Holostratigraphy of the Berriasian - Aptian Carbonate Platform Deposits from the Zagros Fold-thrust Belt, SW Iran

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Le jury, signatures
The geological study presented in this thesis draws a new time-rock synopsis and stratigraphic framework for the studied succession, covering Berriasian to Aptian shallow-platform deposits in the Zagros fold and thrust belt, SW Iran. The dataset includes 19 outcrops and five subsurface wells located in the Bandar Abbas Hinterland to the East and the Dezful Embayment, Khuzestan area, to the West. Acquired data pertain to biostratigraphy, facies interpretation, lithostratigraphy, sequence stratigraphy, chemostratigraphy (carbon-oxygen and Sr-isotopes) and outcrop gamma-ray spectrometry.

From the Late Triassic to the Early Cretaceous, the Zagros region was located on the extensional, passive Neo-Tethyan margin of the Arabian Plate. Shallow-platform, tropical carbonates precipitated in an area now located in southeast Zagros (Fars and Khuzestan areas), while pelagic facies were deposited in the Lurestan area.

A new lithostratigraphic nomenclature is introduced: extant units, as established by the authors, are re-defined and new units are formally delimited, in accordance to the regulations issued by the International Commission on Stratigraphy. As a result, in its type-locality of the Izeh zone in the Khuzestan area, the Fahliyan Formation is subdivided into three units, namely the Fahliyan Formation spanning the Berriasian and the earliest Valanginian, the Sar Bisheh Formation (Valanginian) and the Ghari Formation (Hauterivian). Laterally, onshore and offshore in the Fars High and Bandar Abbas Hinterland, Haurterivian and Aptian deposits previously assigned to the Gadvan and Dariyan formations are assigned to the new Chahoo Formation. The limits of these units correspond to Type I and/or Type II sequence boundaries which are traceable and correlated over considerable lateral distances from the type locality.

A new regional biostratigraphic pattern including 12 biozones is put forward for the studied shallow-platform deposits. It is based on benthic foraminifera, dasycladalean algae and tintinnids, and cross-checked with Sr-isotope dating. This biostratigraphic scheme enabled us (1) to separate the Berriasian, Valanginian, Haurterivian and Barremian stages, and (2) to detect regional unconformities across the platform. It reveals the presence of two regional unconformities, one at base of the Berriasian and the other at top of the Valanginian. The first one separates the Upper Jurassic Hith / Surmeh Formation from the newly defined Fahliyan Formation. It becomes younger from the west (Izeh Zone, Khuzestan) towards the south-east (Fars High, Bandar Abbas Hinterland). The second unconformity is recorded at top of the Sar Bisheh Formation and time equivalent to the upper part of the Fahliyan Fm. It becomes older from the west (Izeh Zone, Khuzestan) towards the south-east (Fars High, Bandar Abbas Hinterland). These unconformities call for the presence of paleo-highs, whose origin may be due either to regional uplifts of the Arabian Plate (such as for the Qatar Arch), or local tectonic activities such as basement faults and/or salt diapirs. These paleo-highs are distributed only in the Fars area and Bandar Abbas Hinterland, e.g. at Assaluyeh, Genow, Kalagh, Khartang, Khurmoj and Surmeh. The presence of Haurterivian deposits is proved for the first time in the Zagros FTB, in the lower part of the Gadvan Formation and time-equivalent deposits assigned to the new Ghari Formation.

Depositional environments call for inner to mid-platform settings during the Berriasian and Valanginian, except for the Bandar Abbas Hinterland and offshore area containing basinal deposits with tintinnids and radiolarians, evidencing for a drowning (very fast flooding) event. Mid-platform to slope depositional environments occurred during the Haurterivian and Barremian in the Khuzestan and western parts of Fars area, while at the same time the eastern parts of Fars, Bandar Abbas Hinterland and offshore area, still record an inner platform setting, representing the back-stepping response to sea-level rise and the migration of the platform margin towards the east. This period coincides with significant siliciclastic input from the west.

Facies maps show that the platform geometry varied both in time and space, due to local tectonic activity and global sea-level changes, resulting in four evolutionary stages of platform growth: rimmed platform during the Early - Middle Berriasian, rimmed isolated platform in the Middle Berriasian to earliest Valanginian, non-rimmed open platform to open sea ramp in the Valanginian, and finally mixed siliciclastic-carbonate platform to open sea ramp in the Haurterivian and Barremian. Trophic levels, as deducted from the biofacies fit the carbonate platform geometry: photozoan ecosystems correspond to rimmed platform during the Berriasian and earliest Valanginian, while heterozoan carbonate factories coincide with a ramp during the Haurterivian and the Barremian.
Sequence stratigraphic analyses (T-R sequences) call for the presence of five large-scale, assigned 2nd-order sequences, subdivided in 17 small-scale, assigned 3rd-order sequences, throughout the studied succession. In ascending order, the large-scale sequences respectively cover the Berriasian and earliest Valanginian, the Valanginian, the Hauterivian, the early Barremian to late Barremian pro parte, and the late Barremian pro parte to early Aptian. Globally, these high and low-frequency sequences match the relative sea-level curve so far proposed by the authors for the Arabian Plate. Regionally however, large differences are observed among the number of small-scale sequences over a short lateral distance. Based on the literature, these differences may result from: (1) autocyclic processes hiding or overprinting the effect of global sea-level change on the platform, or (2) the presence of missing/non-deposition intervals at the boundary of small-scale sequences. Another possible interpretation is that the Fahliyan platform became broken up, and is suggested by its step-like morphology enabling to recognize geometries interpreted as lowstand systems tracts for large-scale sequences in the platform. In the Khuzestan and Bandar Abbas areas, results show the effect, of two basement fault zones, namely the Kazerun zone located at the boundary between the Khuzestan and Fars areas, and the Hendurabi zone at the border between the Fars and Bandar Abbas Hinterland areas. These zones were responsible for local increases of accommodation space during the Berriasian, Valanginian and Barremian. In the Fars area, on the other hand, sedimentation was controlled by the Qatar High during the Berriasian, the Valanginian and the Barremian. During the Hauterivian, thickness variations were governed by carbonate production potentials typical of the inner part of the platform in the Bandar Abbas Hinterland, and of the platform margin in Khuzestan.

Seventy chemostratigraphic analyses ($\delta^{13}$C and $\delta^{18}$O) were carried out on samples from two outcrops (Fahliyan and Gadvan). They revealed episodes of global carbon-cycle perturbations which are reported for the first time from this area. The principal episode corresponds to the Weissert Event, dated from the Early to Late Valanginian boundary. It is characterized by a distinct positive carbon-isotope excursion (>2.03 ‰ in $\delta^{13}$C) and, as shown by $\delta^{18}$O records, it is associated with warm climate conditions and expanding oxygen-depleted zones suggesting a possible anoxic event. The presence of this environmental change is confirmed by a biotic crisis that occurred regionally in the same interval. Some possible mechanisms for the Valanginian Weissert Event in this part of the Tethyan domain, comprising both global and local factors are discussed in details.

Finally, the role of uranium (U), thorium (Th) and potassium (K) on the total gamma-ray values in the deposits was systematically investigated on 3448 points using a portable gamma-ray (GR) spectrometer. Results show that the presence of Th and K is associated with the siliciclastic fraction and clay content, usually in marls and marly limestones. On the other hand, the U values do not follow the lithology, showing no significant correlation with the Th and K contents. Consequently, and as shown by a strong corresponding correlation coefficient, the total GR values are controlled by the U content. Comparatively, Th and K values are still significant, but show a far lower correlation index. In an effort to better understand the relationships between the GR signal and the total amount of organic carbon (TOC), 30 samples were analyzed using a Rock-Eval device. As a result, very low values of the U/TOC ratio were recorded in the studied shallow-platform carbonates, revealing that the amount of total and authigenic U does not follow the TOC, and suggesting that, in carbonate-dominated systems, the U content cannot be used as proxy for the amount of organic matter.

**Key-words:** Zagros, Iran, Shallow-Platform, Berriasian, Aptian.
Ce travail de thèse porte sur la stratigraphie des calcaires de plate-forme du Crétacé inférieur, affleurant dans une vaste région du sud de l’Iran, dans les montagnes de la chaîne plissée du Zagros. L’étude porte sur 19 affleurements et cinq puits pétroliers, couvrant au total une période allant du Berriasien à l’Aptien. La région étudiée est large de plus de 1'000 km, géographiquement entre le Khuzestan à l’ouest et la région de Bandar Abbas à l’est soit, d’un point de vue paléogéographique, du Golfe de Dezful (Dezful Embayment) à l’Arrière-pays de Bandar Abbas (Bandar Abbas Hinterland). Les méthodes systématiquement employées sont la biostratigraphie, l’interprétation des faciès, la lithostratigraphie, la stratigraphie séquentielle et la radioactivité. Accessoirement, les travaux portent sur la géochimie, avec les isotopes du carbone, de l’oxygène et du strontium, et la matière organique.

Dès le Trias supérieur et au Crétacé inférieur, la région du Zagros était située en zone tropicale, sur la marge néo-téthysienne, passive et extensive, de la Plaque Arabique. Des calcaires de plate-forme peu profonds se déposaient dans une région actuellement située dans le sud-est du Zagros, dans le Fars et le Khuzestan, alors que des sédiments pelagiques se déposaient plus à l’ouest, dans le Lurestan.

La nomenclature lithostratigraphique existante est révisée, dans le sens que la distribution des unités telles que définies par les auteurs est modifiée et de nouvelles unités sont formellement introduites, en accord avec les règles de la Commission Internationale de Stratigraphie. Partant de sa localité-type située dans le domaine de la Zone d’Izeh dans le Khuzestan, la Formation de Fahliyan est subdivisée en trois unités, à savoir la Formation de Fahliyan (nouvelle version) datée du Berriasien et du Valanginien basal, la Formation de Sar Bisheh (nouvelle) datée du Valanginien, et la Formation de Ghar (nouvelle) datée de l’Hauterivien. Latéralement, sur terre et sur mer (offshore) dans les domaines du Haut Fars (Fars High) et de l’Arrière-pays de Bandar Abbas (Bandar Abbas Hinterland), les dépôts d’âge Hauterivien et Aptien attribués auparavant aux formations de Gadvan et Dariyan, sont rattachés à la nouvelle Formation de Chahoo, datée de l’Hauterivien, du Barrémien et de l’Aptien. Ces nouvelles unités sont encadrées par des limites de séquences transgressives / régressives (T/R sequences), marquées ou non par des dépôts subaériens ou des lacunes et servant de base à des corrélations portant sur des distances considérables.

La biostratigraphie des dépôts de plate-forme s’articule en 12 biozooïdes fondée sur les foraminifères benthiques, les algues dasycladales et les tintinnides. La chronologie, fondée sur la littérature, est vérifiée par des analyses isotopiques du strontium. Elle conduit (1) à différencier les étages du Berriasien, Valanginien, Hauterivien et Barrémien, et (2) d’identifier deux discontinuités régionales, l’une à la base du Berriasien, l’autre au sommet du Valanginien. La première discontinuité sépare le Jurassique supérieur, avec les formations de Hith / Surmeh, de la Formation de Fahliyan, telle que nouvellement définie. Partant de l’ouest (Zone d’Izeh dans le Khuzestan), elle devient progressivement plus jeune en direction du sud-est, dans les domaines du Haut Fars et de l’Arrière-pays de Bandar Abbas. La seconde discontinuité est placée au sommet de la Formation de Sar Bisheh et de son équivalent latéral, la Formation de Fahliyan, nouvelle version. Partant de l’ouest (Zone d’Izeh), elle devient progressivement plus ancienne vers le sud-est, en direction du Haut Fars et de l’Arrière-pays de Bandar Abbas. Ces discontinuités sont dues à la présence de haut-fonds structuraux (paleo-highs) dont la présence peut être attribuée soit à des bombements structuraux de la Plaque Arabique analogues à l’anticlinalium du Qatar (Qatar Arch), soit à des accidents affectant le socle, soit encore à des diapirs de sel (halokynèse). L’effet de tels haut-fonds structuraux est toutefois enregistrée uniquement dans le Fars et l’Arrière-pays de Bandar Abbas, par exemple dans les régions d’Assaluyeh, Genow, Kalagh, Khartang, Khurmoj et Surmeh. Pour la première fois, la présence de l’Hauterivien est prouvée dans la chaîne du Zagros, dans la partie inférieure de la Formation de Gadvan ainsi que dans des dépôts synchrones placés dans la nouvelle Formation de Ghar (anciennement la partie supérieure de la Formation de Fahliyan).

Au Berriasien et au Valanginien, les milieux de dépôt sont partout du type plate-forme moyenne (mid-platform), à l’exception de l’Arrière-pays de Bandar Abbas ainsi qu’en mer (offshore) où la présence de tintinnides et de radiolaires fait état d’une période d’inondation (drowning). A l’Hauterivien et au Barrémien, dans le Khuzestan ainsi que dans la partie occidentale du Fars, les milieux sont également ceux d’une plate-forme moyenne, alors que dans la partie orientale du Fars ainsi que dans l’Arrière-pays de Bandar Abbas et en mer (offshore), les milieux sont ceux d’une plate-forme...
interne correspondant à une rétrogradation et migration en direction l’est, en réponse à une élévation du niveau de la mer. Cette même période coïncide avec un afflux significatif de matériel silicoclastique provenant de l’ouest.

Les cartes de faciès montrent qu’en raison de l’activité tectonique susmentionnée et des variations globales du niveau de la mer, la géométrie de la plate-forme a évolué à la fois dans le temps et l’espace, produisant les quatre étapes suivantes: plate-forme à rebord (rimmed platform) au Berriasien inférieur et moyen; plate-forme isolée à rebord au Berriasien moyen et au Valanginien basal; plate-forme ou rampe en mer ouverte au Valanginien; plate-forme ou rampe mixte, silicoclastique et carbonatée, à l’Hauterivien et au Barrémien. Les différents niveaux trophiques, tels que déduits de l’étude des biofaciès, s’accordent avec la géométrie de ces différentes étapes, à savoir que les éco-systèmes du type photozoan sont présents dans les plate-formes à rebord du Berriasien et du Valanginien basal, alors que ceux du type heterozoan correspondent aux rampes carbonatées de l’Hauterivien et du Barrémien.

L’analyse des cortèges transgressifs et régressifs de dépôt (T-R sequences) montre la présence, dans l’ensemble de la région étudiée, de cinq grandes séquences, considérées de 2ème ordre, et de 17 séquences de moindre importance, considérées de 3ème ordre. Successivement, les grandes séquences intéressent le Berriasien et le Valanginien basal, le Valanginien, l’Hauterivien, le Barrémien inférieur et supérieur pro parte et, finalement, le Barrémien supérieur pro parte suivi de l’Aptien inférieur. Dans l’ensemble, ces séquences correspondent aux variations du niveau de la mer telles que publiées par les auteurs pour la Plaque Arabique. À l’échelle régionale toutefois, le nombre de petites séquences varie considérablement d’un endroit à l’autre, même sur de modestes distances. Citant certains auteurs, de telles différences peuvent s’expliquer (1) par des processus autocycliques masquant ou se substituant, en milieu de plate-forme, à l’effet des variations générales du niveau de la mer, (2) par la présence de lacunes de dépôt à la limite de certaines séquences de moindre importance. Ici, il est fait état d’une autre hypothèse: la plate-forme de Fahliyan devint morcelée, comme suggéré par les différentes étapes de sa morphologie. Par conséquent, certaines séquences à grande échelle reconnues sur la plate-forme peuvent être interprétées en termes de cortèges de bas niveau. Au Berriasien, au Valanginien ainsi qu’au Barrémien, on observe localement les effets de deux accidents du socle, la zone de Kazerun à la frontière entre le Fars et le Khuzestan, et la zone de Hendurabi, à la frontière entre le Fars et l’Arrière-pays de Bandar Abbas. Toutes deux sont responsables d’une augmentation de la subsidence, alors que dans la région du Fars, la sédimentation demeurait sous l’influence de l’anticlinalorium du Qatar (Qatar Arch). À l’Hauterivien enfin, les variations d’épaisseur résultent du différentiel de production de sédiments carbonatés (carbonate factory) typique de la marge de plate-forme dans le Khuzestan et, d’autre part, de la plate-forme interne dans l’Arrière-pays de Bandar Abbas.

Des analyses isotopiques ($\delta^{13}$C et $\delta^{18}$O) ont été entreprises sur 70 échantillons prélevés dans les affleurements de Fahliyan et de Gadvan. Les résultats montrent la présence de perturbations du cycle du carbone enregistrées pour la première fois dans la région. L’épisode principal correspond à l’Événement Weissert (Weissert Event) daté de la limite entre le Valanginien inférieur et supérieur. Il s’agit d’une excursion positive de plus de 2.03‰ de la courbe de $\delta^{13}$C, associée comme le montrent les valeurs de $\delta^{18}$O, à une augmentation de la température ainsi qu’à un déficit en oxygène suggérant un événement anoxique. Ce changement de milieu est confirmé par la présence concomitante d’une crise biotique d’extension régionale. Plusieurs hypothèses, nouvelles ou fondées sur la littérature, sont envisagées pour expliquer l’Événement Weissert tant à l’échelle globale que régionale.

Enfin, 3448 points de mesure au total ont été enregistrés au moyen d’un spectromètre portable gamma, un appareil qui différencie, suivant leurs longueurs d’onde respectives, la part des éléments radioactifs de l’uranium (U), du thorium (Th) et du potassium (K) dans le signal total. Les résultats montrent que la présence de Th et K est associée à la fraction silicoclastique du sédiment, habituellement dans les marnes et les calcaires marneux. Les valeurs de U sont toutefois indépendantes de la lithologie, les coefficients de corrélation montrant qu’il n’y a pas de rapport clair avec les valeurs de Th et K, qui peuvent être importantes. Ainsi, l’amplitude du signal gamma total est essentiellement contrôlée par la quantité d’uranium. Pour mieux comprendre les rapports pouvant exister entre le signal gamma et la quantité de Carbone Organique Total (TOC), une sélection de 30 échantillons de calcaires de plate-forme a été pyrolisée dans un appareil Rock-Eval. Les rapports U/TOC, toujours très faibles, montrent que les quantités d’U total et authigène sont indépendantes du TOC, suggérant que dans un système essentiellement carbonaté, la teneur en U ne peut être mise en rapport avec Carbone Organique Total.

Mots-clé: Zagros, Iran, Plate-forme carbonatée, Berriasien, Aptien.
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  and

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Introduction

1.1 Morphology, topography and climate of Iran

Geographically, Iran is located in West Asia and has borders with the United Arab Emirates, Qatar, Bahrain, Kuwait, Iraq, Turkey, Armenia, Azerbaijan, Turkmenistan, Pakistan and Afghanistan (Fig. 1.1). Iran lies to the NE of the Arabian Peninsula, and has a contrasting geography with two important mountain chains, the Alborz with an E-W orientation in the North and the Zagros with NW-SE trend in the South-West. The eastern part of the land contains two salt deserts, Dasht-e Kavir and Dasht-e Lut (Fig. 1.1). The average elevation in the central part of the land is around 900 m above sea-level, while in the Zagros Mountains there are several peaks which exceed more than 3000 m above sea-level (Fig. 1.2).

Iran has two lowlands, the Khuzestan Plain in the SW and the Caspian Sea Coastal Plain in the North, just a few meters above sea-level and always covered by marshes.

Iran has a very variable climate. The northwest part has heavy snowfall and freezing in the winter and relatively mild weather in the fall and spring. In contrast, the southern part has mild weather in the winter and very hot and dry conditions in the summer with temperatures of more than 60 °C. In summer, the margins of both the Caspian Sea and the Persian Gulf (Bandar Abbas and Khuzestan) contain high humidity.

The average precipitation in Iran is around 250 mm/year, but in the valleys of the Zagros Mountains and along the margins of the Caspian Sea, it reaches up to 500-1000 mm/year.

Less than 7% of Iran is covered by forests (such as: oak, ash, elm, cypress) that are found mostly in the mountains at the margin of the Caspian Sea. Other parts of the land have wild plants and shrubs that appear in the spring, but the summer sun burns them away.

Fig. 1.1: General topography and relief map of Iran, showing major mountain chains and depressions (modified from Pirouz, 2013).
1.2 A brief tectonic history of the Zagros region

The Arabian Plate, the Zagros basin (Iran, Iraq), the Taurus Mountains (Turkey), the Levant (Syria) and North Africa correspond to the former northeastern margin of Gondwana (Sharland et al., 2001; Kendall et al., 2010) (Fig. 1.3).
The geodynamic evolution of the Zagros region can be described as follows (Fig. 1.4):

1) During the Early Paleozoic, the Zagros region was part of the passive margin of Gondwana at the edge of the Palaeo-Tethys Ocean (Berberian and King, 1981) or ProtoTethys (Stampfli and Borel, 2002) to the north. The oldest exposed deposits belong to the Hormuz Formation (salt), and are of Late Cambrian age (Player, 1969). They reach a thickness of 2000 m in the eastern Fars, Bandar Abbas Hinterland and offshore area (Talbot and Alavi, 1996; Sepehr and Cosgrove, 2005; Jahani, 2009).

2) Rifting along the eastern margin of the Afro-Arabian plate was initiated during the Late Carboniferous to Permo-Triassic boundary (Stampfli and Borel, 2002). This event and the associated basaltic volcanic activity led to the opening of the Neo-Tethys Ocean between the Arabian Plate and the Eurasian Plate (which included the Iranian micro-plate).

3) In the Late Triassic, the Palaeo-Tethys Ocean was subducted (Stampfli et al., 2001). Therefore, during this event (the subduction), the Central Iran and Sanandaj-Sirjan microcontinents were separated from Gondwana and positioned along the southern margin of the Eurasian Plate (Glennie, 2010).

4) The oceanic crust of the Neo-Tethys began to be subducted beneath the Eurasian Plate/Iranian micro-plate during the latest Jurassic to Early Cretaceous (Stampfli and Borel, 2002; Alavi, 2004, 2007), and the first emplacement (obduction) of the Neo-Tethys oceanic slivers (ophiolites) over the Afro-Arabian passive continental margin occurred in the Late Cretaceous (Alavi, 2004, 2007; Piryaei et al., 2010). The final continent-continent collision probably occurred in the Middle Tertiary. However, the exact timing of this event is still under discussion (Alavi, 2004; Agard et al., 2005; Mouthereau et al., 2007; Allen and Amstrong, 2008; Ballato et al., 2011; Pirouz, 2013).

The Arabian Plate comprises passive margins at the southwest and southeast, while the northern and north-eastern boundaries are compressional due to the collision of the Arabian Plate with the Turkish and Iranian continents (Jassim and Goff, 2006).

Therefore, the Zagros Basin is defined as lying between the Arabian Plate in the west/southwest and the Eurasian Plate in the east and north (Falcon, 1967; Takin, 1972; Stocklin, 1968; Berberian and King, 1981; Jackson and McKenzie, 1984; Alavi, 1994; Talbot and Alavi, 1996).

1.3 Sedimentary-tectonic subdivisions of the Zagros region

The Zagros region is subdivided into three major zones with a NW-SE trend including (1) the Uromieh-Dokhtar magmatic zone, (2) the Sanandaj-Sirjan metamorphic zone, and (3) the Zagros sedimentary rocks (Zagros fold-thrust belt) (Fig. 1.5). The Zagros FTB can be further subdivided into four major structural units: (1) the Zagros imbricated belt, (2) the Zagros simply folded belt, (3) the Zagros foredeep, and finally (4) the Mesopotamian-Persian Gulf (Fig. 1.6).

Based on the position of N-S trending, strike-slip basement faults, which were active before the final collision (Berberian, 1995), the Zagros fold-thrust belt can be subdivided in four zones: the Bandar Abbas Hinterland, the Fars (Interior Fars, Subcoastal Fars, and Coastal Fars), the Khuzestan (Dezful Embayment, Abadan Plain, Izeh Zone), and the Lurestan (Motiei, 1993) (Fig. 1.7).

The Zagros region was thus located on the passive Neo-Tethyan margin of the Arabian Plate from the Late Triassic to the Early Cretaceous. On this margin, the sedimentation pattern was controlled by major basement faults trending in both N-S and E-W directions. Shallow platform carbonates were deposited in the Fars and Bandar Abbas areas in the East, whereas deeper pelagic marls accumulated in the Lurestan region in the West (Setudehnia, 1978; Sepehr and Cosgrove, 2005) (Fig. 1.8).
Fig. 1.4: Paleozoic and Mesozoic plate tectonic model showing the evolution of the Southern Tethys Ocean closure, the Middle East (Arabian Plate) and North Africa. Location of the Zagros Basin is shown by a red asterisk (modified from Stampflí and Borel, 2002).
Introduction

Fig. 1.5: Main subdivisions of the Zagros region, SW Iran (modified from Berberian, 1995).

Fig. 1.6: Subdivisions of the Zagros fold-thrust belt, SW Iran (modified from Berberian, 1995).

Fig. 1.7: Local subdivisions of the Zagros fold-thrust belt and the location of some basement faults (modified from Motiei, 1993).
1.4 Description of the project

This research is a multi-proxy investigation, including a revision of the lithostratigraphic nomenclature, high-resolution biostratigraphy, chemostratigraphy, and regional sequence stratigraphic analysis of the Lower Cretaceous shallow-platform carbonate deposits of southwest Iran, in the Zagros FTB. The studied sedimentary succession includes the Fahluyan and Gadvan formations, ranging in age from the Barremian up to the Barremian. The studied area covers, from East to West, the Bandar Abbas Hinterland, the Fars, and the Khuzestan areas (Fig. 1.8). This study first focuses on the type localities of these two formations (Fahluyan and Gadvan), and thereafter presents the best exposures and subsurface sections across the area (details in chapter 2).

Fig. 1.8: Platform to basin transect of the Khami (Surmeh, Hith, Fahluyan, Gadvan and Dariyan formations) and Bangestan (Kazhdumi, Sarvak, Surgah and Ilam formations) groups in the Zagros Basin (modified from James and Wynd, 1965). Red rectangle shows the study interval in this work.

1.4.1 Geological background on the Lower Cretaceous succession from the Zagros FTB

The first report on the Khami Group (including of the Surmeh, Hith, Fahluyan, Gadvan, and Dariyan formations) was established by Strong (1928) at Kuh-e Khami, to the northeast of the town of Gachsaran. This succession was subsequently studied by Thomas and Slinger (1948) who made some informal subdivisions in the Jurassic-Cretaceous deposits. Another informal subdivision of the Khami Group was proposed by Wells (1965) who introduced a lithostratigraphic scheme.

The first formal lithostratigraphic nomenclature was proposed by James and Wynd (1965) for the Paleozoic-Tertiary deposits of the Zagros Basin (Fig. 1.9). The first biozonation pattern of Lower Cretaceous deposits was carried out by Wynd (1965) (Fig. 1.10) and, other one by Gollastaneh (1965). These zonation schemes were based on the assemblage zones of benthic foraminifera, and attributed a specific age to different stratigraphic units.

Several biostratigraphers and sedimentologists have also worked on these Mesozoic deposits, especially on the Fahluyan and Gadvan formations under the umbrella of the National Iranian Oil Company during the previous decades (Shepherd and James, 1959; Gollastaneh, 1965, 1974, 1979; Kheradpir, 1975; Setudehnia, 1978; Murriss, 1980; Sedaghat, 1982; Motiei, 1993). Moreover, a sequence stratigraphic analysis of the entire Cretaceous succession (from platform to basin) of the Zagros region was worked by the IFP (Institut Français du Pétrole), in collaboration with the NIOC during the years of 2002-2006 (NIOC internal report; van Buchem et al., 2010; Vincent et al, 2010).
Introduction

Stage Lurestan Khuzestan Coastal Fars Interior Fars

Aptian

Neocomian

Late Jurassic

Lithology: 

Fig. 1.9: Formation correlation chart of Lower Cretaceous deposits in the Zagros Basin (modified from James and Wynd, 1965).

Fig. 1.10: Biozonation pattern of Lower Cretaceous deposits in the Zagros Basin (modified from Wynd, 1965).

While acknowledging this considerable amount of work, this thesis presents a high-resolution biochronostratigraphy and sequence stratigraphy analysis of the Fahliyan and Gadvan formations to provide more precise time lines and a more detailed sequence stratigraphic framework for these rock units. A revision of both bio-chronostratigraphy and sequence stratigraphy analyses was needed because the sequence stratigraphic model proposed by the IFP-NIOC was based on the old biozonation of Wynd (1965).

1.4.2 Studied sites

A total of 24 sites, including 19 outcrops and 5 exploration wells have been investigated in the framework of this study (Fig. 1.11). All rock specimens from outcrops, as well as cutting samples from drilled wells have been studied in detail for biostratigraphy, facies interpretation, depositional environments, sequence stratigraphy and chemistratigraphy (see appendices 2 and 4). The distribution of studied sites according to the Zagros subdivision zones (Fig. 1.12) are the following:

- Bandar Abbas Hinterland and offshore area
  2 wells (Suru # 1, Qeshm # 4)
  2 outcrops (Genow, Khush)

- Coastal Fars
  5 outcrops (Nakh, Gavbast, Assaluyeh, Khurmoj, Khartang)

- Subcoastal Fars
  3 outcrops (Burkh, Kalagh, Surmeh)

- Interior Fars
  1 well (Ahmadi # 1)
  2 outcrops (Gadvan, Darbast)

- Khuzestan (Dezful Embayment)
  2 wells (Nargesi # 8, Seh Qanat # 1)

- Khuzestan (Izeh Zone)
  7 outcrops (Fahliyan, Kuzeh Kuh, Dasht-e Gul, Anneh, Lar, Mish, Mangasht)
Most of the studied outcrops have been measured and sampled during the 1960's, 1970's and 2000's by the geologists of the National Iranian Oil Company (NIOC) (Table 1.1). Rock samples and thin-sections from these missions were available in the storage of the company. Three new outcrops (2 sections in the type localities of the Fahliyan and Gadvan formations and one section in the Bandar Abbas Hinterland) have been measured again by the author, to obtain more detailed sedimentological observations, to identify key surfaces which are significant for sequence stratigraphic analysis, to make new logs with photos, to measure the in-situ natural gamma-ray emission (uranium, thorium and potassium) and, finally, to systematically re-sample (every 1.5 m) for microfacies analysis, biostratigraphy and chemostratigraphy.

