits (facies F1) capped the stromatolites of the facies F5.

Sequence II- DS II:

Sequence PII is bounded by SB P1 at base and SB P2 at top (Fig. IV.35A). SB P1 is an unconformity corresponds to change from cross bed sandstones of shoreface (F13-F14) to upper offshore environments (Fig. IV.35B). In Kuh e Gahkum is marked by erosional surface that shows basal contact of the conglomerates belong to coastal plain environment (F1) (Fig. IV.36B). In Kuh e Surmeh, it represented by change in depositional environment from wave-dominated estuarine to flood-tided delta. The capping sequence boundary (SB P2) is described in the next section below.

The TST is characterized by bioturbated shales and sandstones deposited in an upper offshore environment (F15). Toward north, in shallower part Kuh e Gahkum, after the sea level that produced unconformity surface (SB P2) was considerable and TST is in order of fluvial incision of coastal plain environments (F1-F2) (Fig. IV.36B) into tidal flat facies association (F9-F10). The transgressive trend (TST) of DS P2 in Kuh e Surmeh is characterized by an aggradation and finning upward of tide-dominated facies (F9).

Depending of the area, bioturbated shales deposited in upper offshore (F15) and tidal flat (F9-F10) characterized the maximum flooding surface (MFS).

The HST consists of cross bed sandstones in high-energy regime shorface (F12 to F14) indicating a shallowing-upward trend toward the end of HST (Fig. IV.35D). In contrast, in Kuh e Gahkum section, the HST characterized by tidal sandy flat (F9) (Fig. IV.36C). It shows the DS PII in this area, is a retrogradational sequence. In Kuh e Surmeh, (Fig. IV.30I) the HST evolves vertically from flood-tide delta to a progradation of the bay-head delta and alluvial plain.

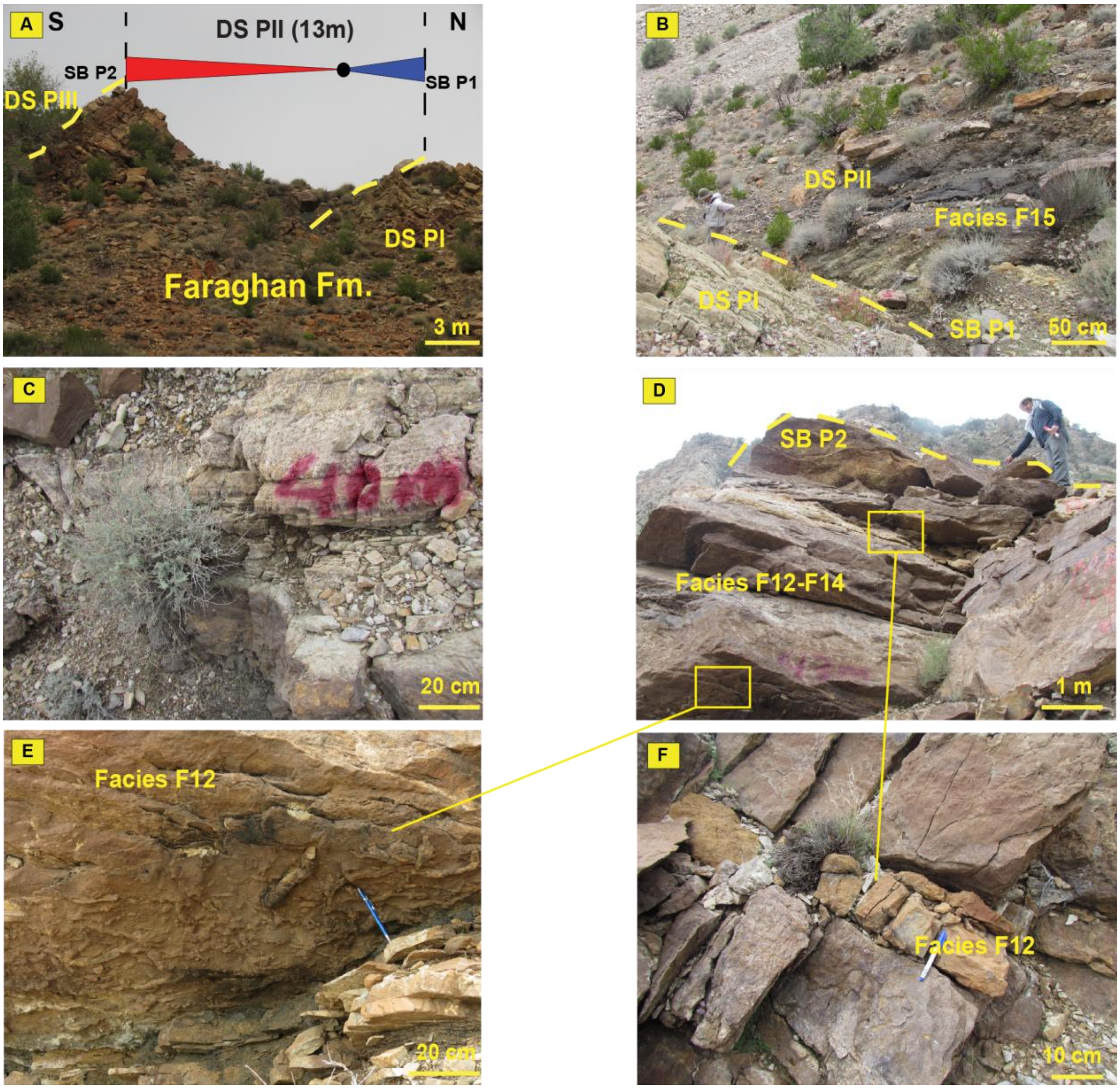

Fig. IV.35: (A) Sequences and sedimentary structures of DS PII for the Faraghan Formation exposed in Kuh e Faraghan; (B) Shally part in upper offshore environment ; (C) Bioturbated sandstones in upper offshore environment; (D) Shoreface sandstones showing HST of sequence PII ; (E) Load cast in the lower surface of shoreface sandstones; (F) Dolomitized sandstones in shoreface environment.

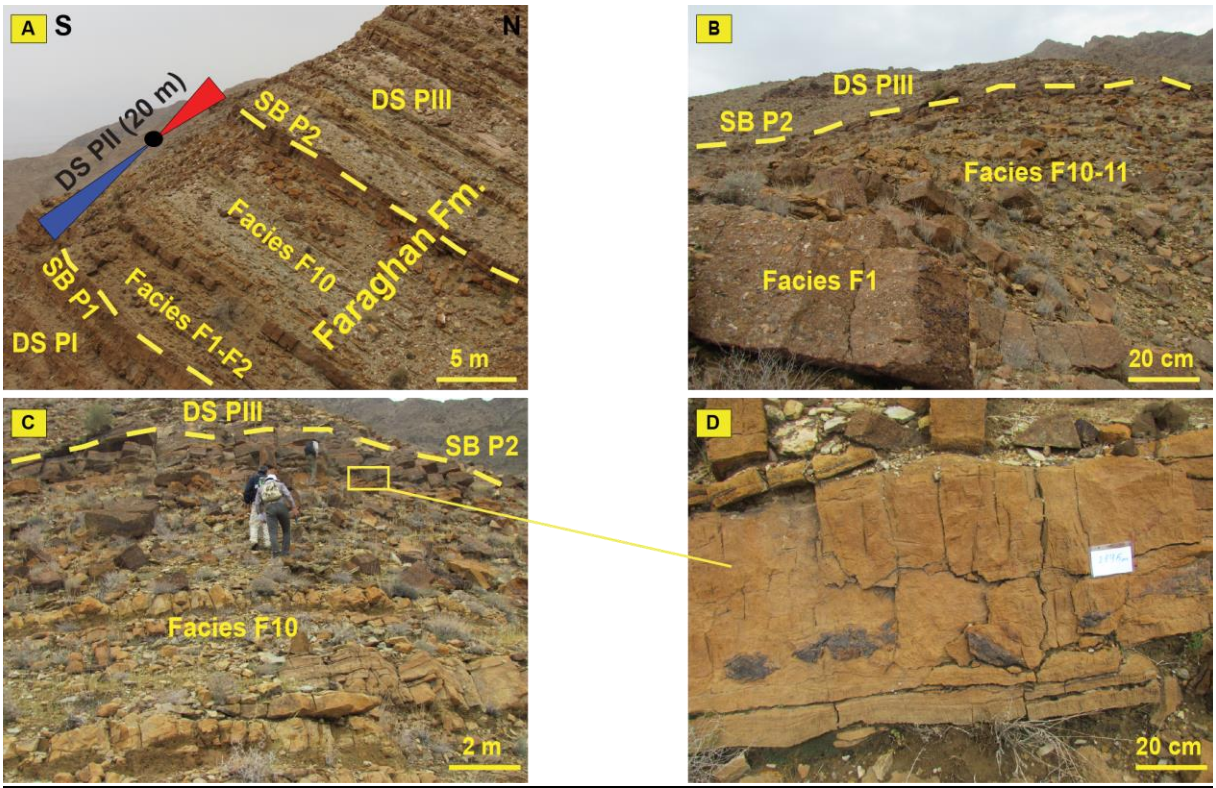

Fig. IV.36: (A) Sequences and sedimentary structures of the DS PII for the Faraghan Formation exposed in Kuh e Gahkum; (B) Coastal plain conglomerates at base of Sequence PII; (C) Low angle cross bedding sandstones in sandy tidal flat environment; (D) Bidiectional lamination dolomitized sandstones in sandy tidal flat environment.

Sequence III:

This sequence is limited by SB P2 and topped by SB P3 (Fig. IV.37A). The SB P2 is marked by a transgression of upper offshore deposits (F15) (Fig. IV.37B) onto cross-bed sandstones of shoreface (F12 to F14) belonging to DS PII (Fig. IV.37C). At Kuh e Gahkum, the first sediments above SB P2 corresponded to coastal plain environments (F1- F2) (Fig. IV.38B). In the Fars area, at Kuh e Surmeh, SB P2 is marked by a major transgressive surface characterized by open marine fossiliferrous limestones of the Dalan Formation (Fig. IV.37E), where the DS PIII in not deposited.

TST is identifieded by bioturbated shale and sandstones of the upper offshore environment (F15). In Kuh e Gahkum, the coastal plain environments (F1-F2) deposits and continuing with tidal flat facies association (F9-F10).

Depending of the area, bioturbated shales deposited in upper offshore (F15) and tidal flat (F10) characterized the maximum flooding surface (MFS).

Highstand deposits are characterized by cross-bed sandstones in shoreface environment (F12 to F14) (Fig. IV.37C).

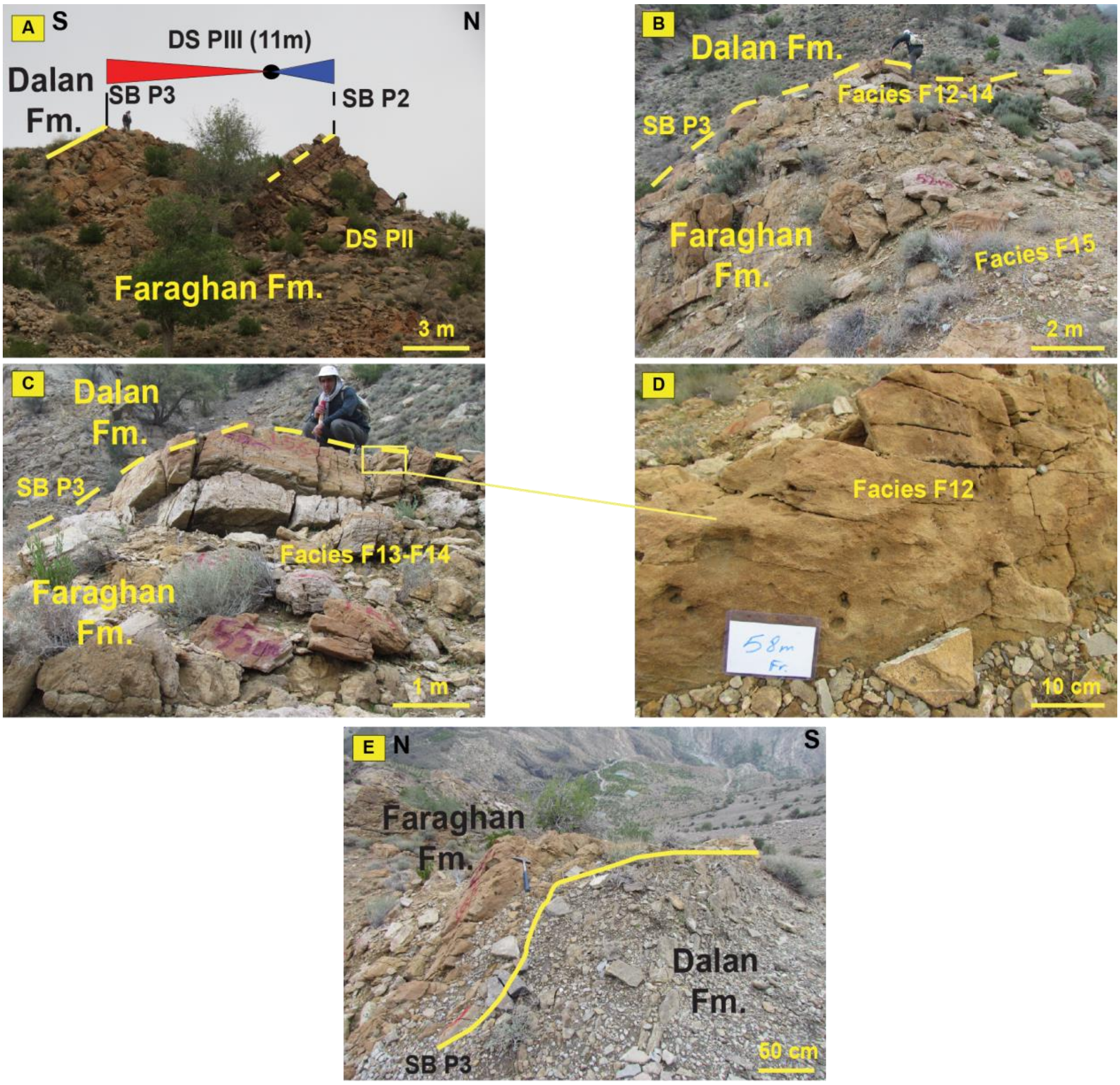

Fig. IV.37: (A) Sequences and sedimentary structures of DS PIII for the Faraghan Formation exposed in Kuh e Faraghan; (B) Shale of upper offshore environment change upgrade to shoreface environment; (C) HST in upper part of DS PIII in shoreface environment; (D) Bioturbated sandstones at the uppermost part of Faraghan Formation observed in shoreface environment; (E) Boundary between Early Permian Faraghan Formation and Middle to Late Permian Dalan Formation.

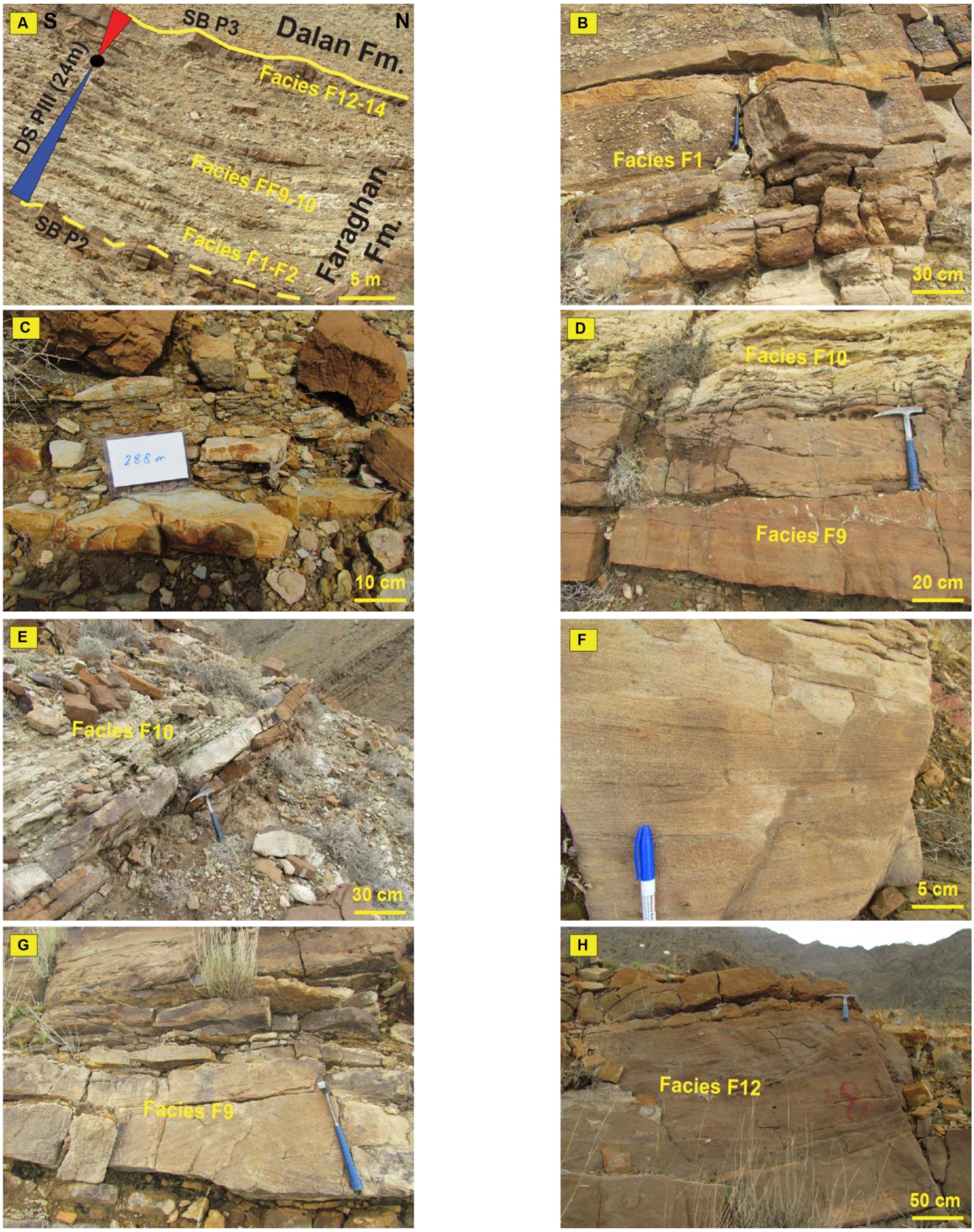

Fig. IV.38: (A) Sequences and sedimentary structures of DS PIII for the Faraghan Formation exposed in Kuh e Gahkum; (B) Coastal plain conglomerates at base of DS PII; (C) Ripple mark in central part of estuary; (D) Bidrectional lamination dolomitized sandstones intercalation with low-angle cross lamination sandstones in sandy tidal flat environment; (E) Low-angle cross lamination sandstones in sandy tidal flat environment; (F) Horizontal lamination sandstones in sandy tidal flat environment; (G) Bidrectional lamination sandstones in shoreface environment; (H) Bidrectional lamination dolomitized sandstones in shoreface environment.