A number of 4882 thin-sections were used and a total of 8823 m of sediment thickness in outcrops and wells were studied (Table 1.1). Most of these thin-sections had already been prepared by the NIOC. Moreover, 623 rock specimens were collected from the three newly measured sections (Fahliyan, Gadvan and Genow). Thin-sections from these new samples were prepared either at the NIOC or at the thin-section laboratory of the Department of Geology (UNIGE, Switzerland).
<table>
<thead>
<tr>
<th>No.</th>
<th>Outcrop/well</th>
<th>Geographical co-ordinates</th>
<th>Measured/studied Thickness (m.)</th>
<th>Number of studied thin-sections</th>
<th>Author-s of measured surface/subsurface sections (References)</th>
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<td>Anneh</td>
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<td>Piryaei et al., 2003</td>
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<td>52°31’31.00”E 27°35’58.70”N</td>
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<td>122</td>
<td>NIOC &amp; IFP, 2003</td>
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<td>Burkh</td>
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<td>Morsal Nezhad, 2002</td>
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<td>53°37’15.50”E 28°23’32.60”N</td>
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<td>96</td>
<td>Player &amp; Perry, 1962</td>
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<td>Dasht-e Gul</td>
<td>51°33’3.85”E 30°5’15.72”N</td>
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<td>Kavoosi et al., 2008</td>
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<td>Gavbast</td>
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<td>196</td>
<td>NIOC &amp; IFP, 2003</td>
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<td>468</td>
<td>Parker, 1959</td>
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<td>Genow (Chahoo)</td>
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<td>380</td>
<td>190</td>
<td>NIOC, 2005</td>
</tr>
</tbody>
</table>

| Total: | 8823 | 4882 |

Table 1.1: Summary data of the studied outcrops and wells in the Zagros FTB. The newly measured and described outcrops have been highlighted in light green colour.
1.4.3 Aims of this study

A fundamental revision of the stratigraphic range of previously reported calcareous green algae from the Zagros area (Gollestan, 1965, 1974, 1979) will be proposed here. Moreover, several new stratigraphically important taxa of dasycladalean algae are reported from the Fahliyan and Gadvan formations. Therefore, a new bio-chronostratigraphical zonation will be established based on integrated biostratigraphic data (benthic foraminifera, dasycladalean algae and tintinnids), providing a greatly increased stratigraphic resolution of these Berriasian - Barremian shallow-platform deposits. Biostratigraphic dating will be calibrated with the Sr-isotope method (Howarth and McArthur, 2004; McArthur et al., 2012). Moreover, in the studied intervals, the age of benthic foraminifera and dasycladalean algae will be further calibrated through a correlation with tintinnid zones identified in interbedded deeper marine intervals.

Based on the time lines detected throughout the studied succession, a regional sequence-stratigraphic model will be presented for the Berriasian - Barremian shallow-platform deposits from SW Iran. A new insight on the geometrical relationship between the traditional lithostratigraphic units will be proposed, providing data for reconstructing the platform evolution. Moreover, the Lower Cretaceous lithostratigraphic nomenclature will be revised and the role of local tectonics and/or eustatic sea-level fluctuations on sedimentation patterns will be discussed. Finally, for the first time, a precise chemostratigraphic interpretation will be proposed based on stable-isotope (carbon and oxygen) analysis to reconstruct climate changes and paleo-environmental conditions of these shallow-platform deposits.

1.4.4 Output and presented data

The important synthetic documents which are presented and enclosed in this report are:

- 6 regional correlation charts (including 4 longitudinal and 2 transverse transects) for litho-chronostratigraphic interpretations.
- 2 regional correlation charts for sequential interpretations.
- 24 fossil distribution range charts based on outcrops and subsurface sections.
- 24 sequence patterns based on outcrops and subsurface sections.
- 6 paleofacies maps for each sequence or stage.
- 14 isopach maps for each sequence, lithostratigraphic unit and/or time unit.
- A new bio-chronostratigraphic summary chart.
- A revised lithostratigraphic pattern.
- A new sequence stratigraphic summary chart.
- 11 plates of identified microfossils.

1.4.5 Outline of the thesis

Chapter 1. It provides general information and demonstrates the importance of the study.

Chapter 2. It presents the lithostratigraphy of the Lower Cretaceous shallow-water deposits from the Zagros FTB (revised lithostratigraphic nomenclature).

Chapter 3. It discusses the regional geology, and presents a synthesis of the Lower Cretaceous stratigraphy of the Zagros FTB, representing a new time-rock synopsis.

Chapter 4. It deals with the identified marker taxa of dasycladalean algae, benthic foraminifera and tintinnids for providing a new bio-chronostratigraphic pattern.

Chapter 5. It discusses facies types, depositional environments and platform reconstruction.

Chapter 6. It presents the first reliable high-resolution regional sequence stratigraphic framework.

Chapter 7. It presents data and interpretations based on the natural gamma-ray measured from outcrops.

Chapter 8. It presents stable-isotope data (δ¹³C and δ¹⁸O) from whole-rock samples and discusses isotope stratigraphy and climate change.

Chapter 9. It provides the Sr-isotope data and the calibration with the biostratigraphy.

Chapter 10. It summarizes the main findings of this study and outlines future work.
Chapter 1


2.1 Introduction and previous studies

The Khami Group was first established by Strong (1928, in Kheradpir, 1975) at Kuh-e Khami, Northeast of Gachsaran. It was named as "Khami Limestone", comprised a thickness of more than 1000 m of massive limestone, and was assigned a Jurassic and Neocomian age. Subsequently, Thomas and Slinger (1948) as well as Kent et al. (1950) (both in Kheradpir, 1975) further subdivided this interval into the "Khami Massive Limestone" (Jurassic to Neocomian) and the "Khami Bedded Alternation (Neocomian - ?Aptian). These lithologies were revised and re-defined by James and Wynd (1965), and recorded as a group which includes five formations; the Surmeh, Hith, Fahliyan, Gadvan and Dariyan (Fig. 2.1).

Three informal subdivisions, the Lower Khami (Surmeh Formation), Middle Khami (Surmeh and Hith formations) and Upper Khami (Fahliyan, Gadvan and Dariyan formations) have been proposed by Wells (1965, in Kheradpir, 1975). This lithostratigraphic scheme was mostly used by the geologists of National Iranian Oil Company. The Khami Group was revised by Kheradpir (1975) for lithostratigraphy, biostratigraphy and hydrocarbon potential.

The sedimentology of the upper part of the Khami Group (Early Cretaceous) was investigated by Sedaghat (1982). Following this, the Upper Khami Group was subdivided into the Garau, Fahliyan, Gadvan, Lower Dariyan, Kazhdumi tongue and Upper Dariyan formations (Fig. 2.1).

In addition, the Fahliyan Formation was subdivided informally into the Lower Fahliyan and the Upper Fahliyan (Wynd, 1965). This terminology is still used in internal company reports and papers.

This study revises this complex lithostratigraphic nomenclature and re-defines the Fahliyan and Gadvan formations based on the regulations of the International Commission on Stratigraphy (ICS) and scientific criteria.

![Fig. 2.1: Summarized schematic subdivisions of the Khami Group in the Zagros Basin.](image)
2.2 Methods

2.2.1 Field work

Two field excursions were achieved in the year of 2011 to sample and measure three outcrops, including of the Fahliyan, Gadvan and Genow sections in the Zagros FTB. The true thickness of the successions was measured using a Jacob’s staff equipped with a Brunton-type compass-clinometer and systematically sampled. Detailed sedimentological observations and field descriptions of rock specimens were documented with photos in the sedimentological logs.

2.2.1.1 Sampling

Systematic sampling was performed every 1.5 m for paleontology, microfacies examination and geochemical analyses. Rock specimens are stored at the National Iranian Oil Company, and some essential samples have been transported to the University of Geneva for geochemical analyses (stable isotopes and Sr-isotopes).

2.2.1.2 Outcrop gamma-ray spectrometry

A portable gamma-ray spectrometer (Gamma Surveyor I) was used to measure the in-situ radioactivity and also to quantify three major naturally radioactive elements: uranium (U), thorium (Th) and potassium (K) on the studied outcrops. The sections were logged by measuring total gamma radiation every 30 cm with a time integration of 60 s. The methodology was based on the recommendation of the manufacturer (GF Instruments, Czech Republic) and has been used in other similar works (e.g. Pereira et al., 2003; Correia et al., 2012). All the radiation data were measured in counts per second (cps). U and Th are reported in parts per million (ppm) and K is recorded in percentage (%) (details in chapter 7).

2.3 Lithostratigraphic nomenclature

The lithostratigraphic nomenclature introduced here is based on the pattern defined by James and Wynd (1965) and Wynd (1965). Therefore, the studied lithostratigraphic units are the Fahliyan and Gadvan formations, ranging in age from the Berriasian to the Barremian. Revised ages of these lithostratigraphic units will be presented in chapter 4.

2.3.1 Fahliyan Formation

The type locality of the Fahliyan Formation is located on the south flank of the Kuh-e Dul or Dul Mountain (coordinates: E 51° 27’ 36” and N 30° 11’ 19”) as described by James and Wynd (1965). Lithologically it consists of grey to brown, massive oolitic to peloidal limestone and has a thickness of 400 m (Fig. 2.2). In its type locality, the Fahliyan Formation rests on the dark brown dolomites of the Upper Jurassic Hith equivalent or the Surmeh Formation and is overlain by marls and thin limestone beds of the Gadvan Formation. Originally, both contacts were believed to be conformable (James and Wynd, 1965).

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**Fig. 2.2:** Type locality of the Fahliyan Formation, south flank of the Kuh-e Dul (modified from James and Wynd, 1965).
2.3.2 Gadvan Formation

The type locality of this formation is located in the eastern part of the Kuh-e Gadvan (Gadvan Mountain), northeast of Shiraz city (James and Wynd, 1965), and comprises 100 m of grey to green and brownish-yellow marls or shales, and dark grey argillaceous limestones (Fig. 2.3). Both contacts with the Fahluyan Formation (below) and the Dariyan Formation (above) are transitional.

Fig. 2.3: Type locality of the Gadvan Formation, Kuh-e Gadvan (modified from James and Wynd, 1965).

2.4 Key stratigraphic sections

The studied intervals in the Fahliyan and Gadvan formations range from the Bandar Abbas Hinterland to the Khuzestan area, covering nineteen outcrops and five drilled wells (details in chapter 1).

The presented and described stratigraphic sections include only the newly measured and sampled outcrops, namely the Fahluyan, Gadvan and Genow (Tang-e Chahoo) exposures, respectively located in the Khuzestan (Izeh Zone), Interior Fars and Bandar Abbas Hinterland (see chapter 1 for location map). The other outcrops and subsurface data have only been used to build the litho-chronostratigraphic models fitting in the defined regional transects. Also, the lithostratigraphical subdivisions, as explained here, are built on the pattern (lithostratigraphic nomenclature) introduced by James and Wynd (1965), and revised based on the new findings.

2.4.1 Fahliyan section (Khuzestan: Izeh Zone) (Figs. 2.4-2.8)

Kuh-e Fahluyan, the type locality of the Fahluyan Formation, is close to the eastern margin of the Arabian Plate. It is exposed in the Fahluyan Anticline, 19 km NE of NurAbad city, 5 km west of the Fahluyan village. The Fahluyan Formation overlies brecciated brown dolomites of the Upper Jurassic equivalent of the Hith Formation in this area (Figs. 2.4, 2.5 a-c).

The Fahluyan Formation reaches a thickness of 336 m. The lower part, 293 m thick, is made of shallow-water carbonates. Generally, the Fahluyan Formation is informally subdivided in two parts: the Lower Fahluyan and the Upper Fahluyan (Wynd, 1965). In this outcrop, the two parts are present. The Lower Fahluyan Formation is more or less cream to light gray in color, poorly bedded, and forms mostly massive intervals (Figs. 2.4, 2.6 a-c), including oolitic grainstones and bioclastic wackestones to packstones. Some intervals of peloidal grainstone with fenestral structures are also observed. They contain abundant ostracods, indicating a protected lagoonal environment. In mud-dominated lithologies, traces of microbial activity (algal mats) increase, as shown by the presence of Lithocodium/Bacinella and oncocids. Bindstone intervals occur in the Lower Fahluyan Formation with abundant Lithocodium/Bacinella and stromatopores, denoting a tidal flat depositional environment. The massive beds of the Lower Fahluyan are structureless, except for some fractured stylolites and small-sized karstification figures (vuggy structure) toward the top of the beds.
Moreover, an intense bioturbation and large *Thalassinoides* are commonly present in shallowing-up successions.

The lower part of the Fahliyan Formation is poor in macrofauna, but locally pieces of bivalves, gastropods, corals and echinoderms are found. On the other hand, it contains abundant calcareous green algae (mainly dasycladales) and benthic foraminifera.

Towards the top of the Lower Fahliyan Formation, the bedding pattern changes, as shown by the presence of dark gray nodular limestone (Fig. 2.4, 2.6 a, e). Gray, thin- to medium-bedded argillaceous limestone with some intercalations of marl, record an increase in siliciclastic input, with high values in the ratios of Th/U and K/U (see Fig. 2.4, details on gamma-ray data in chapter 7).

The top of the lower part of the Fahliyan Formation is marked by an interval of intense bioturbation, accompanied by karstification and vuggy structures, associated with iron crusts, borings and brecciated materials filling fractures. This contact coincides with a significant negative shift in $\delta^{13}$C$_{\text{carb}}$, indications of subaerial exposure and the influence of light, soil-derived C (details in chapter 8).

The upper part of the Fahliyan Formation (Upper Fahliyan sensu Wynd, 1965) is characterized by the alternation of carbonate beds and marly intervals. The thickness of this part is 43 m, and the bedding pattern varies from thin to thick. It contains more molluscs, is mud-dominated with a microfauna including mainly benthic foraminifera and few calcareous green algae, associated with echinoids and sponge spicules in marly intervals. This part of the Fahliyan Formation reveals a period of significant clay supply (high value for K/U) and siliciclastics (high value for Th/U) originating from the west. It is marked by high values of Th and K as shown by gamma ray logs.

The top of the Upper Fahliyan is marked by a very well-developed hardground surface with abundant iron nodules, denoting a short break in sedimentation (diastem), and covered by debris of corals and bivalves.
Fig. 2.4: Stratigraphical column of the studied intervals in the Fahliyan outcrop; formation separation based on the old lithostratigraphic nomenclature (sensu Wynd, 1965) and new formation definition of this work are shown.
Fig. 2.5: Fahliyan outcrop exposed in the Fahliyan anticline. 

- **a:** boundary between the Jurassic Hith dolomites and Fahliyan Fm.;
- **b-c:** close-up of the Hith dolomite;
- **d:** bivalve shells in the massive limestones of the lower part of the Fahliyan Fm.
Fig. 2.6: Details of the Fahliyan Formation in the type locality, Fahliyan anticline. a: overview of the massive and bedded limestones of the Lower Fahliyan Fm.; b-d: close-up of thick-to massive limestones of the Lower Fahliyan Fm.; e: bedding pattern of nodular limestone beds at top of the Lower Fahliyan Fm.
The Fahliyan Formation is overlain by the Gadvan Formation in this area (Figs. 2.4, 2.7). The Gadvan Formation consists mainly of extensive gray to green marl intervals, with intercalations of thin to medium-bedded, dark gray argillaceous limestone (Fig. 2.8 a-d). Dominant macrofauna in the Gadvan Formation includes bivalves (Fig. 2.8 g), oysters, gastropods, corals and echinoids. Microfauna includes benthic foraminifera and very rare dasycladacean algae, associated with sponge spicles, shell debris and echinoids. Siliciclastic materials decrease upward and, consequently, this unit is overlain by a white-cream and pure limestone unit of the Khalij Member, which is regionally recognized along the basin and has a thickness of 8 m. It consists of 5-6 individual beds that clearly thicken and then thin upward (Fig. 2.8 h).

Orbitolinids are frequent in the Khalij Member and the main marker for this unit is Montseciella arabica which is commonly found in coeval rock units through all of the Arabian Plate (Schroeder et al., 2010; van Buchem et al., 2010). Just above the Khalij Member, the Gadvan Formation shows significant deepening conditions, with basinal marls containing planktonic foraminifera, including frequent hedbergellids and globigerinelloids, accompanied by ammonites, bivalves (Exogyra sp.), that reveal a marked flooding and the corresponding formation of an intrashelf basin (shelf graben) in the Khuzestan area. In this area, sedimentation continued in the Aptian with the orbitolinid-dominated facies of the Dariyan Formation which transitionally overlies the Gadvan Formation.

Fig. 2.7: Distant view of the section with the exposure of the Upper Fahliyan, Gadvan and Dariyan formations in the Fahliyan anticline. Lithostratigraphic subdivisions are based on the model of James and Wynd (1965).
Fig. 2.8: Details of the Gadvan Formation in the Fahliyan anticline. a-d: typical Gadvan bedding pattern, consisting of an alternation of marl and thin-bedded argillaceous and nodular limestone; e-f: close-up of the lower contact of the Gadvan Formation with the Upper Fahliyan Formation, showing a distinct hardground with abundant iron-oxide nodules; g: bivalve in the marly intervals of the Gadvan Fm.; h: the Khalij Mbr., a marker bed in the upper part of the Gadvan Fm.
2.4.2 Gadvan section (Interior Fars) (Figs. 2.9-2.11)

In the Fars area, the so-called "Fars High", a complete stratigraphic section was measured and sampled at Kuh-e Gadvan, at about 40 km from the Shiraz city. This location includes the type locality of the Gadvan Formation in the Zagros FTB (James and Wynd, 1965).

The base of the Cretaceous is placed at the top of the thick brown dolomite beds which are equivalent of the Upper Jurassic Hith Formation (Figs. 2.9, 2.10 a).

All parts of the Fahliyan Formation are observable and easily accessible at this outcrop. The Fahliyan Formation (lower part of the Lower Fahliyan sensu Wynd, 1965) begins with thick bedded to massive, light-gray dolomitic limestones, followed by more pure limestones. The thickness of the Lower Fahliyan Formation is 202 m, with bioclastic wackestones to packstones, and rare oolitic grainstones. It contains an association of benthic foraminifera and dasycladalean algae, accompanied by rare bivalves, gastropods and echinoderms, denoting a shallow-water platform. Intense bioturbation is observed at the top of the thick beds, associated with karstification, vuggy structures (Fig. 2.10 c) and dissolved shells. Deposits of microbial origin are frequent in this interval, including of Lithocodium/Bacinella, oncoids and coated grains. Bindstone horizons are marked by the appearance of Lithocodium/Bacinella patches and stromatopores.

The upper part of the Lower Fahliyan Formation is moderately bedded, marked by an increase in the amount of clay and influx of siliciclastics (Figs. 2.9, 2.10 b, d), corresponding to a significant signal in the gamma-ray logs and increasing values of Th/U and K/U. This bedded upper part of the Lower Fahliyan Formation rests on the massive limestones by means of considerable karstification, iron-oxide nodules and intense bioturbation, showing a marked hardground and sedimentary break (Fig. 2.10 c). The amount of macrofauna increases in this interval and texture varies from wackestone to packstone, with bioclasts, including benthic foraminifera, dasycladalean algae, bivalves, gastropods and echinoids.

The Upper Fahliyan Formation is separated from the Lower Fahliyan Formation by a conspicuously expressed surface filled by iron crusts and karstified (Fig. 2.11 a) denoting a major subaerial exposure, corresponding with a regional stratigraphic gap (details in chapter 4). This interval is 60 m thick, with thin-to medium-bedded, cream to gray limestones with intercalations of dark-gray argillaceous limestone and thin intervals of green marl (Fig. 2.11 b). Macrofauna includes bivalves, gastropods and echinoids, while the microfacies typically shows mud-dominated mudstones to wackestones, containing benthic foraminifera, very rare dasycladalean algae, associated with shell fragments.

The overlying Gadvan Formation is 125 m thick in this outcrop, with rather thin-bedded, dark-gray argillaceous limestones in the lower part, followed by gray to green marly intervals. This formation rests on the Upper Fahliyan Formation by means of a conspicuous hardground filled by iron crusts and karstified (Fig. 2.11 c-d), again indicating an important hiatus in sediment accumulation and a possible short stratigraphic gap.

Macrofauna is frequent in the Gadvan Formation, and comprises bivalves, echinoids and gastropods. The microfacies consist mainly of skeletal wackestones to packstones, with benthic foraminifera, rare dasycladalean algae, and pieces of macrofossil shells.

The Khalij Member, a white to cream, medium-to thick bedded carbonate unit (Fig. 2.11 e), is very well-developed, with a distinctive signal in the gamma-ray logs, and the presence of a marker, Dictyoconus arabicus (Montseciella arabica).

Finally, the Gadvan Formation is conformably overlain by the orbitolinid-rich limestone beds of the Dariyan Formation, dated from the Aptian.
Fig. 2.9: Stratigraphical column of the studied intervals at Kuh-e-Gadvan outcrop; formation separation based on the old lithostratigraphic nomenclature of James and Wynd (1965) and revised formations of this work are shown.
Fig. 2.10: Gadvan outcrop corresponding to the sedimentological log shown in Fig. 2.9. a: lower boundary of the massive Fahliyan Fm., with the underlying Jurassic Hith dolomite and Surmeh Fm.; b: overview of the Fahliyan, Gadvan and Dariyan formations; c: hardground surface with iron-oxide at the boundary of massive and bedded intervals of the Lower Fahliyan Formation; d: typical bedding pattern of the bedded Lower Fahliyan Fm. Formations subdivisions are based on James and Wynd (1965).
Fig. 2.11: Details of the Upper Fahliyan and Gadvan formations at Kuh-e Gadvan. a: close-up of the boundary between the Lower Fahliyan and Upper Fahliyan formations, showing karstification and iron-oxide nodules; b: typical bedding pattern of the Upper Fahliyan Fm.; c: boundary of the Upper Fahliyan and Gadvan formations; d: close-up of the hardground surface between the Upper Fahliyan and Gadvan formations; e: the Khalij Member, a marker bed in the Gadvan Fm. Formation subdivisions are based on James and Wynd (1965).
2.4.3 Genow section (Bandar Abbas Hinterland) (Figs. 2.12-2.14)

The oldest sediments in the Bandar Abbas Hinterland belong to the Jurassic/Cretaceous boundary, exposed only at Kuh-e Genow, in Tang-e Asboo. Their presence was reported for the first time by Parker et al. (1959).

These geologists measured about 1100 feet of dark gray to blackish hard, recrystallized, porcellaneous, and slightly fetid limestones, assigned to the Kimmeridgian. This carbonate succession was part of a thick sedimentary sequence (about 3000 feet) introduced as the "Asbu Group" in the Bandar Abbas Hinterland, ranging from the Kimmeridgian to the Aptian (Parker et al., 1959; Shepherd and James, 1959).

In this sequence, the bedding pattern varies from thin- to medium-bedded to thick and massive limestones, with several recognizable erosion surfaces (Parker et al., 1959).

At Kushk Kuh, the lower part of the Asbu Group is the Kushk Kuh Formation which is covered by a fully exposed carbonate sequence that there was no reason to further subdivide both in Kushk Kuh and Kuh-Genow (Shepherd and James, 1959). But toward the west and north, at Kuh-e Shu and Galeh Shur, the upper part of the Asbu Group was subdivided, in ascending stratigraphic order, in two formations, Shu (thick-bedded, dark gray dolomitic limestones) and Galeh Shur (well-bedded, oolitic grey limestones), which is overlain by the Albian Abbad Formation (chocolate marls; Shepherd and James, 1959).

Later on, the same limestone successions at Kuh-e Genow (Tang-e Asboo) were revised both for paleontology and lithostratigraphy, and reported as the "Fahliyan-Dariyan Formation", and assigned a Neocomian-Aptian age (Wynd, 1965; Khalili, 1967; Setudehnia, 1968).

In order to improve the dating of this section, and to obtain data sufficient for a semi-quantitative facies interpretation of these rock units in the Bandar Abbas Hinterland, one outcrop was selected in Kuh-e Genow. The Tang-e Asboo section (type locality of the Asbu Group) was however unaccessible and replaced by a new location chosen at Tang-e Chahoo (Fig. 2.12 right), about 1 km away from the previous location. Moreover, the rock specimens and thin-sections of Parker’s section at Tang-e Asboo were also studied in detailed and revised by the author (Fig. 2.12 left). They led to separate the lithostratigraphical units (Fahliyan, Gadvan and Dariyan formations) and identify the precise chronostratigraphical positions of the strata.

The Tang-e Chahoo section starts with the shallow-water carbonates of the Fahliyan Formation. The lowermost 8 m of this section belong to the uppermost part of the Fahliyan Formation (Fig. 2.12 right). Here, the oldest exposure includes a significant hardground surface, with intense bioturbation, borings, and abundant iron crusts (Fig. 2.13). The bedding pattern of the Fahliyan Formation includes here thick-bedded, gray limestones, with some thin intercalations of dark gray argillaceous limestone. The macrofauna includes fragments of bivalves and gastropods. The microfauna comprises benthic foraminifera (mostly trocholinids) and abundant dasycladalean algae, indicating a shallow subtidal depositional environment in the internal part of the platform.

The Fahliyan Formation is separated from the overlying Gadvan Formation by a marked discontinuity surface (Fig. 2.13 b; for more information, see chapter 4). The thick lenticular beds (more than 50 cm thick) at the base of the Gadvan Formation lack of silicilastic intertidal sediments, mudcracks, bioturbation and thin beds as episodic suspension transport, indicating these structures cannot be assumed as sediment movement by waves or channel deposits (Fig. 2.13 b). Therefore, these lenticular-bedded carbonates of the Gadvan Formation can be interpreted as re-sedimented deposits by mass flow (slump) and/or onlap sedimentation patterns during the sea-level rising on the formerly exposed Fahliyan platform in this area, where the Hauterivian is missing.

The Gadvan Formation has a thickness of about 75 m of well-bedded (thin to thick-bedded) pure limestones of cream to light gray color, with some thin beds of dark gray argillaceous limestone (Fig. 2.14 a-d). Karstification features developed very well in the thick carbonate levels of this formation (Fig. 2.14 c), which are favorable for a reservoir in terms of hydrocarbon exploration. Macrofauna include bivalves, gastropods and echinoids, and microfacies includes bioclastic wackestones to packstones with benthic foraminifera and frequent dasycladalean algae, revealing a shallow inner-platform setting.

As a result of lateral facies change, and because the Gadvan Formation in this area consists of pure carbonate sediments, the Khalij Member cannot be separated as an individual lithostratigraphic unit, but
probably corresponds to the medium to thick-bedded limestones with *Dictyoconus arabicus*, which reaches a thickness of 15 m in this outcrop (Fig. 2.14 c-d).

The Gadvan Formation is covered by the orbitolinid-rich limestones of the Dariyan Formation, dated from the Aptian. Based on field observations, there is no significant surface or stratigraphic break at the boundary between these two formations (Fig. 2.14 e). However, based on gamma-ray data and elemental-radioactive analyses, the Dariyan Formation is picked out in an interval where the total gamma curve shows a negative trend that corresponds with a main decrease in clay content (K) and siliciclastics (Th), as a result of the cleaning up in the environment. The top of the Dariyan Formation is marked by the presence of iron-oxide nodules and solution surfaces, indicating an exposure and discontinuity (Fig. 2.14 f). This discontinuity is confirmed by the biostratigraphy, where the Albian Kazhdumi Formation overlies the Dariyan Formation of Early Aptian age.

![Diagram showing stratigraphical columns of the studied intervals in the Genow outcrop, left: Tang-e Asboo (Parket et al., 1959, revised here), and right: Tang-e Chahoo (this study).](image-url)
Fig. 2.13: Overview of the Fahliyan, Gadvan and Dariyan formations at Kuh-e Genow (Tang-e Chahoo) outcrop. a: showing the general view of the studied formations; b: clear disconformity surface at the boundary of Fahliyan and Gadvan formations, where the Haueterivian is missing; indicating by lenticular-bedded carbonates at the base of the Gadvan Formation that can be interpreted as re-sedimented deposits by mass flow (slump) on the formerly exposed Fahliyan platform; c: the oldest exposure surface in this outcrop, showing a hardground surface in the Fahliyan Fm.; d: close-up of the thick beds of the Fahliyan Fm. in this section.
Fig. 2.14: Details of the Gadvan and Dariyan formations at Kuh-e Genow (Tang-e Chahoo). a-b: intercalations of thin marly limestone beds, Gadvan Formation; c-d: medium to thick-bedded with karst cavities in limestones of the Gadvan Fm., probably equivalents of the Khalij Member; e: close-up of the boundary of Gadvan and Dariyan formations, showing no significant surface or stratigraphic break; f: top of the Dariyan Fm., with abundant iron-oxide nodules and evidence for exposure surface.
2.5 Revision of the studied Lower Cretaceous lithostratigraphy in the Zagros FTB: New lithostratigraphic nomenclature

A revision of the Lower Cretaceous (Berriasian - Aptian), Fahliyan, Gadvan and Dariyan formations is presented for a better understanding of the significance and areal extent of the formations described.

The Fahliyan Formation was originally considered as a part of the “Khami Massive Limestone” by Thomas and Slinger (1948). In some other reports and papers published on the Fahliyan Formation from 1950’s to 1980’s, it was dealt as a part of the Khami Limestone (Kent et al., 1950), of the Upper Khami Group (Wells, 1965), and finally subdivided in two informal units, the Lower Fahliyan (Neocomian) and the Upper Fahliyan (Barremian - Aptian) (Wynd, 1965). This informal terminology is still used in the literature and needs to be revised.

In this work, the Fahliyan Formation is split into three formations at the type locality: one covers the Berriasian - earliest Valanginian interval and includes the lower part of the Fahliyan type section (sensu James and Wynd, 1965), the two new formations, named Sar Bisheh and Ghari, are attributed to the Valanginian and the Hauterivian respectively (Fig. 2.15).

Moreover, in such a case of lateral change in the lithologic composition (example for the Gadvan and Dariyan formations at the East in Fars and Bandar Abbas areas), where these units are merged, they are mapped as a new lithostratigraphic unit, named the Chahoo Formation, with the Hauterivian - Aptian age (Fig. 2.15).

These units display distinctive facies associations and are defined according to the regulations issued by the International Commission on Stratigraphy (chapter 3, part B and chapter 5, part D: Murphy and Salvador, 1999), calling for: lithostratigraphic units to be defined and recognized by observable physical features and diagnostic lithological composition. These new units and their boundaries are directly defined from field observations. In this new classification, new names are introduced and unit boundaries have been changed, but there is no real change in unit rank.

Fig. 2.15: A brief comparison between the new lithostratigraphic subdivisions of the Fahliyan and Gadvan formations in this work with the model of James and Wynd (1965) and Wynd (1965). The recorded stratigraphic gap at top of the Sar Bisheh and Fahliyan formations is shown in vertical hatches.

2.5.1 Re-definition of lithostratigraphic units

2.5.1.1 Fahliyan Formation

The Fahliyan Formation is re-defined here and the suggested changes relate to the unit boundaries, thickness, geological age and regional extent. It replaces the already established Fahliyan Formation which authors (James and Wynd, 1965) did not follow the rules of the International Commission on Stratigraphy suggested by Waller (1960). It is duly discussed as following:

Name: From the Fahliyan village on the south flank of the Kuh-e Dul (James and Wynd, 1965).
Type locality (stratotype): The type section was measured on the south flank of Kuh-e Dul. Geographical coordinates are: 51° 27' 36'' E and 30° 11' 19'' N.

Description and boundaries of unit: This unit has a thickness of 218 m and includes grey to brown, thick to massive-bedded, oolitic to peloidal limestones. This unit unconformably rests on the Upper Jurassic Hith Formation which comprises brown brecciated dolomite. The upper contact of this unit with the overlying Sar Bisheh Formation is conformable.

Geological age: Berriasian - Valanginian

Regional aspects: This unit is present in the Khuzestan, Fars and Bandar Abbas areas in the Zagros FTB.

Correlation with other units: Toward the west, in the Lurestan area, this formation passes into dark shales and pelagic limestones of the Garau Formation. In the Khuzestan and Fars areas, the Valanginian part of this unit is equivalent to the Sar Bisheh Formation. This unit is a time-equivalent of the Habshan, Bu Haseer and Belbazem formations in the UAE, Qatar and Rayda Formation in Oman (Granier, 2008), Yamama Formation in Iraq and Saudi Arabia (Sharland et al., 2004) and Minagish Formation in Kuwait (Sharland et al., 2004).

Genesis: This unit includes oolitic grainstones and bioclastic wackestones to packstones. In mud-dominated facies, ostracods, algal mats and oncoids become frequent, indicating a protected lagoonal environment. Benthic foraminifera and dasycladalean algae increase toward the top of this unit, indicating a shallow subtidal depositional environment. Intervals which contain stromatopores and Lithocodium/Bacinella, denote a tidal flat depositional environment.

References to the literature: This unit corresponds to the lower part of the former Fahliyan Formation (sensu James and Wynd, 1965).

Remarks:

Toward the East, in the Bandar Abbas Hinterland and offshore area, the basal part of the Fahliyan Formation includes hemipelagic deposits containing tintinnids and radiolarians (details in chapter 4). In this work, this part of the Fahliyan Formation was recorded from four locations including the Khush outcrop, the Genow (Tang-e Asboo) outcrop, the Suru well #1 and the Qeshm well #4, with a thickness of 85, 80, 105 and 88 m respectively (see appendix 3, fossil distribution charts). Based on the previous lithological descriptions and drawn stratigraphical columns (e.g. Shepherd and James, 1959; Khosravi Said, 1959 revised by Setudehnia, 1968; Wynd, 1965; Khalili, 1967), this part of the Fahliyan Formation comprises bedded limestones with some intercalations of thin shaly to marly deposits.

According to the rules of International Commission on Stratigraphy and the Code of Stratigraphic Nomenclature (chapter 5, part F-2), whenever a change in geographic location is associated with major variations in lithologic composition, a new name should be applied for a lithostratigraphic unit. It is therefore suggested that the Fahliyan Formation should be properly again re-defined and split into two units in this area: one that covers the hemipelagic deposits bearing tintinnids with the Middle Berriasian - earliest Valanginian age and the other corresponding to the shallow-platform deposits containing dasycladalean algae and benthic foraminifera (type Fahliyan Formation) with the Early - Late Valanginian age.

The name and characteristics of this suggested new lithostratigraphic unit is open for further study. The area where these hemipelagic deposits are exposed (e.g. Kuh-e Genow, Tang-e Asboo), is considered as a confidential area by the army, and it was impossible to visit the outcrop to document important parameters for defining this new lithostratigraphic unit (lithological description, key bounding surfaces).

2.5.2 Establishing new lithostratigraphic units

2.5.2.1 Sar Bisheh Formation (Figs. 2.16-2.18)

Name: The name of this formation is derived from the Sar Bisheh village, approximately 5 km away from the northern part of the Fahliyan Anticline (Fig. 2.16).

Type locality (stratotype): The type locality stands at the north side of the Ghari valley, in the Fahliyan Anticline, 17.5 km north-east of the city NurAbad. Geographical co-ordinates are: 51°26'34.75''E,
30°11'20.49"N at base and 51°26'32.32"E, 30°11'18.86"N at the top of the section. The co-ordinates are based on the Geodetic system and datum is WGS-84.

The main route to access the type locality is an asphalt road from Nur Abad city toward the Fahliyan village which is around 12 km (the road passes Bajgah, Pol-e Fahliyan, Fahliyan and Janjan villages). From the last village (Janjan), around 5.5 km westward toward the core of the Fahliyan anticline, a dirt road which was established and used by tribal and stockbreeders provides excellent access towards the outcrop in the Ghari valley (Tang-e Ghari).

**Description and boundaries of unit:** This new lithostratigraphic unit has a thickness of 73 m. It consists of very well bedded (varying from thin to thick), dark gray argillaceous limestone and gray nodular limestone with some intercalations of green marl (Figs. 2.17, 2.18 a). The lower boundary of this unit coincides with top of the first large-scale (second-order) sequence of the underlying Fahliyan Formation and the upper boundary corresponds to the post-Valanginian unconformity (details on age determinations in chapter 4).

The top of this unit is intensely bioturbated with the development of karstic and vuggy structures, associated with iron crusts, as well as bored and brecciated materials filling fractures (Fig. 2.18 b-c). This boundary coincides to a major stratigraphic gap which can be followed regionally across the platform.

**Geological age:** Valanginian

**Regional aspects:** This unit is present in the Khuzestan and western part of the Fars area.

**Correlation with other units:** Towards the East, in the east Fars, also in the Bandar Abbas Hinterland and offshore area, the Sar Bisheh Formation laterally grades into the shallower carbonates of the Fahliyan Formation. Regionally, in the Arabian Plate, this unit is a time-equivalent of the Zakum Formation in the UAE, Oman and Qatar (Granier, 2008), and of the upper part of the Yamama limestone and Ratawi shale in Iraq, Kuwait and Saudi Arabia (Sharland et al., 2004).

**Genesis:** The bedding pattern of this unit changes comparing to the underlying and overlying units, as shown by the presence of dark gray nodular limestone, indicating a rise of sea level, and gray, thin to medium-beded argillaceous limestone with some intercalations of marl, recording an increase in shale supply and siliciclastic input. This unit is poor in macrofauna, but locally pieces of bivalves, gastropods,
corals and echinoderms are found. On the other hand, it contains abundant calcareous green algae (mainly dasycladales) and benthic foraminifera.

References to the literature: This new unit corresponds to the upper part of the former Lower Fahliyan Formation (sensu Wynd, 1965).

**Fig. 2.17:** Field photo of the Sar Bisheh Formation at the type locality, Kuh-e Fahliyan, Zagros FTB.
Fig. 2.18: Details of the Sar Bisheh Formation in the Fahliyan anticline. a: typical bedding pattern, almost nodular argillaceous limestone inter-bedded with marls; b-c: karstification, intense bioturbation and iron staining at top of the Sar Bisheh Formation, indicating an exposure surface.
2.5.2.2 Ghari Formation (Figs. 2.19-2.20).

**Name:** The formation is named after the Ghari valley (Tang-e Ghari) where the exposure is located on the south limb of the Fahliyan Anticline (see Fig. 2.16).

**Type locality (stratotype):** This lithostratigraphic unit corresponds exactly to the former Upper Fahliyan Formation (sensu Wynd, 1965) and is defined at its former type section. Geographical co-ordinates are: 51°26'31.99"E, 30°11'19.42"N at the base and 51°26'30.98"E, 30°11'18.28"N at the top of the section. The co-ordinates are based on the Geodetic system and datum is WGS-84. Accessibility for this unit is same as above-mentioned for the Sar Bisheh Formation.

**Description and boundaries of unit:** It is characterized by an alternation of carbonate beds and marly intervals (Figs. 2.19, 2.20 a), with a thickness of 43 m. The bedding pattern of limestone beds varies from thin to thick. This unit corresponds to a period of significant clay supply (high value of the K/U ratio) and siliciclastic input (high value of the Th/U ratio) from the west. The lower boundary of this formation corresponds to the pre-Hauterivian unconformity. The upper boundary corresponds to the top of the former Fahliyan Formation (sensu James and Wynd, 1965), marked by a very well-developed hardground surface with abundant iron nodules (Fig. 2.20 b) indicating a short break in sedimentation (diastem), and covered by a fauna of corals and bivalves (Fig. 2.20 c).

**Geological age:** Hauterivian

**Regional aspects:** This unit is present in the Khuzestan and Fars areas.

**Correlation with other units:** Eastward in the shallower part of the platform, in the Fars High, Bandar Abbas Hinterland and offshore area, this formation laterally grades into the shallow-water carbonates of the Gadvan Formation, where again the Gadvan Formation revised here and introduced as the Chahoo Formation in this study. Regionally, in the Arabian Plate, this unit is a time-equivalent of the Lekhwair Formation in the UAE, Oman and Qatar (Granier, 2008), and of the lower part of the Zubair Formation in Iraq, Kuwait and Saudi Arabia (Sharland et al., 2004).

**Genesis:** This unit contains more molluscs, and it is mud-dominated with a microfauna including benthic foraminifera and few calcareous green algae, associated with echinoids and sponge spicules in marly intervals.

**References to the literature:** This new unit corresponds to the former Upper Fahliyan Formation (sensu Wynd, 1965).

![Fig. 2.19: Distant field view of the Ghari Formation in the Fahliyan anticline. The lower contact with the Sar Bisheh Formation corresponds to a major exposure surface and discontinuity (see Fig. 2.18 b-c) and the upper contact with the Gadvan Formation shows a significant hardground, indicated by a diastem (see Fig. 2.20 b-c).](image)
Fig. 2.20: Details of the Ghari Formation in the Fahliyan anticline. a: close-up of typical bedding pattern with an alternation of marl and limestone beds; b: upper contact of the Ghari Formation with the Gadvan Formation, a hardground surface containing iron-oxide nodules, suggesting a time break/diastem; c: macrofauna including corals at the top of the Ghari Formation.
2.5.2.3 Chahoo Formation (Figs. 2.21-2.23)

James and Wynd (1965) noticed that in the Fars High and Bandar Abbas Hinterland, the Gadvan Formation is replaced by shallow-platform carbonates, and that in these areas the Fahliyan, Gadvan and Dariyan formations cannot be differentiated. Consequently, these authors introduced a new unit, the Fahliyan-Dariyan Formation.

The present study, however, reveals that a significant regional hiatus exists at the top of the Sar Bisheh Formation (in western Fars and Khuzestan) and at the top of the Fahliyan Formation in eastern Fars, Bandar Abbas Hinterland and offshore area (details in chapters 3, 4). Consequently, the Fahliyan Formation cannot be merged and named along with other younger deposits. This is based on the regulations issued by the International Commission on Stratigraphy (Murphy and Salvador, 1999), calling for: *stratigraphic sequences of similar lithologic composition but separated by regional unconformities or major hiatuses should be mapped as separate lithostratigraphic units* (ICS, chapter 5, part D3).

On the other hand, there is little difference in the lithological composition of the Gadvan and Dariyan formations in the studied area (Kuh-e Genow), in that the Gadvan Formation is simply more argillaceous compared to the Dariyan Fm. Indeed, some signals are observed on the gamma-ray curve (Fig. 2.21), but there is no significant contrast in lithology and in the absence of a visible hardground surface, it is not possible to regionally follow and map the boundary between Gadvan and Dariyan formations.

![Lithostratigraphic column of the Chahoo Formation at the type locality, Kuh-e Genow, Tang-e Chahoo. Old formation subdivisions of James and Wynd (1965) and the newly defined unit are shown.](image)

In such a case of lateral change in the lithologic composition accompanied with changes in geographic position, a new lithostratigraphic name should be proposed (ICS, chapter 7 E). Therefore, we introduce here the name of Chahoo Formation which comprises the shallow-carbonate deposits equivalent of the Gadvan and Dariyan formations in the western parts of the Fars and Khuzestan areas on top of the Fahliyan Formation.

*Name:* The name of this formation is derived from the Chahoo river (in Persian language called Darreh or Tang), in the Genow Mountain, approximately 26 km north of Bandar Abbas city.
**Type locality (stratotype):** The type locality is located at Tang-e Chahoo and the geographical co-ordinates are: 56°12'40.49"E and 27°24'21.48"N (Fig. 2.22). The co-ordinates are based on the Geodetic system and datum is WGS-84.

Accessibility is using an asphalt road from Bandar Abbas city towards the Telecommunication Support Facility at top of the Genow Mountain at the North, where the road passes Sarkhun, Baba Gholam and Tazian villages (around 28 km). From the last village (Tazian), after approximately 25 km (on the asphalt road), a dirt road (around 3 km) branches towards the Chahoo tribal camp. The section is reached after 25-30 minutes of walking (around 1 km) towards the Chahoo valley (Tang-e Chahoo).

**Description and boundaries of unit:** This new unit has a thickness of 135 m and is very well-bedded. The bedding pattern varies from thin to thick, and includes limestones of cream to light gray color. Both the lower and upper contacts of this new lithostratigraphic unit are unconformable: the Late Valanginian and all of the Hauterivian are missing on top of the underlying Fahlavan Formation, and on top of the Chahoo Formation, the Kazhdum Formation is believed to be Albian in age, indicating a hiatus corresponding to the Late Aptian (Fig. 2.23).

**Geological age:** Barremian - Early Aptian. It should be mentioned that the age of this formation extends from the Hauterivian in the eastern parts of Fars area, where the shallow-carbonate deposits of the Gadvan Formation have an Hauterivian age.

**Regional aspects:** This unit is present in the East Fars, Bandar Abbas Hinterland and offshore area.

**Correlation with other units:** Towards the west, this unit is equivalent of the Ghari, Gadvan and lower part of the Dariyan formations in the western part of the Fars and Khuzestan areas.

**Genesis:** Karstification features developed extensively in the thick carbonate levels of this formation. Macrofauna includes bivalves, gastropods and echinoids. The microfacies comprises bioclastic wackestone to packstone with benthic foraminifera and frequent dasycladalean algae, revealing a shallow inner platform setting. Towards the top of this unit, orbitolinid-rich limestones prevail.

**References to the literature:** This unit corresponds to the former Fahlavan-Dariyan Formation (sensu James and Wynd, 1965).

**Fig. 2.22:** Geological map of the Genow Anticline with the type locality of the Chahoo Formation (yellow asterisk), located at the southern part of the Chahoo river. Location of the Genow outcrop is shown in Fig. 1.11 (modified from Geological map of Bandar Abbas, Drawing No. 43007; NIOC, 2011).
Fig. 2.23: a: Another view of the Chahoo Formation in Tang-e Chahoo; b: very frequent iron-oxide nodules on the hardground surface at the top of the Chahoo Formation, representing an exposure surface at the base of the Albian Kazhdumi Formation (Location map in Fig. 1.11, Kuh-e Genow).
2.6 Conclusions

This study shows that the Fahliyan Formation, as originally considered, must be subdivided into three formations namely: the Fahliyan Formation (Berriasian - Valanginian), the Sar Bisheh Formation (Early - Late Valanginian) and the Ghari Formation (Hauterivian). Moreover, where these units are merged, they are mapped as a new lithostratigraphic unit, named the Chahoo Formation with an Hauterivian - Early Aptian age.

The main characteristics of these re-defined and/or newly established lithostratigraphic units are:

- The Fahliyan Formation (re-defined) is 218 m thick at the type locality, and includes grey to brown, thick to massive-bedded, oolitic to peloidal limestones. A prominent erosional hiatus exists between the Fahliyan Formation and the underlying Upper Jurassic Hith Formation (brown brecciated dolomite). The top of the Fahliyan Formation coincides with an abrupt break in sedimentation from shallow-water carbonates to rubbly limestones with intercalations of marl (Sar Bisheh Formation). This formation has a Berriasian - Early Valanginian age and extends in the Khuzestan, Fars, Bandar Abbas Hinterland and offshore area.

- The Sar Bisheh Formation has a thickness of 73 m. It consists of very well bedded (thin to thick), dark gray argillaceous limestone and gray nodular limestones with some intercalations of green marl, denoting a global sea-level rise and recording an increase of clay supply and siliciclastic input. The lower boundary of this unit corresponds to a clear change in lithology (pure carbonates of the Fahliyan Formation in below) and also coincides with top of the first second-order sequence of the underlying Fahliyan Formation. The upper boundary corresponds to the post-Valanginian unconformity. An Early - Late Valanginian age is attributed to this formation and it extends in Khuzestan and in the western parts of Fars area.

- The Ghari Formation is characterized by an alternation of carbonate beds and marly intervals, with a thickness of 43 m. The bedding pattern of limestone beds varies from thin to thick. This unit corresponds to a period of significant clay supply and siliciclastic input from the southeast and is marked by high values of Th and K. The lower boundary of this formation corresponds to the pre-Hauterivian unconformity and the upper boundary corresponds to the top of the former Fahliyan Formation (sensu James and Wynd, 1965), marked by a well developed hardground surface with abundant iron nodules, indicating a short break in sedimentation (diastem). This formation is of Hauterivian age and it occurs in Khuzestan and in the western parts of Fars area.

- The Chahoo Formation has a thickness of 135 m. It is very well bedded and bedding pattern varies from thin to thick, including limestones of cream to light gray color. Both the lower and upper contacts of this new lithostratigraphic unit are unconformable: the Late Valanginian and all of the Hauterivian are missing on top of the underlying Fahliyan Formation and on top of the Chahoo Formation, the Kazhdumi Formation is believed to be Albian in age, indicating a hiatus corresponding to the Late Aptian. The age of this formation is Barremian - Early Aptian (at the type locality) and it is present in the eastern parts of Fars, Bandar Abbas Hinterland and offshore area. Towards the west, in the Fars area, this formation starts from the Hauterivian.
References:


3.1 Introduction

The study area is covered by six regional well log and outcrop cross-sections, showing correlations of stratigraphic units based on the new lithostratigraphic terminology of this work (see Appendix 1). All cross-sections were datumed (flattening surface) on top of the Khalij Member. This unit is a stratigraphic unit clearly identifiable from a biostratigraphic point of view (occurrence of *Montseciella arabica*), lithological characteristics (pure carbonate bed within the marly intervals of the Gadvan Formation), and finally with a clear log signature (low gamma-ray values). Moreover, this marker bed is present throughout all of the Khuzestan, Fars, Bandar Abbas Hinterland and offshore area.

Twenty four control points, including 19 outcrops and 5 subsurface sections were used. The distribution of these NW-SE and N-S regional transects are (Fig. 3.1):

*Transect 1 (NW-SE):* Mangasht, Lar, Mish, Anneh, Fahliyan, Kuzeh Kuh, Dasht-e Gul, Gadvan, Ahmadi well - 1, Darbast and Khush.

*Transect 2 (NW-SE):* Anneh, Nargesi well - 8, Khurmoj, Khartang, Kalagh, Surmeh, Burkh and Suru well - 1.

*Transect 3 (NW-SE):* Lar, Fahliyan, Seh Qanat well - 1, Khurmoj, Assaluyeh, Gavbast, Nakh and Qeshm well - 4.

*Transect 4 (NE-SW):* Khush, Genow, Suru well - 1, Qeshm well - 4.

*Transect 5 (N-S):* Gadvan, Ahmadi well - 1, Darbast, Burkh, Nakh and Gavbast.

*Transect 6 (N-S):* Gadvan, Ahmadi well - 1, Surmeh, Khurmoj, Khartang, Kalagh and Assaluyeh.

![Fig. 3.1: Distribution of regional transects across the platform in the Zagros FTB (details in Appendix 1).](image-url)
3.2 Paleogeographical and isopach maps

Based on the spatial distribution of the lithostratigraphic units, a new time-rock synopsis and stratigraphical framework was constructed for the studied succession. The discussion presented here is based on the newly defined lithostratigraphic units which are interpreted at a regional scale.

3.2.1 Fahliyan Formation (Berriasian - Valanginian)

The corresponding isopach maps show two depocenter accumulations for the Fahliyan Formation in the Zagros FTB (Fig. 3.2). The thickest deposits occur west of the Kazerun Fault in the Fahliyan, Anneh and Lar anticlines. This increased thickness may be the result of the re-activation of the Kazerun basement fault zone and its vertical displacement during the Early Cretaceous (Sepehr and Cosgrove, 2005).

Towards the East, in the Bandar Abbas Hinterland and offshore area, Middle Berriasian to lowermost Valanginian deposits contain tintinnids and rare radiolarians (see chapter 4 and Appendix 2) and form a narrow tongue of deep-marine origin. It appears that the eastern side of the Fars and Bandar Abbas Hinterland subsided rapidly to below the storm-wave base (below the euphotic zone), forming a local embayment.

Fig. 3.2: Regional isopach map of the newly defined Fahliyan Formation throughout the studied area, Zagros FTB. Abbreviations: HZTF: High Zagros Thrust Fault, KZF: Kazerun Fault, ZMFF: Zagros Mountain Front Fault, NZF: Nezamabad Fault, RZF: Razak Fault, HDF: Hendurabi Fault, BSF: Bastak Fault. (Basement faults map from Bahroudi and Talbot, 2003, with modification).

Taking the horizontal distance of about 100 km between the areas including Suru-1, Qeshm-4 and Genow to the East, and Nakh and Burkh to the West, lateral drowning (shoreline displacement) proceeded at a rate of about 140 km/Ma or 140 m/1000 yr. during a time interval of approximately 3 Ma, which is quite rapid compared to other Cretaceous platform growth (Schlager, 1981, 1999).

According to the literature and theoretical predictions, platform drowning may happen either due to extreme environmental stress reducing carbonate production (extreme changes in sea-surface temperature and nutrient levels during oceanic anoxic events), relative sea-level rise exceeding carbonate accumulation as a result of fault-driven pulses of tectonic subsidence and/or global sea-level rising generated by the melting polar ice caps (Kim et al., 2012). Applied to the study area, a "give-up" phase of platform growth happened in response to a relative sea level rise.

Plotting sedimentation rates on a regional transect (Fig. 3.3) shows that for the Berriasian, maximum rates (between 10 to 50 mm/1000 yr.) occurred West of the Kazerun Fault, whereas, toward the east, in the Fars, Bandar Abbas Hinterland and offshore area, the rates decreased to 2.9-35 mm/1000 yr., showing the effect of basement faults and tectonic subsidence in the west, and rapid sea-level rise, and corresponding drowning conditions in the east. This drowning, with very low sedimentation rate (between 2 to 10 mm/1000 yr.) in the Bandar Abbas Hinterland and offshore area (Fig. 3.3), was certainly controlled by tectonic subsidence and
movements related to wrench-faults, such as the Bastak and Hendurabi fault zones or tectonic activities of salt diapirs, most of which as well as salt plugs, are distributed in the eastern parts of the Fars area in the Zagros FTB (Jahani, 2009).

In contrary, the Valanginian deposits have the most thickness in the Bandar Abbas Hinterland, Izeh Zone, and Interior Fars respectively (Fig. 3.4), while a significant thinning of these deposits is observed in coastal Fars and sub-coastal Fars, such as: Khurmoj, Khartang, Kalagh, Surmeh, Assaluyeh, Darbast, Gavbast, Burkh and Nakh (see Appendix 1).

This difference of sediment accumulation rates between 38.8 to 73.2 mm/1000yr in Bandar Abbas Hinterland and offshore area (Khush, Genow, Qeshm-4 and Suru-1), which is more than twice that of other areas westward over a distance of less than 100 km, such as Burkh and Nakh with sedimentation rates of 12.6 -15.4 mm/1000yr (Fig. 3.5), is interpreted as related to basement faults (block faulting), such as the Hendurabi and Bastak fault zones. This tectonic activity has changed the relief and morphology of the former Fahliyan platform, creating a strong increase in subsidence and providing enough accommodation space for carbonate factories (chlorophycean green algae, benthic foraminifera) in the Bandar Abbas Hinterland and offshore area.
at the East. Another mechanism may be related to the tectonic activities of salt diapirs (Jahani, 2009), and/or the role of the Qatar Arch High, the northern extension of which reaches to the Fars area in the Zagros FTB (van Buchem et al., 2010), making several local paleo-highs, resulting in low subsidence or even condensation sections in the Fars area (e.g. Kalagh, Surmeh, Assaluyeh, Darbast, Gavbast, Nakh and Burkh).

Westward, in the western part of the Kazerun Fault, the thickness of the Valanginian deposits strongly increases and the sedimentation rates vary from 18.6 to 51 mm/1000yr (Fig. 3.5), again suggesting a considerable vertical displacement of the Kazerun Fault during the re-activation of this fault which began in the Early Cretaceous (Sepehr and Cosgrove, 2005).

Fig. 3.5: Sediment accumulation rates of deposited sediments during the Valanginian in the studied area. The highlighted interval shows typical sedimentation rates for Cretaceous carbonate platforms (Schlager, 1981, 1999).

### 3.2.2 Sar Bisheh Formation (Valanginian)

The Valanginian Sar Bisheh Formation also has the most thickness to the west of the Kazerun Fault in the Khuzestan (Izeh Zone and Dezful Embayment) in Anneh, Lar, Mish, Fahliyan, Seh Qanat-1, and Nargesi-8, revealing the role of this basement fault zone in creating additional accommodation space (Fig. 3.6).

Facies interpretation shows a significant deepening of the depositional environment in the area west of the Kazerun Fault during the Valanginian and the Hauterivian, demonstrating the role of the Kazerun and Izeh fault zones, which included major sedimentary thickness and facies variations along this belt (Hosseini and Conrad, 2010).

Fig. 3.6: Regional isopach map of the Sar Bisheh Formation throughout the studied area in the Zagros FTB. As shown, the Sar Bisheh Formation has the most thickness in the Khuzestan area and is not present in the eastern Fars, Bandar Abbas Hinterland and offshore area, where this formation is replaced by the newly defined Fahliyan Formation (see appendix 1).
In terms of platform-basin transect, the Valanginian interval has a thickness of about 100 m in the basinal part, within the Garau Formation at Tang-e Haft, Lurestan Basin (Navidtalab et al., 2014). This reveals a rate of accumulation of about 14.5 mm/1000yr, which is acceptable for such planktonic carbonate factories. In another similar case study, a thickness of about 40 m has been reported for the Valanginian interval in the type locality of the Garau Formation at Kabir Kuh (Akhtari, 2010), calling for a sedimentation rate of about 5.8 mm/1000yr. These points are additional evidences that the recorded low sedimentation rates in the shallow-platform deposits in the Fars area during the Valanginian (around 10 mm/1000yr, see Fig. 3.5) is as a result of the Qatar Arch High and/or due to erosional processes with some parts of the early Valanginian and entire late Valanginian missing in this area.

Biostratigraphy and Sr-isotope dating (see Fig. 3.7; details in chapter 9) show that the tops of the Sar Bisheh and Fahliyan formations are not coeval, pointing to the presence of so far un-noticed paleo-highs, presumably due to regional uplifts of the Arabian Plate, such as the Qatar Arch, or due to local tectonic activities, forming thinning (pinch-outs) such as: Surmeh, Kalagh, Khartang and Assaluyeh or thickening sequences with corresponding onlap sedimentation such as: Qeshm-4, Suru-1 and Genow in Bandar Abbas Hinterland and Lar, Mish, Anneh in Izeh Zone.

This major discontinuity (at the boundary of the Valanginian and the Hauterivian) has been reported from the entire the Arabian Plate (Fig. 3.8) (Powers et al., 1966; Alsharhan and Kendall, 1991; Shebl and Alsharhan, 1994; Al-Fares et al., 1998; Sharland et al., 2004; Jassim and Goff, 2006; Granier, 2008).