CHAPTER V:

DISCUSSION

The aims of this study were to identify:

(i) The main facies evolution of the palaeozoic to discuss the depositional environments and propose new paleogeographical maps of the Palaeozoic succession.

(ii) The hiatuses observed all along the Palaeozoic succession and the controlling factors on their development.

The first part of this chapter deals with regional scale main depositional environments and sequence stratigraphy. The second part introduces the major unconformities and erosional surfaces and discusses the main controlling factors at their origin.

V.1. Depositional environments and sequence stratigraphy

The depositional environments evolution and the correlation of sequences across the Zagros area allow dividing the Palaeozoic succession in five cycles. They are bounded by regional erosional surfaces and unconformities and are organized in transgressive-regressive cycles (Fig. V.1).

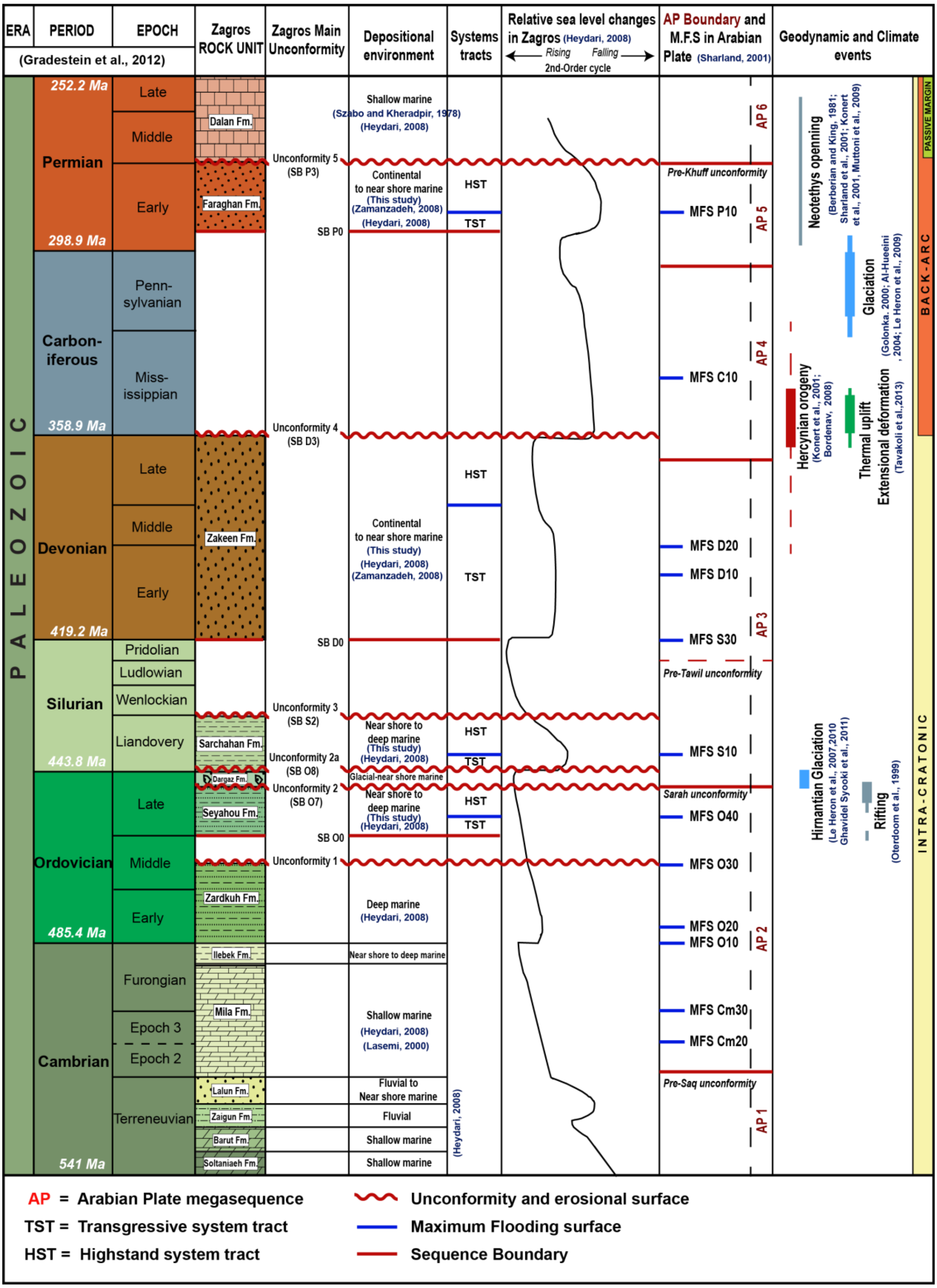

Fig. V.1: The cycles, major unconformities, geodynamic events, depositional environments, depositional sequences and the relative sea-level change of the 2nd-order sequence in the Zagros area correlated with Arabian Plate megasequences of Sharland et al. (2001).

V.1.1. Cycle 1: Cambrian

Definition

This cycle corresponds to the Cambrian deposits and lasts some 40 million years. It rests on a Late Precambrian-Early Cambrian Hormuz salt (Berberian and King, 1988; Motiei, 2003) and covered by Early-Middle? Ordovician (Ghavidel Syooki, 1996) Zard Kuh Formation. Cycle 1 consists Early Cambrian Soltanieh, Barut, Zaigun, Lalun (Hamdi, 1989) and Middle-Late Cambrian Mila (Setudehnia, 1975; Ghavidel Syooki, 1990a,b) Formations.

Main depositional environment and sequence stratigraphic framework

This cycle is characterized by deepening-upward siliciclastics and mixed carbonates succession. It evolves vertically from a thick dolomitic unit of Barut Formation at the base to carbonate package of Mila Formation followed by sandstones and shales of Ilebek Formation at top.

Barut Formation: stromatolitic crystalline dolomite and shales. It corresponds to shallow marine depositional environment (Motiei, 2003; Heydari, 2008).

Zaigun Formation: thick units of thickening-upward red shales and sandstones. It corresponds to shallow marine depositional environment following Setudehnia (1975); Berberian and King (1981); and Heydari (2008) and to fluvial depositional environment following Alavi (2004) and Konert et al. (2011) interpretations.

Lalun Formation: cross-bedded red sandstones are widespread in west High Zagros (Kuh e Dena, Kuh e Garreh and Ushtoran Kuh) except for the Zard Kuh. It corresponds to shallow marine depositional environment following Setudehnia (1975); Berberian and King (1981); and Heydari (2008) and to fluvial depositional environment following Alavi (2004) and Konert (2011) interpretations. However the presence of Cruziana trace fossils (Setudehnia, 1975), Redlichia trilobites (Wolfart, 1983) and correlations established with other part of Iran (Hamdi, 1989), suggest a near-shore depositional environment.

Mila Formation: thick units of carbonate and shales with some salt pseudomorphs in the middle part. It rest as a possibly unconformably (Setudehnia, 1975). The Middle to late Cambrian Mila Formation (Setudehnia, 1975; Berberian and King, 1981; Ghavidel Syooki, 1990a,b; Motiei, 2003) is exposed along the southwest flanks of several thrust-faulted structures between Zard Kuh and Kuh e Dena, along the High Zagros thrust in Ushtoran Kuh, Zard Kuh, Chal i Sheh, Kuh e Garreh (Fig. I.2), Kuh e Dena, Kuh e Lajin and Kuh e Sabzu (Setudehnia, 1975) (Fig. III.8). It represents the first marine deposition phase of carbonate deposits (Setudehnia, 1975; Berberian and King, 1981; Motiei, 2003, Heydari, 2008, Konert et al., 2011). Lasemi (2000) informed that Mila Formation deposited in shallow marine to open marine platforms evolving from tidal flat and lagoon to barrier Island and deep marine depositional environments.

Ilebek Formation: Sandstones and trilobite-bearing shales intercalation with rare brachiopod-bearing limestones. It preserved in Chal I Sheh, Zard Kuh surface section and Darang and

Zirreh subsurface sections. Ilebek Formation corresponds to near-shore marine deposits (Setudehnia, 1975; Ghavidel Syooki, 1990a,b) and fluvial to near-shore marine deposits (Heydari, 2008).

In term of sequential framework, Lasemi (2000) focused on Mila Fm. and identified three 3rd-order depositional sequences for Mila Fm. He proposed a second order sequence with tidal flat and near-shore carbonate deposits at lower part related to sea-level falling. This sediments grade up to marginal platform deposits indicates TST and HST.

Palaeogeographical reconstitution of the Zagros area

During the Cambrian time, the Zagros area was located at 5°–20° S latitude (Fig. I.3) (Heydari, 2008). The first deposition is the syn-rift Hormuz salt (Berberian and King, 1981; Al-Husseini, 1989; Beydoun, 1991; Talbot and Alavi, 1996, Alavi, 2004; Heydari, 2008; Jahani, 2009) and its equivalent (Soltanieh) (Motiei, 2003) was deposited in latest Precambrian-Early Cambrian. The first sediments accumulated in an extensional pull-apart setting related to the late Precambrian–Early Cambrian Najd strike-slip fault system (Al-Husseini, 1989) that affected the Zagros as a northeastern part of the Gondwanan (Al-Husseini, 1989; Talbot and Alavi, 1996, Alavi, 2004). Hormuz salt acted as an important detachment horizon during structural evolution of the Zagros fold-thrust belt, and have complicated the structural pattern of the region by forming numerous complex salt diapirs (Talbot and Alavi, 1996).

The Early Cambrian Soltanieh and Barut Formations resulted from a relative sea-level rise (Heydari, 2008). These deposits are topped by the post-rift Zaigun and Lalun Formations (Berberian and King, 1981). In detailed, according to the sea-level model proposed by Heydari (2008) (Fig. V.1), the fluvial deposition of the Zaigun Formation is the result of a relative sea-level fall and the near-shore marine deposits of the Lalun Formation correspond to a relative sea-level rise. By the beginning of the Late Cambrian, a fully marine environment with the deposition of fossiliferous limestones prevailed. This rising of sea-level in Late Cambrian, ended by minor sea-level fall at base of Ordovician which marked onset of second cycle proposed by Heydari (2008).

Regional comparisons

According to Sequence stratigraphic model of Sharland et al. (2001), Hormuz salt located at upper part of AP1, and form a TST of the third sequence inside of this megasequence. Following this extensional phase, massive post-rift continental clastics of late Early Cambrian age were deposited over most of the Arabian plate in the south to the Alborz Mountains in the north (Berberian and King, 1981; Konert et al., 2001, Sharland et al., 2001). These were sourced from interior Gondwana to the south and west (Konert et al., 2001). In northern Arabia, after the increasing of the clastic sediments in the Late Cambrian (e.g. Saq Formation in Saudi Arabia; Mahata Group in Oman), a prograding clastic system was deposited conformably over the Middle Cambrian carbonates. Whereas, in interior Iran and Zagros area, carbonate deposition persisted into the Late Cambrian (Berberian and King, 1981, Al-Husseini, 1990; Sengor, 1991; McGillivray and Al-Husscini, 1992; Loosveld et al., 1996; Konert et al., 2001, Sharland et al., 2001; Heydari, 2008). These carbonates follow by siliciclastics sediments at uppermost Cambrian (Ghavidel and Vecoli, 2008).

The Formation observed in Iran in Alborz mountains in north (Stocklin, 1969; Motiei, 2003) are determined as Middle to Late Cambrian and may be compared with the TST of the first sequence of AP2 introduced for the whole Arabian plate by Sharland et al. (2001). The transgression culminated over the northern Arabia by the Middle Cambrian Burj Formation (MFS) in Jordan and Syria. This is equivalent with Koruk Formation in Turkey (Konert et al., 2001) and corresponds to the Mila Fm. in Zagros (this study).

V.1.2. Cycle 2: Ordovician

Defenition

Cycle 2 lasts some 42 million years and corresponds to Ordovician deposits. It rests on Late Cambrian Ilebek Formation and is topped by Early Silurian Sarchahan Formation. In most parts of Zagros, the upper boundary marks an unconformity 2a ("Hirnantian hiatus") at top of the Seyahou Fm. whereas in Kuh e Faraghan, it covers the top of Hirnantian glaciar deposits of the Dargaz Fm. (Ghavidel Syooki et al., 2011) and corresponds to a second unconformity, named 2b. Cycle 2 consists Zard Kuh (Tremadocian-Dapingian? (Ghavidel Syooki and Vecoli, 2008; Ghavidel Syooki et al., 2014), Seyahou (Floian to Katian) (Ghavidel Syooki et al., 2011) and Dargaz (Hirnantian) (Ghavidel Syooki et al., 2011) Formations.

Main depositional environment and sequence stratigraphic framework

This cycle is characterized by coarsening-upward siliciclastics succession. In complete succession, it evolves vertically from conglomerates, sandstones of the Zard Kuh Formation, to the sandstones and shales of the Seyahou Fm. and ended with the coarse clastic deposits of Dargaz Formation.

Zard Kuh Formation: a thick unit of trilobite-bearing and/or brachiopod-bearing, partly graptolitic micaceous shales and thin-bedded sandstones locally rich in volcanic clasts (Alavi, 2004). It presents intercalations of polymict conglomerates in the southeast Fars province (Alavi, 2004). Zard Kuh Formation is cropping out in Kuh e Faraghan (Ghavidel Syooki et al., 2014), in Kuh e Zard Kuh surface section and in Darang, Kabir Kuh and Zirreh wells. It corresponds to deep-marine deposits (Setudehnia, 1975; Heydari, 2008). Recently, the upper part of the Zard Kuh Fm. have been described in Kuh e Faraghan (Ghavidel Syooki et al., 2014). There, it consists of conglomerates, sandstones corresponding to continental (?) to near-shore depositional environments. In this study, a near-shore marine depositional environment has been proposed for Zard Kuh Formation (see chapter IV for detailed).

Seyahou Formation: a thick 721 m package of sandstones and shales intercalation with some brachiopod-bearing limestones. It has been observed in Kuh e Faraghan and Kuh e Surmeh surface sections and in Zirreh, Kabir Kuh, Kuh e Siah, Darang subsurface wells. Seyahou Fm. is interpreted as evolving from offshore environments under storm-induced conditions to tidalites and shoreface environments and is capped by a glaciogenic Hirnantian succession (Ghavidel Syooki et al., 2014). In this study,when the Seyahou Formation preserved, it is interpreted as shallowing-upward shallow to deep marine platform that evolve through time from shoreface to offshore and shoreface environments (from O1 to O8) (Table IV.1, and see chapter IV for detail study.

Dargaz Formation: a unit of diamictites, shales and sandstones. In the Zagros area, it is only preserved in Kuh e Faraghan. It was introduced for the first time by Ghavidel Syooki et al. (2011) and characterized as glaciogenic deposits.

A first attempt of sequence stratigraphy modeling is proposed by Ghavidel Syooki et al. (2014) for the lower part of the Ordovician deposits and the Dragaz Fm. (Ghavidel Syooki et al. (2011). They considered, the Zard Kuh Formation as a TST of a transgressive-regressive trend in 3rd-order sequence, following by Seyahou Formation. They proposed three transgressive-regressive cycles for Dargaz Fm. and overlying Early Silurian Sarchahan Formations including GES1, GES2, and GES3. The first cycle marked by glaciogenic scouring into a pre-glacial Seyahou Formation and deposition of transgressive glaciomarine diacmictites. Second cycle is characterized by progradation/retrogradation (or advance/retreat) of an ice front, with recording of shoal complex/glaciomarine diamictite unit. The last and third cycle is the same of cycle two, although its lower part is dominated by coastal plain deposits that were succeeded by a final deglaciation, which led to the definitive flooding of the platform and the record of the kerogenous Sarchahan black shales.

In this study, considering the hiatus individualized by Ghavidel Syooki et al. (2014) in the lower unit of the Seyahou Fm., seven medium-scale shallowing-upward sequences (DS OI to DS OVII) have been proposed (Fig. V.2). DS OI and DS OII correspond to the sequence described by Ghavidel Syooki et al. (2014). In Kuh e Surmeh a small unit (36m) of the Seyahou Formation is observed and consists of three sequences, the latter being eroded. Regarding their depositional environments, strtaigraphical position and facies evolution, they may be compared with DS OIII, DS OIV and DS OV in Kuh e Faraghan (Fig. V.2). The upper shallowing-upward trend of the Seyahou Formation (DS OVII) is follow by one sequence (DS OVIII) subdivided to two small sequences (Seq. DzI and Seq. DzII) corresponding to the glaciogenic Hirnantian Dargaz Fm. (Fig. V.2). These two transgressive/regressive small sequences are topped by Glacial Erosional Surface (GES) of the Hirnantian ice sheet in Kuh e Faraghan. Sequence DzI shows a shalowing-upward trend from diamictite (Dz1a) to offshore (Dz5), shoreface and foreshore (Dz3) environments. Sequence DzII rests on GES 2 and is characterized by shallowing-upward trend from diamictite (DZ1b) to offshore (DZ5), shoreface (D4) and lagoonal (DZ2) environments. Presence of GES at base of each sequence represent erosive unconformity and the diamictites at base of sequence are controlled by advance or retreate of ice sheet (Le Heron et al., 2009).