Beyond the Arabian Plate, this Early to Late Valanginian drowning unconformity occurs in southern France, Estremadura, the eastern Prebetique and Betique areas (Rey, 1979; Garcia Hernandez et al., 1982), Helvetic Alps (Funk et al., 1993; Godet, 2013), Central Atlantic and Western Mediterranean (Granier, 1994), Helvetic zone in eastern Switzerland (Föllmi et al., 1994), southern Italy (Bosellini and Morsilli, 1997) and Catalan Pyrenees, NE Spain (Conrad et al., 2004).
3.2.3 Ghari Formation (Hauterivian)

The Hauterivian Ghari Formation, which is characterized by mixed siliciclastic/carbonate sediments (intercalations of thin-to medium-bedded argillaceous limestone and hemipelagic marl), is thicker in the Khuzestan area (Izeh Zone and Dezful Embayment) and in the western part of the Interior Fars respectively (Fig. 3.9). From the West (Dezful Embayment and Izeh Zone) towards the East, this formation becomes thinner which finally pinched-out in the areas of Sub-coastal Fars, Coastal Fars, eastern part of Interior Fars and entire Bandar Abbas Hinterland and offshore area (see Appendix 1).

An eastward shallowing trend of this formation (see Appendix 1) is supported by the occurrence of the coeval facies of the Gadvan Formation (newly Chahoo Formation) covering some parts of the Fars, Bandar Abbas Hinterland and offshore area (Fig. 3.10). Consequently, a flap-top platform extended during the Hauterivian in areas such as: Kalagh, Nakh, Burkh, Gavbast, Darbast and Khush. These carbonate deposits at the East (called Gadvan/Chahoo Formation) show that the shelf margin migrated eastward in response to sea-level rise (back-step) during the Hauterivian.
Due to the influence of the Qatar Arch High or local tectonic activities, some parts of the Fars area, Bandar Abbas Hinterland and offshore area (such as: Surmeh, Khurmoj, Khartang, Assaluyeh, Genow, Suru-1 and Qeshm-4) formed a topographic high and experienced non-deposition during the Hauterivian (see Appendix 1 and Fig. 3.10), whereas the Hauterivian deposits of the Gadvan Formation and its lateral equivalent, the Chahoo Formation, were recorded in some locations such as Kalagh, Darbast, Gavbast, Burkh, Nakh and Khush outcrops. It is now concluded that the lower boundary of the Gadvan Formation is diachronous in these areas, where it is significantly older than originally believed, dating from the Hauterivian stage eastward in the Fars High and Bandar Abbas Hinterland (for more information, see chapter 4).

Rates of sediment accumulation vary between 2 to 40 mm/1000yr during the Hauterivian, showing again the role of local tectonic activity in creating more accommodation space or local uplift (Fig. 3.11).

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**Fig. 3.10:** Regional isopach map of the Hauterivian deposits (Ghari and Gadvan/Chahoo formations) throughout the studied areas in the Zagros FTB.

**Fig. 3.11:** Sediment accumulation rates of deposited sediments during the Hauterivian in the studied area. The highlighted interval indicates the typical sedimentation rates for Cretaceous carbonate platforms (Schlager, 1981, 1999).
3.2.4 Gadvan Formation (Barremian)

The maximum thickness of the Barremian Gadvan Formation occurs in the Bandar Abbas Hinterland, offshore area and the western part of the Interior Fars (Fig. 3.12), where it essentially comprises shallow-water carbonates and includes the proximal part of the platform. These deposits are photozoan-dominated with assemblages comprising bivalves, gastropods, stromatoporoids, calcareous green algae, and diversified benthic foraminifera (details on the platform ecosystems in chapter 5). In some locations, benthic foraminifera are less diversified, and orbitolinids appear for the first time in the Early Barremian (e.g. at Khartang). Toward the west, in the Izeh Zone and Dezful Embayment in Khuzestan, marly intervals contain hemipelagic fauna with frequent bivalves (Exogyra sp.), but without any microbial production, indicating that heterozoan conditions prevailed. Sediment thickness decreases in these areas, calling for a low sedimentation rate (13.8-26.5 mm/1000yr), as a result of reduced carbonate production, or less tectonic activity, resulting in a small accommodation space (Fig. 3.13).

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**Fig. 3.12:** Regional isopach map of the Gadvan Formation throughout the studied area in the Zagros FTB.

**Fig. 3.13:** Sediment accumulation rates of deposited sediments during the Barremian in the studied area. The highlighted interval suggests normal sedimentation rates for Cretaceous carbonate platforms (Schlager, 1981, 1999).
3.3 Tectono-stratigraphic phases

The tectono-stratigraphical model proposed here is based on regional transects across the basin (Figs. 3.14). In summary, four distinctive evolutionary phases are suggested in the studied sequences:

**Phase 1**- The Fahliyan platform started to grow on the previously almost exposed Surmeh platform, and covered most areas of the Zagros FTB, except the Bandar Abbas Hinterland and offshore area which remained exposed. Brecciated dolomites at the boundary of the Jurassic / Cretaceous (Hith Formation), point to the presence of a probable regional and significant tectonic event. While sedimentation continued in a shallow-platform setting matching up with sea-level rise (*keep-up* mode) in Fars and Khuzestan during the Middle - Late Berriasian, hemipelagic sediments with tintinnids were deposited with a very low accumulation rate (*give-up* mode) in the Bandar Abbas Hinterland and offshore area. The suggested mechanisms of this drowning are block faulting resulting from basement fault movements creating intra-shelf grabens, or the tectonic activity of salt diapirs.

**Phase 2**- A general flooding occurred on the platform during deposition of the Early Valanginian Sar Bisheh Formation. This flooding is a world-wide event that is accompanied with argillaceous sedimentation (Granier, 1994). This event is well known from the Arabian Plate, with the deposition of the Ratawi shales in Iraq, Kuwait and Saudi Arabia (Sharland et al., 2004).

**Phase 3**- The Fahliyan platform became exposed during the early Late Valanginian, due to a major global eustatic sea-level lowstand which is marked on the entire Arabian Plate (Haq et al., 1987; Al-Fares et al., 1998; Sharland et al., 2004; Simmons et al., 2007). Therefore, a hiatus is present at the top of the Sar Bisheh Formation and its time equivalent the Fahliyan Formation. This stratigraphic gap includes the Late Valanginian in the Izeh Zone and Dezful Embayment in Khuzestan, whereas it becomes older in the Fars High, Bandar Abbas Hinterland and offshore area (Fig. 3.15).

**Phase 4**- A series of transgressive-regressive events occurred on the former platform during the Hauterivian - Barremian, with the deposition of mixed siliciclastic-carbonate sediments in the Izeh Zone and Dezful Embayment in Khuzestan (e.g. Ghari and Gadvan formations). On the other hand, a carbonate factory (e.g. the Chahoo Formation) was located in the Fars High, Bandar Abbas Hinterland and offshore area and the shelf margin migrated eastward. The eastern part of the platform (at Khurmoj, Khartang, Surmeh, Assaluyeh, Suru-1, Genow and Qeshm-4, Fig. 3.15) still remained a topographic high and was exposed during the Hauterivian. Finally, the limestone beds of the Khalij Member prograded on the hemipelagic marls of the lower Gadvan Formation across the basin.
Fig. 3.14: Suggested tectono-stratigraphy model showing the main evolutionary stages of the development of the Fahliyan, Sar Bisheh, Ghari, Gadvan and Chahoo formations, Zagros FTB.
3.4 Conclusions

Based on the spatial distribution of the lithostratigraphic units, a new time-rock synopsis and stratigraphical framework is suggested for the studied succession (Fig. 3.15).

Palaeogeographic reconstruction shows that during the Middle - Late Berriasian, the eastern side of the platform, in the Bandar Abbas Hinterland and offshore area, subsided rapidly as a result of extensive tectonic subsidence accompanied with thermal subsidence, led to deposition of basinal facies containing tintinnids and radiolarians. The Valanginian is marked by a worldwide drowning and accompanying by argillaceous sedimentation in this area of the Zagros FTB.

The termination of the Fahliyan Formation, as defined here, was associated with a relative sea-level fall triggering the Late Valanginian unconformity and generating karstic features on top of the Sar Bisheh Formation and its equivalent the Fahliyan Formation, across the shallow platform.

Siliciclastic influx and tongues of deltaic, shallow-marine sands were deposited during a subsequent rise of the sea-level within the Hauterivian. The corresponding Kushk Sandstone (NIOC internal reports) in the SW part of the Zagros FTB, is an equivalent of the Zubair Sandstone in Iraq and Kuwait (Alsharhan and Kendall, 1991; Sharland et al., 2004; Jassim and Goff, 2006).

A second drowning occurred in the Hauterivian with hemipelagic marls being deposited in the west, while the platform margin migrated eastward, with the corresponding sedimentation of shallow-platform carbonates (Chahoo Fm.), accompanied by several emergent paleo-highs at the East.

Based on a biostratigraphic study and also sediment thicknesses, it is concluded that up to 50% of the Valanginian stage is missing at the type locality of the Fahliyan Formation. This interpretation is based on rates of accumulation in the Late Valanginian interval, which is around 3.5 mm/1000yr., which is quite low by comparison to the normal sedimentation rates in shallow-carbonate platforms (Schlager, 1981, 1999, 2005). The sedimentary equivalent of the Valanginian hiatus is present in the far distal part of the basin, in the complete section of the Garau Formation, which has been studied for dinoflagellates, planktonic foraminifera and ammonites (Akhtari, 2010; Navidtalab et al., 2014). By contrast, eastward in the far proximal part of the basin, this stratigraphic gap spans most probably the uppermost early Valanginian and entire late Valanginian (Fig. 3.15), as confirmed by biostratigraphy and Sr-isotope dating.
Fig. 3.15: Suggested litho-chronostratigraphic scheme of Berriasian - Barremian deposits along a NW-SE transect, Zagros FTB. (Explanations in the text and assigned ages were shown in chapter 4). Previous lithostratigraphic names are shown in italic and new defined units are illustrated on a blank (white) background.
References:


4.1 Introduction and previous investigations

In the Zagros region, the first biozonation pattern on Lower Cretaceous deposits Wynd (1965), introduced one biozone (Pseudocyclammina lituus - Trocholina assemblage zone # 14) for the Lower Fahliyan Formation, and another biozone which covered both the Upper Fahliyan and the Gadvan formations as Choffatella - Cyclammina assemblage zone # 15. Moreover, for the deeper facies of the Fahliyan Formation (sensu James and Wynd, 1965), another biozone as Calpionella zone # 11a was suggested (Wynd, 1965).

Later on, the microfossil content of the Khami Group, including the Surmeh, Fahliyan, Gadvan and Dariyan formations was studied by Gollestaneh (1965, 1974, 1979), who suggested two biozones for the Fahliyan Formation (sensu James and Wynd, 1965) as: Tintinnid zone # III and Pseudocyclammina lituus – Pseudochrysalidina arabica – Algal zone # II. He suggested another biozone for both the Gadvan and Dariyan formations as: Orbitolina-Choffatella-Salpingoporella dinarica zone # I.

In recent years, an algal biozonation scheme was introduced for the Fahliyan Formation by Parvaneh Nejad Shirazi and Mosadegh (2009), including: (1) Salpingoporella spp. assemblage zone (S. annulata, S. steinhauseri, Clypeina cf. marteli, Boueina sp., Actinoporella podolica and Coptocampylodon fontis) and (2) Salpingoporella muehlbergi assemblage zone (S. dinarica, Lithocodium aggregatum, Permocalculus ampulacea and P. inopinatos), suggesting a Neocomian age.

A few other authors have presented either the microfossil content (benthic foraminifera and algal associations), or the sedimentology, facies analysis and sequence stratigraphy of the Fahliyan and Gadvan formations only in particular areas of the Zagros Basin (Maleki et al., 2008; Rastegar Lari, 2009; van Buchem et al., 2010; Peyman et al., 2010; Adabi et al., 2010; Maleki and Lasemi, 2011; Jamalian et al., 2011; Parvaneh Nejad Shirazi et al., 2013; Sahraeyan et al., 2013). These recent bio-chronostratigraphic analyses and sequence interpretations are still based on the old published datasets, such as Wynd (1965) and Gollestaneh (1979).

The new biozonation pattern presented here is the first one to unify bio-chronostratigraphic approaches for the former Fahliyan and Gadvan formations (which were revised here and separated in the Fahliyan, Sar Bisheh, Ghari, Gadvan and Chahoo formations, see chapter 3) throughout the Zagros FTB. This study provides a highly increased biostratigraphic resolution based on new age dating (detailed biostratigraphic data calibrated with Sr-isotope analysis) of the Berriasian-Barremian interval in SW Iran. The results presented here are based on a large dataset from outcrops and the subsurface.

The following subjects are discussed in this chapter:

First, micropaleontological assemblages of the studied formations are mentioned throughout the entire studied areas. Then, new biozonation schemes are introduced based on the distribution of tintinnids, benthic foraminifera and dasycladalean algae, followed by a description of the proposed biozones. Thereafter, the stratigraphic significance of some index taxa and their comparison with other areas in Iran and on the Arabian
Plate are explained. Finally, a uniform bizonation is suggested for the studied stratigraphic intervals in the Zagros FTB.

4.2 Materials and methods

The approach used for the biostratigraphic characterization involved the study of 4882 thin-sections which were taken from rock specimens in nineteen outcrops and from cutting samples in five drilled wells.

The biostratigraphic data of this work are compared with the results from the broader Tethyan region (Carras et al., 2006 for dasycladalean algae; Velić, 2007 for benthic foraminifera in general; Blau and Grün, 1997 for tintinnids).

Taxonomy of trocholinids was performed based on the new classification proposed by Rigaud et al. (2013). Concerning orbitolinids, the proposed phylogenetic lineages for the Arabian Plate (Schroeder et al., 2010) and also the stratigraphic distribution of orbitolinids, which was calibrated with ammonite zones in southeastern France and in the Swiss Jura (Clavel et al., 2010, 2013), have been used in this study.

The final data was used to modify the traditional biozonation pattern (Wynd, 1965; Gollestaneh 1965, 1974, 1979), and introduce a new local biozonation for the studied intervals.

Biostratigraphic zones (biozones) were defined on the basis of their microfossil assemblage (a single taxon, combination of taxa, relative abundances of taxa) in accordance with the regulations of the International Commission on Stratigraphy (chapter 7, part D: Murphy and Salvador, 1999).

4.3 Micropaleontological content

All the determinations of the studied microfossils in thin-sections were confirmed by several specialists including:

- Dr. Marc A. Conrad, Switzerland (dasycladalean algae).
- Dr. Nicolaos Carras, Greece (benthic foraminifera in general).
- Bernard Clavel, France (orbitolinids).
- Prof. Roland Wernli, Switzerland (tintinnids).

4.3.1 Fahliyan Formation (Berriasian - Valanginian)

Within the Fahliyan Formation, the micropaleontological assemblages are usually frequent, very well diversified and include benthic foraminifera and dasycladalean algae. In some parts of the Zagros FTB, the Fahliyan Formation begins with a deep-water facies containing tintinnids (see appendices 2 and 3 for fossil distribution range charts and some plates of identified microfossils).

4.3.1.1 Benthic foraminifera

Among the benthic foraminifera, Pseudocyslammina lituus, Coscinoconus alpinus, C. elongatus, C. campanellus, C. delphinion, Protopeneroplis ultragranulata, Mohlerina basiliensis, Redmondoides lugeoni, Praechrysalidina infracretacea, Montsalevia salevensis, Nautiloculina oolithica, Vercorsella camposaurii and Torinosuella peneropliformis are frequent in the lower part. Upward, close to the top of this formation, Coscinoconus chouberti, C. sagittarius, C. mol estus, C. cherchiae, Valdanchella miliani and Paravalvulina arabica are appeared.

4.3.1.2 Dasycladalean algae

A well-preserved assemblage of dasycladalean algae is observed within the thick- to massive limestones of the Fahliyan Formation including: Salpingoporella annulata, S. circassa, S. granieri, S. istriana, S. katzeri, S. piriniae, S. pygmaea, S. steinhauseri, C. dragastani, C. solkani/parasolkani, C. sulcata (jurassica), Holosquarella arabica, Otternella lemmensis, Pseudoclypeina crnogorica, Selliporella neocomiensis, Rajkaella barteli, Actinoporella podolica, Zergabriella embergeri, Irenella inopinata and Mizia zagarthica n. sp. Close to the top of the Fahliyan Formation, Actinoporella jaffrezoii, Clypeina estevezii, Salpingoporella cf. parapiriniae and Korkyrella texana appear.
4.3.1.3 Tintinnids

The important tintinnids which are present in the lower part of the Fahliyan Formation (in the Bandar Abbas Hinterland and offshore area) are: *Remaniella cadischiana*, *Calpionella alpina*, *Calpionella elliptica*, *Tintinopsella longa*, *Tintinopsella carpathica*, *Calpionellopsis simplex*, *Calpionellopsis oblonga* and *Calpionellites darderi*.

4.3.2 Sar Bisheh Formation (Early - Late Valanginian)

Most of the taxa observed in the Fahliyan Formation are also present in this formation, and are accompanied by a few taxa that appear here (see appendices 2 and 3 for fossil distribution range charts and some plates of identified microfossils).

4.3.2.1 Benthic foraminifera

They comprise a high frequency of *Paravalvulina arabica*, *Coscinoconus cherchiae*, *C. chouberti*, *C. delphinensis*, and *Valdanchella miliani*, with the first occurrence of *Haplophragmoides joukowskyi*. The last occurrences of *Mohlerina basiliensis* and *Protopeneroplis ultragranulata* is in accordance with the base of the Sar Bisheh Formation.

4.3.2.2 Dasycladalean algae

Among the dasycladalean algae, *Actinoporella jaffrezoi* and *Clypeina estevezii* represent the most frequent species in this formation. Also this formation corresponds with the last occurrences of *Clypeina sulcata* (jurassica), *Zergabriella embergeri*, *Salpingoporella steinhauseri*, *Clypeina dragastani* and *Salpingoporella granieri*. Moreover, *Salpingoporella cf. parapiriniae*, *S. dinarica*, *S. hispanica* and *Similicypeina cf. conradi* first appear in this interval. The remaining portions of the dasycladalean algae of the Fahliyan Formation extend all within the Sar Bisheh Formation.

4.3.3 Ghari and Gadvan/Chahoo formations (Hauterivian)

See appendices 2 and 3 for fossil distribution range charts and some plates of identified microfossils.

4.3.3.1 Benthic foraminifera

Most of the benthic foraminifera of the previous rock units became extinct in these formations, except for *Coscinoconus alpinus*, *C. elongatus*, *C. molestus* and *C. Sagittarius*. Some new forms of benthic foraminifera with a stratigraphically important range appear here such as: *Nezzazata simplex var. germanica*, *Campanellula capuensis*, *Choffatella arcana*, *Choffatella cruciensis* (decipiens), *Debarina hahounerensis*, and *Vercorsella laurentii*.

4.3.3.2 Dasycladalean algae

This interval is marked by the last occurrences of *Salpingoporella circassa* and *S. annulata*. Among the other dasycladalean algae, *Salpingoporella pygmaea*, *S. dinarica*, *Iaranella inopinata*, *Actinoporella podolica*, *Salpingoporella cf. parapiriniae*, *Korkyrella texana*, *Similicypeina cf. conradi* and *Salpingoporella hispanica* have ranges from the older deposits. Moreover, this interval is characterized by levels rich in *Terquemella* sp., and the first occurrence of *Salpingoporella cemi* and *S. cf. biokovensis*.

4.3.4 Gadvan and Chahoo formations (Barremian)

See appendices 2 and 3 for fossil distribution range charts and some plates of identified microfossils.

4.3.4.1 Benthic foraminifera

Benthic foraminifera assemblage of these formations are characterized by the first occurrence of orbitolinids; *Falsurgonina pileola* and *Orbitolinopsis debelmasi* in the lower part, that are followed upward by the presence of *Eopalorbitolina transiens*, *Palorbitolina lenticularis* and *Montseciella arabica* (in the Khalij Member). Among the other benthic foraminifera, *Debarina hahounerensis*, *Choffatella arcana*, *Choffatella cruciensis* (decipiens), *Coscinoconus sagittarius*, *C. molestus*, and *Vercorsella laurentii* continue from the
previous intervals. Moreover, *Hemicyclammina sigali* is commonly present in the lower and upper part of the Gadvan Formation.

### 4.3.4.2 Dasycladalean algae

Among the dasycladalean algae, *Montiella elitzae* and *Salpingoporella hasi* appear for the first time in the Gadvan Formation and/or the Khalij Member. Others, such as *Salpingoporella cemi*, *S. dinarica*, *S. cf. biokovensis*, *S. hispanica*, *S. pygmaea*, *S. cf. parapiriniae*, *Korkyrella texana*, *Similiclypeina cf. conradi* and *Iranella inopinata* continue from the older deposits.

### 4.4 Biostratigraphic zonation and subdivisions

Up to now, no commonly accepted uniform biozonation has been defined based on neither benthic foraminifera nor dasycladalean algae for the Lower Cretaceous (Berriasian - Barremian) deposits in the Arabian Plate or in Southern Tethyan realm. Therefore, each person uses his own local scheme. In our biozonation, we worked separately on all benthic foraminifera, dasycladalean algae and tintinnids to propose some biozones. The final pattern is based on a compiled scheme of these defined biozones. This model can serve as a standard model, where the definition of biozones are based on the regulations of the International Commission on Stratigraphy (ICS), and also the age of the base and top of the suggested biozones have been calibrated by Sr-isotope dating (details in chapter 9).

The taxa represented here as references to establish the biozonation pattern were selected among the most frequent forms that are: (1) easy to identify and (2) abundant in the studied intervals. In this study, we preferred to define biozones rather than biostratigraphic intervals that allow us to determine more accurate ages and precise time lines to be used for sequence interpretation.

#### 4.4.1 Tintinnids (Figs. 4.1-4.4)

As tintinnids are the only fossil group allowing a biostratigraphic zonation as precise as ammonites, three new biozones are suggested for the tintinnids throughout the Zagros FTB in the studied interval (Berriasian-Barremian). This zonation pattern is based on the last version and revised pattern of tintinnid biozonation of *Blau and Grün* (1997), performed on the samples from the Vocontian Trough, and the resolution of this pattern is comparable to the ammonite subzones.

The here introduced tintinnid biozones are present in the lowermost part of the Fahliyan Formation in the eastern part of the Zagros FTB, in the Bandar Abbas Hinterland and offshore area.

#### 4.4.1.1 Calpionella Zone

*Cadischiana* Subzone (Fig. 4.1)

The base of this subzone is the first occurrence (FO) of *Remaniella cadischiana* (Colom) and the top of that is marked by the FO of *Calpionellopsis simplex* (Colom) and *Calpionellopsis oblonga* (Cadisch). This subzone spans the late Middle Berriasian (*Blau and Grün*, 1997). In the Zagros FTB, where the Fahliyan Formation starts with the basinal facies containing tintinnids, the formation contains *Remaniella cadischiana*, indicating that the base of this formation is of late Middle Berriasian age. The other important tintinnids in this interval are *Calpionella alpina* and *C. elliptica*. 
Fig. 4.1: *Remaniella cadischiana* (Colom) from the Fahliyan Formation, Zagros FTB; a: sample depth 3843-45 m, Suru well-1; b: sample LETP 4966, Genow outcrop (Tang-e Asboo); c: sample GAJ 1674, Khush outcrop. Scale bars: 30 µm.

### 4.4.1.2 Calpionellopsis Zone

*Simplex / Oblonga* Subzone (Fig. 4.2)

This subzone (interval zone) includes the FO of either *Calpionellopsis simplex* (Colom) or *Calpionellopsis oblonga* (Cadisch) to the FO of *Calpionellites darderi* (Colom). These two species have ranges up to the Late Berriasian (Blau and Grün, 1997). This subzone is present within the entire basinal facies of the Fahliyan Formation, in the Bandar Abbas Hinterland and offshore area (Khush, Genow, Suru well-1 and Qeshm well-4). Among the other important taxa of tintinnids, *Remaniella cadischiana, Calpionella alpina* and *C. elliptica* are still present in this interval, but two other significant tintinnids, *Tintinopsella longa* and *T. carpathica* appear for the first time in this biozone.

Fig. 4.2: *Calpionellopsis simplex* (Colom) from the Fahliyan Formation, Zagros FTB; a: sample depth 3814-16 m, Suru well-1; b: sample GAJ 1673, Khush outcrop; c: sample LETP 4951, Genow outcrop (Tang-e Asboo). Scale bars: 30 µm.

### 4.4.1.3 Calpionellites Zone

*Darderi* Subzone (Fig. 4.3)

This subzone is defined by the FO of *Calpionellites darderi* (Colom), and corresponds to the base of the Valanginian (Blau and Grün, 1997). In the Zagros FTB, this subzone is the last tintinnid zone within the Fahliyah Formation and it occurs in the Bandar Abbas Hinterland and offshore area (Khush, Genow, Suru well-1 and Qeshm well-1). Other tintinnids which have ranges within this biozone are: *Calpionella alpina, C. elliptica, Tintinopsella longa* and *T. carpathica* (Fig. 4.4).
Chapter 4

Berriasian Early Valanginian Age (Ma)

Biozones (Blau and Grün, 1997)

<table>
<thead>
<tr>
<th>Biozones</th>
<th>Tintinnids</th>
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<tr>
<td></td>
<td>Calpionellites (C. darderi)</td>
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<td></td>
<td>Calpionellopsis (C. simplex / C. oblonga)</td>
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<td></td>
<td>Calpionella (R. cadischiana)</td>
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Fig. 4.4: Biostratigraphic subdivisions in the basinal facies of the Fahliyan Formation based on the range of tintinnids (Remaniella cadischiana, Calpionellopsis simplex / C. oblonga and Calpionellites darderi), Zagros FTB. The identified stratigraphic gap during the Early Berriasian in the studied area is shown in oblique hatches.

Regionally, similar assemblages of tintinnid fauna have been reported from several localities in the Arabian Plate (the United Arab Emirates and Abu Dhabi), in the Berriasian (probably Middle Berriasian) - Valanginian interval, within the Rayda and Salil formations (Toland et al., 1993 in Granier, 2008). This assemblage has also been recorded from the Rayda Formation in Oman, in Jabal Akhdar, suggesting a Middle - Late Berriasian age (Rousseau et al., 2005).

4.4.2 Benthic foraminifera (Figs. 4.5-4.13)

Benthic foraminifera are quite frequent and commonly well preserved in the studied intervals. They can be used for age determination and stratigraphic subdivision of the shallow-water carbonates in the Lower Cretaceous, Zagros FTB. A total of 6 biozones, from total-range zone to assemblage zone, are defined within the studied stratigraphic intervals from the Berriasian to the Late Barremian. This zonation enabled us to
establish a detailed biostratigraphic subdivision reported for the first time in the Zagros area and even in the entire Arabian Plate. As the studied area belonged to the Southern Neotethyan bioprovince during the Early Cretaceous, range and composition of foraminiferal assemblages are controlled by the biozonation defined by Velić (2007) for the Karst Dinarides (SE Europe). Furthermore, the stratigraphic distribution of orbitolinids was compared with latest models suggested for the Arabian Plate (Schroeder et al., 2010) and the Urgonian facies from the Jura fold-thrust belt, SE France and Switzerland (Clavel et al., 2010, 2013).

4.4.2.1 Protopeneroplis ultragranulata, Mohlerina basiliensis assemblage zone (Fig. 4.5)

**Boundaries:** The lower boundary of this biozone is the FO of *Protopeneroplis ultragranulata*, corresponding to the base of the Cretaceous in the Zagros FTB, where the Fahliyan Formation rests on the Upper Jurassic Hith anhydrite or its time equivalent (brecciated dolomites) at the top of the Surmeh Formation. According to the biozonation scheme of Velić (2007), *Mohlerina basiliensis* starts from the Middle Jurassic (Callovian). In the Zagros area, the LO of this taxon is in the Late Berriasian, which is considered as the upper boundary of this biozone.

**Important associated taxa:** Coscinocmus alpinus, C. elongatus, C. campanellus, C. chouberti, C. molestus, C. sagittarius, C. delphinensis, Pseudocyclammina lituus, Montsalevia salevensis, Vercorsella camposaurii, Torinosuella peneropliformis, Redmondoides lugeoni and Nautiloculina oolithica.

**Stratigraphic range:** Berriasian

**Distribution:** This biozone is present within the Fahliyan Formation in the Khuzestan (Izeh Zone and Dezful Embayment) and in entire parts of the Fars areas (interior, subcoastal and coastal) in the Zagros FTB. A time equivalent interval of this biozone is marked by either a non-deposition condition (stratigraphic break) or the presence of tintinnids in Bandar Ababs Hinterland and offshore area.

**Stratigraphic significance of some index taxa:**

- *Mohlerina basiliensis* (Mohler, 1938), Mohler (1938) originally described this form from Upper Oxfordian rocks in northern Switzerland (as Conicospirillina basiliensis). It ranges from the Middle/Late Bathonian to the Valanginian (Bassoulet, 1997). In the Northern Calcareous Alps of Austria (Weitenau, Mount Hoherstein Plateau, Mount Zwercwchwand, Mount Trisselwand), *Mohlerina basiliensis* has been reported as a widely distributed foraminifer in the Late Jurassic-earliest Cretaceous (Schlagintweit, 2012). This form has been reported mostly from the Berriasian and less from the
Valanginian interval in several locations in the North and Central Tethyan realm (Darsac, 1983; Salvini-Bonnard et al., 1984; Boisseau, 1987; Granier, 1987; Bucur, 1988; Chioccini et al., 1988; Altiner, 1991; Chioccini et al., 1994; Bucur and Sasaran, 2011; Bucur et al., 2012). This species has also been reported form the Mozduran Formation (Late Jurassic) in the Kopet Dagh Basin, NE Iran (Bucur et al., 2012).