Palaeogeographical reconstitution of the Zagros area

The Zagros region was located around 30°-35° S latitude and drifted to 40° S by the end of the Ordovician time (Cocks and Torsvik, 2002; Heydari, 2008). The Ordovician is a period of stability in a passive margin setting, which lasted until the Permian Period (Golonka, 2000). After the deposition of the shallow-marine carbonate of Late Cambrian Mila and siliciclastics of Ilebek Formation, a major relative sea level rise is recorded and sediments graded into mostly deep marine environments of Early-Middle Ordovician (Tremadocian-Dapingian?) Zard Kuh Formation (Heydari, 2008) (Fig. V.1). The Seyahou Formation (Floian- Katian) corresponds to a gently dipping, wide and stable marine shelf bordering the Paleo-Tethys Ocean. The shelf was subsiding toward the Bandar Abbas area to provide accommodation space and it corresponds to a depocenter for a huge siliciclastics succession (Fig. V.2). In uppermost Ordovician, a major sea level fall resulting from Hirnantian glaciation event took place (Bell et al., 2007; Ghavidel Syooki et al., 2011). Toward in northwest of Zagros, in the west High Zagros area, no Late Ordovician deposits have been preserved. In this area, the Early Permian deposits rest directly on the Cambrian Mila Formation (i.e. Kuh e Dena) and Early-Middle Ordovician Zard Kuh Formation (i.e. Zard Kuh; Setudehnia, 1975; Ghavidel Syooki, 1996) (Fig. III.12). In this area, the hiatus spent from Early Ordovician to Early Permian (ie. Kuh e Dena) (Setudehnia, 1975) and Middle Ordovician to Early Permian (i.e. Zard Kuh) (Ghavidel Syooki and Vecoli, 2008).

Regional comparisons

When, in the Zagros area, Zard Kuh Formation is characterized mostly by deep-marine deposits, it corresponds to a period during the Ordovician, in which the Arabian Plate occupied an intra-cratonic setting, and drifted towards higher southerly latitudes (McKerrow, 1990; Beydoun, 1993). A passive margin is interpreted between this part of gondowana and Palaeo-Tethys (Sengor, 1990). During the Early Ordovician (Tremadocian and Floian), deeper marine environments become established basinward in the north of Arabian plate (Swab Formation in Syria; Bedinan Formation in southeast Turkey). Along the basin margin, braid-plain to braid-delta environments were followed by coastal-plain to inner-neritic clastic environments (Umm Sahm Formation in Jordan and Saq Formation in Saudi Arabia) (Konert et al., 2001). Mixed clastic and carbonate settings are found on the central Iran microplates (Rickards et al., 1994).

In the Middle Ordovician subsidence increased and a rapid transgression resulted in deposition of middle to outer neritic shales over most of the Arabian Plate (Sharland et al., 2001). In the Late Ordovician, a gently dipping, wide and stable marine shelf bordering the Palaeo-Thetys (Senalp and Al-Duaiji, 2001) record the deposition of the Qasim Formation in Saudi Arabia and is considered as equivalent to the Seyahou Fm. in Zagros (Iran, this study).

In uppermost late Ordovician, in the study area, no evidence for major glacially related tunnel valleys (e.g. Saudi Arabia) was identified. However, evidence for scour of important local extent were recognised in Kuh e Faraghan for Dargaz Formation (Ghavidel Syooki et al., 2011). However, Hirnantian glacial deposits and tunnel valleys have been reported from Arabian margin of Gondowana (McClure, 1978; McGillivary and Al-Husseini, 1992; Le Heron et al., 2010). In the Arabian Plate, Hirnantian tunnels represent up to 400 m deep and 80 km wide (Melvin et al., 2006). They are described in the Al Qasim district and the Wajid and Widyan plateaux of Saudi Arabia (McClure, 1978; Hughes-Clark, 1988; Vaslet, 1990; Clark-Lowes, 2005), and southern desert of Jordan (Armstrong et al., 2005; Turner et al., 2005; Armstrong et al., 2009). In Oman, Miller and Melvin (2005) identified at least one major unconformity within the Hasirah Formation (Late Ordovician) that is associated with the sudden influx of significant amounts of fluvial to deltaic sands on top of deep marine sediment. They related this terrigenous influx with major continental glaciations that have been reported from the Ashgill to ?Early Llandovery of Saudi Arabia and that caused valley incisions with a relief of more than 200 m (Vaslet, 1989; 1990).

The cycle 2 is compared with the upper part of megasequence AP2 of Sharland et al. (2001) (Fig. V.1). Maximum flooding surfaces (MFS) are designated as Ordovician 20, Ordovician 30 and Ordovician 40 (MFS O20, O30 and O40), and occur in Zard Kuh Formation (MFS O20) and the Seyahou Formation (MFS O30 and O40), reperctively. According to Sharland et al. (2001), the O30 maximum flooding event caused deposition of 'outer shelf' shales far into western areas of the Arabian Plate. Earlier sequences of mainly continental sediments (TST) were rapidly transgressed by outer shelf shales in Jordan (Hiswah Fm.), Saudi Arabia (Qasim Fm.), and Oman (Amdeh Fm.). Sharland et al. (2001) interpret the environmental change as most likely due to increased rates of subsidence resulting from a phase of rifting. They consider that the subsidence may have been enhanced by a 'lower order' rise in eustatic sea level and that a rapid transgressive systems tract (TST) was followed by a long-lived period of deposition during highstand conditions. In the Arabian Plate, MFS O40 (Late Ordovician; Early Caradocian, Gradstein and Ogg, 1996) is ovserved in deep-water shales near the base of the Ra'an Member of the Qasim Formation in Saudi Arabia (Vaslet et al. 1987), Afendi Fm. in Syria, Bedinan Fm. in south east Turkey, Tubeiliyat Fm. in Jordan, Sinat Fm. in north Iraq and shales of lower Hasirah Fm. in Oman. In the Zagros area, MFS O30 may be compared with the phosphorous Ghavidel Syooki et al. (2014) layer observed in Zard Kuh Formation. This MFS is followed by a condensation layer or hiatus ranging from Dapingian and Early Darriwilian Ghavidel Syooki et al. (2014). In this area, MFS O40 (Sharland et al., 2001) may be compared with MFS of DS OIII corresponding to the deepest offshore shales in the Seyhou Formation.

Stratigraphic correlation

The first synthesis of stratigraphic correlation for Ordovician deposits has been presented in (Fig. V.2.) containing Main unconformities, depositional environments and sequence stratigraphy.

The Ordovician deposits composed of 731 m thick of shoreface to foreshore Zard Kuh, offshore to shoreface Seyahou and glaciogenic Dargaz Formations in Kuh e Faraghan as a complete section. It consists of 8 third-order depositional sequences (Fig. V.2.). Toward Kuh e Gahkum, as will discusse later, Ordovician deposits are not preserved and Silurian Sarchahan Formation capped the un-aged conglomertaes (Ghavidel Syooki et al., 2011). In Kuh e Surmeh (Fars area) the incompelete and small part of Seyahou Formation with Katian age (Ghavidel Syooki, 1994e) represented containing 3 third-order depositional sequences (Fig. V.2.). Based on three members distinguished by Ghavidel Syooki et al. (2011) [(1) a lower conglomeratic member (2) a mid heterolithic shale and sandstone alternations bearing interbedded phosphatic and bioclastic carbonate siltstones member and (3) an upper Member, recognizable by thin-bedded, rhythmic claystone and sandstone couplets rich in ichnofossils], only the middle part of Seyahou Formation composed of three depositional sequences (DS OIII, OIV and OV) observed in Kuh e Surmeh. It is confirmed by age-dating (Katian) and depositional environments. Toward the south, Seyahou Formation represented in Zirreh (Ghavidel Syooki, 1993c) and Kuh e Siah (Ghavidel Syooki, 1994b) (Fars area). In these areas, recognition of depositional environments and sequences is impossible due to lack of enough data (Fig. V.2.).

Three main unconformities recognized in these sediments and named unconformity 1, unconformity 2 and unconformity 2a. The term *unconformity 1* is adopted here for the flooding events (Droste, 1997; Ghavidel Syooki et al., 2014) in the Seyahou Formation and marked the hiatus ranging from Dapingian to Early Darriwilian proposed by Ghavidel Syooki et al. (2014) in Kuh e Faraghan. In Kuh e Gahkum in Bandar Abbas area, unconformity is not present where the Silurian Sarchahan Formation topped Cambrian deposits (Fig. V.2.). In Kuh e Surmeh and Kuh e Siah only the upper part of Ordovician deposits present and unconformity 1 is not obvious. Furthermore, in Kuh e Zirreh in Fars area, this unconformity marked the boundary between Zard Kuh and Seyahou Formations (Ghavidel Syooki, 1993c).

Unconformity 2 marked top of the Floian-Katian Seyahou Formation (Fig. V.2). At Kuh e Faraghan in Bandar Abbas area, because of presence of Hirnantian Dargaz Fm., unconformity 2 is located at the base of Hirnantian glaciogenic Dargaz Formation (Fig. V.2) (Ghavidel Syooki et al., 2011). It indicates the base of Early Silurian Sarchahan Formation and named as unconformity 2a related to marine flooding organic-rich shales (Ghavidel Syooki et al., 2011) (Fig. V.2). In Kuh e Gahkum, unconformity 2 shows the hiatus with Ordovician age (Fig. V.2.). In Zirreh (Fars area) (Ghavidel Syooki, 1993c) it rests at base of hiatus with Hirnantian age (Fig. V.2). In Kuh e Surmeh and Kuh e Siah (Fars area), unconformity 2 marked the base of major hiatus ranging from Late Ordovician to Early Permian (Fig. V. 2).

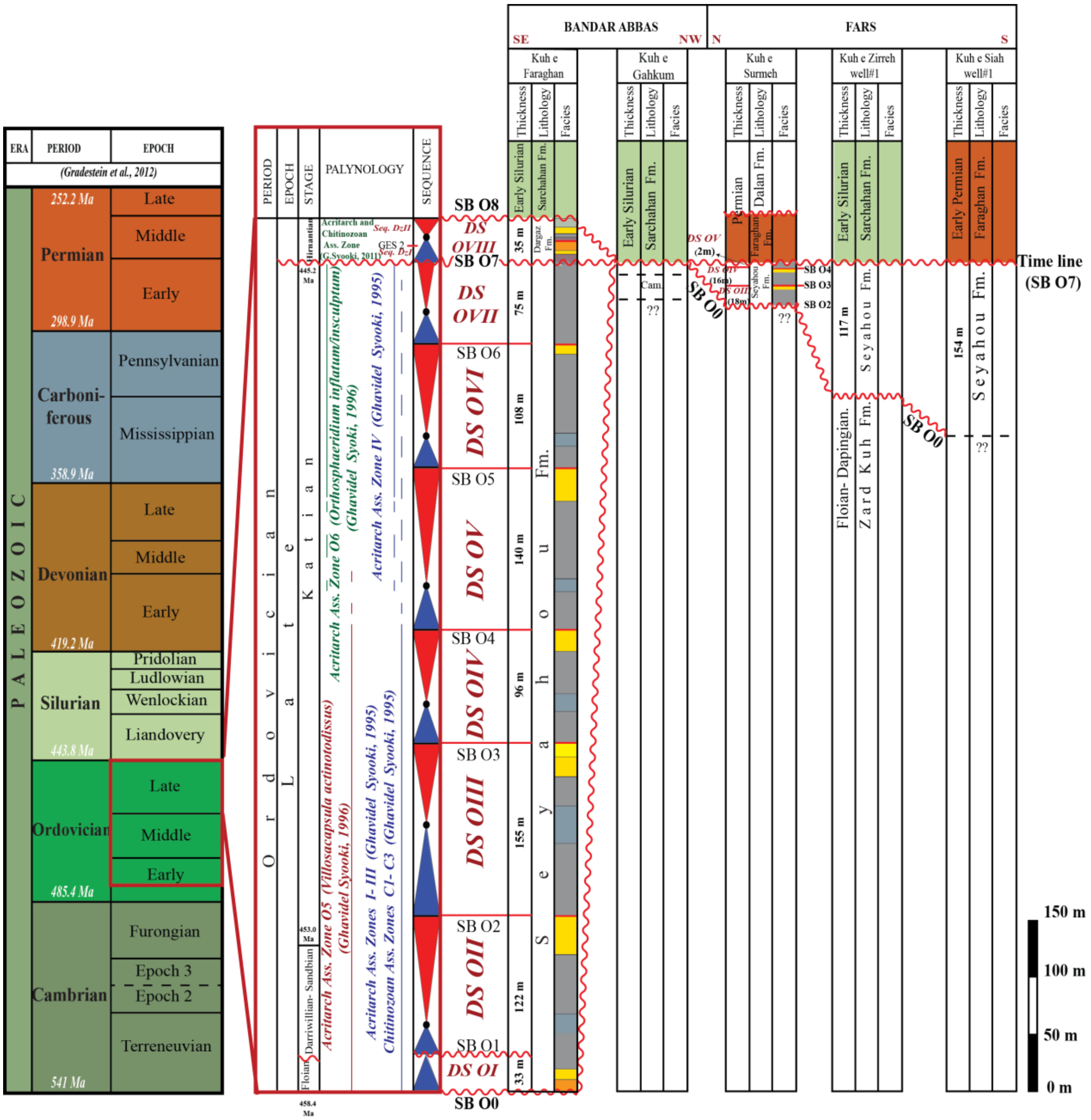

Fig. V.2: Sequence- stratigraphic correlation integrating outcrops and wells in the Zagros area for the Ordovician deposits. *See Table IV.1&2. for explanation of facies code and Figure I.2 for location of outcrops and wells.*

V.1.3. Cycle 3: Early Silurian

Definition

Cycle 3 lasted some 10 million years and is dominated by Early Silurian Sarchahan Formation deposits. The cycle is bounded by an Upper Ordovician unconformity (unconformity 2a) (Fig. V.1). In almost all the Zagros area, this unconformity is a boundary between Ordovician (Late Floian-Katian) Seyahou (Ghavidel Syooki et al., 2014) and Early Silurian (Liandovery) Sarchahan Formations (Ghavidel Syooki, 1995b, Ghavidel Syooki and Winchester-Seeto, 2004). However, in Kuh e Faraghan, the unconformity (unconformity 2b) (Fig. V.1) rests at the top of the Dargaz Formation corresponding to Late Ordovician (Hirnantian) glaciogenic deposits (Ghavidel Syooki et al., 2011). The upper boundary of cycle 3 is the unconformity (unconformity 3) (Fig. V.1) placed at top of Sarchahan Formation (Ghavidel Syooki, 2003).

Main depositional environment and sequence stratigraphic framework

The Sarchahan Formation is observed in Kuh e Faraghan, Kuh e Gahkum surface sections. It is also preserved in Zirreh, Darang and Golshan subsurface sections (Fig. V.3). This Formation has been removed from many areas or not deposited such as in the west high Zagros (Setudehnia, 1975; Ghavidel Syooki, 1990a,b), Kuh e Surmeh (Ghavidel Syooki, 1994e) and Kuh e Siah (Ghavidel Syooki, 1994b) during several Palaeozoic erosional episodes (Setudehnia, 1975; Berberian and King, 1981; Al-Husseini, 1991; Alavi, 2004; Heydari, 2008).

Based on interpretation of Al-Husseini (1991), Heydari (2008) and Alavi (2004), a deep-marine environment is attributed for transgressive organic-rich and graptolite shales of the Early Silurian deposits in Zagros. Konert et al. (2001) indicated shallow to open marine environments for early Silurian deposits in Zagros as a marginal Arabian plate. Ghavidel Syooki et al. (2011) compared depositional environments of Sarchahan Formation in Kuh e Faraghan and Kuh e Gahkum. They interpreted the balck shales in the lowermost part of the Sarchahn in Kuh e Faraghan, form in the marine bottom waters whereas in Kuh e Gahkum, they proposed a fan-shaped clastic wedge of amalgamated conglometare sheets, followed by turbiditic conglomerates and shales intercalation.

This study shows that the Early Silurian Sarchahan Formation observed in the Zagros area corresponds to a shallowing-upward succession. It is established in open marine condition from upper offshore to deep Offshore (S4 to S5) depositional environments in a marginal area of the Arabian Plate (Fig. V.3). Locally, in Kuh e Gahkum, the Sarchahan Formation is subdivided into 2 informal units. The lower unit records continental and near-shore-marine (S1 to S3) with a thinning-upward trend from conglomerate package to some meter-thick shale unit, finally followed by coarsening-upward cross-bedded gravelly sandstones, representing deposition in seaward trend evolves from fan-delta (S1) to lagoon (S2) and shoreface shoal (S3). The upper unit is composed of open-marine (S4 to S5) deposits. It shows intercalation of shales and thin-bed conglomerates, with scouring bases marked by sole, tool and flute marks at base; and asymmetric ripples at top. They are interpreted as in slope-apron environment as confirmed by Ghavidel Syooki et al. (2011) (Fig. IV.17G).

Such lateral rapid and important variation of facies and thickness in the same area may be explain by local phenomena as the possible structural high position of the Kuh e Surmeh regarding Kuh e Faraghan and may be related by salt plug tectonic activities (Jahani, 2008).

In term of sequential framework, the Early Silurian Sarchahan Fm. is interpreted as a 'second order' depositional sequence with transgressive-regressive trend. The Deepening-upward TST of this sequence is topped by an MFS located in the rich-organic shales (Ghavidel Syooki et al., 2011) and followed by relatively thick HST containing coarsening- and shallowing-upward sediments. It has been divided in two 3rd-order transgressive-regressive sequences (DS SI and DS SII) (Fig. V.3) with variation in thicknesses.

Palaeogeographical reconstitution of the Zagros area

The Zagros region drifted southwestward reaching near 55° S latitude by the end of Silurian time (Fig. I.3). In Early Silurian, after the eustatic sea level rising occurred and led to the flooding of wide areas, triggering the deposition of transgressive black, organic-rich shales (Berberian and King, 1981, Sharland et al., 2001; Konert et al., 2001, Heydari, 2008). It is possibly due to the melting of glaciers, during the latest Ordovician (Heydari, 2008) and a major phase of global warming developed during the Llandovery (Konert et al., 2001). Following the Early Silurian, the effect of epeirogenic movements, led to a regional regression and general emergence of the region by Silurian time (Berberian and King, 1981). The influence of a major global sea level fall (Vail et al., 1977; Heydari, 2008) combined with the regional Silurian progradation (Al-Husseini, 1991) resulted in a Late Silurian major hiatus. It is confirmed by the absence of Late Silurian deposits in Fars (Zirreh and Darang), Bandar Abbas (Kuh e Gahkum and Kuh e Faraghan) areas and Persian Gulf (Golshan, Fig. V.3). The absence of Sarcharan Formation, locally (Kuh-e Surmeh and Kuh-e Siah) and some part of the Zagros area (west high Zagros) will be discuss latter in this chapter.

Regional comparisons

During the Silurian, the Turkish and Iranian plates (e.g. Sanandaj-Sirjan) (Fig. I.1) were attached to Arabia and Africa in Gondwana (Smith et al., 1981). In most parts of the Arabian Plate, the post-glacial transgression deposited thick, deep-marine, organic-rich, graptolite shales directly atop the glaciogenic and periglacial clastics and related unconformity surfaces (Al-Husseini, 1991). The post-glacial transgression in the Arabian Plate terminated in the Early Silurian when the coastline of Gondwana prograded across Arabia depositing upward-coarsening marginal marine clastics over the deeper marine shales (Berry and Boucot, 1973). In Oman, the Sahmah Formation (Early Silurian) corresponds to a major flooding event with the deposition of organic-rich sediments (Doroste, 1997). It is interpreted as a sea-level rise resulting from the melting of the ice cap (Miller and Melvin, 2005). During the Late Silurian, the influence of a major global sea level drop (Vail et al., 1977) combined with the regional Silurian progradation resulted in a Late Silurian major hiatus in most parts of the Arabian Plate. Flugel (1971) and Berberian and King (1981) proposed epeirogenic uplift associated with the Caledonian orogeny for Late Silurian hiatus.

The Early Silurian Sarchahan Formation and the proposed DS SI and DS SII in this study may be compared with the Lower part of tectonostratigraphic megasequence AP3 of the Arabian sequence stratigraphy framework of Sharland et al., (2001) (Fig. V.3). Likewise other parts of the Arabian plate, the Sarchahan Fm. is followed by progradational stacking pattern corresponding to an overall relative sea level fall (Sharland et al., 2001; Haq, 2005). The Silurian (Llandovery) is interpreted as eustatic in origin (McKerrow, 1979) and flooded much of the Gondwana platform area and corresponds to Silurian deposits in Zagros area.

Stratigraphic correlation

In the studied area, the Early Silurian deposits composed of Sarchahan Formation present in Kuh e Faraghan and Kuh e Gahkum (Bandar Abbas area), Zirreh (Fars area) and Golshan (Persian Gulf) (Fig. V.3). In Kuh e Faraghan, lower Offshore to upper offshore Sarchahan Formation capped the glaciogenic Dargaz Formation and topped by Devonian Zakeen Formation. In Kuh e Gahkum, the Sarchahan Formation is represented by an unnamed Formation (probably pre-Floian in age due to the lack of the Floian-Katian Seyahou Formation) (Ghavidel Syooki et al., 2011) and overlies by Devonian Zakeen Formation (Fig. V. 3). It is deposited in deltaic fan system at the basal part that played a palaeotopographic role during the Silurian. At the beginning of the Liandovery, this palaeorelief became a passive source of erosion. It shed enough sediment to form a prominent fan-shaped clastic wedge of amalgamated conglomerate sheets (Ghavidel Syooki et al., 2011). Jahani (2008) proposed the Salt plug tectonic activities for high position of Kuh e Gahkum. In Fars area, Sarchahan Formation represented in Zirreh whereas in neighboring area Kuh e Surmeh and Kuh e Siah is absent. It is may be explain by local structural high position and may be related to salt plug tectonic activities (Jahani, 2008).

The Sarchahan Formation deposited in two 3rd-order depositional sequences in the studied areas when it is preserved (Fig. V. 3).

A part from unconformities 2 and 2a (Fig. V. 2) at the base of Sarchahan deposits which described in previous session, *unconformity 3* located at top of Liandovery, and marked the hiatus ranging from Wenlockian to Pridolian proposed by Ghavidel Syooki (1995b) and Ghavidel Syooki and Winchester-Seeto (2004) (Fig. V. 3). *Unconformity 3* is adopted to an uplift of the Middle East area associated with epeirogenic movements (Berberian and King, 1981), probably Caledonian orogeny (Ghavidel Syooki, 2000; Ghavidel Syooki and Winchester-Seeto, 2004) and a major sea level drop (Al-Husseini, 1991, 1992; Haq and Al-Qahtani, 2005). In Kuh e Surmeh and Kuh e Siah (Fars area), unconformity 3 marked the base of major hiatus ranging from Late Ordovician to Early Permian (Fig. V. 3).

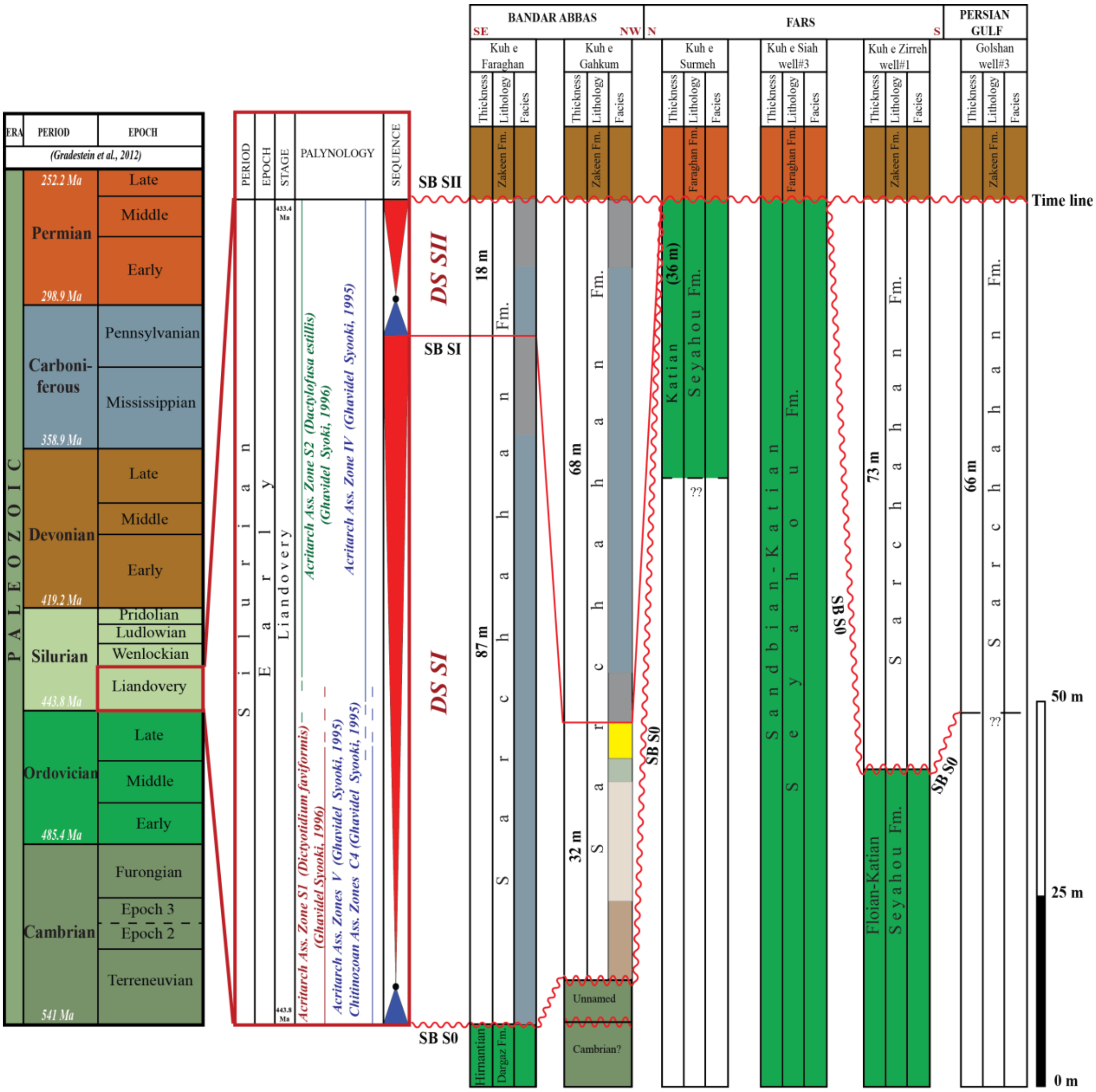

Fig. V.3: Sequence- stratigraphic correlation integrating outcrops and wells in the Zagros area for the Early Silurian Sarchahan Formation. *See Table IV.3. for explanation of facies code and Figure I.2 for location of outcrops and wells.*

V.1.4. Cycle 4: Devonian

Definition

The Cycle 4 lasts some 60 million years and corresponds mainly to Zakeen Formation Devonian deposits. In the Zagros area, the lower boundary corresponds to an unconformity (unconformity 3) ranging from Wenlockian to Pridolian satges (Ghavidel Syooki and Khosravi, 1995a; Ghavidel Syooki and Winchester-Seeto, 2004). In Kuh e Gahkum, this unconformity prolongate to Eifelian stage of Devonian (Ghavidel Syooki, 2003). The upper boundary is a Late Devonian unconformity (unconformity 4) and spent between the Devonian Zakeen and Early Permian Faraghan Formations (Ghavidel Syooki, 2003) (Fig. V.1).

Main depositional environment and sequence stratigraphic framework

Lithologically, Devonian Zakeen Formation reflects a vertical shift in sedimentation from siliciclastics to mixed siliciclastics-carbonates. It is well-observed in Kuh e Faraghan and Kuh e Gahkum outcrops and Zirreh, Dalan, West Aghar, Naura, Kish, Golshan and Salman 2SKD-1 subsurface sections. This Formation is not preserved in many areas such as west high Zagros (Setudehnia, 1975; Ghavidel Syooki, 1990a,b), Kuh e Surmeh (Ghavidel Syooki, 1994e) and Kuh e Siah (Ghavidel Syooki, 1994b).

Depositional environment of the Zakeen Formation corresponds to shallow marine siliciclastic shelf (Szabo and Kheradpir, 1978; Zamanzadeh, 2008; Zamanzadeh et al., 2009a). Fluvial to deltaic deposits depositional environment for the Zakeen Formation in the Zagros suggested by Heydari (2008). In this study, the Devonian Zakeen Formation is interpreted as alluvial to estuarine clastics deposits during the Early and Middle Devonian (D1 to D4) (Table IV.4) and passing to mixed marine siliciclastics and carbonates (D5) at the end of Devonian, in most parts of Zagros (Fig. V.4). It is characterized by a shallowing-upward succession in Kuh e Gakum and Kuh e Faraghan.

In term of sequential framework, Zamanzadeh (2008) and Zamanzadeh et al. (2009a) proposed to oragnize the sedimentary record in Kuh e Gahkum and Kuh e Faraghan in a second order shallowing-upward trend depositional sequence. They proposed three 3rd-order transgressive-regressive sequences for Zakeen Formation. In this study, a primary synthesis of the sequence stratigraphy of the Devonian in the Zagros area is presented in Figure (FigV.4). The Zakeen Formation is interpreted as a second-order depositional sequence (Fig. V.1) bounded by SB D0 at base and SB D3 at top. In Kuh e Faraghan, it consists of three 3rd-order sequences (DS DI to DS DIII). In this area, sequences numbered in DS DI to DS DIII evolve from estuarine (D4) to mud tidal flat (D3) environments. In Kuh e Gahkum, sequences (DS DI, DS DII and DS III) characterized by transgressive-regressive trend evolve from alluvial to estuarine depositional environments (D1 to D4). The rapid lateral variation of thickness and sequences numbers between both Kuh e Faraghan and Kuh e Gahkum and the presence of alluvial (D1) and fluvial (D2) environments in Kuh e Gahkum may be related to a high paleorelief and a possible activity of salt plug (Jahani, 2008).

Figure V.4, proposes a correlation scheme between outcropping areas and wells in the Zagros area. It is based on “Age model for the Zakeen Formation” in Kuh e Faraghan proposed by Ghavidel Syooki (2003). Based on this age determination, Lochklovian-Frasnian is proposed for Zakeen Formation in Kuh e Faraghan whereas; Eifelian-Famennian is identified for Kuh e Gahkum. As late Devonian is absent in Kuh e Fraraghan, the most complete succession and observe in Kuh e Ghakum in a high relief position, therefore, either we can consider, than the depositional sequences are not correlatable regionally or the biostratigraphical data have to be precise.

Palaeogeographical reconstitution of the Zagros area

The Zagros region started its northerly drift, reaching nearly 30° S latitude by the end of Devonian time (Heydari, 2008) (Fig. I.3). In general, The Denonian time presents a shallowing upward stacking pattern which indicates a fall in relative sea-level (Vail et al., 1977; Heydari, 2008). This fall is follow by an extensive regional exposure (80 million years hiatus in Zagros) during Carboniferous period (Ghavidel Syooki, 2003).

Tha lateral variation of sedimentation as the absence of Early Devonian deposits in Kuh e Gahkum and Early to Middle Devonian sediments in Zirreh and Golshan may be attributed to local uplift. This suggestion previously related to salt motion inducing palaeo-high structures in Kuh e Gahkum (Jahani, 2008; Ghavidel Syooki et al., 2011). The Zakeen Formation is not preserved in some area such as Kuh e Surmeh and Kuh e Siah, but observed in 30 km neighboring areas (Naura, West Aghar, Zirreh and Dalan). It is related to a hiatus from Silurian to Carboniferous interpreted by Ghavidel Syooki (1994e), Faqira (2009), Jahani (2008) and Tavakoli et al. (2013). Again, the absence of Devonian deposits is discussed later in this discussion chapter

Regional comparisons

The Devonian cycle is absent by erosion over much of the northern Arabian Plate, possibly by thermal doming prior to the latest Devonian rift events (Sharland et al., 2001). It is may be one of the reasons for absence of Devonian Zakeen Formation in east high Zagros. Sedimentary rocks of North Africa and the Middle East comprise a generally coarsening-upwards , progradational sequence along the passive margin of northeastern Gondwana that commenced in the Silurian and culminated in the Late Devonian times (Al-Hajri et al., 1999). The Late Silurian hiatus was followed by a Devonian transgression caused by global sea-level rise (Vail et al., 1977). This regional transgressive-regressive depositional sequence extends across the Arabian Plate from Turkey, Iraq and Zagros (Zakeen Fm.) in north to Saudi Arabia and Oman in south (Al-Husseini and Matthews, 2006). In Saudi Arabia, the Early Devonian, continental deposits of Tawil Formation are followed by marine Middle Devonian Juaf Formation (Al-Hajri et al., 1999). In central Arabia, Syria and Iraq, continental clastic Jubah Formation were deposited in Middle to Late Devonian, whilst marginal marine environments persisted in Turkey and Oman (Konert, 2011) and corresponds to upper part of the Zakeen Formation in Zagros area in this study. In Turkey, Syria and Iraq, the pre-Emsian deposits are not preserved (Al-Husseini, 1991; Sharland et al., 2001; Konert, 2001) and Konert et al. (2001) proposed a structural high position to explain this absence in Saudi Arabia. This suggestion is confirmed by Al-Husseini (1991) for the Devonian in the Arabian Plate. In this study, the absence of the Early Devonian deposits in Kuh e Gahkum, as well as Middle to Late Devonian deposits in Zirreh and Golshan may be compared with the model proposed for the Arabian Plate. Furthermore, presence of thick Early to Middle Devonian deposits in the Salman 2SKD#1 (Fig. V.4) can be related to depocenter position in Saudi Arabia as proposed by Konert et al. (2001).

The sequential framework of the Devonian Zakeen Formation in the Zagros is compared to in to second cycle of megasequence AP3 in Arabian Plate (Sharland et al. (2001). This transgressive-regressive cycle is a second order sequence and bounded by Pre-Tawil unconformity (Late Silurian) at base and Hercynian unconformity (Late Devonian). AP3 is characterized by short TST, which consists of continental to near-shore marine deposits which evolved to an Emsian Marine carbonate sediments during MFS. It is followed by thick continental environment deposits of the HST. Sharland et al. (2001) argue that the HST indicates sediment supply in excess, and therefore a limited subsidence. The MFS of this cycle is probably interpreted as a global eustatic fluctuation (Vail et al., 1977).

Stratigraphic correlation

The first synthesis of stratigraphic correlation for Devonian Zakeen Formation has been presented in (Fig. V.4.). In Kuh e Faraghan, it consists of 158 m, tide dominated estuarine sandstones and shales, deposited in three 3rd-order depositional sequences (DS DI, DS DII and DS DIII) . In Kuh e Gahkum, Zakeen Formation consists of 117 m alluvial, fluvial to tide dominated estuarine sandstones and shales, deposited in three 3rd-order depositional sequences (DS DIIa, DS DIIb and DS DIII) (Fig. V.4.).