- **Protopeneroplis ultragranulata** GORBATCHIK, the most frequent occurrence of this species coincides with the Berriasian-earliest Valanginian. It has been reported from several locations in the Tethyan realm (Azema et al., 1977; Azema et al., 1979; Salvini-Bonnard et al., 1984; Boisseau, 1987; Granier, 1987; Zaninetti et al., 1988; Bucur, 1988; Chiocchini et al., 1988; Velić, 1988; Bucur et al., 1995; Bucur et al., 2000; Velić, 2007; Bruni et al., 2007).

### 4.4.2.2 Paravalvulina arabica or Valdanchella miliani - Coscinocus campanellus / C. delphinensis interval zone (Fig. 4.6)

**Boundaries:** The lower boundary of this biozone corresponds to the FO of *Paravalvulina arabica* or *Valdanchella miliani*. This biozone covers also the stratigraphic range of *Haplophragmoides joukowskyi* and *Coscinoconus cherchiae*. The upper limit of this interval zone is the LO of *Coscinoconus campanellus* and/or *C. delphinensis*.

**Important associated taxa:** Most of the benthic foraminifera present in the Berriasian interval, have wider stratigraphic range and continue in this biozone.

**Stratigraphic range:** Valanginian (mostly Early Valanginian as callibrated with dasycladalean algae and Sr-isotope dating).

**Distribution:** This biozone is present within the Sar Bisheh Formation and the upper part of the Fahliyan Formation in the entire parts of the shallow-platform deposits (Khuzestan, Fars, Bandar Abbas Hinterland and offshore area).

**Stratigraphic significance of some index taxa:**

- **Paravalvulina arabica** (HENSON) was first described as *Dukhania arabica* by Henson (1948a) from the well Dukhan no 2 in Qatar. Later on, topotypes of this form were illustrated by Schroeder (1975) under the name of *Pseudochrysalidina (?)* arabica (HENSON). This form has also been reported as: *Chrysalidina*, *Valvulinella*, *Broekinella*, *Paravalvulina* or *Valvulines* (see Granier, 2008 and references here). This form (*Paravalvulina arabica*) is identified as an important marker in the Valanginian Yamama Formation in several locations in the Arabian Plate (such as: Saudi Arabia, Qatar, United Arab Emirates, Kuwait, Bahrain, Iraq) (Granier, 2008).

- **Pseudocyclammina lituus** (YOKOYAMA) has been reported as: *Cyclammina* sp. from the Buwaib Formation of Hauterivian age in Saudi Arabia by Powers in 1968 (Granier, 2008). Some *Cyclamminid* samples have been reported as: *Pseudocyclammina sulaiyana* REDMOND that is a synonym of *Pseudocyclammina lituus* from the Sulayti and Yamama formations in Saudi Arabia (Granier, 2008). The association of *Pseudocyclammina lituus* with *Paravalvulina arabica* provides a highly reliable marker over most parts of Saudi Arabia and neighbouring countries within the Valanginian Yamama Formation. In the Offshore Sharjah (Oman), this form is commonly associated with the high-spired *Trocholina* spp. in the Zakum Member of the former Habshan Formation in the Early Valanginian age (Granier, 2008).
Fig. 4.6: Index taxa of the Valanginian interval from the Sar Bisheh Formation, Zagros FTB; a-c: *Paravalvulina arabica*, a: samples AFA 178, Khartang outcrop; b: sample LETP 5004, Genow outcrop (Tang-e Asboo); c: sample ARP 914, Lar outcrop; d-f: *Valdanchella miliani*, samples JHT 2072, 2073, Kalagh outcrop; g-i: *Coscinoconus delphinensis*, g: sample ASL 2517, Assaluyeh outcrop; h: sample ARP 151, Anneh outcrop, i: sample MAK 4943, Kuzeh Kuh outcrop; j-l: *Coscinoconus campanellus*, j: sample ARP 102, Anneh outcrop, k: sample MAK 5237, Fahlivan outcrop, l: sample JTH 2063, Kalagh outcrop. Scala bars: 200 µm.

- *Valdanchella miliani* was described by Pfender (1938) from the Valanginian of Provence as: *Dictyoconus valnutensis*. It was later described as *Simplorbitolina miliani* from the Valanginian of Spain by Schroeder and finally transferred to the new genus as *Valdanchella* by Canerot and Moullade in 1971. This form has also been reported from the Upper Valanginian of the Eastern Pyrenees (Peybernes and Rey, 1975), Lower Valanginian of Spain (Azema et al., 1977), France (Jaffrezo, 1980; Darsac, 1983) and Spain (Canerot, 1984).
• *Haplophragmoides joukowskyi* was described by Charollais et al. (1966) from the Valanginian to Hauterivian deposits from Switzerland. This species has been reported from several locations: Valanginian deposits in the Southern Jura and Salève Mountains, SE France (Kobayashi and Wernli, 2012) and other locations in the Tethyan realm, again always in the Valanginian stage (Dragastan, 1978; Darsac, 1983; Bucur, 1988; Altiner, 1991). Therefore, a reliable Valanginian age can be assumed for this species which corresponds to its occurrence in the Zagros FTB.

• *Coscinoconus chouberti* has been reported (as *Trocholina chouberti*) from the Valanginian deposits of Morocco (Arnaud-Vanneau, 1988) and also as a Valanginian marker form the platform sediments of the Central-Southern Apennines (Italy) (Mancinelli and Coccia, 1999).

• *Coscinoconus cherchiae* was reported (as *Trocholina cherchiae*) from the Latest Berriasian-Valanginian of Romania (Arnaud-Vanneau, 1988), the Valanginian deposits of the Central-Southern Apennines, Italy (Mancinelli and Coccia, 1999), the Berriasian-Valanginian of Romania (Bucur and Sasaran, 2005) and the Valanginian deposits of the Southern Jura and Salève Mountains, France (Kobayashi and Wernli, 2012).

• *Coscinoconus campanellus* has been reported (as *Trocholina campanella*) from the Berriasian-Latest Valanginian (Arnaud-Vanneau, 1988), the Late Berriasian-Valanginian (Mancinelli and Coccia, 1999) and the Berriasian-Valanginian of Romania (Bucur and Sasaran, 2005).

• *Coscinoconus delphinensis* has been reported (as *Trocholina delphinensis*) from the Berriasian (Arnaud-Vanneau, 1988), the Late Berriasian-Valanginian (Mancinelli and Coccia, 1999), the Berriasian-Valanginian of Romania (Bucur and Sasaran, 2005) and the Valanginian of the Tethyan realm (Velić, 2007).

4.4.2.3 Choffatella decipiens - *Nezzazata simplex var. germanica / Campanellula capuensis* interval zone (Fig. 4.7)

**Boundaries:** The FO of *Choffatella decipiens* and the LO of *Nezzazata simplex var. germanica* and/or *Campanellula capuensis*.

**Important associated taxa:** *Coscinoconus alpinus, C. elongatus, C. sagittarius, Vercorsella camosaurii* and *Pseudocyclammina lituus* which have ranges from the Valanginian, and also the first occurrence of *Debarina hahounerensis*.

**Stratigraphic range:** Hauterivian as confirmed by dasycladalean algae and Sr-isotope dating.

**Distribution:** This biozone includes the Ghari Formation (hemipelagic marls and intercalations of thin, argillaceous limestone beds), is observed ideally in the Khuzestan area (Izeh zone and Dezful embayment), but continues into the western part of the interior Fars area (Gavdan and Ahmadi-1). Time-equivalent of this biozone, which is dominated by dasycladalean algae is present in the Gavdan Formation (such as at the Gavbast outcrop) and in the new lithostratigraphic unit, the Chahoo Formation in the eastern part of the Fars area (Darbast, Burkh and Nakh) and in the eastern part of the Bandar Abbas Hinterland (Khush) and offshore (Qeshm-4).

**Stratigraphic significance of some index taxa:**

- *Nezzazata simplex var. germanica* was described from Germany by Omara and Strauch (1965), and the type section includes dark shales of Hauterivian age. This species has also been reported from the *Campanellula capuensis* zone of Hauterivian age from the Logatec Plain (Slovenia) (Sribar, 1979). It has been reported as an index marker of the Late Hauterivian from the Karst Dinarides, SE Europe (Velić, 2007).

- *Campanellula capuensis* has been reported as the sub-species *Orbitolinopsis capuensis* from the Barremian in the Prebetic Zone, Spain (Garcia-Hernandez, 1979). This species has also been reported as *Orbitolinopsis capuensis* of Hauterivian age from the Logatec Plain, Slovenia (Sribar, 1979). It was also reported of Hauterivian age from the Fara San Martino section (Italy) in association with *S. annulata* and *C. solkani* (Bruni et al., 2007). Finally this species represents an index marker of the Late
Hauterivian that has been reported from the Adriatic Plate and Southern Tethyan domains in the Karst Dinarides, SE Europe (Velić, 2007), but it has never been reported from the southern Tethyan realm.

- **Debarina hahounerensis**: The stratigraphic range of this species is Late Hauterivian to Albian in the Karst Dinarides, SE Europe (Velić, 2007) and Late Hauterivian to Aptian in Italy (Campania, Abruzzo and Apulia) (Sartorio and Venturini, 1988). The species has also been reported from the Aptian deposits of the Maiella platform, Italy (Bruni et al., 2007).

![Fig. 4.7: Index taxa of the Hauterivian interval from the Ghari and Chahoo formations, Zagros FTB; a-b: Campanellula capuensis, sample ASL 2645, Gavbast outcrop; c: Choffatella decipiens, sample MZY 333, Fahliyan outcrop; d-e: Nezzazata simplex var. germanica, samples GAJ 1712 and DMS 355, respectively from Khush and Burkh outcrops. Scale bars: a-b: 500 µm, c: 300 µm, d: 50 µm and e: 100 µm.]

4.4.2.4 *Falsurgonina pileola - Orbitolinopsis debelmasi concurrent-range zone* (Fig. 4.8)

**Boundaries**: This biozone includes the overlapping part of the range of these two specific orbitolinid taxa. This biozone includes the interval between two important biohorizons, the LO of *Campanellula capuensis* and the FO of *Eoparorbitolina transiens* and/or *Palorbitolina lenticularis*.

**Important associated taxa**: No important other taxa, except for some forms with wider stratigraphic range: *Coscinococcus molestus, C. sagittarius, Debarina hahounerensis* and *Choffatella decipiens*.

**Stratigraphic range**: Early - earliest Late Barremian

**Distribution**: Typically, this biozone is present within the shallow-water carbonates of the Gadvan/Chahoo Formation in some locations of the Fars areas (e.g. Khartang, Burkh).
Fig. 4.8: Important taxa of the Early Barremian interval from the Gadvan/Chahoo Formation, Zagros FTB; a-c: Orbitolinopsis debelmasi and d-f: Falsurgonina pileola, all sections from sample AFA 183, Khartang outcrop.

Stratigraphic significance of some index taxa:

- *Falsurgonina pileola* and *Orbitolinopsis debelmasi*, two index orbitolinids, are quite frequent in the Urgonian platform carbonates from Southeastern France and the Swiss Jura Mountains. *Falsurgonina pileola* appears from the Late Hauterivian (*Ligatus* ammonite zone) which continues with a highest frequency within the late Early Barremian and its LA is in the Late Barremian (*Giraudi* ammonite zone). By comparison, the first occurrence of *Orbitolinopsis debelmasi* is in Late Hauterivian (*Ligatus* ammonite zone), becomes quite frequent within the *Hugii* and *Nicklesi* ammonite zones (Early Barremian) and its LA is in earliest Late Barremian (*Vanden* ammonite zone) (Clavel et al., 2010, 2013).

4.4.2.5 *Choffatella decipiens, Coscinoconus sagittarius, Iranella inopinata* assemblage zone (Fig. 4.9)

**Boundaries:** This biozone is defined based on the appearance of an assemblage of *Choffatella decipiens, Coscinoconus sagittarius* and *Iranella inopinata*. Lower boundary of this biozone corresponds to the LO of *Campanellula capuensis, Nezzazata simplex* var. *germanica, Salpingoporella annulata, S. circassa* and the FO of *Salpingoporella hasi*. The upper boundary coincides with the FO of *Palorbitolina lenticularis* and/or *Eopalorbitolina transiens*.

**Important associated taxa:** Abundant dasycladalean algae such as: *Salpingoporella hispanica, S. cemi, S. dinarica, Terquemella sp.*, *Russoella radiocicae, Korkyrella texana*, with *Coscinoconus molestus, Debarina hahounerensis, Vercorsella laurenti* and *Permocalculus* sp.

**Stratigraphic range:** Early Barremian.
Fig. 4.9: Some assemblage taxa of the Early Barremian interval from the Chahoo Formation, Zagros FTB; a: *Choffatella decipiens*, sample MRN 771, Genow outcrop (Tang-e Chahoo); b: *Vercorsella laurenti*, sample MRN 795, Genow outcrop (Tang-e Chahoo); c: *Coscinoceras molestus*, sample MRN 784, Genow outcrop (Tang-e Chahoo); d: *Coscinoceras sagittarius*, sample MRN 792, Genow outcrop (Tang-e Chahoo); e: *Korkyrella texana*, sample MRN 795, Genow outcrop (Tang-e Chahoo); f-g: *Iranella inopinata*, f: sample MRN 788, Genow outcrop (Tang-e Chahoo), g: sample LETP 5033, Genow outcrop (Tang-e Asboo); h-j: *Terquemella* spp. with *Russoella radoicicae* sample LETP 5022, Genow outcrop (Tang-e Asboo). Scale bars: a-i: 100 µm, j: 500 µm.
**Distribution:** It is present in the carbonate succession of the lower part of the Chahoo Formation in the eastern part of the Fars area (coastal Fars, such as: Nakh), Bandar Abbas Hinterland (Genow, Khush, Suru well-1) and offshore area (Qeshm well-4).

**Stratigraphic significance of some index taxa:**

- *Iranella inopinata* is endemic to the Zagros area. It was previously reported as a marker for the Barremian-Aptian (Gollestaneh, 1965, 1974, 1979). New findings indicate that it appears from the Berriasian and continues until the Aptian, and that its abundance is comparatively higher in the Valanginian and Hauterivian as proven by benthic foraminifera and other dasycladalean algae (Hosseini and Conrad, 2008; Hosseini et al., 2013).

- *Coscinoconus sagittarius* was reported (as *Trocholina sagittaria*) from Hauterivian to Barremian deposits from France (Arnaud-Vanneau, 1988), Valanginian deposits from the Central-Southern Apennines, Italy (Mancinelli and Coccia, 1999), Berriasian-Valanginian from Romania (Bucur and Sasaran, 2005) and Valanginian-Barremian from the Karst Dinarides, SE Europe (Velić, 2007).

**4.4.2.6 Eopalarbitolina transiens - Palorbitolina lenticularis concurrent-range zone** (Fig. 4.10)

**Boundaries:** It is defined by the FO of *Eopalarbitolina transiens* and *Palorbitolina lenticularis* at the base and the LO of *Eopalarbitolina transiens* at the top. Therefore, it almost covers the interval that shows the overlapping parts of the range of *Eopalarbitolina transiens* and *Palorbitolina lenticularis*.

**Important associated taxa:** No other stratigraphically important taxa are present here, except for some forms with wider stratigraphical range from the Valanginian and the Hauterivian, such as: *Coscinoconus molestus*, *C. sagittarius*, *Debarina hahounerensis*, *Vercorsella laurenti* and rare *Choffatella decipiens*. Among the dasycladalean algae, *Salpingoporella dinarica*, *S. hispanica* and *Iranella inopinata* are commonly present.

**Stratigraphic range:** latest Early Barremian - Late Barremian

**Distribution:** This biozone is present in the lower-middle parts of the Chahoo Formation in the eastern parts of the Fars area (Burkh, Nakh and Gavbast), in the Bandar Abbas Hinterland (Genow, Khush and Suru well-1) and offshore (Qeshm well-4). It also extends within the Khalij Member in the entire parts of the platform.

**Stratigraphic significance of some index taxa:**

- *Eopalarbitolina transiens*‘s and *Palorbitolina lenticularis*‘s FAD are Early Barremian. According to the proposed phylogenetic lineages for orbitolinids in the Arabian Plate and the Iranian Zagros Basin (Schroeder et al., 2010), and also to the stratigraphic distribution of orbitolinids which is calibrated with ammonite zones in southeastern France and the Swiss Jura (Clavel et al., 2010, 2013), the first occurrence of *Eopalarbitolina transiens* occurs in the late Early Barremian (*Nicklesi* ammonite zone) and continues until the latest Barremian (*Giraudi* ammonite zone). On the other hand, the first occurrence of *Palorbitolina lenticularis* is in the latest Early Barremian *Pulchella* ammonite zone, with the LO in the Early Aptian (top of Bedoulian). Therefore, the intervals which show the co-occurrence of these two orbitolinids, can be assumed as latest Early to Late Barremian age, as it is observed in the Gadvan and Chahoo formations up to the top of the Khalij Member in the Zagros FTB.
4.4.2.7 Palorbitolina lenticularis - Montseciella arabica concurrent-range zone (Fig. 4.11)

**Boundaries:** This biozone is defined from the LO of Eopalorbitolina transiens to the LO of Montseciella arabica.

**Important associated taxa:** No other stratigraphically important taxa are present here, except for some forms with wider stratigraphical range from the Valanginian and Hauterivian, such as: Coscinoceras molestus, C. sagittarius, Debarina hahounerensis and rare Choffatella decipiens.

**Stratigraphic range:** late Late Barremian. It is worth mentioning that these two orbitolinids, Palorbitolina lenticularis and Montseciella arabica, have an overlapping stratigraphic range until the Early Aptian (Early Bedoulian). But, Sr-isotope analysis performed on one sample (MANA 301) from a bivalve shell from the marly interval in the upper part of the Gadvan Formation in the Fahliyan outcrop suggests that this interval is still of Late Barremian age ($^{87}$Sr/$^{86}$Sr: 0.707445 = 125.5 Ma) (see chapter 9 for details). This interval dated by Sr-isotope can be correlated with the upper part of the Chahoo Formation (which includes shallow-water carbonates) in the eastern part of the Fars, Bandar Abbas Hinterland and offshore area, where it contains both Palorbitolina lenticularis and Montseciella arabica. Therefore, this biozone is considered as the latest Barremian marker for the entire Zagros FTB. This zone has been reported previously as the Montseciella arabica subzone for the southern Arabian and northeastern African plates (Schroeder et al., 2010).

**Distribution:** Within the shallow-water carbonates of the Chahoo Formation in the Fars, Bandar Abs Hinterland and offshore area.

**Stratigraphic significance of some index taxa:**

- **Palorbitolina lenticularis:** The stratigraphic range of this species is in the Late Barremian - Early Aptian (Bedoulian) in the Arabian Platform (Schroeder et al., 2010) and latest Early Barremian - Early Aptian (Bedoulian) in southeastern France and the Swiss Jura (Clavel et al., 2010, 2013).

- **Montseciella arabica:** This form has been reported form the Late Barremian to earliest Bedoulian in the Arabian Platform (Schroeder et al., 2010), southeastern France and the Swiss Jura (Clavel et al., 2010, 2013). In the UAE, Montseciella arabica’s common LAD is Late Barremian in Kharai 1 and 3 sequences (Granier et al., 2003; Granier, 2008).
Fig. 4.11: Index taxa of orbitolinids throughout the Khalij Member and upper part of the Chahoo Formation, representing the latest Barremian age, Zagros FTB; a-d: Palorbitolina lenticularis; e-k: Montseciella arabica; a: sample AFA 191, Khartang outcrop; b: sample JHT 2053, Kalagh outcrop; c: sample ARP 987, Lar outcrop; d: sample RAP 14517, Nakh outcrop; e,g: sample AFA 190, Khartang outcrop; f,h,j: samples ASL 2657, Gavbast outcrop; i,k: samples M-35, M-36 respectively, Mangasht outcrop. Scale bars: 100 µm.

4.4.2.8 Choffatella decipiens acme zone (Fig. 4.12)

**Boundaries:** This biozone is defined based on the highest abundance of Choffatella decipiens. It is also corresponds to the LO of Nezzazata simplex var. germanica and/or Campanellula capuensis at the base to the FO of planktonic foraminifera (Middle Dariyan) and/or orbitolinid-rich deposits in the Dariyan Formation at the top.

**Important associated taxa:** This interval contains very abundant Choffatella cruciensis (decipiens), Ch. arcana, Vercorsella laurenti, Hemicyclammina sigali, echinoids and bivalve shells (Exogyra sp., and rare rudists). In the Upper Gadvan, planktonic foraminifera are commonly present, including of Globigerinelloides spp. and Hedbergella spp. Among the Dasycladalean algae, Terquemella sp. is also commonly present in this interval. This acme is related to a relative lack of competition from other foraminifera.

**Stratigraphic range:** Barremian, as confirmed by other benthic foraminiferal biozones in the shallow platform area and Sr-isotope dating in the Gadvan Formation.

**Distribution:** This biozone covers the entire part of the Gadvan Formation in the western part of the Fars area (Assaluyeh, Surmeh, Kalagh, Ahmadi well-1, Gadvan, Khartang, Khurmoj) and the entire Dezful embayment and Izeh zone in the Khuzestan area (Nargesi well-8, Dasht-e Gul, Kuzeh Kuh, Fahlwan, Anneh, Seh Qanat well-1, Mish, Lar and Mangasht). Moreover, this biozone continues within the Lower Dariyan Formation, with the Lower Aptian (Bedoulian) age.
Stratigraphic significance of some index taxa:

- **Choffatella decipiens**: Several species of the genus *Choffatella* have been reported from the Cretaceous whose characteristics are summarized in Table 4.1. According to the above-mentioned data, there are at least three species of the genus *Choffatella* in the Early Cretaceous. Moreover, there are two other species, *Ch. tingitana* of Late Jurassic age, and *Ch. caronae* of Santonian age (Neagu and Cirnaru, 2004). Apparently, there are two evolution trends on the genus *Choffatella*, in that *Ch. arcana* is the terminal branch of an evolution started in the Late Jurassic (*Ch. tingitana*), and the second stage of evolution includes *Ch. cruciensis* which started in the Early Cretaceous from *Ch. pyrenaica* (Neagu and Cirnaru, 2004).

In the Zagros FTB, *Ch. cruciensis* (*decipiens*) is frequent in Hauterivian-Barremian deposits. *Choffatella arcana* is commonly observed in the Barremian interval. Another species, *Ch. pyrenaica*, is rarely present in the Valanginian deposits throughout the studied area. *Choffatella decipiens* has also been recorded from the Arabian Platform, within the Lekhwair and Kharaib formations of Hauterivian-Aptian age (Witt and Gökdağ, 1994 in Schroeder et al., 2010), and also from the Karst Dinarides, SE Europe, in Lower Aptian deposits (Velić, 2007).

In the Zagros FTB, *Choffatella decipiens* (*cruciensis*), as well as *Ch. arcana*, inhabited two different depositional environments in Hauterivian and Barremian times. A shallow-water environment with a high energy setting, when it is associated with calcareous green algae (mainly dasycladales), *Permocalculus* spp., and rare orbitolinids, but toward the western parts of the basin (in low energy setting), this form is present within marls and thin-bedded, argillaceous limestones containing small benthic foraminifera, pelagic echinoids, bivalve shells and even planktonic foraminifera, representing deeper-water conditions.

These recorded distinctive habitats of the genus *Choffatella*, confirms that this genus is very sensitive to the hydrodynamism, and prefer to settle in low-energy substrates as stated by Rey (1973). Therefore, it cannot be transported from shallow platform to deeper depositional environments. This change in habitat has also been recorded from the Arabian Plate where, in the Hauterivian and possibly in the Early Barremian, it inhabited in shallow-water environments, whereas in the Late Barremian and thereafter it was found only in deeper environments (Granier et al., 2003; Granier and Busnardo, 2013).

<table>
<thead>
<tr>
<th>Species</th>
<th>General geometry and coiling</th>
<th>Diameter (mm)</th>
<th>Aperture</th>
<th>Age</th>
<th>Number of whorls</th>
<th>Number of chambers per whorl</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Choffatella arcana</em></td>
<td>Planispiral involute - evolute</td>
<td>0.43 – 1.20</td>
<td>Numerous, distributed at apertural surface</td>
<td>Barremian - Bedoulian (Palorbitolina lenticularis level)</td>
<td>2</td>
<td>16 - 17</td>
</tr>
<tr>
<td><em>Choffatella decipiens</em> (<em>Ch. cruciensis</em>)</td>
<td>Planispiral involute</td>
<td>1.70 – 2.13</td>
<td>0.60 – 0.72, distributed at apertural surface</td>
<td>Barremian - Bedoulian (Palorbitolina lenticularis level)</td>
<td>2.5 - 3</td>
<td>16 - 18</td>
</tr>
<tr>
<td><em>Choffatella pyrenaica</em></td>
<td>Planispiral evolute</td>
<td>0.87 – 1.40</td>
<td>One linear pores at the apertural surface</td>
<td>Berriasian - Valanginian</td>
<td>2 – 2.5</td>
<td>11 - 15</td>
</tr>
</tbody>
</table>

Table 4.1: Characteristics of different species of the genus *Choffatella* in the Cretaceous deposits (modified from Peybernès and Rey, 1975; Neagu and Cirnaru, 2004).
Fig. 4.12: Some index taxa of the *Choffatella decipiens* acme zone, Gadvan Formation, Zagros FTB; **a:** *Choffatella decipiens*, samples MANA 264, Fayliyan outcrop; **b:** *Choffatella* cf. *arcana*, sample MANA 308, Fahliyan outcrop; **c:** *Choffatella decipiens*, sample ARP 248, Anneh outcrop; **d:** *Globigerinelloides* sp., sample MANA 308, Fahliyan outcrop, **e:** *Hedbergella* sp., sample MANA 299, Fahliyan outcrop, **f:** *Hedbergella* sp., sample ARP 982, Lar outcrop, **g-i:** *Terquemella* sp., **g-h:** samples M 32 and 34 respectively, Mangasht outcrop, **i:** sample ARP 207, Anneh outcrop; **j-l:** *Hemicyclammina sigali*, **j:** sample ARP 976, Lar outcrop, **k:** sample MANA 301, Fahliyan outcrop, **l:** sample ARP 261, Anneh outcrop. Scale bars: **a-c, j-l: 100 µm; d-i: 50 µm.**
### 4.4.3 Dasycladalean algae (Figs. 4.14-4.18)

A detailed study of the dasycladalean algae from the Zagros FTB led to identify several genera and species which are reported for the first time from this area (see appendices 2 and 3). Here in, the stratigraphic range of recognized specimens were compared with the model based on different species of the genus *Salpingoporella* for the Northern and Southern Tethyan domains by Carras et al. (2006), and with several papers from the Tethyan realm (see references here). According to the present study, four biozones and one subzone are suggested for the studied successions (Fahliyan, Sar Bisheh, Ghari, Gadvan and Chahoo formations) in the Zagros FTB.

#### 4.4.3.1 *Salpingoporella circassaa* - *Zergabriella embergeri / Clypeina dragastani* interval zone (Fig. 4.14)

**Boundaries:** The lower boundary of this biozone coincides with the FO of *Salpingoporella circassaa* and the upper boundary is the LO of *Zergabriella embergeri* and/or *Clypeina dragastani*.

**Important associated taxa:** Several stratigraphically important taxa such as: *Clypeina solkani/parasolkani, C. sulcata (jurrassica), Salpingoporella annulata, S. istriana, S. granieri, S. katzeri, S. piriniaie, S. pygmaea, S. steinhauseri, Rajkaella barteli, Selliporella neocomiensis, Actinoporella podolica, Iranella inopinata, Otternstella lammensis, Holosporella arabica and Mizzia zagarthica n. sp.*

**Stratigraphic range:** Berriasian (Middle to Late Berriasian as confirmed by foraminiferal associations and Sr-isotope dating).
Fig. 4.14: Some index dasycladalean algae of the Berriasian interval within the Fahliyan Formation in the Zagros FTB; a-d: *Salpingoporella circassa*, a, b: samples MAK 5245, 5253 respectively, Fahliyan outcrop, c: sample RAP 45, Darbash outcrop, d: sample MAK 4945, Kuzeh Kuh outcrop; e-g: *Zergabriella embergeri*, samples ARP 796 and 797, Lar outcrop; h-j: *Clypeina dragastani*, h: sample AFA 156, Khartang outcrop, i: samples MAK5254, Fahliyan outcrop, j: MAK 5664 Dasht-e Gul outcrop. Scale bars: a-d 100 µm, e-j: 200 µm.

**Distribution:** This biozone is found within the Fahliyan Formation in the Khuzestan (Izeh Zone and Dezful Embayment) and Fars area (interior, subcoastal and coastal). Time equivalent of this biozone is marked by
either a non-deposition condition (stratigraphic break) or the presence of tintinnids in Bandar- Abbas Hinterland and offshore area.

**Stratigraphic significance of some index taxa:**

- **Zergabriella embergeri** (Bouroulec and Deloffre, 1968). An ancestor of this form was reported from Upper Jurassic deposits (Jaffrezo, 1980; Bernier, 1984). But it has been more frequently reported from the Berriasian to Lower Valanginian deposits (Granier, 1987; Masse, 1993). This species has been recently reported from the Berriasian Mozuduran Formation in the Kopet Dagh Basin, NE Iran (Bucur et al., 2012).