Ghavidel Syooki (2003), proposed Lochklovian to Frasnian (Early to Late Devonian) age for the Zakeen Formation in Kuh e Faraghan. Based on this dating and sequence analysis, DS DI; DS DII and DS DIII may be correlated with Early, Mid and Late Devonian, respectively. In this area the upper part of DS DIII (Famennian) is eroded (Ghavidel Syooki, 2003). In Kuh e Gahkum, the Early Devonian deposits are not preserved. In this area, Zakeen Formation is attributed to Eifelian- Famennian (Mid to Late Devonian) (Ghavidel Syooki, 2003). Based on this dating and sequence analysis, three sequences observed in Kuh e Gahkum, may be correlated with Mid and Late Devonian, respectively. As a result, field observations, facies and sequence analysis confirmed that three sequences in Kuh e Faraghan (DS DI, DS DII and DS DIII) can be correlated with DS DIIa, DS DIIb and DS DIII in Kuh e Gahkum (Fig. V.4.).

Toward south, in Fars area (e.g. Naura, West Aghar, Dalan and Zirreh) and Persian Gulf (Kish and Golshan), only the upper part of Zakeen Formation (Late Devonian) preserved. It composed of shallow marine sandstones and carbonates depositional environments.

The absence of Devonian Deposits in Kuh e Surmeh anticline and the presence of 108 m-thick Zakeen succession located 60 km (Naura #1 well) to the northeast; 122 m-thick located 25 km (West Aghar #1 well) to the northwest and 85 m-thick situated 50 km (Dalan #1 well) to the southwest of Kuh e Surmeh, argue for a local mechanism to explain part of the hiatus ranging from Hirnantian to Early Permian in this area.

In Salman 2SKD#1 well, 422 m-thick Zakeen succession preserved and attributed to Early to Mid Devonian (Aria Nasab, 2011a) and the upper part of the Formation is eroded.

In most of the Zagros area, the Zakeen Formation rests discontinuously (*unconformity 3)* on the Early Silurian Sarchahan Formation and is overlain unconformably (*unconformity 4)* by the Early Permian Faraghan Formation. The term *unconformity 4* at top of Zakeen Formation is adopted here for the Hercynian orogeny ranging from the Late Devonian up to the Carboniferous (Al-Hosseini, 1992; Sharland et al., 2001; Konert et al., 2001, Faqira et al., 2009), and the Late Carboniferous glaciation induced a general emergence of the region (Berberian and King, 1981; Al-Hosseini, 1992; Sharland et al., 2001; Konert et al., 2001) and marked the hiatus ranging from Carboniferous to Early Permian.

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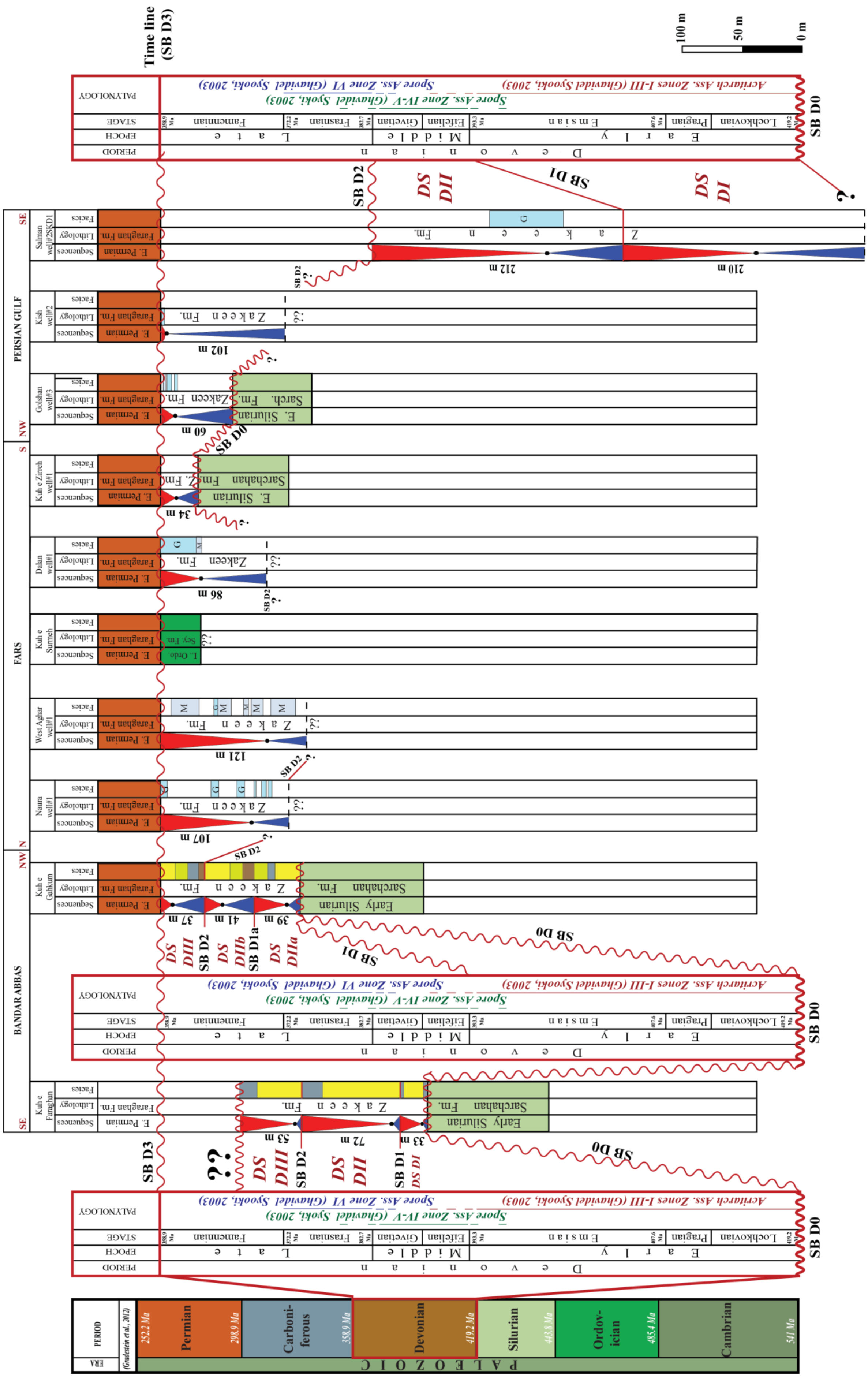
Fig. V.4 (Next page): Sequence- stratigraphic correlation integrating outcrops and wells in the Zagros area for the Devonian Zakeen Formation. *See Table IV.4. for explanation of facies code and Figure I.2 for location of outcrops and wells.*


Time line (SB D3)
100 m
50 m
0 m
PERSIAN GULF
FARS
BANDAR ABBAS
Salman well#2SKD1
Kish well#2
Golshan well#3
Kuh e Zirreh well#1
Dalan well#1
Kuh e Surmeh
West Aghar well#1
Naura well#1
Kuh e Gahkum
Kuh e Faraghan
Faraghan Fm.
E. Permian
Zakeen Fm.
Sarchahan Fm.
Early Silurian
SB D0
SB D1
SB D2
SB D3
DS DI
DS DII
DS DIII
Acritarch Ass. Zones I-III (Ghavidel Syoki, 2003)
Spore Ass. Zone IV-V (Ghavidel Syoki, 2003)
Spore Ass. Zone VI (Ghavidel Syoki, 2003)
Lochkovian
Pragian
Emsian
Eifelian
Givetian
Frasnian
Famennian
Early
Middle
Late
Devonian
Permian
Carboni-ferous
Silurian
Ordov-ician
Cambrian
PALEOZOIC
PERIOD
EPOCH
STAGE
PALYNOLOGY
(Gradestein et al., 2012)

V.1.5. Cycle 5: Early Permian

Definition

Cycle 5 lasted some 23 million years (from Sakmarian to Kungurian) and consists of Faraghan Formation in the Zagros area. The lower boundary (SB P0) (Fig. V.5) corresponds to the well-known "Hercynian unconformity" throughout arabian Plate (Al-Husseini, 1992; McGillivray and Al-Husseini, 1992; Sharland et al., 2001). In most parts of the Zagros area this boundary is placed between Devonian Zakeen and Early Permian Faraghan Formations. However, in some areas as in Kuh e Surmeh, Kuh e Siah and west high Zagros (e.g. Kuh e Dena, Chal I Sheh and Zard Kuh), it is placed between the boundary between Ordovician or Cambrian Fm. and Faraghan Fm. The upper boundary corresponds to the "Pre-Khuff unconformity" (unconformity 5) (Fig. V.1) (Szabo and Kheradpir, 1978, Al-Husseini, 1992; McGillivray and Al-Husseini, 1992; Senalp and al-Duaiji, 1995; Sharland et al., 2001). This boundary is placed between the Faraghan and Middle to Late Permian Dalan Fm. and its duration corresponds to the Kungurian following Szabo and Kheradpir (1978) and Hughes Clarkes (1988).

Main depositional environment and sequence stratigraphic framework

The Faraghan Formation is widespread over most of the Zagros area with variation in thickness (Fig.V.5). Based on sedimentological study carried out by Szabo and Kheradpir (1978), a near-shore shallow marine environment is proposed for the Faraghan Formation in Kuh e Surmeh whereas fluvial to deltaic deposits are proposed in Chal I Sheh area. Zamanzadeh (2008) and Zamanzadeh et al. (2009a) focused on Faraghan Fm. in Kuh e Gahkum and Kuh e Faraghan and proposed a shallow marine environment. In this study, a new synthesis on detailed depositional environments is proposed for the Faraghan Formation in the Zagros area (Fig. V.5). It corresponds to an evolution rom near-shore to shallow-marine depositional environments evolving from coastal plain (F1), tidal flat (F2), delta (F3), estuary (F4), lagoon (F5), shorface (F6) and upper offshore (F7).

In term of the sequential framework, Zamanzadeh (2008) focused on the Faraghan Formation in Kuh e Gahkum and Kuh e Faraghan and proposed a retrogradational (deepening upward) stacking pattern organized in a TST second order sequence. This transgressive trend is subdivided in three 3rd-order transgressive-regressive sequences. Heydari (2008) proposed the same transgressive evolution organized in TST of a second order sequence. In this study, a sequence stratigraphy model have been proposed for the Early Permian Faraghan Formation (Fig. V.5). The vertical stacking pattern of Faraghan Formation in the Zagros area is interpreted as a deepening-upward cycle. The sequence architecture is driven by the superposition of three 3rd-order sea-level cycles (DS PI, DS PII and DS PIII). In Kuh e Surmeh, Faraghan Formation is an incomplete sequence and consists of two 3rd-order depositional sequences.

Palaeogeographical reconstitution of the Zagros area

The Zagros region continued drifting northward reaching approximately 10° S latitude during the Permian interval (Heydari, 2008). Devonian deposits are overlain unconformably by the basal conglomerates and sandstones of the overlying epi-Pangean platform succession of Permian to Triassic age (Szabo and Kheradpir, 1978; Sharief, 1982). Alavi (2004) indicated that the Permian is diachronous and corresponds to a northeast transgression over a platform flanking Pangea. The regional transgression during the Lower Permian seems responsible for rising in relative sea level in Zagros area and development of shallow clastic marine shelf in which the Faraghan Formation was deposited (Zamanzadeh, 2008; Heydari, 2008). A part from relative sea level change, local tectonic activity is one of the most important mechanisms for deposition of the cycle 5. The absence of the third sequence and its low thickness in Kuh e Surmeh is described by the high-relief position defined by Faqira et al. (2009); Jahani, (2008); and Tavakoli Shirazi et al. (2013). In Kuh e Gahkum, deposition of the stromatolites in lagoon environments (F5) reveals a decrease in the rate of clastic sediment supply.

Regional comparisons

After the glaciation in Late Carboniferous-lower Early Permian (Al-Husseini, 1992, Al-Sharhan and Nairn, 1997; Konert et al., 2001, Sharland et al., 2001) and during the Permian the Arabian Plate moved from the relative low latitudes to higher latitudes (Konert et al., 2001; Haq and Al-Qahtani, 2005). In Early Permian another phase of major crustal extension in Arabian Plate weakened the crust enough to allow sediment load alone to drive subsidence and aid in the accumulation of thick carbonate sediments in subtropical latiludes (Haq and Al-Qahtani, 2005). Unlike the Permian basal glacial deposits of Arabian Plate (lowermost part of the Unayzah Formation in Saudi Arabia and Al-Khlata Fm. in Oman; Senalp and Al-Duaiji, 1995), no clastics of glacial origin have been found in Zagros and (or) Central Iran. This suggests that the late Palaeozoic glaciation of southern Gondwana (Africa, India, and Australia) did not affect the Iranian continental fragments (Berberian and King, 1981).

In the Late early Permian (Sakmarian-Kungurian) in Saudi Arabia Early Permian Unayzah A and upper part of Unayzeh B members is made up of braided plain, channel fill, and eolian deposits that were deposited in semi-arid conditions (Senalp and Al-Duaiji, 1995). Towards the southeast, marine influence is evident with shallow-marine carbonates being deposited in Oman (Konert, 2001). These two Formations are equivalent of Faraghan Fm. where it deposited in shallow-marine platform.

The sequence stratigraphic model proposed in the Zagros area for the Early Permian (cycle 5) is organized in DS PI To DS PIII (Fig. V.1) which lasts from Sakmarian to Kungurian. It is compared with the transgressive part of tectonostratigraphic megasequence AP5 proposed by Sharland et al. (2001). Unlike the Late Carboniferous- Early Permian basal glacial deposits of Arabian Plate (Senalp and Al-Duaiji, 1995), there is no clastics of glacial origin in the TST of cycle 5 in the Zagros area. The base of the megasequence is marked by the ' Hercynian Unconformity" (Al-Husseini, 1992; McGillivray and Al-Husseini, 1992; Sharland et al., 2001) and the top by the 'pre-Khulf unconformity" (Al-Husseini, 1992;

McGillivray and Al-Husseini, 1992; Sharland et al., 2001). The onset of this second order sequence in Arabian Plate corresponds to the top of Late Carboniferous-Early Permian glacial sediments and is presented around the more southerly regions of the plate, specifically in Yemen, Oman and southern Saudi Arabia (McClure et al., 1988: McGillivray and Al-Husseini, 1992). The TST of the AP5 consists of glacial deposits and following sandstones of continental environments (Unayzeh Formation in Saudi Arabia) (Sharland et al., 2001; Konert et al., 2001). Towards the end of Early Permian most of the area is interpreted to have been infilled with the HST sediments. The Gharif (in Oman) and upper Unayzah (A Member) (in Saudi Arabia) are of relatively constant thickness. Erosion of the Unayzah and Gharif Formations by the pre-Khuff unconformity may have significantly modified the preserved thicknesses of these sediments (Sharland et al., 2001). AP5 is topped by tectonostratigraphic megasequence AP6 (Sharland et al., 2001) and marked by Khuff transgressive carbonates (Al-Husseini, 1992; McGillivray and Al-Husseini, 1992; Sharland et al., 2001).

Stratigraphic correlation

The Early Permian (Sakmarian- Kungurian) Faraghan Formation spans throughout of the study area with diferrent thicknesses (Fig. V.5). In Kuh e Faraghan it consists of 58 m-thick deposited in tide-dominated sandy tidal flat, shoreface to offshore environments. By comparison with the neighbouring Kuh e Gahkum, the basal part of the Faraghan Formation at Kuh e Gahkum is represented by coastal plain and lagoonal stromatolithic dolomite. It upgrades to tide-dominated tidal flat and shoreface. Toward Fars area, the Faraghan Formation preserved in Sepidar, Naura, West Aghar, Kuh e Surmeh, Kuh e Siah, Dalan, Zirreh, Homa, Nar and West Assaluyeh. In Kuh e Surmeh as only place that Faraghan Formation cropped out, it consists of 36 m-thick sandstones and shales deposited in wave and tide-dominated estuarine and deltaic systems. In Persian Gulf, Faraghan Formation represented in Golshan, Kish and Salman 2SKD#1 topped Zakeen Formation and cappesd by Dalan Formation.

The First synthesis of the sequence stratigraphy for Faraghan Formation presented in Fig. V.5. It considered that this Formation deposited in three 3rd-order dpositional sequences (DS PI to DS PIII) in most part of the Zagros area. In Kuh e Surmeh, only DS PI and DS PII preserved and the last sequences (DS PIII) is absent.

In most of the Zagros area, the Faraghan Formation rests unconformably (*unconformity 4)* on the Devonian Zakeen Formation and is overlain unconformably (*unconformity 5)* by the Mid to Late Permian Dalan Formation. In Kuh e Surmeh and Kuh e Siah, this Formation topped the Late Ordovician Seyahou Formation and unconformity 4 marked a hiatus renging from hirnantian to Carboniferous (Fig. V.5). *Unconformity 5* is a homogenous unconformity and widespreads in most part of the Zagros area at top of Kungurian stage (Fig. V.5). It marked the boundary between Early Permian Faraghan and Middle to Late Permian Dalan Formations and adapted to Late Permian-Triassic Zagros Rift associated to a major Permian transgression (Al-Husseini, 1992).