- **Salpingoporella granieri** and **Clypeina dragastani** were introduced by Dieni and Radoičić (1999), based on samples from the Berriasian deposits of Eastern Sardinia (Italy). *S. granieri* has also been reported from the Berriasian of Pulg Campana (Province of Alicante, SE Spain) by Granier (1987) and the Western Pontides (Turkey) (Farinacci and Radoičić, 1991). Recently, the general stratigraphic range of this species spans the Berriasian - ? Early Valanginian (Carras et al., 2006).

### 4.4.3.2 Actinoporella jaffrezoï - Salpingoporella katzeri interval zone (Fig. 4.15)

**Boundaries:** The lower boundary is marked by the FO of Actinoporella jaffrezoï and the LO of Salpingoporella katzeri determines the top of this biozone.

**Important associated taxa:** All dasycladalean algae present in the Berriasian also occur in this interval, except for Clypeina sulcata (jurassica). Moreover, the first occurrence of some dasycladalean algae occur in this interval, such as: Salpingoporella dinarica, S. hispanica, S. cf. parapiriniae, Clypeina estevezii, Similicypeina cf. conradi, and Korkyrella texana.

**Stratigraphic range:** Valanginian

**Distribution:** This biozone is present in the upper part of the Fahliyan and in the entire Sar Bisheh Formation in the shallow-platform deposits of the Zagros FTB.

**Stratigraphic significance of some index taxa:**

- **Salpingoporella katzeri** was introduced from the Valanginian deposits of Herzegovina and Montenegro (Conrad and Radoičić, 1978). This species has been reported from several localities in the Tethyan domain, from Berriasian and Valanginian deposits (see Carras et al., 2006). Therefore, the stratigraphic range of this species was assigned to the Berriasian - Valanginian and unconfirmed in younger deposits (Carras et al., 2006).

- **Actinoporella jaffrezoï** has been introduced as a marker for the Early Valanginian in the type locality, Maitérie-Haute, Corbières (France) within the "Calcaires roux I" (Granier, 1995). This age is confirmed by the Sr-isotope dating performed in the Fahliyan and Gadvan outcrops at the base and top of the interval containing this species (details in chapter 9).

**Remarks:**

Given the fact that the FO and LO of Actinoporella jaffrezoï occur in the lower part of this biozone, a subzone is proposed here as Actinoporella jaffrezoï taxon-range zone which corresponds to the stratigraphic range of this species, a marker for the Early Valanginian age in the Zagros FTB. This subzone is present within both the Fahliyan and Sar Bisheh formations.
4.4.3.3. Salpingoporella cemi - S. annulata / S. circassa interval zone (Fig. 4.16)

**Boundaries:** From the LO of *Salpingoporella katzeri* and/or the FO of *Salpingoporella cemi* to the LO of *Salpingoporella annulata* and/or *Salpingoporella circassa*.

**Important associated taxa:** Some new forms are appearing in this interval such as: *Salpingoporella* cf. *biokovensis* and *S. dinarica*. Some other forms cited in the previous zone are also present here such as: *Salpingoporella hispanica*, *S. cf. parapiriniae*, *S. pygmaea*, *Actinoporella podolica*, *Similiclypeina* cf. *conradi*, *Iranella inopinata*, and *Korkyrella texana*.

**Stratigraphic range:** Hauterivian.

**Distribution:** This assemblage of dasycladalean algae is present in the lower part of the Chahoo and Gadvan formations in the Fars High (Kalagh, Drabast, Gavbast, Burkh, Nakh) and Bandar Abbas Hinterland (Khush). Towards the west, in the Khuzestan area (Izeh Zone and Dezful Embayment), the time equivalent of this biozone is rich in *Choffatella decipiens* that occurs in the hemipelagic marls and argillaceous limestone beds of the Ghari Formation.
Fig. 4.16: Some important dasycladalean algae from the Hauterivian interval, lower part of the Chahoo and Gadvan formations, Zagros FTB; a-c: Salpingoporella cemi, sample DMS 353, Burkh outcrop; d-f: Salpingoporella circassa, d: sample GAJ 1704, Khush outcrop, e: sample ARP 176, Anneh outcrop, f: sample JHT 1353, Surneh outcrop; g-k: Salpingoporella annulata, g: sample JHT 2061, Kalagh outcrop, h: sample MAK 5587, Fahliyan outcrop, i: sample JHT 2067, Kalagh outcrop, j: sample ARP 56, Anneh outcrop, k: sample ARP 775, Lar outcrop. Scale bars: a-c: 200 µm, d-f: 100 µm, g-k: 200 µm.
Stratigraphic significance of some index taxa:

- **Salpingoporella cemi** has been reported by several authors from the Valanginian to the Albian, but a Late Hauterivian-Barremian age was confirmed as reported from the Dinarides and Hellenides which biogeographically cover the Central and Southern Tethys (Carras et al., 2006; Sokac and Grgasovic, 2008). This species has been reported from the Tirgan Formation in the Kopet Dagh Basin, NE Iran, with a Barremian-Aptian age (Taherpour Khalil Abad et al., 2010).

- **Salpingoporella annulata** which is cosmopolitan in both the Northern and Southern Tethys, has a long stratigraphic range, from the Middle Jurassic (Bathonian) to the Early Barremian (Carras et al., 2006). This species became extinct in the Northern Tethys in the Late Valanginian, while it is still found in the Southern Tethyan realm in the Hauterivian (Carras et al., 2006).

- **Salpingoporella circassa** is reported from the Berriasian - Valanginian of Eastern Serbia (Bucur et al., 1995) and the Berriasian-Hauterivian of the Eastern Pontides, Turkey (Bucur et al., 2000). Therefore, the stratigraphic range of this species is determined as Berriasian-Hauterivian in the Northern margin of the Tethys (Carras et al., 2006).

4.4.3.4 Salpingoporella hasi, S. cemi, S. dinarica, Montiella elitzae assemblage zone (Fig. 4.17)

**Boundaries:** This biozone is defined based on the appearance of an assemblage of *Salpingoporella hasi*, *S. cemi*, *S. dinarica* and *Montiella elitzae*. Therefore, the lower boundary begins at the LO of *Salpingoporella annulata* and/or *Salpingoporella circassa* that corresponds with the FO of *Salpingoporella hasi* and *Montiella elitzae*. This biozone shows also the highest frequency for *Salpingoporella dinarica*.

**Important associated taxa:** Some forms with wider stratigraphic range such as: *Salpingoporella cf. biokovensis*, *Salpingoporella hispanica*, *S. cf. parapiriniae*, *S. pygmaea*, *Actinoporella podolica*, *Similiclypeina cf. conradi*, *Iranella inopinata*, and *Korkyrella texana*.

**Stratigraphic range:** Barremian

**Distribution:** This biozone covers the Chahoo Formation in the eastern part of the Fars area, Bandar Abbas Hinterland and offshore area.

Stratigraphic significance of some index taxa:

- **Salpingoporella hasi** was introduced from the Late Albian - Middle Cenomanian of Metohija (Yugoslavia) and Lisbon (Portugal) by Conrad et al. (1977). Later on, this form was reported by several authors almost from the Barremian/Aptian to the Cenomanian of different localities (see Carras et al., 2006). Furthermore, an affinity of this species is assumed to have appeared from the Barremian in the Southern Tethyan domain (Carras et al., 2006). Some specimens with an affinity to this species have been reported from the Tirgan Formation in the Kopet Dagh Basin, NE Iran, with the Barremian-Aptian age (Taherpour Khalil Abad et al., 2010).

- **Montiella elitzae**, which is probably a junior synonym of *Turkmenaria adducta* MASLOV, ranges from the Late Hauterivian to the Albian and is very frequent in the Tirgan Formation in the Kopet Dagh Basin, NE Iran (Taherpour Khalil Abad et al., 2010).

- **Salpingoporella dinarica**, which is extremely abundant in many localities in the Southern and Central Tethys, and also in the Southern Caribbean Province, ranges from the Berriasian up to the Albian, with the highest frequency in the Aptian (see Carras et al., 2006). This species is totally missing in the North Tethyan realm and in Europe, except in North Italy it occurs very rare since the Valanginian. While the FO of this species is in the Berriasian in the Arabian Platform, and the LO occurs in the Lower Aptian, where it is commonly present as *Hensonella dinarica* within the Bu Hasser, Bel Bazem, Zakum, Lekhwair, Khaireb, Hawar and Shu'aiba formations in the United Arab Emirates, Oman, and Qatar (Granier, 2008). In Saudi Arabia, this species is present only within the Shu'aiba Formation of Early Aptian age (Hughes, 2005). In the Zagros FTB, the FO of this species is in the Valanginian, the highest occurrence in the Barremian - Early Aptian and the LO occurs normally in the Late Aptian of the Dariyan Formation.
Fig. 4.17: An assemblage of index dasycladalean algae throughout the Khalij Member and Chahoo Formation, the Zagros FTB. a: Salpingoporella cemi, sample RAP 67, Darbast outcrop; b: Montiella elitzae, sample LETP 5043, Genow outcrop (Tang-e Asboo); c: Similiclypeina cf. conradi, sample LETP 5028, Genow outcrop (Tang-e Asboo); d-f: Salpingoporella dinarica, d: sample JHT 2053, Kalagh outcrop, e: sample M31, Mangasht outcrop, f: sample LETP 5048, Genow outcrop (Tang-e Asboo); g: Salpingoporella hispanica, sample RAP 45, Darbast outcrop; h: Iranella inopinata, sample ASL 2651, Gavbast outcrop; i: Salpingoporella hasi, sample AFA 189, Khartang outcrop. Scale bars: 100 µm.
Chapter 4

4.5 Application of biozones on outcrops and subsurface

The biozones, tables and biozonation scheme proposed here are entirely based on outcrop data. In the studied subsurface sections, definitions of the suggested biozones, both for index taxa and their boundaries should therefore be modified. Because subsurface stratigraphic sections are penetrated and studied from top to bottom from cuttings, samples are often contaminated by younger drilled sediments and the LO of taxa are not reliable. Therefore, in subsurface sections, it is strongly recommended to use only interval zones instead of taxon-range zones, concurrent-range zones, acme zones and assemblage zones.

Also it is worth mentioning that there is a significant difference between defining an interval zone in surface and subsurface sections. Because in surface sections, the lower boundary is the lowermost occurrence of a taxon (FO) and the upper boundary coincides with the highest occurrence of another taxon (LO), whereas in subsurface, both lower and upper boundaries should be considered as the highest occurrence (FO) for both taxa (Fig. 4.19). Subdivisions and biozones on surface and subsurface sections throughout the Berriasian - Barremian interval are summarized as following (Table 4.2).

4.6 Palynology

From two outcrops (Fahliyan and Gadvan), a total of 30 samples (from Sar Bisheh, Ghari, Chahoo and Gadvan formations) were analyzed for palynology. Slides have been prepared at the geological laboratory of the University of Geneva, Switzerland. An amount of about 200-300 g of sample was crashed to a grain size of ~2 mm. Carbonates have been removed by dissolution in heated HCL. Also, for removing silicates, heated 70% HF was used between min. 2 to max. 24 hours. After that, samples were sieved under alternating vacuum with a 10 µm mesh size. By this process, larger particles of amorphous organic matter are removed. Sample materials were stored in glass vials. After 12 hours, a small amount of sample material was transferred to a glass slide using a dropping bottle. The strew slides were prepared for permanent using with synthetic resin (Elvacite 2044, of Tennants) dissolved in Xylol (18 g to 30 ml).
Identification of particles was performed with a Nikon transmitted-light microscope, connected to a camera (Leica 500 imaging system). All investigated samples were barren in palynomorphs (spore, pollen or dinocysts), except for highly fragmented pieces of organic material. Only a few samples had rare bisaccate pollen and spores, the identification of which was impossible due to poor preservation, fragmentation or a cover of amorphous organic matter.

4.7 Calcareous nannofossils

A total of 40 samples from marly intervals collected in two outcrops (Fahliyan and Gadvan) were selected for calcareous nannofossil analysis. Preparation was performed in the geological laboratory of the University of Geneva. Investigation of taxa was performed on smear slides and checked using a Nikon light microscope with cross-polarized light at a magnification of ×1250. Samples have been checked also using a Scanning Electron Microscope (SEM). All the investigated samples were barren of calcareous nannofossils and didn't allow the recognition of any event or biozone.

Fig. 4.19: Definition of interval zones in surface and subsurface sections.
Chapter 4

<table>
<thead>
<tr>
<th>Age</th>
<th>Biozone (Surface section)</th>
<th>Biozone (Subsurface section, top to bottom)</th>
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<tr>
<td>Latest Barremian</td>
<td><em>P. lenticularis</em> – <em>M. arabica</em> overlapping parts</td>
<td>FO of <em>M. arabica</em> to FO of <em>E. transiens</em></td>
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<tr>
<td>Late Barremian</td>
<td><em>E. transiens</em> – <em>P. lenticularis</em> overlapping parts</td>
<td>FO of <em>E. transiens</em> to FO of <em>F. pileola</em> and / or <em>O. debelmasi</em></td>
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<td>Early – Late Barremian</td>
<td><em>F. pileola</em> – <em>O. debelmasi</em> overlapping parts</td>
<td>FO of <em>F. pileola</em> or <em>O. debelmasi</em> to FO of <em>N. simplex</em> and / or <em>C. capuensis</em></td>
</tr>
<tr>
<td>Hauterivian</td>
<td>FO of <em>S. cemi</em> to LO of <em>S. annulata</em> / <em>S. circassa</em></td>
<td>FO of <em>N. simplex</em> / <em>C. capuensis</em> and / or <em>S. circassa</em> / <em>S. annulata</em> to FO of <em>S. katzeri</em> and / or <em>H. joukowskyi</em> / <em>C. cherchiae</em></td>
</tr>
<tr>
<td>Hauterivian</td>
<td>FO of <em>Ch. decipiens</em> to LO of <em>N. simplex</em> / <em>C. capuensis</em></td>
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<td>Valanginian</td>
<td>FO of <em>A. jaffrezoi</em> to LO of <em>S. katzeri</em></td>
<td>FO of <em>S. katzeri</em> to FO of <em>Z. embergeri</em> / <em>C. dragastani</em></td>
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<tr>
<td>Berriasian</td>
<td>FO of <em>S. circassa</em> to LO of <em>Z. embergeri</em> / <em>C. dragastani</em></td>
<td>FO of <em>Z. embergeri</em> / <em>C. dragastani</em> to FO of <em>S. grudii</em></td>
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Table 4.2: Comparison between significant taxa for defining interval zones in surface and subsurface sections.

4.8 Conclusions

This is the first systematic and integrated biostratigraphic correlation scheme based on a large dataset of outcrops and subsurface wells from the shallow-platform deposits in the Zagros FTB, covering the Khuzestan (Izeh Zone, Dezful Embayment), Fars, Bandar Abbas Hinterland and offshore area. This pattern is based on a calibration between benthic foraminifera, dasycladalean algae and tintinnids, and also checked with Sr-isotope dating. This study determines three biozones based on tintinnids, six biozones for benthic foraminifera and four biozones and one subzone (taxon range-zone) based on the data from dasycladalean algae. Finally, a uniform biostratigraphic pattern is presented for the shallow-platform deposits including 12 biozones for the studied stratigraphic intervals (Fig. 4.20).

Moreover, it is concluded that:

- a sedimentary break (exposure) is present at the base of the Berriasian across the platform, and this hiatus becomes younger from west toward the east.
- a regional hiatus is detected at the top of the Sar Bisheh Formation and its equivalent the Fahliyan Formation, which is quite diachronous, varying from the Early to Late Valanginian. The largest hiatus occurs in the Fars area which is in continuation of the Qatar High Platform. This paleo-high was characterised by slow subsidence leading to condensed sections and the presence of long hiatus in the studied outcrops.
- the boundary between the Sar Bisheh Formation and the Ghari / Chahoo formations (the former Lower Fahliyan and Upper Fahliyan / Gadvan formations), de-linedated where the Ghari Formation (Upper Fahliyan sensu Wynd, 1965) and its time equivalent begins, is in the Hauterivian not in the Barremian.
- a new species of dasycladalean alga *Mizzia zagarthica* n. sp. is introduced from the Zagros FTB. It ranges from the Late Berriasian to the Early Valanginian, and was found in the upper part of the Fahliyan and the lower part of the Sar Bisheh formations (details in Hosseini et al., 2013).
- the FO of *Salpingoporella dinarica* occurs in the Early Valanginian within the Sar Bisheh Formation in the Zagros FTB, which is in accordance with its occurrence in the Arabian Platform.

- *Iranella inopinata* is quite endemic to the Zagros area in the southern Tethyan realm, extending from the Berriasian to the Aptian, with an acme zone in the Valanginian. It shows traces of reproductive organs (cysts) in the basal stalk, either in the stipe or the laterals (details in Hosseini et al., 2013).
Fig. 4.20: Suggested biozonation pattern for the Fahliyan, Sar Bisheh, Ghari, Gadvan and Chahoo formations in the Zagros FTB. (Explanation of biozones is shown in the text). Previous formation names are shown in italic fonts.
## Benthic Foraminifera

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<td>Choffatella arcana</td>
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<td>Vercorsella laurentii</td>
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## Dasycladalean Algae

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Salpingoporella hasi Conrad, Radoičić & Rey 1977
Salpingoporella hispanica Conrad & Grabner 1975
Salpingoporella istriana (Gušić) Conrad, Praturlon & Radoičić 1973
Salpingoporella katzeri Conrad & Radoičić 1978
Salpingoporella melitae Radoičić 1975
Salpingoporella parapiriniae Conrad, Carras & Radoičić 2008
Salpingoporella piriniae Carras & Radoičić 1991
Salpingoporella pygmaea (Gümbel 1891)
Salpingoporella steinhauseri Conrad, Praturlon & Radoičić 1973
Selliporella neocomiensis (Radoičić 1965) Barattolo 2002
Similicypeina conradi Bucur 1993
Zergabiella embergeri (Bouroullec & Deloffre 1968) Granier 1989

Tintinnids
Calpionella alpina Lorenz 1902
Calpionella elliptica Cadisch 1932
Calpionellopsis oblonga Cadisch 1932
Calpionellopsis simplex Colom 1939
Calpionellites darderi (Colom 1934) Colom 1948
Remaniella cadischiana Colom 1948
Tintinopsella carpathica Murgeanu & Filipescu 1933
Tintinopsella longa (Colom 1939) Colom et al., 1953
References


References


References


5.1 Introduction

This chapter is organized in two main parts. The first one is about general depositional environments, and in the second part, the platform reconstruction will be proposed.

Based on facies associations, a relative water depth has been assigned to distinct depositional environments. The remarkable parameters for distinguishing these depositional environments are: faunal content, texture, lithology and sedimentary patterns/structures. According to these data, a semi-quantitative microfacies analysis was carried out based on the study of thin-sections from outcrop rock specimens and also cutting samples from the subsurface, accompanied with natural gamma-ray data on outcrops and Schlumberger logs of wells (see Appendix 4). These data of facies interpretation with continuous paleontological logs for both outcrops and subsurface sections are important as source of information for sequence stratigraphic interpretation.

5.2 Materials and methods

A number of 4882 thin-sections, including samples from outcrops and wells, were used for microfacies analyses and the study of depositional environments.

Facies description is based on the macroscopic observations (lithology, macrofaunal content, bedding pattern, sedimentary surfaces, sedimentological structures and depositional geometries), and microscopic descriptions (lithology, texture, faunal content, frequency and diversity of microfossils).

Description of the major categories of carbonate grains used for facies analysis was carried out based on the standard model of Flügel (2004). The classification scheme of Dunham (1962, revised by Embry and Klovan, 1971) was used for texture description.

5.3 Depositional environments

5.3.1 Basin (pelagic environment) (Fig. 5.1)

This depositional environment is positioned below the storm save base (SWB), and is estimated to be at a few hundreds of meters of depth. The main faunal content of this environment includes planktonic foraminifera (globigerinellids and hedbergellids), tintinnids and radiolarians. Rock texture is always mud rich.

This depositional environment is recorded at two different stratigraphic levels in the study area. The first one occurs at the basal part of the Fahliyan Formation in Bandar Abbas Hinterland and offshore area (such as: Khush, Genow, Suru well # 1 and Qeshm well # 4), where the Jurassic shallow platform deposits (Surmeh Fm.) are capped by basinal facies containing frequent tintinnids and radiolarians. The texture of these pelagic deposits are mudstones and rare wackestones. Another one occurs in some marly intervals of the Gadvan Formation below and above the Khalij Member in the Khuzestan area (e.g. Fahliyan, Lar). It contains Globigerinelloids spp. and hedbergellids, associated with thin filaments of bivalves and ammonites (see Appendix 1, fossil distribution range charts).
5.3.2 Platform slope (hemipelagic depositional environment) (Fig. 5.2)

This depositional environment starts from the photic zone and its maximum depth reaches to the storm wave base. Faunal assemblage is marked by mixed pelagic and benthic organisms, including sponge spicules, rare planktonic foraminifera (hedbergellids), pelagic echinoids (Saccocoma), deep-water bivalves (*Exogyra* sp.), frequent echinoid fragments, very abundant hyaline benthic foraminifera (*Epistommina* sp., *Lenticulina* sp.) that are markers for deeper-water depth, and occasionally associated with shallower-depth benthic fauna that probably was brought in by storms or during sea-level falls.

The lithology is an alternation of thin-bedded limestone and marly intervals, with significant clay content. The texture consists of wackestones and rare packstones.

One of the main components of this environment is an index taxon of benthic foraminifera, the genus *Choffatella*, which is very abundant in the studied area (Fig. 5.2 e-f). This genus is believed to be very sensitive to the hydrodynamism and inhabited mostly in low-energy environment (Rey, 1973). In the Arabian plate, this form is commonly found in deeper-water environments during the Barremian and the Aptian in the Kharaib, Hawar and Bab formations (Granier et al, 2003; Granier and Busnardo, 2013).

In the Zagros FTB, this depositional environment is commonly observed in the marly intervals and argillaceous limestones of the Gadvan Formation, from the Hauterivian up to the Barremian, covering almost the Khuzestan area, but reaching also to western part of the sub-coastal and interior Fars. Moreover, this environment is also observed, but more rarely, within the deeper-water facies (nodular limestone) of the Sar Bisheh Formation and the marly limestones of the Ghari Formation, again in the Khuzestan and western part of the sub-coastal and interior Fars area (e.g. Anneh, Lar, Fahliyan, Kuzeh Kuh, Dasht-e Gul, Nagesi well-8, Seh Qanat well-1, Gadvan, Ahmadi well-1).
5.3.3 Mid-platform to platform top (margin) (Fig. 5.3)

This depositional environment is dominated by benthic foraminifera. During the Berriasian and Valanginian, assemblages contained well-diversified, low-spiral trocholinids (Fig. 5.3 a) and cyclamminids, while during the Barremian, they included large and discoidal orbitolinids (e.g. *Palorbitolina lenticularis*, *Eopalorbitolina transiens*) at the platform margin (Fig. 5.3 b). Other benthic foraminifera comprise textularids, valvulinids and rare miliolids. *Lithocodium/Bacinella* nodules are present occasionally in deep, open lagoons. Other components are rudstone to floatstone containing rudists (Fig. 5.3 d), larger echinoid shell fragments, rare sponge spicules, oncoids, intraclasts and very rare peloids. Among the calcareous green algae, few dasycladales are present in this environment (such as: *Salpingoporella pygmaea*). As a result, a rather open marine depositional environment is confirmed for *S. pygmaea* as stated by Carras et al. (2006).

The lithology is carbonate dominated and contains little clay. The texture varies from low-energy wackestones to high-energy grainstones. It is estimated that water depth is around 30 m., between just above storm-wave base at the base, and above the fair-weather wave base at the top.

This depositional environment is commonly recorded in the Sar Bisheh Formation, at the type locality, and in Khuzestan and in the western part of the Fars area. It is also observed within the limestones of the Ghari Formation and in some pure limestone beds within the Gadvan Formation (e.g. Khalij Member) in Khuzestan and in the western part of the Fars area. Towards the east, in the Bandar Abbas Hinterland and offshore area, this depositional environment is observed within the newly defined Chahoo Formation at the type locality, where the uppermost Barremian - Lower Aptian deposits include orbitolinid-rich limestones (details in Appendix 4).
Fig. 5.3: Microfacies types of the mid-platform to platform margin settings; a: Benthic foraminifera (trocholinid) wackestone, samples MANA 203, Fahliyan outcrop; b: orbitolinid (Palorbitolina lenticularis) wackestone, sample ASL 2655, Gavbast outcrop; c: rudist shells (rudstone to floatstone), sample MANA 290, Fahliyan outcrop. Scale bars: a, c: 500 µm, b: 300 µm.

5.3.4 Inner platform (shoal, lagoon, intertidal flat and supratidal / sabkha) (Figs. 5.4-5.6)

This depositional environment covers the photic zone above the fair weather wave base, with a water depth around a few meters (>10 m.). The widest distribution of this environment is in the Berriasian Fahliyan Formation, and covers the entire studied area, except for the Bandar Abbas Hinterland and offshore area.

This environment is partitioned in four subdivisions as:

- oolitic and bioclastic shoal, medium to high-energy environment (Fig. 5.4 a-c). Components are ooids, bioclasts, benthic foraminifera, rare calcareous green algae, molluskan shell fragments, intraclasts, rare peloids, rare oncoids and aggregate grains. Lithology is dominated by carbonates, and the texture is always grainstone.
- shallow subtidal, protected lagoon, dominated by diversified and frequent calcareous green algae (Fig. 5.5 a), patches of Lithocodium/Bacinella (Fig. 5.5 b), stromatoporid (Fig. 5.5 c), high-spired trocholinids and small porcelaneous foraminifers (miliolids). Lithology is carbonate dominated, and the texture ranges from wackestone to packstone and rare grainstone.
- intertidal flat comprises ostracods (Fig. 5.6 b), small miliolids, thin-shelled gastropods, textularids, rare calcareous green algae and Thaumatoporella parvovesiculifera (incertae sedis seaward) (Fig. 5.6 c). Lithology is carbonate dominated, and the texture varies from mudstone to grainstone with frequent peloids. Sedimentary features include fenestrae, and dissolution cavities from shells.
- supratidal/sabkha intertidal flat lithologically comprises dolostone to dolomudstone, fine-grained sand and silt (Fig. 5.7 c). Faunal assemblage is very poor in this environment, almost barren in fauna, or contains very rare ostracods, gastropod shells and microbialites.

Remarks:

In the more distal parts of the basin, clastics (fine-grained sands and silts) were deposited within the marly intervals of the Gadvan Formation (Fig. 5.7 a-b). These land-driven siliciclastic deposits are allochthonous elements in this carbonate succession and are known as “Kushk Sandstone” (NIOC internal reports) in the SW Zagros FTB, which is equivalent of the ‘Zubair Sandstone’ in Iraq and Kuwait. The source was likely the exposed Arabian Shield at the west (Alsharhan and Kendall, 1991; Sharland et al., 2004; Jassim and Goff, 2006).
Fig. 5.4: Microfacies types of the inner platform setting (shoal); a: ooid grainstone (high energy sea ward shoal), sample ASL 2478, Assaluyeh outcrop; b: bioclastic grainstone (gastropods, dasycladalean algae, small benthic foraminifera) (landward shoal), sample ARP 775, Lar outcrop; c: bioclastic and lithoclastic grainstone, sample ARP 784, Lar outcrop. Scale bars: a: 500 µm, b-c: 1000 µm.

Fig. 5.5: Microfacies types of the inner platform setting (lagoon) to intertidal flat; a: Algal (dasycladals) packstone, sample M7, Mangasht outcrop; b: Patch of *Lithocodium* (bindstone), sample MANA 155, Fahliyan outcrop; c: patches of stromatoporid (*Cladocoropsis* sp. cf. *C. mirabilis*), samples ARP 112, Anneh outcrop. Scale bars: 1000 µm.

Fig. 5.6: Microfacies types of the inner platform setting (intertidal flat); a: peloidal grainstone with fenestrae, sample ARP 791, Lar outcrop; b: peloidal-ostracod grainstone, sample MANA 86, Fahliyan outcrop; c: bioclastic peloidal grainstone with *Thaumatoporella parvovesiculifera* (incertae sedis seaward), sample MANA 108, Fahliyan outcrop. Scale bars: 500 µm.

Fig. 5.7: Sand-rich wackestone in the carbonate succession; a: sample ASL 2527B, Assaluyeh outcrop, b: sample depth 3570 m., Nargesi well-8; c: sample RAP 60, Darbast outcrop. Scale bars: 500 µm.
Fig. 5.8: Depositional environments of the studied stratigraphic intervals, Zagros FTB (see text for explanation).
5.4 Platform configuration

The classification of carbonate platforms presented here is based on microfacies studies, a tool for understanding ancient facies belts and depositional areas related to particular marine settings. The well-defined categories of shallow-marine depositional settings and platform types are illustrated by Pomar, 2001 and Flügel, 2004 (Fig. 5.9).

Fig. 5.9: Classification of platform types (modified from Pomar, 2001; Flügel, 2004)

In this study, four main platform types are presented based on the drawn paleogeographic (paleofacies) maps throughout the studied area. These maps were prepared according to the distinguished facies belts of the studied stratigraphic intervals from the Berriasian to the Barremian (details in Appendix 4). Therefore, the fundamental controls for reconstructing the platform are specific faunal content and lithological composition, in combination with geometrical properties provided by stratigraphic reconstruction and NW-SE regional correlations (details in Appendices 1 and 4). They are:

- a rimmed platform (Early - Middle Berriasian)
- an isolated rimmed platform (Middle Berriasian - earliest Valanginian)
- a non-rimmed open platform / ramp (Valanginian)
- a mixed siliciclastic-carbonate platform / ramp (Hauterivian - Barremian)

5.4.1 Rimmed platform (Early - Middle Berriasian) (Figs. 5.10, 5.16 a).

This setting includes the lowermost part of the Fahliyan Formation. It starts most probably in the late Early Berriasian and continuous until the Middle Berriasian (Fig. 5.10). This shallow-water platform developed on the old Surmeh platform (Oxfordian - Kimmeridgian). The large, flat Cretaceous platform prograded out from the South toward the North and East, covered the entire parts in the Zagros FTB, except for the Bandar Abbas Hinterland and offshore areas (Genow, Khush, Suru well-1 and Qeshm well-4), which were exposed. The seaward margin of this platform comprises oolitic deposits, indicating a high-energy shoal system, and covered the Khuzestan and most parts of the Fars area. On the contrary, the eastern part of the Fars area (Nakh and Burkh), were dominated muddy and algal facies, indicating low energy shallow-subtidal and lagoonal environments.
According to the available information, this platform continued with the slope depositional setting (Fahliyan/Garau inter-fingering) and finally the deep marine basin deposits of the Garau Formation toward the northwestern part of the Zagros FTB (Lurestan basin) (van Buchem et al., 2010, and references therein).

**5.4.2 Isolated rimmed platform (Middle Berriasian - earliest Valanginian)** (Figs. 5.11, 5.16 b).

This model spans the Middle Berriasian and the earliest Valanginian interval (Fig. 5.11) and corresponds with the middle and upper part of the Fahliyan Formation. During this time interval, the Bandar Abbas Hinterland and offshore area which were exposed until the Middle Berriasian, were flooded and covered by basinal facies dominated with tintinnids, rare radiolarians and sponge spicules, indicating that a platform drowning occurred in the eastern part of the Zagros FTB at that time. Concurrently, a tidal-flat depositional environment, dominated by coarse-grained microbialites (oncoids), bindstones and stromatolites extended throughout the Fars areas (Interior and sub-coastal Fars), which was surrounded by muddy and algal deposits indicating a protected lagoonal environment. These lagoonal deposits covered most parts of the Fars and the eastern part of the Khuzestan area. Finally, two shoal belts including oolitic to bioclastic grainstones extended at western and eastern margin of these lagoonal deposits, grading to slope sediments to both the East and West (Fig. 5.11).
Therefore, the shallow-carbonate deposits built an isolated platform during the Middle Berriasian - earliest Valanginian in the Zagros FTB. This platform shows different rates of sedimentation, which were controlled by the basement faults (details in chapters 2 and 3).

5.4.3 Non-rimmed open platform / ramp (Valanginian) (Figs. 5.12, 5.16 c).

During the Valanginian, the platform was affected by one large and regional transgressive-regressive event. In the Bandar Abbas Hinterland and offshore area (Khush, Genow, Suru well-1 and Qeshm well-4), the deep basinal deposits (Middle Berriasian - earliest Valanginian) graded into a flat-top platform dominated by muddy algal mats and microbialites in inner-platform settings and lagoonal environments, representing a major regressive cycle (Fig. 5.12). This shallow restricted platform extended westward and covered the entire parts of the Fars area. Some parts of the interior and sub-coastal Fars area (Kalagh, Surmeh, Ahmadi well-1 and Gadvan) which were represented by tidal-flat environments during the previous time-interval, show a somehow deeper environment, such as open lagoons dominated by dasycladalean algae and benthic foraminifera, indicating a transgressive event. Close to the boundary of Fars and Khuzestan areas (nearby the Kazerun Fault zone), this shallow platform was deeper, dominated by benthic foraminifera, echinoid remains, bivalve shells, sponge spicules and rare dasycladalean algae, indicating a mid-platform setting (Fig. 5.12), which extended westward and covered the whole studied area, and finally connected to the platform slope in the Khuzestan area in the far west.

Towards the south, a local (possible) supratidal environment is suggested by the occurrence of the dolostones exposed in the Khurmoj outcrop (see Fig. 5.12).

These data reveal the presence of a non-rimmed open platform or a ramp in the studied area, which corresponds to the bedded limestone deposits of the Sar Bisheh Formation in Khuzestan and the western part of Fars and its time equivalent Fahliyan Formation in the eastern part of Fars, Bandar Abbas Hinterland and offshore areas.

![Fig. 5.12: Paleogeographic map during the Valanginian in the Zagros FTB.](image)

5.4.4 Mixed siliciclastic-carbonate platform /ramp (Hauterivian - Barremian) (Figs. 5.13, 5.16 d).

During the Hauterivian, this model of sedimentation corresponds with the Ghari Formation in the Khuzestan area and with the Gadvan/Chahoo Formation in the Fars, Bandar Abbas Hinterland and offshore area.

During this time (Hauterivian), most parts of the Bandar Abbas Hinterland and coastal Fars areas were exposed possibly due to the tectonic activity of salt diapirs that created local paleo-highs (Jahani, 2009), the role of the Qatar Arch High (van Buchem et al., 2010), the occurrence of a major global lowstand during the Late Valanginian (Haq et al., 1987), or the presence of some paleohighs created during the regional uplift of
the Arabian Plate which occurred around 130 Ma ago (Al-Fares et al., 1998). Therefore, the subsequent Hauterivian flooding started from the north and expanded throughout the NW and SE, leading to the accumulation of shallow lagoonal deposits in the Fars area, while at the same time, intercalations of hemipelagic marls and thin-bedded limestones were deposited in a mid-platform to platform margin setting in the western part of the Fars area and in Khuzestan (Izeh Zone and Dezful Embayment).

During the Hauterivian - Barremian, tongues of siliciclastics, including fine-grained sands and silts (such as at Khurmoj, Seh Qanat well-1 and Nargesi well-8) entered into the hemipelagic marls over long distances from a source that was located in the west (Figs. 5.13, 5.14). These siliciclastic deposits are equivalent of the Zubair Sandstone (Alsharhan and Kendall, 1991; Sharland et al., 2004; Jassim and Goff, 2006). The time equivalent deposits from the Zagros FTB are known as the Kushk Sandstone (NIOC internal reports), which is assumed to be more distal than the Zubair Sandstone in Iraq and Kuwait. On the Arabian Plate, the Biyadh Formation in Saudi Arabia (Powers et al., 1966) and a succession of sandstones interbedded with marls and limestones of Valanginian - Barremian age in Jabal Abdul Aziz in Syria (Jassim and Goff, 2006) are equivalents to the Zubair Formation.
This depositional setting continued until the Late Barremian, and is represented by the Gadvan Formation in the Khuzestan area, and by the newly defined Chahoo Formation in Fars, Bandar Abbas Hinterland and offshore areas.

During the Barremian, most parts of the Khuzestan and the western part of the Fars area corresponded to a platform slope, characterized by hemipelagic marls containing abundant *Choffatella decipiens*, echinoid remains, ammonite shells, oysters (*Exogyra* sp.) and sponge spicules, whereas the Bandar Abbas Hinterland and offshore areas still corresponded to an inner to mid-platform setting with a well-diversified microfauna, including stromatoporoids, *Lithocodium/Bacinella* and dasycladalean algae throughout the proximal depositional setting (Bandar Abbas Hinterland) and mixed benthic foraminifera-dasycladalean algae within a mid-platform setting in the Fars area (Fig. 5.14).

Finally, during a regional progradation in the Late Barremian, the Khalij Member (containing the fossil marker *Dictyoconus arabicus = Montseciella arabica*) extended throughout the entire studied area, showing two different depositional environments: shallow lagoonal setting (in the Bandar Abbas Hinterland and offshore area) and platform margin to mid-platform setting throughout the entire Fars and Khuzestan areas (Fig. 5.15).

Therefore, a very extensive, flat platform or ramp, with some siliciclastic input, is proposed as the depositional model during the sedimentation of Hauterivian - Barremian deposits in the Zagros FTB (Fig. 5.16 d).

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**Fig. 5.15:** Paleogeographic map of the Late Barremian during the sedimentation of the Khalij Member, Zagros FTB.
Chapter 5

Fig. 5.16: Reconstruction and evolutionary trend of the Fahliyan platform during the Berriasian - Barremian interval, Zagros FTB (explanation in the text).
5.5 Changes in trophic levels response to the platform geometry, Zagros FTB

Changes in trophic levels are controlled by the style and architecture of a platform, denoting a link between the platform evolution and paleocenographic changes (Föllmi et al., 2006).

In the Zagros FTB, the Lower Cretaceous shallow-platform carbonates were influenced by sea-level changes, siliciclastic influx and also changes in trophic levels. A correlation diagram (Fig. 5.17) is suggested here which shows changes in the platform ecology at different studied sites along a 2000 km proximal-distal transect in this Neo-Tethyan carbonate platform (Zagros FTB). In this carbonate platform, three types of carbonate production occurred in Khuzestan and in the western part of the Fars area: (1) an oligotrophic photozoan community during the Berriasian and earliest Valanginian, (2) a mixed photozoan-heterozoan ecosystem in the Valanginian, and (3) a mesotrophic heterozoan community during the Hauterivian-Barremian. At the same time, the eastern part of Fars, Bandar Abbas Hinterland and offshore area were exclusively characterized by a photozoan community, except during the Berriasian, where an hemipelagic carbonate factory was active in Bandar Abbas Hinterland and offshore area.

In the studied area, the photozoan community included abundant calcareous green algae and stromatoporids, associated with rare corals and rudists, the hard parts of which were predominantly precipitated in aragonite (Wefer and Berger, 1991). This assemblage is present in the Fahliyan Formation, across the platform, and also in the Chahoo Formation eastward in Fars and Bandar Abbas areas. By contrast, the heterozoan ecosystem contains echinoids, siliceous sponge spicules, few benthic organisms and rare thick bivalves (e.g. oyster), that precipitated their hard parts mainly in calcite (Flügel, 2004). This community is frequent in the Ghari and Gadvan formations in the study area.

Changes in carbonate-platform geometry and its influence on the ecosystem and carbonate production was also investigated here. It reveals that the photozoan platform corresponds with a distally steepened ramp to rimmed-platform with temporary connections to the basin. This occurred during the Berriasian and earliest Valanginian (see Fig. 5.16 a-b). On the contrary, the heterozoan ecosystem always coincides with an open, ramp-like (non-rimmed platform) architecture with good connections to the basin. This occurred during the Hauterivian - Barremian in the studied area (see Fig. 5.16 c-d).

Fig. 5.17: Suggested diagram showing the evolution of carbonate platform ecosystems along a NW-SE transect (distal-proximal), Zagros FTB.
5.6 Conclusions

The main conclusions of this chapter are summarized below:

- sedimentary systems are represented by inner to mid-platform settings during the Berriasian and Valanginian, except for the Bandar Abbas Hinterland and offshore area which were covered by basinal deposits containing tintinnids and radiolarians. The system is marked by a mid-platform to slope depositional environment with temporary basinal seaways during the Hauterivian and Barremian. This time coincides with significant siliciclastic input from the east and west.

- four successive architectures were observed in the platform growth: rimmed platform during the Early - Middle Berriasian, isolated rimmed platform in the Middle Berriasian - earliest Valanginian, non-rimmed open platform to ramp in the Valanginian, and finally a mixed siliciclastic-carbonate platform to ramp in the Hauterivian - Barremian.

- an excellent match is observed between the geometry of the carbonate platform and trophic levels: photozoan ecosystems correspond with the rimmed platform during the Berriasian to the earliest Valanginian and heterozoan carbonate factories coincide with a ramp-like platform during the Hauterivian - Barremian.

References:


6.1 Introduction

The sequence stratigraphy framework provides the context within which to interpret the evolution of depositional systems through space and time. The major tools used in sequence stratigraphy are: key surfaces, stacking patterns (upstepping, forestepping, backstepping, downstepping) and the geometry of stratal units (Catuneanu et al., 2011).

Unlike other methods in stratigraphy, such as biostratigraphy and lithostratigraphy that are purely descriptive, sequence stratigraphy uses a genetic approach, involving conceptual depositional models and focusing on the mechanism of formation of specific stratal stacking patterns and bounding surfaces (Catuneanu et al., 2011).

The sequence stratigraphic model presented here for the Berriasian - Barremian sedimentary succession in the Zagros FTB is based on outcrop sections, in combination with subsurface data, and constrained by new biostratigraphic results and age dating of this work.

The sequence stratigraphic analyses of the Arabian Plate by Sharland et al. (2004) and Simmons et al. (2007) provided few information about Iran. Moreover, the sequence stratigraphic model of van Buchem et al. (2010) and others that have been published in internal reports of the Iranian Oil Company are still based on old biostratigraphic datasets for this time interval.

The purpose of this chapter is to provide a detailed sequence stratigraphic analysis on each outcrop/subsurface section to suggest a uniform sequence stratigraphic framework for the studied stratigraphic interval which is important for the understanding of the petroleum systems in this area, and to illustrate the role of eustatic sea-level fluctuations and/or tectonic control on sedimentation patterns. Therefore, in this chapter, characteristics of the defined sequences are briefly described from the Fahliyan outcrop (as a key section), and then, a regional comparison of the defined sequences will be discussed together with isopach maps.

6.2 Methodology

There are several alternative approaches for sequence stratigraphy interpretation, some of which are shown in Figs. 6.1, 6.2. The differences between these methodologies are basically the definition, principles, and ranks of sequence boundaries and their importance.

The T-R sequence approach is used in this study. Transgressive-regressive (T-R) sequences are a type of sequence bounded by a composite surface that includes the subaerial unconformity and the marine portion of the maximum regressive surface (correlative conformity, Embry and Johannessen, 1992). This method has been used for separating sequences and their elements (transgressive trend, maximum transgressive, regressive trend and maximum regressive surface) in one measured and sampled outcrop or subsurface section. This model (T-R) is the most adapted when the sequence stratigraphic framework is based on sequence intervals rather than on sediment bodies or geometry of strata. This model is comparable with the sequence definitions of van Wagoner et al. (1988) and Vail et al. (1991), who proposed a succession comprising a highstand systems tract - a sequence boundary - a lowstand systems tract - a transgressive systems tract - a maximum flooding surface and a highstand systems tract for each sequence (see Figs. 6.2, 6.3).
Fig. 6.1: Evolution and subdivisions of sequence stratigraphic approaches (modified from Catuneanu et al., 2011).

Fig. 6.2: Various sequence stratigraphic approaches, showing differences in timing, sequence boundaries and systems tracts. The T-R approach used in this study is shown in colored column. Abbreviations: RSL- relative sea level; T- transgression; R- regression; FR- forced regression; LNR- lowstand normal regression; HNR- highstand normal regression; LST- lowstand systems tract; TST- transgressive systems tract; HST- highstand systems tract; FSST- falling-stage systems tract; RST- regressive systems tract; T-R- transgressive-regressive; CC*- correlative conformity in the sense of Posamentier and Allen (1999); CC**- correlative conformity in the sense of Hunt and Tucker (1992); MFS- maximum flooding surface; MRS- maximum regressive surface (modified from Catuneanu et al., 2011).
In order to recognize the possible presence of lowstand systems tract (identification of stratal stacking patterns) in the studied platform based on the T-R sequence framework, we used the principles of cyclostratigraphy and small-scale sequences by making two laterally correlated sections across the platform and creating a synthetic composite section for a time-series analysis.

Although the lowstand systems tract (LST) was called “shelf-margin systems tract”, associated only with a correlative conformity (CC) at the base (Posamentier et al., 1988; see Figs. 6.2, 6.3), this term is redundant, and can be bounded by the subaerial unconformity or a correlative conformity at the base (Catuneanu, 2006; Catuneanu et al., 2011).

In this work, two types of sequence boundaries have been distinguished: sequence boundaries with evidence for exposure (Type I boundary) and surfaces which cap a shallowing-upward succession (Type II boundary). Moreover, the maximum flooding surfaces (MFS) are named after the standard model introduced for the Arabian Plate (Sharland et al., 2004; Simmons et al., 2007).

Several authors have defined various orders of depositional sequences since 1977 (see Schlager, 2005). In this study, we used from terms large-scale and small-scale sequences which probably correspond to the second-order (3-50 Ma) and third-order (0.5-3 Ma) sequences of Haq et al. (1988) and Vail et al. (1991), respectively.

6.3 Key stratigraphic section (Fahliyan outcrop) (Fig. 6.5)

The presented sequence stratigraphic analysis of the Fahliyan outcrop illustrates the thickness, age, facies characteristics, depositional environment, and boundaries for each sequence. The age assignment for each sequence is based on the biozonation and chronostratigraphy defined in this work.
6.3.1 Berriasian - lowermost Valanginian sequence (Fig. 6.6)

This sequence has a thickness of 220 m and stratigraphically includes the entire thickness of the Fahliyan Formation in this outcrop. The transgressive part of this sequence includes the thick to massive beds of the Fahliyan Formation, containing benthic foraminifera, dasycladalean algae, ostracods, rare echinoids and very rare bivalve shells. The sequence starts with shallow lagoonal environment, followed by a high-energy oolitic and bioclastic shoal system. The maximum transgressive/flooding surface (mfs) corresponds to a thin interval of well-bedded argillaceous limestone, containing diversified benthic foraminifera and echinoid remains, interpreted as a mid-platform setting and showing a little contrast in the gamma-ray log. In a regional correlation, this mfs is positioned within the tintinnid-dominated pelagic sediments in the Bandar Abbas and offshore area (e.g. Genow, Khush and Qesm-4). The regressive systems tract shows a significant shallowing-upward trend, changing from shoal to lagoonal and intertidal flat depositional environment.

The basal sequence boundary is located at top of the Jurassic Surmeh/Hith Formation, corresponding to a regional stratigraphic hiatus. Therefore, this surface is defined as a Type I boundary, showing a diachronous surface of Kimmeridgian to Early Berriasian age in this area (Khuzestan), and Kimmeridgian to Middle Berriasian age in the East (Bandar Abbas Hinterland and offshore area). Regionally, this surface is comparable to other parts of the Arabian Plate, where, a regional unconformity between the AP7 and AP8 megasequences (149 Ma) is reported as a result of a possible phase of ocean-floor spreading around the northern margin of the Arabian Plate linked to the opening of the southern Neo-Tethys Ocean (Sharland et al., 2004; Jassim and Goff, 2006).

No evidence of subaerial erosion has been documented at the upper surface of this sequence in this section, calling for a Type II sequence boundary. But it corresponds to an obvious regional facies change and comprises remarkable sedimentary patterns such a hardground and an iron-crusted surface in the Fars area (e.g. Gadvan outcrop, see chapters 2 and 3).

According to our high-resolution dating (basically obtained from benthic foraminifera and dasycladalean algae calibrated with Sr-isotope analysis), the basal part of the Early Berriasian is missing in whole parts of the Khuzestan and Fars areas. The best age control is for the Bandar Abbas Hinterland and offshore areas by using tintinnids. It indicates that the entire Early Berriasian is missing. Therefore, a late Early Berriasian - earliest Valanginian is suggested for this sequence, with a duration of ~ 4 Ma.
Regional Sequence Stratigraphic Analysis

Fig. 6.5: Stratigraphic log with sequential interpretation throughout the studied intervals, Fahliyan outcrop, Zagros FTB. Symbols and colours are shown in Fig. 6.4.
The mfs of this large-scale sequence matches the sequence framework of the Arabian Plate (K20, Sharland et al., 2004; Simmons et al., 2007) and is also in accordance with the long term sea-level curve suggested by Haq et al. (1987).

This sequence includes 4 smaller sequences (B1-B4) at the type locality of the Fahliyan Formation (Figs. 6.5, 6.6). The arrangements of these small-scale sequences that make up this large-scale sequence are:

- **B1**: early transgression
- **B2**: late transgression to almost the maximum flooding zone
- **B3**: early regression
- **B4**: late regression

In a regional correlation, this large-scale sequence contains one to three small-scale sequences (B1-B3) in the Fars area (e.g. in Khartang, Kalagh, Assaluyeh, Gavbast, Darbast, Nakh; see Appendix 4). The difference between the numbers of smaller sequences can result from: (1) autocyclic processes or (2) missing/non-deposition time at the boundary of small-scale sequences (Strasser et al., 2006). Another possible interpretation is that the Fahliyan platform has broken up during this period of time and is suggested by its step-like morphology (Fig. 6.7). Based on this scenario, it can be assumed that the B1 and B2 sequences in the west correspond to the lowstand deposits for the large-scale sequence in the east (Fig. 6.8).
Fig. 6.7: Suggested model for carbonate sequence development during the Berriasian-Barremian in the Zagros FTB. The tectonically-derived relief and basin floor topography can control the extent of accommodation space and accumulation during the transgressive-regressive trends. Such rapid variations in relative relief can generate facies changes and affect the number of small-scale sequences over a short lateral distance as shown in Fig. 6.8. Relative falls in sea-level produce subaerial exposure and potential karstification or non-depositional condition in the shallower parts of the platform (modified from Gerdes et al., 2010). Abbreviations: RSL: relative sea level; a: end of regression phase; b: transgression phase; c: regression phase.
Fig. 6.8: Regional correlation of large and small-scale sequences along the E-W transects (see chapter 1 for location map), illustrating stratal geometries, showing the lowstand systems tracts (LST) colored green. Time controls for small-scale sequences were done by biostratigraphy and/or Sr-isotope dating.
6.3.2 Valanginian sequence (Fig. 6.9)

This sequence has a thickness of 73 m and comprises the thin to medium-bedded argillaceous limestones of the new Sar Bisheh Formation. It is marked by an increase in clay influx in the environment, as shown by a significant signature in the gamma-ray log. Therefore, its lower surface corresponds to the change from pure carbonates to marl-limestone alternation with a higher clay content. The upper surface of this sequence is well documented in all outcrops, and represented by an iron-crusted hardground, with bioturbation and extensive karstification (see chapter 2), indicating a Type I sequence boundary.

The transgressive trend of the sequence starts with a facies containing an assemblage of mixed benthic foraminifera and dasycladalean algae, belonging to an inner to mid-platform setting. The maximum flooding surface of this sequence coincides with nodular limestone beds, containing sponge spicules, echinoid fragments and few small benthic foraminifera (e.g. low-spiral trocholinids), providing a good signal on the gamma-ray log. The regressive part of the sequence is characterized by a lagoonal environment on this outcrop. Regionally, in the Darbast outcrop (Fars area), the regressive systems tract of this sequence is associated with a marked siliciclastic input (fine-grained sand and sandy wackestone).

This sequence has a duration between 3 and 6 Ma (depending on the amount of stratigraphic gap across the basin). The age control is based on dasycladalean algae with short stratigraphic ranges and benthic foraminifera both calibrated with Sr-isotope analyses (details in chapter 4).

As shown by biostratigraphic analysis, there is an important and regional hiatus at the top of this Valanginian sequence in large parts of the platform, which coincides with a main global sea-level fall (Haq et al., 1987; Alsharhan and Kendall, 1991; Sharland et al., 2004; Simmons et al., 2007; Granier, 2008). Moreover, in the Fahliyan outcrop, as well as in regional correlations, the greatest thickness of this sequence corresponds to the transgressive systems tract rather than to the regressive phase, confirming that most parts of the regressive deposits have been eroded during the eustatic sea-level lowstand. Therefore, the top of this sequence is diachronous. Towards the east, the surface gets older and the oldest surface is recorded in the central part of the Fars area (mainly coastal Fars), where most parts of the Late Valanginian is missing (e.g. Kalagh, Khartang, Surmeh, Assaluyeh and Khurmoj outcrops).

![Fig. 6.9: Field overview of the Valanginian large-scale sequence containing six small-scale sequences (V1-V6) in the bedded limestone with marly intercalations of the Sar Bisheh Formation in the Fahliyan outcrop.](image)

In the Fahliyan outcrop, this large-scale sequence includes six small-scale sequences with a duration of probably less than 1 Ma. These small-scale sequences which make up this large-scale sequence are:

- V1-V2: early transgression
- V3-V4: late transgression
- V5: latest transgression to maximum flooding zone
V6: early regression

In regional correlations, the number of these small-scale sequences are quite different, varying from 2 to 6 sequences (see Fig. 6.8). The succession is almost complete in the Khuzestan area in the west, whereas, towards the east in the Fars area, only two sequences are exposed, representing again evidence for a major erosional surface and a large stratigraphic gap.

The trends of transgressive, flooding surface (K30) and regressive stage of this large-scale sequence correspond with the long term eustatic sea-level curve of Haq et al. (1987) and the sequence model proposed by Sharland et al. (2004) and Simmons et al. (2007) for the Arabian Plate.

Remarks on the Late Valanginian unconformity

The sequence boundary K40 SB lies between the K30 and K40 maximum flooding surfaces. It has been reported as an important erosive surface from several localities in the Arabian Plate (Sharland et al., 2004; Simmons et al., 2007). The reference section for this SB is at the base of siliciclastic sediments of the Seroula Formation in the Tunisian Dorsale outcrop (Peybernes et al., 1994; Simmons et al., 2007). In the Arabian Plate, this SB has been reported from the base of the Zubair Formation in Kuwait and Iraq (Davies et al., 2002) and between the Sa’ar and overlying Furt Formation in Yemen (Holden and Kerr, 1997), showing that the Late Valanginian is also missing at these locations. Globally, this important event has been reported from the Carpathians of Romania, the Neuquen Basin in Argentina, the Texas Gulf Coast, NE Mexico, and Alaska (see references here and in Simmons et al., 2007).

There is no uniform and precise dating for this global boundary, which varies in age from the late Early Valanginian to the Valanginian/Hauterivian boundary (references here and in Simmons et al., 2007). This difference in age assignment could be the result of: (1) inadequate biostratigraphic resolution, (2) local tectonic overprint, (3) local sequences which do not match global patterns, and finally (4) unclear relation between sequences and global events (Simmons et al., 2007).

In this work, we are dating this erosive surface with a high resolution using biostratigraphy and Sr-isotope dating. We suggest an age of ~135 Ma, which represents a good match with the equivalent surface in the Arabian Plate (Al-Fares et al., 1998), but contrasts with the results of the reference section which is around 139.5 Ma (Fig. 6.10).

Fig. 6.10 Distribution of K40 SB on a global reconstruction, representing of this surface in different basins and domains, indicating that eustacy is the only controlling factor. Result from the Zagros FTB was added to the map, showed by asterisk (modified from Simmons et al., 2007).
6.3.3 Hauterivian sequence (Fig. 6.11)

This sequence with a thickness of 43 m has a relatively short time span, approximately 3 Ma and consists of one large-scale depositional sequence. In terms of lithostratigraphy, this sequence covers the Ghari Formation in its type locality in the Fahliyan outcrop. Towards the East, in Fars, Bandar Abbas Hinterland and offshore area, this sequence includes the lower part of the Gadvan and Chahoo formations.

From the Valanginian to the Hauterivian, several changes occurred on the platform. The dominant fauna changed, including a mixed photozoan-heterozoan assemblage in the Khuzestan and the western part of the Fars area, whereas, only photozoan communities persisted in the eastern Fars. Therefore, the Khuzestan area is marked by mid-platform depositional setting, while the Fars area is in the inner platform setting. At the same time, most parts of the Bandar Abbas Hinterland (such as Genow, Suru-1), offshore (e.g. Qeshm-4) and costal Fars (such as Assaluyeh, Surmeh, Khartang, Khurmoj) areas were still in a high topographic situation and they were exposed.

In the Fahliyan outcrop, the early transgressive deposits include benthic foraminifera, rare Hedbergellids, sponge spicules, bivalve shells, echinoid remains and very rare dasycladalean algae. The late transgressive and maximum flooding zone are characterised by hemipelagic marls with *Choffatella decipiens*, echinoid remains and thin filaments of bivalve shells. The regressive deposits contain an assemblage of mixed benthic foraminifera and dasycladalean algae.

As previously mentioned, there is an erosive surface between the Valanginian and the Hauterivian in the studied area. This stratigraphic gap is much larger in the Fars area (especially in the coastal and sub-costal Fars). In some locations (e.g. Burkh, Nakh and Darbast outcrops, see Appendix 4), the Hauterivian is marked by an extremely asymmetric transgressive-regressive cycle that comprises a small transgressive and a large regressive cycle. In the Burkh outcrop particularly, the transgressive surface is stacked with the maximum flooding surface, implying a fast sea-level rise or possibly reworking during sea-level rise that tends to erase facies records. Our final interpretation is the presence of an uplift in this area.

The lower surface of this sequence is characterized by the pre-Hauterivian unconformity that is regionally recorded in the studied area, and interpreted as Type Ι sequence boundary. The top surface is marked by an iron-crusted hardground, but shows no obvious evidence for exposure, indicating a Type Π sequence boundary.

![Fig. 6.11: The Hauterivian large-scale sequence, containing two small-scale sequences (H1, H2) in the Fahliyan outcrop.](image-url)
The top of this sequence is quite synchronous across the platform, as shown by stratigraphically important benthic foraminifera and dasycladalean algae, calibrated by Sr-isotope analysis. The best age control is based on the presence of an index taxon of orbitolinids, *Campanellula capuensis*, a marker for the Hauterivian stage which was found in the Gavbast outcrop in the Fars area.

This large-scale sequence contains two small-scale sequences in the type locality of the Fahliyan Formation. These small-scale sequences which make up the large-scale sequence are:

- H1: early to late transgression
- H2: latest transgression and regression

Towards the west in the Khuzestan area (Lar and Anneh outcrops), it contains three small-scale sequences (see Appendix 4), while eastward in the Fars area and Bandar Abbas Hinterland, this sequence (large-scale) is either not present (such as at Khartang, Assaluyeh, Surmeh, Genow, Qeshm well-4 and Suru well-1) or it has just one sequence (such as at Kalagh, Nakh and Burkh). It shows that in most parts of the Fars area (Costal Fars) and Bandar Abbas Hinterland, the top surface of the Valanginian and Hauterivian sequence are amalgamated in one surface (see Fig. 6.8).