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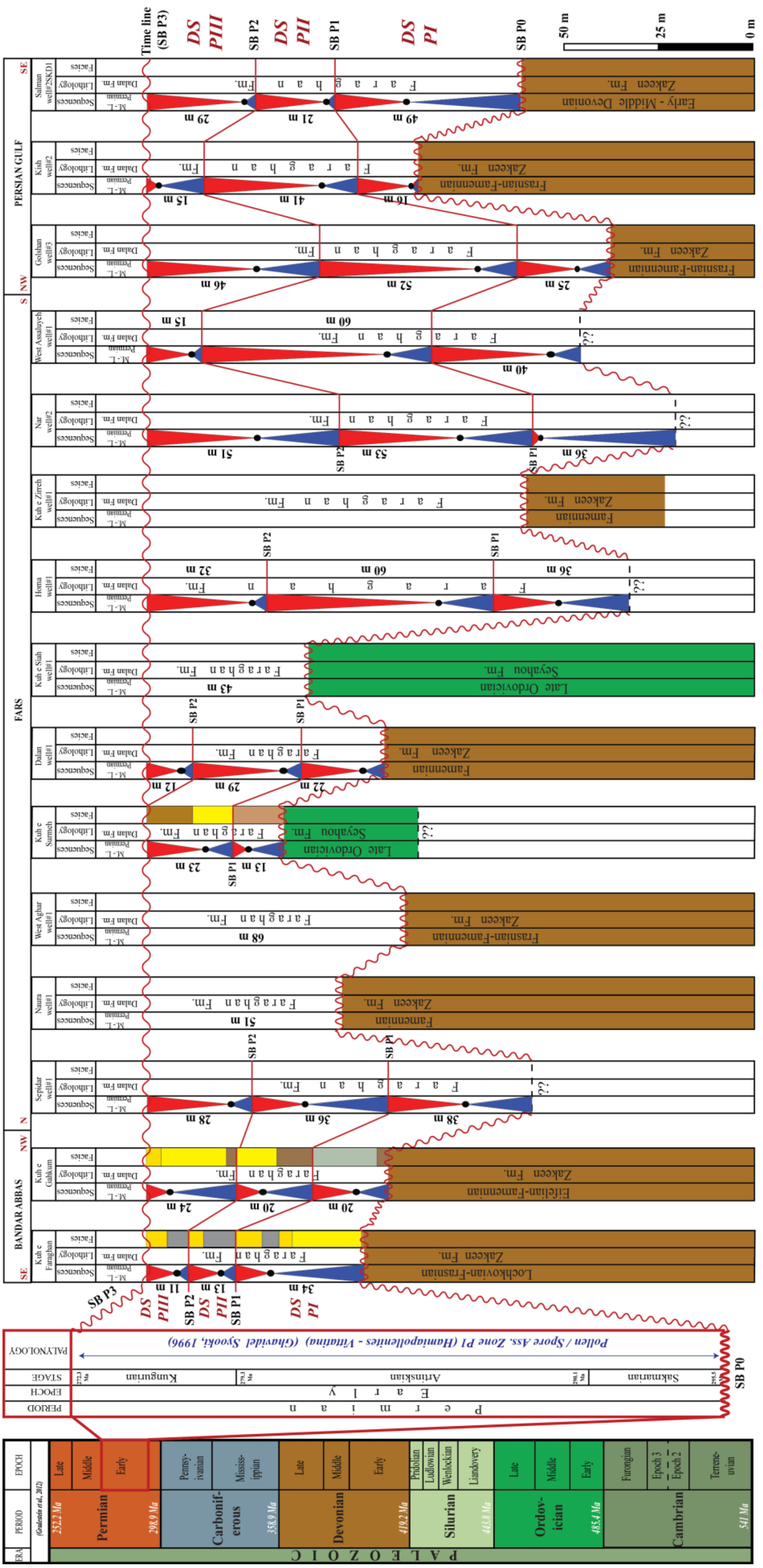
Fig. V.5 (Next page): Sequence- stratigraphic correlation integrating outcrops and wells in the Zagros area for the Early Permian Faraghan Formation. *See Table IV.5. for explanation of facies code and Figure I.2 for location of outcrops and wells.*


Time line (SB P3)
DS PIII
SB P2
DS PII
SB P1
DS PI
SB P0
50 m
25 m
0 m
PERSIAN GULF
FARS
BANDAR ABBAS
Faraghan Fm.
Zakeen Fm.
Seyahou Fm.
Late Ordovician
Pollen / Spore Ass. Zone P1 (Hamiapollenites - Vittatina) (Ghavidel Syooki, 1996)
Kungurian
Artinskian
Sakmarian
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
PALEOZOIC

V.2. Unconformities and major erosional surfaces

A cursory look at the Ordovician to Permian Palaeozoic stratigraphy of the Zagros area shows the presence of significant hiatuses separated by major unconformities (Fig. V.1).

Unconformity 1: In the Middle Ordovician, the First major unconformity (unconformity 1) marked the top of Tremadocian-Dapingian? Zard Kuh Formation (Fig. V.1). This unconformity spans from Fars (in Darang and Zirreh) (Ghavidel Syooki, 1993c) to Lurestan (in Kabir Kuh) (Ghavidel Syooki, 1994a). Ghavidel Syooki et al. (2014) focused on middle Ordovician hiatus in Kuh e Faraghan and they proposed a hiatus ranging from Dapingian to Early Darriwilian.
In comparison to neighboring area, unconformity 1 may be correlable with Middle Ordovician unconformity in Oman where the Middle Ordovician Saih Nihayda Formation is separated by a major unconformity from the Lower Ordovician Ghudun Formation (Droste, 1997).

Unconformity 2: In the Late Ordovician, the second major erosional surfaces (Unconformity 2) marked the top of the Floian-Katian Seyahou Formation (SB O7) (Fig. V.1). It present the onset of hiatus dated as top of Katian. Figure (V.1) shows the situation of this unconformity in the Zagros. It rests at the base of Silurian and span from Fars area (e.g. Darang and Zirreh) (Ghavidel Syooki, 1993c) to Lurestan area (Kabir Kuh) (Ghavidel Syooki, 1994a) (Fig. III.12). In Kuh e Surmeh and Kuh e Siah (Fars area), unconformity 2 marked the base of major hiatus ranging from Late Ordovician to Early Permian (445.2- 295.5 Ma) (Fig. V. 2).

At Kuh e Faraghan in Bandar Abbas area, the only place where Hirnantian Dargaz Fm. has been observed, unconformity 2 is an important unconformity (GES 1: Glacial Erosive Surface 1), which formed at the base of Hirnantian glaciogenic Dargaz Formation (Fig. V.1) (Ghavidel Syooki et al., 2011). The abrupt end of the Hirnantian (Ghavidel Syooki et al., 2011) is marked by an extensive marine flooding that deposited organic-rich shales in this area (Ghavidel Syooki et al., 2011). This indicates the base of the Early Silurian Sarchahan Formation (SB O8) and known as unconformity 2a in this study (Fig. V.1). Therefore, in comparison, in other parts of Zagros, as mentioned above, unconformities 2 and 2a has been fused as absence of Hirnantian Dargaz deposits.

In the Arabian Plate, unconformity 2 is correlated with major Arabian Plate sequence boundary at base of AP3 (Fig. V.1).

Unconformity 3: Third major unconformity (unconformity 3) (Fig. V.1) marked the top of Sarchahan Formation (SB S2). Biostratigraphical data (Ghavidel Syooki, 1995b) indicated Liandovery age for Sarchahan Formation (Ghavidel Syooki, 2003) (Fig. II.3). Unconformity 3 marked the hiatus spanning from Early Silurian up to Early Devonian from Fars area (Zirreh and Darang) to Bandar Abbas area (Kuh e Faraghan and Kuh e Gahkum) and Persian Gulf (Golshan). This unconformity is uplift of the Middle East area associated with epeirogenic movements (Berberian and King, 1981), probably Caledonian orogeny (Ghavidel Syooki, 2000; Ghavidel Syooki and Winchester-Seeto, 2004) and a major sea level drop (Al-Husseini, 1991, 1992; Haq and Al-Qahtani, 2005). It probably corresponds to unconformity at top of Sahmah Formation in Oman and top of Qalibah Formation in Saudi Arabia (Fig. I.4).

Unconformity 4: is Fourth major unconformity in the Zagros area (Fig. V.1). It is top of Devonian Zakeen Formation (SB D3) (Fig. II.3). Uncoformity 4 spans from Fars area (Zirreh, Naura, West Aghar, Dalan and Darang) to Bandar Abbas area (Kuh e Gahkum, Finu and Namak) and Persian Gulf (Kish and Golshan). It shows a hiatus spanning from Late Devonian (Famennian) to Early Permian (Fig. III.12). In Kuh e Faraghan in Bandar Abbas area, this erosional surface is at top of Frasnian stage (Ghavidel Syooki, 2003) (Fig. III.12). In Salman 2SKD#1, unconformity 4 marked the top of Middle Devonian deposits (Aria Nasab, 2011b). Unconformity 4 is probably correlated with major sequence boundary at base of AP4 of Sharland (2001), (Fig. V.1).

Following this unconformity, during Carboniferous period, an extensive regional exposure affected the entire Arabian Plate. This exposure corresponds to a 80 million years (Ghavidel Syooki, 2003) hiatus in Zagros. In comparison to the other parts of the Arabian plate, this hiatus correlated with megasequence AP4 of Sharland (2001) (Fig. V.1) and marked the Hercynian orogeny ranging from the Late Devonian up to the Carboniferous (Al-Hosseini, 1992; Sharland et al., 2001; Konert et al., 2001, Faqira et al., 2009), and the Late Carboniferous glaciation induced a general emergence of the region (Berberian and King, 1981; Al-Hosseini, 1992; Sharland et al., 2001; Konert et al., 2001).

Unconformity 5: The Fifth major unconformity (unconformity 5) spans throughout the Zagros area and is top of Kungurian stage in most part of the area (Fig. V.1). It marked the boundary between Early Permian Faraghan and Middle to Late Permian Dalan Formations (SB P3) (Fig. III.12). In Naura (Fars area) (Ghavidel Syooki, 1993b), Kish (Persian Gulf) (Aria Nasab, 2011a) and Kabir Kuh (in Lurestan) (Ghavidel Syooki, 1994a), unconformity 5 is located at top of Artinskian. It is top of Sakmarian in Zirreh (Fars area) (Ghavidel Syooki, 1993) (Fig. III.12). In comparison to Arabian Plate framework, unconformity 5 correlated with major sequence boundary (Pre-Khuff unconformity) at base of tectonomegasequence AP6 of Sharland (2001) (Fig. V.1).

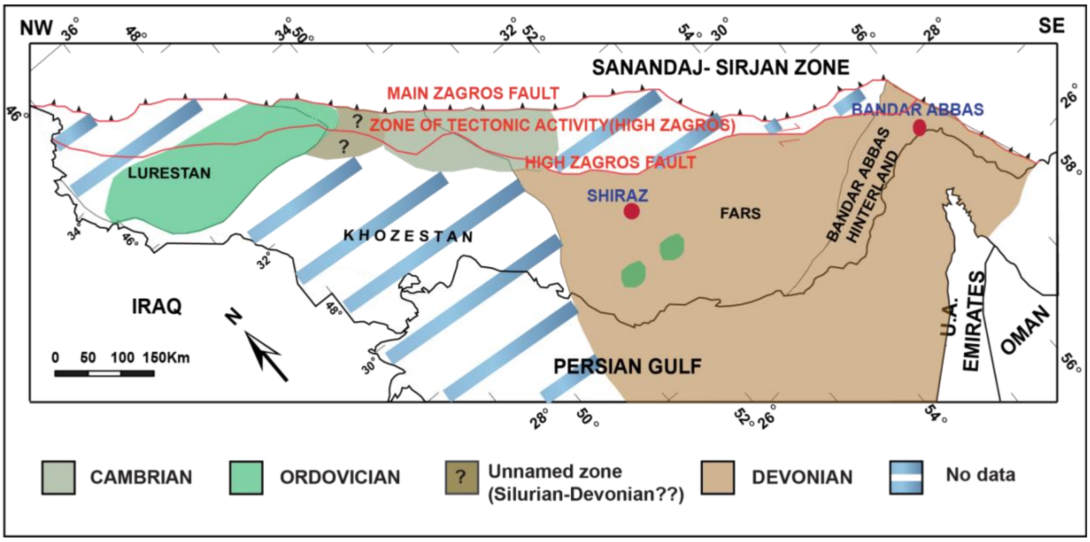


Fig. V.6: Hercynian subcrop map in the Zagros area. Occurrences of Devonian sequences are preserved under the Hercynian unconformity in Fas and Bandar Abbas areas. In other areas of the Zagros (e.g. Wast High Zagros), the Silurian, Devonian and Carboniferous are largely missing and older Palaeozoic rocks subcrop under the unconformity.

As a result, the Early Palaeozoic geological history of the Zagros and Arabian Plate may be summarized with four key events: (1) An extensional-Mid Ordovician rift pulse on the Arabian Peninsula and associated uplifts (Oterdoom, 1999); (2) A major sea-level fall at the end of the Ordovician related to the Hirnantian glaciation (Ghavidel-Syooki et al., 2011); (3) An uplift at the end of the Silurian associated with epeirogenic movements (Ala et al., 1980; Berberian and King, 1981; Al-Sharhan and Nairn, 1997) and (4) a major sea-level drop at the end of the Silurian (Al-Husseini, 1991,1992; Sharland et al., 2001; Konert et al., 2001; Haq and Al-Qahtani, 2005). This hiatus (Late Silurian) is recorded in Southeast Turkey, Syria, Iraq and Oman and probably corresponds to the “Pre Tawil Unconformity” in Saudi Arabia (Sharland et al., 2001).

The late Palaeozoic geological history of the Arabian Plate and Zagros area records three key events: (1) A Hercynian orogeny spending from the Early to Mid-Devonian up to the Early Carboniferous; (2) A Late Carboniferous-Early Permian glaciation; and (3) A Late Permian-Triassic Zagros Rift associated to a major Permian transgression (Al-Husseini, 1992).

The hiatus and the sedimentary record in Zagros questioned these key events. Figure (V.I) proposes a synthesis of the different controlling factors on sedimentation and erosion and is discussed as follow:

V.2.1. ***Eustatism as major control on sedimentation and unconformities***

As previously suggested the Floian-Katian Seyahou Fm. in Zagros correspond to a medium scale transgression belonging to a large Ordovician transgressive-regressive cycle. These deposits probably overlain a major deepening event in the Zagros Platform, recorded in

Kuh e Faraghan (Ghavidel Syooki et al., 2014) as a complete succession and corresponding to condensed horizon covered by an omission surface and representing non-deposition or starvation of Dapingian-lower Darriwilian ages. This gaps reported in the Seyahou Fm. are correlatable with gaps reported in Oman, Saudi Arabian and others areas (Ghavidel Syooki et al., 2014). This major deepening during the *Siphonochitina formosa* zone, is not preserved in Kuh e Surmeh but reported in Kuh e Faraghan where it may coincides with Nielsen's (2004) Helskjer Drowning Event and with the onset of a transgressive cycle (O30, MFS, Sharland et al., 2001) observed at the base of the Hanadir Mb, Qasim Fm. (Vaslet, 1990). The Ra'an Shales (Safiq Group) observed in Saudi Arabia are interpreted as deposited during a major MFS O40 (Sharland et al., 2001; Oterdoom et al., 1999) and may be compared with the flooding event observed in Kuh e Faraghan (DS O3). This deepening event is followed in the Arabian plate by a significant global sea-level fall (Vail et al., 1977; Sharland et al., 2001). This trend is not observed in Kuh e Surmeh where an abrupt interruption of the deep lower offshore deposition is observed. The preservation of Late Ordovician deposits in other Fars sectors (Kuh e Faraghan) and closed to the Kuh e Surmeh area, in Zireh#1 (30 km South of Kuh e Surmeh; Ghavidel Syooki, 1993c), Kuh-e Siah (160 km South of Kuh-e Surmeh; Tavakoli et al., 2013) may explain the global changes observed in depositional environments but do not allowed to precise the global characters and the role of the sea-level fall on local erosion as observed in Kuh e Surmeh.

The presence of Silurian Sarchahan and Devonian Zakeen Fms. traduces of several "flooding" event reaching the Iranian plates during the Silurian and Middle-late Devonian. Important lateral facies and thicknesses variations of Devonian Zakeen sandstones reservoirs and Silurian black shales source rocks are expected. It is indeed assumed that the Sarchahan Fm. contributed to huge gaz accumulations found in the Permo-Triassic Dalan and Kangan Fms. and underlying strata in Iran, Qatar and Saudi Arabia (Bordenave, 2008). A detail discussion on the distribution of the Silurian deposits is developed in Bordenave (2008), which insists on the development of anoxic conditions of the water column probably triggered by transgression events thanks to the melting ice cap of the end-Ordovician Hirnantian glaciation (Konert et al., 2001). The Zakeen Fm. is interpreted as a progradational-stacking pattern indicating an overall relative sea-level fall during the Middle to Upper Devonian (Zamenzadeh et al., 2009) and it has been compared with the Devonian deposits records in whole Arabian Plate (Al Laboun, 1990).

The description of the Faraghan Fm. in this study confirmed the presence of an angular unconformity covered by Early Permian deposits on older Palaeozoic. Because the unconformity follows a long-term hiatus in Zagros, this first continental to marine transitional facies coincides probably with the late Sakmarian flooding event (MFS P10, Sharland et al., 2001). The Faraghan Fm. therefore preserved a spectacular fossil example of a shoreline transgression from estuarine to a deltaic environment.

Results from the sedimentary record shows that when preserved, the successions follow a global pattern of sea-level variations. However, rapid and local lateral variation in thicknesses and the timing of the different unconformities are not reflected through these variations.

V.2.2. *Climate as major control on unconformity establishment*

The major unconformities may find part of its existence in the development of the Ordovician and Carboniferous glaciations (Fig. V.1). On the Arabian margin, the occurrence of Hirnantian glaciogenic rocks have been described in the Saudi Arabia (McClure, 1978; Hughes-Clark, 1988; Vaslet, 1990; Clark-Lowes, 2005), southern desert of Jordan (Turner et al., 2005; Armstrong et al., 2009), Oman (Hughes-Clark, 1988), and Turkey (Monod et al., 2003; Ghienne et al., 2010). The onset of Hirnantian tunnel valley networks allows a differentiation between the 'areas closest to the ice centre' (Algeria, Arabia, Jordan, Libya, and Mauritania; Ghienne, 2003; Le Heron et al., 2004; Ghienne et al., 2007; Armstrong et al., 2009) and 'ice-marginal areas' (e.g., Morocco and Turkey; Monod et al., 2003; Le Heron et al., 2007). Le Heron and Dowdeswell's (2009) argued that several separate ice sheets developed throughout North Gondwana, and not that a continuous ice sheet straddled North Africa-Arabia, South Africa, and South America. The existence of some satellite ice caps, sited on upland areas during the Hirnantian, has been recognised in platforms fringing North Gondwana (e.g., Le Heron et al., 2007; Gutiérrez-Marco et al., 2010). Although, the major glacigenic tunnel valleys was not identified in Zagros, but the exposures of the Dargaz Formation is recognised in Kuh e Faraghan in Bandar Abbas area by Ghavidel et al. (2011) and this work. None of these cycles have been observed in the other parts of the area where Ordovician deposits correspond to deep Floian/Katian offshore environments. However considering the NW position of Zagros area, ice-proximal strata may have been expected. The erosion unconformity (unconformity 2) of the upper part of the Ordovician deposits related to the Hirnantian glaciation. Whereas, unconformity 2a is related to flooding of the platform in most part of the Arabian Plate and corresponds to the erosion transgressive surface.

Carboniferous-Permian glaciations across the Gondwana were strongly diachronous (Le Heron et al., 2009) and well known in the Arabian Plate from Oman and Yemen (Kruck and Thiele, 1983). The glacially related events show a variable influence upon stratigraphy (Osterloff et al., 2004; Le Heron, et al., 2009). The absence of Carboniferous deposits in the Zagros Mountains and Arabian Peninsula indicates a very low sea-level due to the southern hemisphere glaciations (Golonka, 2000; Heydari, 2008). The glacial deposits of Oman and Saudi Arabia are considered as latest Carboniferous and Asselian/Sakmarian glaciolacustrine to glaciofluvial depositional environments (Martin et al., 2008; Le Heron et al., 2009). Whereas, evidence for Late Paleozoic glaciation are well described in Oman, Melvin and Sprague (2006) pointed out that there is no good referenced works for Saudi Arabia but they were able to present several evidences for glacial influence on sedimentation. The Lower Unazayah in the eastern central Saudi Arabia has confirmed that the effects of the Late Palaeozoic glaciation extended significantly north on the Arabian Plate on the central Arabian Arch (Melvin and Sprague, 2006). Droste (1997) insists on the role of repeated erosion by Late Carboniferous/ Early Permian Glaciations during which land ice covered Oman (Levell et al., 1988). The sedimentary records da Serpukovian initiation for the glaciation and the effects appear to have persisted through the lowermost Permian (Asselian-Sakmarian; Al-Husseini, 2004). In Zagros area, the first preserved deposits correspond to the Sakmarian/Kungurian near-shore environement previously described in this manuscript and following the NIOC palynology studies of Ghavidel Syooki (1996) and Ghavidel Syooki & Winchester-Seeto (2004), no Carboniferous deposits have been recognized in the Zagros. Therefore, despite the absence of glacial evidence in Zagros area, part of the erosion associated by the unconformity may be related to the impact of Carboniferous/Permian glaciations.

V.2.3. Local and regional tectonic as control on unconformity establishment

Throughout the Arabian plate, sedimentary hiatus separates the continental to shallow marine Permian sequence from the older sedimentary Formations (Johnson, 2008). The major unconformities may be related to several Palaeozoic tectonic events, all being considered as potential factor explaining the large hiatus record in the Zagros area.

A particularity of the Ordovician-Silurian transition in the Arabian margin was that the glacial incisions did not take place in a Gondwanan passive margin, like those recorded in northern Africa and southwestern Europe. To explain this absence, two Late Ordovician uplift episodes have been reported from Saudi Arabia: (i) a Katian episode in the Wajid plateau, documented by the uplift and deformation of the Dibsiyah Formation and the penecontemporaneous erosion of valley systems filled by the Sanamah Formation (Oterdoom et al., 1999); and (ii) a second uplift phase recognised across the Ordovician-Silurian boundary interval, marked in the same plateau by the onset of an angular unconformity separating the Sanamah Formation from the Qusaiba Member (Stump et al., 1993 and Stump and Van der Eem, 1995). In addition, in the Lut Block of Central Iran, the Ordovician-Silurian transition is associated with transtensive extension and syn-rift volcanism, as a result of which flood basalts of up to 500 m thick extended over 1000 km in areas that neighboured the Arabian margin and were an integral part of Gondwana during the Ordovician (Berberian and King, 1981, Al-Husseini, 1990, Millson et al., 1996, Sharland et al., 2001, Bagheri and Stampfli, 2008 and Torsvik and Cocks, 2008). The preservation in Kuh e Faraghan of the Hirnantian glacial deposits underplays the role of the Ordovician uplift for the whole Zagros area.

The late Silurian is poorly represented in the rock record in Arabian Plate and Zagros area (Al-Husseini, 1991). The specific tectonic event that causes regional this uplift and hiatus is poorly understood. Al-Husseni (1991) proposed a major global sea-level drop (Vail et al., 1977) combined with regional Silurian progradation resulted in a Late Silurian uplifting and the resulting erosion. Berberian and King (1981) linked this hiatus with Caledonian orogeny affected the North Atlantic region. They proposed Iran being far from this collision zone suffered only epeirogenic movements characterized by regional regression of the Silurian sea.

The hiatus and related unconformity is generally referred to the Hercynian unconformity (Sharland et al., 2001; Abu-Ali et al., 2005; Faqira et al., 2009) suggesting a relationship with the Hercynian orogeny affecting the Western Europe and north-western

Africa during the Carboniferous (Michard et al., 2010). Szabo and Kheradpir (1978) suggest Hercynian orogenetic activity for the unconformity described in top of Devonian (unconformity 4) in the Zagros area. Faqira et al. (2009) discuss the impact of a widespread deformation in the mid-Carboniferous record in Arabia. However, it does not imply that the Hercynian deformation was caused by the Hercynian collision in the north Atlantic region. Faqira et al. (2009) describe the structuration of the Arabian plate in arches and basins and discuss their impact on the petroleum system. They show that Silurian source rocks and Permian reservoirs are present only with the Hercynian basins. The regional pattern of the Hercynian subcrop in the Arabian Plate indicates that it underwent regional uplift and subsidence during the Mid-Carboniferous (Faqira et al., 2009). The facies and thickness variations in the Cambrian to Devonian section indicate that these mega-structures did not form prior to the Hercynian orogeny (Konert et al., 2001). Tavakoli et al. (2013) confirms the existence of an angular unconformity in the Central and High Zagros Belt below the Lower Permian Faraghan Formation. They describe an extensional deformation associated with this unconformity without evidence of compressional deformation. Tectonic architecture is not beyond the scoop of our manuscript, however the hypothesis proposed in literature insists on the non-consensual character of the Hercynian orogeny impact on neither sedimentation nor erosion. The model of Tavakoli et al. (2013) show deep erosion associated with the footwall of their normal faulting Lower Palaeozoic system. Therefore pre-Permian erosion (during the Carboniferous) resulted in removal of huge thickness of Palaeozoic deposits (at least the whole Silurian and Devonian in the central High Zagros Belt). Kohn et al. (1992) and Gavillot et al. (2010) based on thermochronologic data show that the Late Devonian- Early Carboniferous uplift of the whole Arabia and the High Zagros Belt was probably thermal and not tectonic in origin.

V.2.4. How to explain the absence of Silurian and Devonian deposits in Kuh e Surmeh

The presence of 108.8 m-thick Zakeen succession located 60 km (Naura #1 well) to the northeast; 122.3m-thick succession located 25 km (West Aghar #1 well) to the northwest and 85.3m-thick succession situated 50 km (Dalan #1 well) to the southwest of Kuh e Surmeh, and its absence in Kuh e Surmeh anticline argue for a local mechanism to explain at least part of the hiatus (Fig. V.7). The presence of shallow to deep marine sediments deposited during the Middle to Upper Devonian argues for the installation of marine conditions on the whole Iranian plate (Zamanzadeh et al., 2009). The absence of those Devonian deposits in the Kuh e Surmeh anticline again suggests that local mechanisms to may explain its erosion or non-deposition. More than 200 salt-related structures have been recognized in the southern Iranian Zagros and Persian Gulf area (Talbot and Alavi, 1996). Salt diapirs in the Zagros Fold-and-thrust belt are mainly confined to Fars Province (Motamedi et al., 2012). In the Southern Fars, most of the diapirs correspond to the Hormuz series and are observed in association with anticlines and few occurred along thrust faults as in central Zagros and Northern Fars (Sherkati and Letouzey, 2004; Callot et al., 2007). The age of Hormuz diapirism in the Zagros area has been subject to intense study (Harisson, 1930; Kent, 1958; Sherkati et al., 2005;

Callot et al., 2007; Motamedi et al., 2012). Despite a main Neogene age for salt intrusions, Kent (1970) and others (Sherkati and Letouzey, 2004; Callot et al., 2007; Jahani et al., 2009; Motamedi et al., 2012) suggest pre-orogenic salt motion that had a prominent role in determining the location of folds during the Neogene orogeny. Motiei (2003) based on seismic data proposed an early Permian age for some of them. Motamedi et al. (2012) show that the earliest phase of salt mobilization preceded the Silurian in the Kuh e Ghakum anticline as indicated by the presence of exotic clasts composed of salt in Hormuz series. In Kuh e Surmeh Anticline, the 10° unconformity between Permian and Ordovician Formations, the absence of Zakeen Formation preserved in closed neighbouring area, the presence of an extrusive diapir structure less than 5 km to the east and the deposition of Early Permian Faraghan Formation in the whole Fars Province and eastern High Zagros, argue for salt tectonics as the main control of Palaeozoic discontinuities in the Kuh e Surmeh area of Fars Province argue for a local doming of salt plug pre-dating the Faraghan Formation deposition. Except in Kuh e Surmeh area with a 36 m thick succession, deposits of the Faraghan Formation in Naura, West Aghar and Dalan#1 were observed with similar lithology and thicknesses (50-60 m). The reduced thickness of the Early Permian Faraghan Formation and the sedimentary record of the Kuh e Surmeh area suggest a probable salt diapir uplift processes with a doming phase continuing throughout the Early Permian (Fig. V.8).

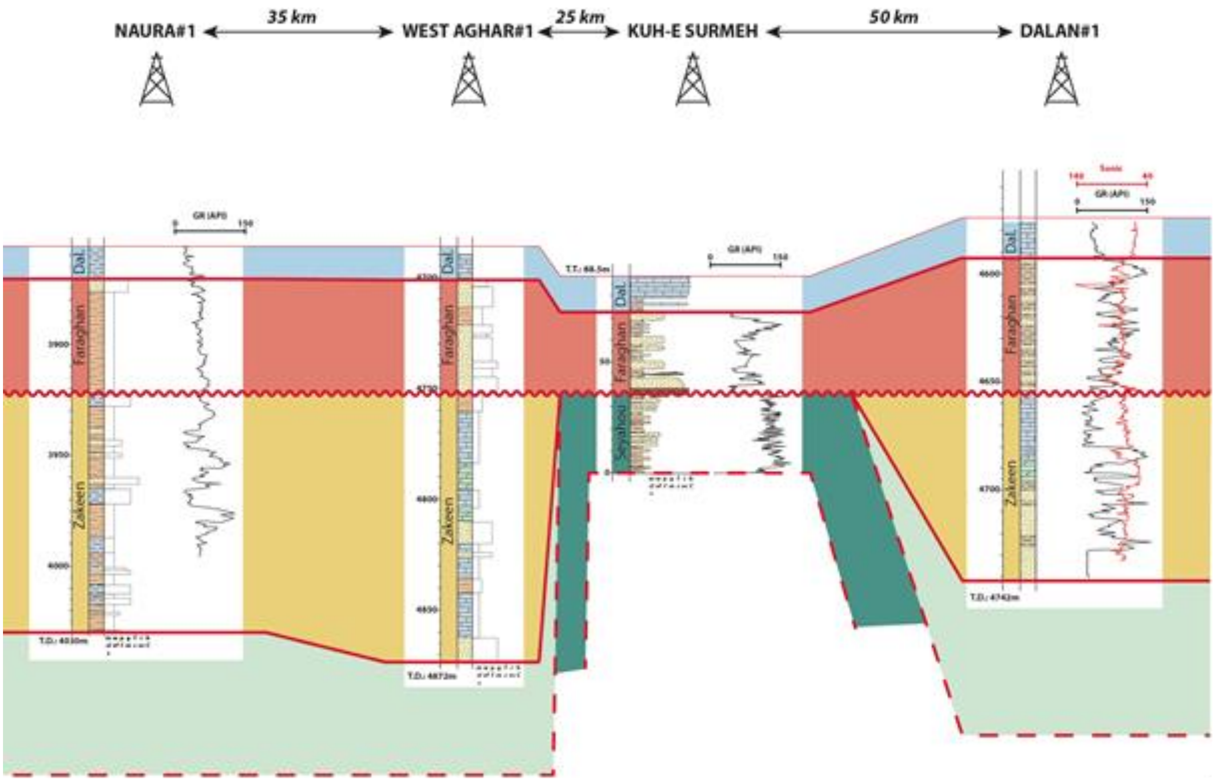


Fig. V.7: Stratigraphic correlation between Kuh-e- Surmeh, Naura#1, West Aghar#1, and Dalan#1. Evidenced of a large hiatus between Ordovician Seyahou and Permian Faraghan Fms in Kuh-e Surmeh where the Devonian Zakeen Fm. is lacking but well recorded in the other drilled sections.

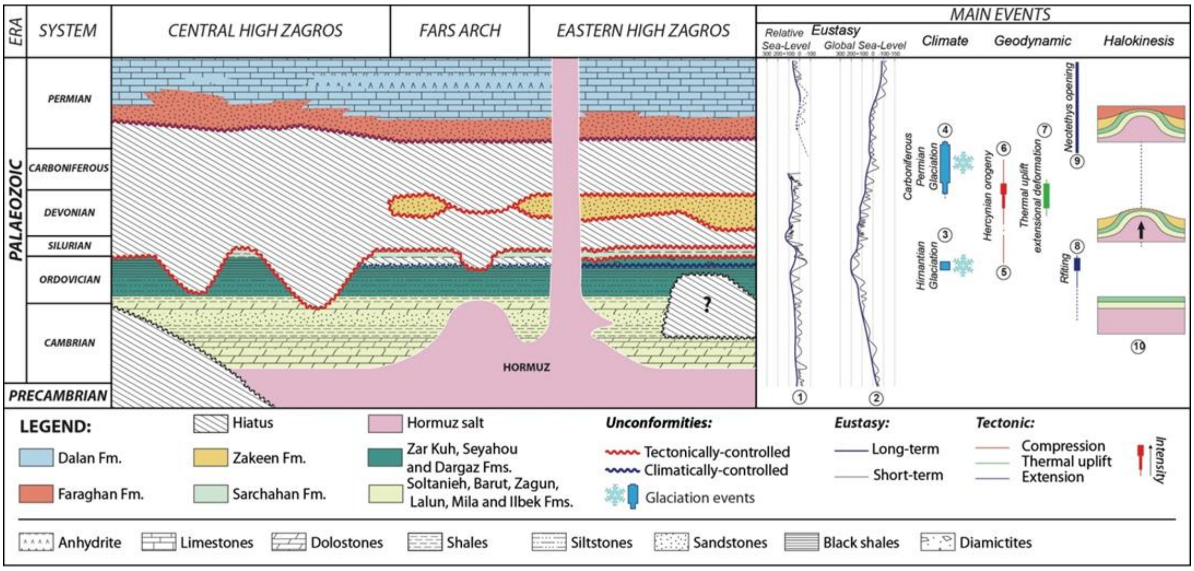


Fig. V.8: Synthesis of the main proposed controlling factors at the origin of the sedimentation and unconformities for the Palaeozoic of Central High Zagros, Fars Arch (Kuh e Surmeh), and Eastern High Zagros. For discussion: 1 & 2. Haq and Al-Qahtani (2005); 3. Le Heron et al. (2007, 2010), Ghienne et al. (2007), Ghavidel Syooki et al. (2011); 4. Golonka (2000), Al-Husseini (2004), Le Heron et al. (2009); 5. Bordenave (2008) ; 6. Konert et al. (2001); Bordenave (2008); 7. Tavakoli et al. (2013); 8. Oterdoom et al. (1999); 9. Muttoni et al. (2009); 10. This study.

V.2.5. How to explain the absence of Ordovician deposits in Kuh e Gahkum

The presence of 765 m-thick Ordovician deposits in Kuh e Faraghan anticline located 25 km to the south of Kuh e Gahkum, and its absence in Kuh e Gahkum anticline related to a local mechanism to explain the hiatus with Ordovician age (Fig. V.2).

A gentle deepening of environment of Palaeozoic succession from Kuh e Gahkum to Kuh e Faraghan (southward) is suggested on the basis of difference in the grain size and frequency of fine grained facies in both studied sections and presence of glauconite and absence of stromatolithic dolomites in the Kuh e Faraghan (Zamanzadeh, 2008; and this study). This result is also has been confirmed from palynological studies (Ghavidel Syooki, 1986). High tectonic activity in the source region is suggested to be responsible for periodic sediment supply to depositional sites of the Formations.

The emergent salt diapirs of the Zagros area are one of the geological wonders of the world (Frust, 1976; Kent, 1979). They are distributed in the southeastern part of the Zagros area. The Hormuz and equivalent series were deposited in an evaporate basin during the Neoproterozoic- Early Cambrian (Motiei, 2003). Coeval salt basin crop out in a large domain including the eastern Zagros, Persian Gulf, Oman, Qatar, Central Iran, Pakistan, and north-northwest India (Stocklin, 1968; Talbot and Alavi, 1996; Edgell, 1996; Al-Husseini, 2000; Konert et al., 2001). Kuh e Faraghan and Kuh e Gahkum affected by two fault segment namely, Faraghan and Gahkum. The core of these giant structures is made of Palaeozoic rocks in contact with the foreland basin deposits along dextral strike slip fault draped with Hormoz salt remnants (Jahani, 2008). For Kuh e Faraghan, he proposed that the core of the fold probably comes up as a flower structure (2600 m vertical offset). This vertical offset could be interpreted the local squeezing of a preexisting salt wall, forming then a vertical weld in the sense of M. Rowan. The absence of all Ordovician succession in the neighboring Kuh e Gahkum may be interpreted as a consequence of local salt dipair activity and structuration of salt-related structural high position (Jahani, 2008).

Initiation of movement of Hormuz salt occurred as early as the Lower Palaeozoic (Fig. V.9) i.e. just short time after the deposition of the Hormuz salt in the Zagros and Persian Gulf, and continued up to the Present. Almost continuous halokinesis strongly influenced on sedimentation with local uplift and downward during the whole Phanerozoic. It suggest thickness variation and facies changes in the litho-stratigraphic pile around and above buried salt diapirs (Jahani et al., 2009).

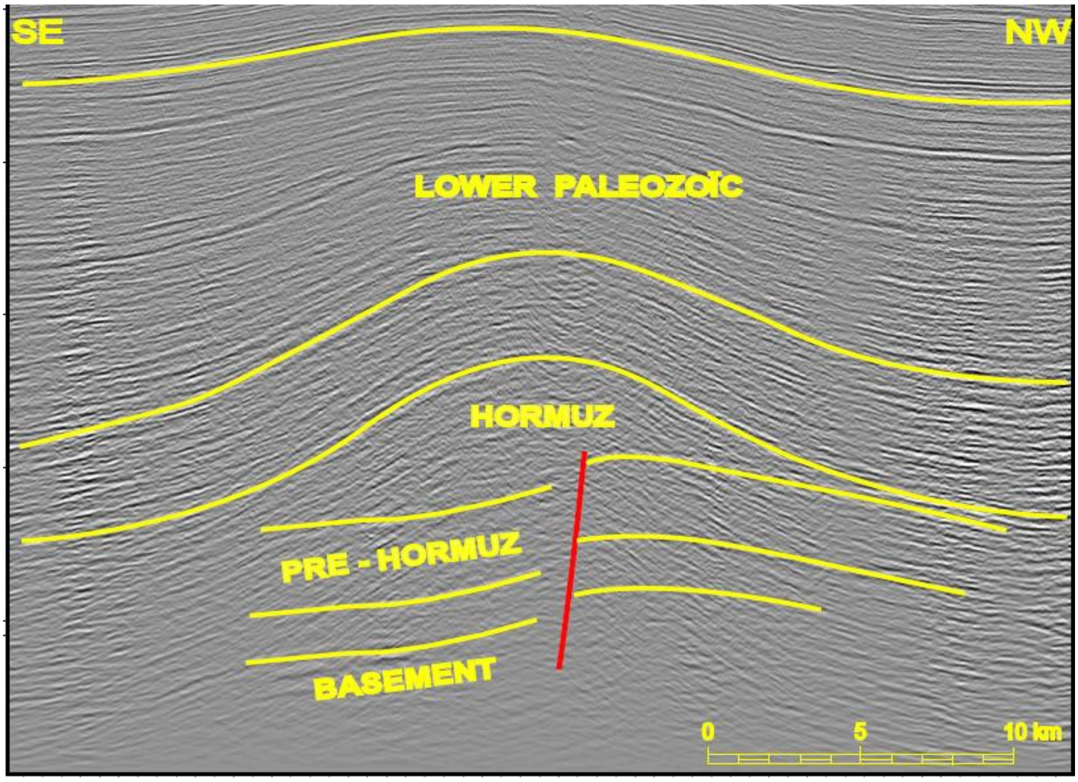


Fig. V.9: A close-up from top of the Hormuz salt and an underlying normal fault probably associated to the initiation of the salt pillow in Early Palaeozoic (Jahani et al., 2009).

Although the effect of salt diapirs in Kuh e Gahkum is not obsereved clearly, but the good example exists in Kuh e Handun (southward of Kuh e Gahkum) presented by Jahani (2008). Progradation and growth strata in Jahrum Formation shows salt plug formed a dome during Oligocene as well recycled Hormuz debris into Miocene rocks indicates salt come to the surface in the Handun salt plug (Fig. V.10). The absence of the Ordovician deposits in Kuh e Gahkum and its sedimentation in Kuh e Faraghan has the same geological history for Miocene deposits in Kuh e Handun (Fig. V.10).

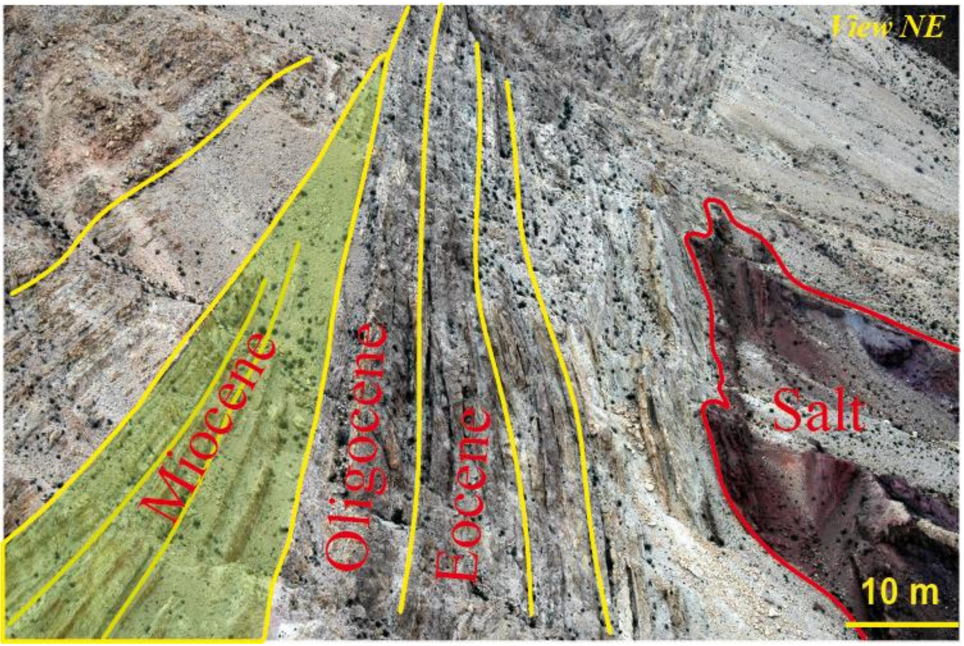


Fig. V.10: Progradation and growth strata in Jahrum Formation shows salt plug formed a dome during Oligocene as well recycled Hormuz debris into Miocene rocks indicates salt come to the surface in the Handun salt plug (Jahani, 2008).

Motamedi et al. (2011) proposed the missing of Ordovician deposits and presence of conglomeratic beds with exotic components derived from the Hormuz series in base-Silurian strata, suggest pre-Silurian phase of doming of Hormuz salt in the Kuh e Gahkum anticline.

In Kuh e Gahkum, Ghavidel Syooki et al. (2011) suggest a possible tunnel-channel shoulder, where deposition of the fan-shaped Sarchahan turbidite system was sourced from an inherited palaeorelief.

Tavakoli Shirazi et al. (2013) proposed the thermal uplift accompanying normal faulting for the pre-Permian geological history for Zagros area and Gahkum anticline. He suggested that the study area is not affected by far effect of the Variscan (Hercynian) orogeny. This suggestion has been confirmed by thermochronologic data got by Kohn et al. (1992) in the north-western end of Arabia as well as the preliminary results by Gavillot et al. (2010) in the Zagros area, show that the uplift of the whole Arabia as soon as the Late Devonian is most probably of thermal and not tectonic origin. Based on thermochronologic data presented by Tavakoli Shirazi (2012) and Tavakoli Shirazi et al. (2013), althought the age of the uplift seems to occur during the Late Devonian-Early Carboniferous, but the absence of some part of the palaeozoic succession and their thickness decreasing could be affected by this phenomenan in Kuh e Gahkum. The subsequent cooling of the lithosphere should be responsible for thermal subsidence and deposition of the Faraghan Formation by the Early Permian.

In this study for Kuh e Gahkum Anticline, proposed that the absence of Ordovician deposits preserved in neighbouring area (Kuh e Faraghan), the presence of an extrusive diapir structure just closed to the anticline, argue for salt tectonics as the main control of Palaeozoic discontinuities in the Kuh e Gahkum area causing a local doming of salt plug pre-dating the Sarchahan Formation deposition. The reduced thickness of the Early Silurian Sarchahan, Devonian Zakeen and Early Permian Faraghan Formations and the sedimentary record of the Kuh e Gahkum area suggest a probable salt diapir uplift processes with a doming phase continuing throughout the Palaeozoic (Fig. V.11).

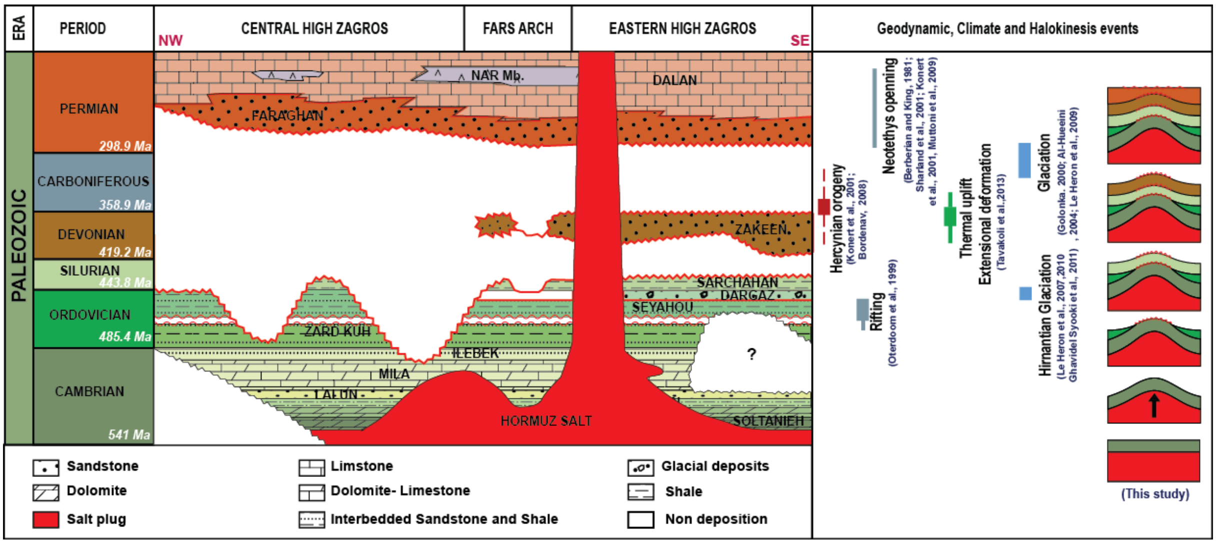


Fig. V.11: Synthesis of the main proposed controlling factor at the origin of the sedimentation and unconformities for the Palaeozoic of Kuh e Gahkun anticline.

CHAPTER VI – CONCLUSION

● The Ordovician deposits crop out in Kuh e Faraghan, north of Bandar Abbas area, as well as, in Kuh e Surmeh in Fars area of the Zagros region. Lithostratigraphically, the predominantly shallow-marine succession comprise the Seyahou Floian- Katian (Ghavidel Syooki et al., 2011) Formation which represents a shales, siltstones, sandstones and subordinate fossiliferous limestones developed in response to the Late Ordovician transgression. This unit topped unconformably by glaciogenic Dargaz (Hirnantian) (Ghavidel Syooki et al., 2011) Formations in Kuh e Faraghan and consists of diamictites and sandstones. Likewise the other part of the Zagros area, the Dargaz Formation is not present in Kuh e Surmeh.

Detailed facies analysis for the Seyahou Formation allowed determining eight facies (O1 to O8) which correspond to two main facies association and depositional environments that corresponds to proximal to distal platform: (i) Shoreface; and (ii) Offshore. The Dargaz Formation, a unit containing evidence for Hirnantian glaciation, contains four facies association. These are (i) glaciogenic diamictites facies association (Dz1 a and b); (ii) highly bioturbated thin bed sandstones and shales of the lagoon (Dz2); (iii) thick to massive horizontal lamination facies association (Dz3); (iv) cross-stratified beds sandstones shoreface facies association (Dz4); and (v) highly bioturbation thin bed hummocky cross stratification sandstones (HCS) upper offshore facies association (Dz5).

A sequence-stratigraphic framework has been specified for the Ordovician Floian- Katian strata of the Zagros area confirming one second-order supersequence, which is subdivided in six third-order sequences numbered from DS OI to DS OVII. It represents one of the best available stratigraphic reference models for the shallow-marine clastic deposits of this stratigraphic interval in northern part of the Arabian plate. In Dargaz Formation two small sequences have been recognised. They bounded by two glacial erosion surfaces (GES) recognised in the Dargaz Formation. These surfaces are related to the advance of an ice sheet and appear when outwash deposits directly overlie deposits of previous sediments.

In Kuh e Gahkum (eastward) and in west high Zagros (westward) of the Zagros area outcrops, the Late Ordovician deposits are not present. Two Early Silurian surface sections (Kuh e Faraghan and Kuh e Gahkum), situated in Bandar abbas area (Eastern part of the Zagros region), as well as, two subsurfaces sections (e.g. well Zirreh in Fars area and Well Golshan in Persian Gulf), have been studied in great detail applying an integrated lithostratigraphic approaoch.

● In Silurian, The mainly shallow to deep-marine succession comprise the the Early Silurian Sarchahan Formation, five main depositional environments evolving from proximal to distal platform: (i) Fan delta; (ii) Lagoon; (iii) Shoreface; (iv) Upper offshore; and (v) Deep offshore environments.

Three sedimentary unconformities (SB S0 to SB S2) have been recognized and well defined positions across the study area. These correlatable surfaces define two 3rd-order depositional sequences (DS SI and DS SII), each consisting of transgressive and high stand systems tracts (TST and HST).

The sequence boundary SB S0 is related to the post-glacial Silurian transgression that is observed in the Arabian plate and characterized by black and organic-rich shales. While, sequence boundary SB S2 related to an uplift in the Middle East area indicated epeirogenic movements (Ala et al., 1980; Berberian and King, 1981; Al-Sharhan and Nairn, 1997) and a major sea level drop (Al-Husseini, 1991, 1992; Sharland et al., 2001; Konert et al., 2001; Haq and Al-Qahtani, 2005) corresponds to a major hiatus recorded in Southeast Turkey, Syria, Iraq and Oman and probably corresponds to the "Pre Tawil Unconformity" in Saudi Arabia.

● The Devonian Zakeen Formation forms extend from Bandar Abbas area to Persian Gulf and correlated with Misfar Formation in Oman; Tawil, Juaf and Jubah Formations in Saudi Arabia. It unconformably (unconformity 3) overlies the Early Silurian Sarchahan Formation, and is unconformably (unconformity 4) overlain by the Early Permian Faraghan Formation. In Kuh e Surmeh outcrop and well Kuh e Siah in Fars area, and in west high Zagros (westward) of the Zagros Mountains outcrops, the Zakeen Formation are not present. In these places, the Early Permian deposits topped the Ordovician or older deposits.

Detailed facies analysis indicates that the Zakeen Formation records an incised valley estuarine system to alluvial and fluvial continental environments. The nature of the valley fill, dominated by tidal-generated depositional setting (mostly including tidal channels, tidal bars), strongly suggests an estuarine origin. Comparison of our depositional framework with core and well log data indicates the lateral facies change from more sandstones-dominated in the north (Bandar Abbas area), to more carbonate in the south (Fars and Persian Gulf) for Late Devonian.

The sedimentary fill within the estuary to shallow-marine environments constitutes a depositional sequence developed during a third order eustatic cycle of Vail et al., (1991). A sequence-stratigraphic framework and model has been defined for Zakeen Formation, distinguishing two orders sequences: one shallowing-upward second-order supersequences, which are subdivided in three third-order sequences (DS DI to DS DIII).

● The Early Permian Faraghan Formation is the widwspread siliciclastic and carbonate deposits deposited throughout the Arabian Plate and the Zagros area. It is the first succession that topped the Hercynian hiatus. In Zagros area, the Faraghan Formation capped the Devonian Zakeen Formation by an unconformity erosional surface (unconformity 4). In Kuh e Surmeh surface section and Kuh e Siah subsurface section (Fars area) and west High Zagros, Faraghan Formation rest on Late Ordovician or older deposits.

Based on facies relationship in Faraghan Formation, Six main depositional environments have been identified, that range from continental coastal plain to shallow marine platform: (i) Coastal plain; (ii) Estuary; (iii) Tidal flat and flood tide delta (iv) Lagoon; (v) Shoreface; and (vi) Upper offshore environments. These facies associations are named from F1 to F15, respectively.

In the Early Permian of the Zagros area, four unconformities and disconformities (SB P0 to SB P3) have been recognized. These correlable surfaces define three 3rd-order depositinal sequences (DS PI to Ds PIII), each consisting of transgressive and high stand systems tracts within a deepening-upward trend 2nd-order megasequence.

● Likewise the other parts of the Arabian Plate, the palaeozoic stratigraphic of the Zagros area is marked by numerous hiatus bounded by major unconformities. They are resuled from (i) A major sea level fall at the end of the Ordovician related to the Hirnantian glaciation (Ghavidel-Syooki et al., 2011); (ii) An uplift of the Middle East area at the end of the Silurian associated with epeirogenic movements (Ala et al., 1980; Berberian and King, 1981; Al-Sharhan and Nairn, 1997) and a major sea level drop (Al-Husseini, 1991,1992; Sharland et al., 2001; Konert et al., 2001; Haq and Al-Qahtani, 2005); (iii) The impact of the Hercynian orogeny spanning from the Late Devonian up to the Carboniferous (Al-Hosseini, 1992; Sharland et al., 2001; Konert et al., 2001, Faqira et al., 2009) and; (iv) major glacial episode of the southern Hemisphere (Golonka, 2000), the absence of carboniferous in the Zagros Mountains and the Arabian plate indicates a very low sea level due to the southern Hemisphere glaciations.

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ANNEXE 1

Regional lithostratigraphic correlation chart in Fars and Persian Gulf sub-surface sections correlated with Kuh e Gahkum, Kuh e Faraghan and Kuh e Surmeh surface sections