### 6.3.4 Barremian sequence (Fig. 6.12)

This sequence covers the Gadvan Formation in the Fahliyan outcrop (Fig. 6.12). We defined two large-scale sequences within the Barremian - Lower Aptian deposits, the first sequence with a thickness of 70 m starts from the base of the Barremian up to the top of the Khalij Member (latest Barremian) and the second one begins from top of the Khalij Member and continues within Aptian deposits. Therefore, only the transgressive deposits of the second sequence are of Barremian age.

The transgressive deposits of the first sequence include hemipelagic marls (with abundant *Choffatella decipiens*, echinoid remains, bivalve shells and sponge spicules) with some intercalations of argillaceous limestone. Rudist rudstone to floatstone characterize mid-platform to platform top settings. The late transgressive and maximum flooding zone are characterized by the appearance of planktonic foraminifera (hedbergellids) and the acme of *Choffatella decipiens* with thin filaments of bivalves and echinoid remains. The regressive phase includes nearly pure carbonates, containing abundant orbitolinids, especially the index marker *Montseciella arabica*, along with *Palorbitolina lenticularis* and *Eopalorbitolina transiens*, indicating a platform top setting. Both the top (Fig. 6.12 e) and the basal surfaces of this sequence correspond to Type Π sequence boundaries, suggesting no obvious pause in sedimentation, probably marked by a short diastem.

The following large-scale sequence comprises a transgression phase represented by a marly interval containing planktonic foraminifera (hedbergellids and globigerinelloids), echinoids, and ammonites, interpreted as a basinal depositional environment. The regression phase is represented by thin-medium bedded argillaceous limestones, containing shell fragments, and continues within the Aptian deposits. Presumably, the top surface of this sequence should be placed at the top of the Lower Dariyan Formation in the Khuzestan area, and also at the top of the former Dariyan Formation (newly the Chahoo Formation) in the Fars and Bandar Abbas areas. The best example of which is observed in the Genow outcrop in the Bandar Abbas Hinterland (see Appendix 4, Genow section, Tang-e Chahoo).

The main trend of transgressive phase, maximum flooding surface and regressive phase of these two sequences is in accordance with the relative sea-level curve for the Arabian Plate (Haq et al., 1987), and also corresponds with the number of sequences proposed by Sharland et al. (2004); Haq and Al-Qahtani (2005) and Simmons et al. (2007), suggesting two maximum flooding surfaces (K50 and K60 at 129 Ma and 126 Ma respectively).

This sequence framework for the Barremian interval is quite different from the interpretation of van Buchem et al. (2010) who proposed that the marly intervals below and above of the Khalij Member belong to a shallow-platform setting (shallow-water marls), and place the maximum flooding surface within the carbonate unit of the Khalij Member. However, these marly intervals contain planktonic foraminifera that indicate a slope depositional environment that can be followed for hundreds of kilometres. These beds confidently represent the maximum transgression phase of this sequence. Moreover, these authors identified the only one
2nd-order sequence for the Barremian, whereas two of these are actually represented here as large-scale sequences.

Fig. 6.12: Field overview of the Barremian - Lower Aptian sequences in the Gadvan Formation, Fahliyan outcrop section; a: general overview of large and small-scale sequences; b-f: close-up of sequence surfaces, b: lower surface of Ba1, c: top surface of Ba 1, d: top surface of Ba2, e: the Khalij Member and the position of sequence boundary between Ba3 and Ba4, f: top surface of Ba4 within the lower carbonate beds of the Aptian Dariyan Formation.

It is believed that the best time control for the Barremian sequence is the Khalij Member with the fossil marker *Montseciella arabica*, characterized by a short age range that is limited to the late Barremian (van Buchem et al., 2010). However, it cannot be confident as a final evidence, because this species has stratigraphic range from the Late Barremian to the earliest Aptian in the Arabian Plate (Schroeder et al., 2010). In several localities in the Zagros FTB, this species is also present both within the Khalij Member and the Dariyan/Chahoo formations, proving that it continued into the Aptian. The best example is the Genow outcrop (Tang-e Chahoo) in the Bandar Abbas Hinterland where this species is recorded in the Chahoo
Formation and is also present within the Khalij Member (see Appendix 1, fossil distribution range chart of the Genow outcrop, Tang-e Chahoo).

In this work, a bivalve shell from the marly interval above the Khalij Member in the Fahliyan outcrop was collected for Sr-isotope dating, and gave an age of 125.5 Ma. This age represents a reliable time line for the Khalij Member as well as for the entire Gadvan Formation. It also confirms that from the base of the Barremian up to the top of the Khalij Member must be considered as a 2nd-order sequence, not as a 3rd-order sequence as previously reported (van Buchem et al., 2010).

The Barremian succession is marked by four small-scale sequences here, with a duration of about 1 Ma. The Ba1-Ba3 comprises the lower large-scale sequence and Ba4 corresponds to the transgression stage of the second large-scale sequence which continues within the Aptian. These small-scale sequences that make up the large-scale sequence are:

- **Ba1**: transgression
- **Ba2**: maximum flooding zone and early regression
- **Ba3**: late regression
- **Ba4**: transgression (Barremian - Early Aptian)

In the Khuzestan area at the west, all of these small-scale sequences are present, but towards the east, in most parts of the Fars and Bandar Abbas areas, the lowermost sequences (Ba1, Ba2) are not present, due to a possible fragmentation and step-like morphology of the platform from west to the east, supporting that Ba1 and Ba2 can be interpreted as lowstand deposits for the Ba3 sequence (see Fig. 6.8).

In a regional correlation with the Tethyan realm, the Barremian small-scale sequences are compared with the Arabian Plate and also the Vocontian Basin (SE France and Swiss Jura) (Fig. 6.13).

![Fig. 6.13: Correlation of the Barremian small-scale sequences with the Tethyan realm, showing the best correlation between this work with the new data from the Arabian Plate (Granier et alii, 2003 in Granier, 2008; Busnardo and Granier, 2011) and the Vocontian Basin in the SE France and Swiss Jura (Clavel et al., 2013). Abbreviations: T: Transgression; R: Regression; Ba: Barremian; Bd: Bedoulian; Apt: Aptian.](image_url)
6.4 Regional comparison

6.4.1 Berriasian - lowermost Valanginian sequence

The isopach map of this large-scale sequence shows that there are three depocenters in the studied area (Fig. 6.14). The thickest sediment thickness is located to the west of the Kazerun Fault in the Khuzestan area (e.g. Lar, Anneh, Fahliyan, Mish, Seh Qanat-1). Another thick sediment accumulation appears in the Bandar Abbas Hinterland and offshore area (such as Suru-1, Qeshm-4, Genow and Khush). In the Fars area, the thickness increases from the coast towards the interior, and the greatest thickness is observed at the Gadvan outcrop and Ahmadi well-1.

Sequence thickness ranges from 40 m to 355 m, implying that accommodation space was not uniform. The thickness difference can be due to: (1) difference in accommodation space, (2) differential filling of a homogenous accommodation space (due to currents), and (3) differential preservation.

Two basement fault zones, the Kazerun fault zone at the boundary of Khuzestan and Fars area and the Hendurabi fault zone at the border of Fars and Bandar Abbas area had an important role in controlling subsidence rates and the creation of accommodation space during the deposition of this sequence. On the other hand, reduced sediment thickness in the coastal and sub-costal Fars areas may be due to the role of the Qatar High. The northern extension of this paleo-high reaches the Fars area and is characterised by slow subsidence, creating condensation or even hiatus in stratigraphic intervals during the Cretaceous (van Buchem et al., 2010).

6.4.2 Valanginian sequence

As already mentioned, the Valanginian is characterized by a non-rimmed open platform in our study area. The isopach map (Fig. 6.15) shows that the thinnest sediment accumulations occur in the central Fars area (coastal and sub-coastal Fars, such as Khurmoj, Khartang, Kalagh, Surmeh, Assaluyeh, Darbast, Gavbast, Burkh and Nakh outcrops), which records a non-deposition or erosion phase during the Late Valanginian. By contrast, three main depocenters are recorded, but the largest one occurs in the Khuzestan area (Lar, Anneh, Mish, Fahliyan, Mangasht, Seh Qanat-1 and Nargesi-8) and is located along mid-platform to platform top depositional environments.

The thickness ranges from 10 to 181 m, reflecting the role of tectonic subsidence that created more accommodation space in the Khuzestan area (west of the Kazerun Fault), while at the same time, in the Fars area, the sedimentation pattern was still controlled by the Qatar High. The Late Valanginian corresponds to a main climate change in this area (see chapter 8), and both climate and global sea-level change were probably coupled and played an important role in changing the accommodation potential.
6.4.3 Hauterivian sequence

During the Hauterivian, the thickest sediment accumulation belongs respectively to the Khush outcrop in the Bandar Abbas Hinterland (134 m), the Ahmadi well-1 in the Interior Fars area (110 m) and the Lar outcrop in the Khuzestan area, Izeh Zone (105 m) (Fig. 6.16). Therefore, apart from the Fars area which was exposed due to the role of Qatar High, the other parts of the platform do not show a uniform subsidence rate and accommodation space creation, as shown by the thickness variations of this sequence, between 11 and 134 m in the areas where the Hauterivian deposits are recorded.

As these main depocenters do not coincide with the location of basement fault zones, the sedimentation pattern cannot be controlled by differential tectonic subsidence. Our final interpretation is the distinctive carbonate production potential between the inner platform and platform margin. The Khush outcrop in the Bandar Abbas Hinterland belongs to the inner part of the platform, including pure limestones of the Gadvan and Chahoo formations with abundant benthic foraminifera and dasycladalean algae. Whereas, the Lar section in the Khuzestan area is located at the platform margin, as shown by intercalations of marl-limestone of the Ghari Formation, with less benthic carbonate factories.

Fig. 6.15: Isopach map of the Valanginian large-scale sequence.

Fig. 6.16: Isopach map of the Hauterivian large-scale sequence.
6.4.4 Barremian sequence

The general platform configuration for the Barremian is a large, mixed siliciclastic-carbonate platform, with the shallowest part in the S, SE and a deeper part in the N, NW (see chapter 5).

According to the drawn isopach map for the first large-scale sequence of the Barremian (up to the Khalij Member) there are three main depocenters for this sequence, including Lar, Mish, Anneh, Fahliyan and Seh Qanat-1 in the Khuzestan area, Gadvan and Ahmadi-1 in the interior Fars area, and NaKh, Qeshm-4, Suru-1, Genow and Khush in the Bandar Abbas Hinterland and offshore area (Fig. 6.17). The general thickness variation of this sequence ranges between 8 and 91 m, indicating a quite different subsidence rate and accommodation space creation. The distribution of these depocenters, derived from the differences in sediment thicknesses, reveals the role of basement fault zones. The Hendurabi fault zone at the boundary of Fars and Bandar Abbas is possibly responsible for increased accommodation space in the Bandar Abbas and offshore areas. Westward in the Khuzestan area, the Kazerun fault zone and its extension in the northern part probably created additional subsidence and accommodation. The third depocenter in the interior Fras (Gadvan and Ahmadi-1), does not show a direct correlation with the tectonic structure. The other parts of the Fars areas, especially the coastal and sub-costal, are still affected by the northern part of the Qatar paleo-high, resulting in relative uplift and condensation.

![Isopach map of the Barremian first large-scale sequence up to the top of the Khalij Member.](image-url)
6.5 Conclusions

Based on our detailed study, a regional sequence-stratigraphic framework is proposed for the Berriasian - Barremian succession in the Zagros FTB (Fig. 6.18). The time framework is supported by new biostratigraphic results using benthic foraminifera, dasycladean algae and tintinnids, calibrated by Sr-isotope data.

The sequence stratigraphy study identified five large-scale (? 2nd-order) sequences and seventeen small-scale (? 3rd-order) sequences throughout the studied succession. Large-scale sequences, arranged in ascending stratigraphic order, occur in the Berriasian - earliest Valanginian, Valanginian, Hauterivian, Early to Late Barremian and Late Barremian - Early Aptian. These sequences both in high and low-frequency correspond with the sea-level curve proposed for the Arabian Plate (Haq et al., 1987; Haq and Al-Qahtani, 2005) and also to the sequence models of Sharland et al. (2004) and Simmons et al. (2007).

Rapid variations in the number of small-scale sequences accompanied with facies change over a small lateral distance suggest a step-like structure for the basin floor topography of the Fahliyan platform in the Zagros FTB during the Berriasian - Barremian. Distribution of the small-scale sequences across the platform shows some stratigraphic geometries, assuming lowstand systems tract (LST).

In the Khuzestan and Bandar Abbas areas, two basement fault zones, the Kazerun fault zone at the boundary of Khuzestan and Fars areas, and the Hendurabi fault zone at the border of Fars area and Bandar Abbas Hinterland were responsible for increased accommodation space during the Berriasian, Valanginian and Barremian. While, in the Fars area, the sedimentation pattern was controlled by the Qatar High during the Berriasian to the Barremian. During the Hauterivian, however, the thickness variation in the recorded sequence was controlled by distinctive carbonate production potential between the inner parts of the platform (Bandar Abbas Hinterland) and the platform margin (Khuzestan area).
**Regional Sequence Stratigraphic Analysis**

**Fig. 6.18:** Suggested sequence stratigraphy framework for the Berriasian - Barremian shallow platform deposits of the Zagros FTB in a NW-SE transect. (See chapters 2 and 4 for more explanations on lithostratigraphy nomenclature, biostratigraphy and age dating).
References:


Outcrop Gamma-Ray Spectrometry (GRS)

Outcrop gamma-ray, uranium/thorium/potassium correlations in certain Lower Cretaceous shallow-platform deposits, Zagros fold-thrust belt, SW Iran

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7.1 Introduction

The Gamma-Ray Spectrometry tool (GRS) is a technique for quantitative measurements of uranium (U), thorium (Th) and potassium (K) in strata. Application of natural gamma-ray logs was primarily for lithologic identification, determination of clay type and content, and evaluation of depositional environments. The most important information obtained from natural gamma-ray data are: (1) high values in K and Th in clays, (2) high value of U in siliciclastics and clays, and (3) high value of U as a proxy for organic matter and source rock in black shales (Lüning and Kolonic, 2003; Correia et al., 2012).

According to previous studies, K and Th signals are good indicators for clay abundance in limestones (Serra, 1988; Serra and Rezensionen 2008; Wignall and Myers, 1988; Harris, 1996; Fiet and Gorin, 2000; Lüning and Kolonic, 2003; Bodin et al., 2011; Correia et al., 2012), whereas the U signal is not as straightforward, as it is influenced by the content in organic matter, the thickness of black shales and the type of rocks alternating with black shales (Fiet and Gorin, 2000; Raddadi et al., 2005).

In carbonate sequences, K and Th are mainly concentrated as insoluble residue in detrital minerals (Lucia, 2007; Correia et al., 2012). U is also preserved in the detrital clay fraction and can be carried in solution as uranyl carbonate complexes \((UO_2(\text{CO}_3)_2)^{2-}\) (Langmuir, 1978; Correia et al., 2012). Therefore, authigenic U may be precipitated at the sediment-water interface under oxygen-depleted conditions (Wignall and Myers, 1988).

By using a portable gamma-ray spectrometer for measuring naturally radioactive elements and the concentration of Th, U and K on outcrops, we found several discrepancies between the lithologies and the expected total gamma response as well as the elemental radioactive records (U, Th and K). In order to understand the nature of these contradictions, we made detailed analyses of the ratios of recorded radioactive elements and made a link with other possible causes (such as climate change) in shallow-water carbonates which lack organic matter and clays.

Finally, these data are used to characterize the radiometric signatures of different lithostratigraphic units and lithologies on outcrops and to correlate the results with the gamma-ray response obtained from some exploration wells in the studied areas.

7.2 Experimental procedures

A portable gamma-ray spectrometer (GRS) was used to measure the gamma values and to quantify three major naturally radioactive elements, U, Th and K in the studied outcrops (Fig. 7.1). Field work focused on three outcrops, namely the Fahl'iyan, Gadvan and Genow sections (Fig. 7.2) and measurements were performed of the Fahl'iyan, Sar Bisheh, Ghari, Gadvan and Chahoo formations. Therefore, three composite field gamma-ray logs were prepared for the studied sections.

The purpose of these composite field gamma-ray logs was to measure continuous total gamma-radiation, every 30 cm within a time integration of 60 s. Count times of 1, 10, 60, 100 or 1000 second may be selected, and longer count times generate less statistical errors and greater precision. Periodic comparison of 60 and 100 second count times confirmed that the former was sufficiently accurate for data acquisition used for the purpose of this study.
Fig. 7.1: Images of the gamma-surveyor used in this work (a-b) with some field photos showing the measuring of *in-situ* natural radioactive elements on outcrop using the portable gamma-ray spectrometer, c-d: Gadvan section; e: Genow section, Zagros FTB.

Fig. 7.2: Location map of the studied outcrops (Fahliyan, Gadvan and Genow), Zagros FTB.
Outcrop Gamma-Ray Spectrometry

The methodology is based on the recommendation of the manufacturer and has been used in other similar works (e.g. Wignall and Myers, 1988; Svendsen and Hartley, 2001; Pereira et al., 2003; Bodin et al., 2011; Correia et al., 2012).

The instrument always measures all of radiation in counts per second (cps) and calculates the concentrations of K (%), U (ppm) and Th (ppm). The concentration of K is directly determined by the instrument. The U and Th concentrations are based on the detection of radioisotopes $^{214}$Bi and $^{218}$Tl that are parts of the related disintegration series (see IAEA, 1976).

The natural dose rate (total gamma) value (in nGy/h= nanoGrey per hour) is calculated from the measured concentrations of K (%), U (ppm) and Th (ppm) according to the IAEA recommendations using the following coefficient:

- 1 % K concentration contribution represents 13.078 nGy/h
- 1 ppm U concentration contribution represents 5.675 nGy/h
- 1 ppm Th concentration contribution represents 2.494 nGy/h

The effective area in which the portable gamma-ray spectrometer records radiations is shown in Fig. 7.3. This is an estimated distance (14 cm), because it depends on the density of the rock samples.

The detector-formation contact is of great importance as shown in Fig 7.3, when detector is held against a convex surface, it gives underestimated readings (Fig. 7.3 d), while in concave surfaces, it will give overestimated readings (Fig. 7.3 e). Moreover, the position of detector against thin beds will be significant and can record gross (Fig. 7.3 f) or net readings (Fig. 7.3 g).

As one of the purposes of this study was to correlate the general trend of field gamma-ray logs with subsurface well logs, the detector was placed almost perpendicular to the bedding, except for cliffs or massive beds where it was placed parallel to the bedding plane.

The total gamma-ray units for wireline gamma-ray logging are the API (American Petroleum Institute) which was introduced in 1958 (Frank, 1986). The API unit is computed by using the standard equation as:

$$ GR_{total} = aT + bU + cK $$

Where, $a$, $b$ and $c$ are 4.0, 8.0 and 16.0 respectively (Herron and Herron, 1996).

The portable gamma-ray spectrometer records the total gamma-ray values in counts per second (CPS) or counts per minute (CPM). As already mentioned, the records from wireline and portable spectral gamma-ray data are different. So, the recorded total gamma values of field gamma-ray spectrometer cannot be directly compared with the results of wireline log data. But as we intend to correlate the main trends of total gamma values in outcrops with subsurface data, this is not a problem for this study. The parameters measured on outcrop by a portable gamma-ray spectrometer are shown in Table 7.1.
Fig. 7.3: Comparison between the effective reading areas by a portable gamma-ray spectrometer on outcrops (a-b) and borehole using a wireline sonde (c). The position of gamma-spectrometer and the role of bedding geometries on the effective reading areas on outcrops are also shown (d-g) (modified from Løvbørg et al., 1971 and Parkinson, 1996 in Svendsen and Hartely, 2001).
7.3 Results

All spectral radioactive elements measured from different formations on the studied outcrops are explained individually here and a summary data of measured parameters are presented in Table 7.2.

7.3.1 Fahliyan section (Fig. 7.4)

The 480 m-thick succession comprising the uppermost part of the Surmeh, the entire Fahliyan, Sar Bisheh, Ghari and Gadvan formations and the lowermost part of the Dariyan Formation were logged. The short gap in data in the Gadvan Formation is due to the interval which is covered by rock debris and gravels in a river. The spectral gamma-ray measurements were recorded at 1551 points through this studied section.

7.3.1.1 Total gamma-ray

The total gamma-ray values are rather stable (between 4.82 to 31.71 nGy/h) with two main peaks near the base of the Fahliyan Formation (at about 100 m of thickness). There is an obvious abrupt drop at ~ 150 m where the gamma-ray value decreases immediately to around 1.5 nGy/h. There is no particular sedimentary break or facies changes in this horizon. However, local kartification in these massive limestones possibly influenced the shape and values in radioactive elements. After that, the section shows a progressively increasing trend towards the top of Fahliyan Formation.

There are several high peaks in total GR in the 300-350 m interval, but the highest value (54.95 nGy/h) has been recorded from a thick layer of pure carbonate at the top of the Sar Bisheh Formation, which shows evidence for climate perturbation in the $\delta^{13}$C record.

The base of the Ghari Formation is characterized by a decrease in the value of total GR (17.15 nGy/h). At this level, there are two intervals which generally show a decreasing trend in the values of total GR. These trends correspond with the shallowing-upward sequences, where high total GR values are recorded in marly
intervals (ranges from 27.99 to 39.13 nGy/h), and low values in pure carbonate beds (between 1.90 to 7.04 nGy/h).

The Gadvan Formation corresponds to an intercalation of marl and limestone beds, and records almost regular increasing-decreasing trends in the values of the total GR in adequation with lithologies. The lowest values were recorded in carbonate-dominated intervals, such as the Khalij Member (6.09 nGy/h), and the highest values belong to marly intervals in the uppermost part of the formation (above the Khalij Member) with 60.4 nGy/h.

7.3.1.2 Uranium (U)

The curve for U concentration shows a trend similar to that of the total GR for the Fahliyan Formation in this section. The reason is that the Fahliyan Formation is characterized by pure carbonates which contain very low values in K and Th. The highest U concentration was measured at the top of the Sar Bisheh Formation with a value of 8.98 ppm.

The mean value of the U concentration decreases in the Ghari Formation, ranging from 0 to 4.87 ppm. The main trend of the U curve in this formation does not follow the lithology, recording high values either in marly intervals or in pure carbonates.

There is no major change in U concentration in the Gadvan Formation, which is characterized by a nearly consistent trend (with values ranging between 0.15 to 4.47 ppm).

As the Ghari and Gadvan formations contain considerable K and Th, the main trend of the U curve has no clear match with the main trend of the total GR.

7.3.1.3 Thorium (Th)

The Th concentration shows an almost regular trend, with the highest values in the marly intervals and the lowest values in pure carbonate units. Therefore, the lowest Th concentration is observed in the Fahliyan Formation (values between 0 to 2.9 ppm). The Ghari Formation is marked by an increase in Th concentration (values between 0 to 4.6 ppm). Towards the top of the section, the Gadvan Formation shows a strong increasing trend in the Th values, reaching up to 6.7 ppm. The most enrichment of the Th occurs in marly intervals and clay-rich carbonates.

7.3.1.4 Potassium (K)

The K values record exactly the same trend as the Th curve, with the highest concentrations in marls and marly limestones and the lowest values in pure carbonates. Therefore, it shows values between 0 to 0.6 % in the Fahliyan and Sar Bisheh formations, 0 to 1.3 % in the Ghari Formation and 0 to 1.7% in the Gadvan Formation, representing an increasing trend from the base toward the top of the studied section.
**Fig. 7.4:** Composite field gamma-ray log of the Fahliyan section, Zagros FTB, constructed using a portable gamma spectrometer. The gap interval in the Gadvan Formation is due to the covered zone by rock debris and vegetation.
7.3.2 Gadvan section (Fig. 7.5)

The studied succession in this outcrop is stratigraphically equivalent to the previous section, including the Fahliyan, Sar Bisheh, Ghari and Gadvan formations. The total logged thickness is 425 m and the natural radioelements were measured at 1416 points of rock volumes.

7.3.2.1 Total gamma-ray

The Fahliyan is marked by the presence of an intercalation of limestone and dolomitic limestone. In the basal part of this formation (up to 150 m marker), total GR values show a symmetric trend, including of an increasing-decreasing cycle, with the lowest value at 140 m (11.5 nGy/h) and the highest value at 90 m (76 nGy/h).

A sharp increase in the value of total GR is observed in an interval of well-bedded limestones at the base of the Sar Bisheh Formation (values up to 89.6 nGy/h). Then, towards the top of this formation, values decrease, and again increase in the uppermost carbonate unit at the top of the Sar Bisheh Formation (with a value of 78.8 nGy/h). This pure carbonate unit with specific radioactive properties can be considered as a benchmark in the regional correlation with other studied outcrops and also subsurface well logs.

The Ghari Formation which comprises marly limestone and intercalations of thin limestone beds, shows regular positive-negative excursions in all radioactive elements, and the total GR values range between 43.2 to 100 nGy/h.

In the Gadvan Formation, the total GR response ranges between 23.4 and 100 nGy/h, with higher values in marls and marly intervals and the lowest values in carbonate deposits.

7.3.2.2 Uranium (U)

The U curve in the Fahliyan follows the main trend of the total GR. The minimum U concentration of this formation (0.01 ppm) is recorded in the massive carbonates in the lower part, and the maximum enrichment occurs in the uppermost part of the Sar Bisheh Formation with a value of 7.57 ppm.

The U concentration in the Ghari Formation ranges between 0 to 6.12 ppm, showing no significant changes with the main trend, and no correlation with lithologies.

In the Gadvan Formation, the U content is marked by slightly negative-positive pulses, ranging between 0.1 and 5.81 ppm.

7.3.2.3 Thorium (Th)

The lowest values in Th concentration are recorded in the Fahliyan Formation, which ranges from 0 to 3.36 ppm. Towards the top of the section, this radioactive element increases progressively, with moderate values, up to 6.12 ppm in the Ghari Formation, and the highest values which reach up to 6.23 ppm in the Gadvan Formation.

7.3.2.4 Potassium (K)

The K content shows minimum values in the Fahliyan and Sar Bisheh formations, and ranges from 0 to 0.57 %. By contrast, in the Ghari Formation, the Th concentration records the highest values up to 1.92 %. In the upper part of the section, the concentration of this radioactive element decreases and records a value ranging from 0 to 1.86 % in the Gadvan Formation.
Fig. 7.5: Composite field gamma-ray log of the Gadvan section, Zagros FTB, constructed using a portable gamma spectrometer. The gaps in data are due to the covered zone by rock debris and vegetation.
<table>
<thead>
<tr>
<th>Formation / Member</th>
<th>Radioactive elements</th>
<th>Values</th>
<th>Fahliyan outcrop</th>
<th>Gadvan outcrop</th>
<th>Genow outcrop</th>
<th>Result (mean values)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Max.</td>
<td>55</td>
<td>89.6</td>
<td>31</td>
<td>58.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min.</td>
<td>0.2</td>
<td>0</td>
<td>8.7</td>
<td>2.97</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ave.</td>
<td>27.6</td>
<td>44.8</td>
<td>19.87</td>
<td>30.7</td>
</tr>
<tr>
<td></td>
<td>GR</td>
<td>Max.</td>
<td>9</td>
<td>7.57</td>
<td>5.2</td>
<td>7.26</td>
</tr>
<tr>
<td></td>
<td>U</td>
<td>Min.</td>
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<td>0.01</td>
<td>1.2</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ave.</td>
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<td>3.79</td>
<td>3.2</td>
<td>3.83</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max.</td>
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<td>3.36</td>
<td>1.4</td>
<td>2.55</td>
</tr>
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<td></td>
<td>Min.</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ave.</td>
<td>1.45</td>
<td>1.68</td>
<td>0.7</td>
<td>1.28</td>
</tr>
<tr>
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<td></td>
<td>Max.</td>
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<td>0.57</td>
<td>0.4</td>
<td>0.52</td>
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<td></td>
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<td>0</td>
<td>0</td>
</tr>
<tr>
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<td></td>
<td>Ave.</td>
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<td>0.29</td>
<td>0.2</td>
<td>0.26</td>
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<td></td>
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<td>100</td>
<td>-</td>
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</tr>
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<td></td>
<td>Min.</td>
<td>1.90</td>
<td>43</td>
<td>-</td>
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</tr>
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<td></td>
<td>Ave.</td>
<td>20.5</td>
<td>71.5</td>
<td>-</td>
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<td>6.77</td>
<td>-</td>
<td>5.82</td>
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<tr>
<td></td>
<td></td>
<td>Min.</td>
<td>0</td>
<td>0.63</td>
<td>-</td>
<td>0.32</td>
</tr>
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<td></td>
<td></td>
<td>Ave.</td>
<td>2.44</td>
<td>3.7</td>
<td>-</td>
<td>3.07</td>
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<tr>
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<td>Max.</td>
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<td>6.12</td>
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<td>5.36</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min.</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ave.</td>
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<td>3.06</td>
<td>-</td>
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<tr>
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<td></td>
<td>Max.</td>
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<td>1.92</td>
<td>-</td>
<td>1.63</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min.</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
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<tr>
<td></td>
<td></td>
<td>Ave.</td>
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<td>0.96</td>
<td>-</td>
<td>0.82</td>
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<td>100</td>
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<td></td>
<td></td>
<td>Min.</td>
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<td>5.5</td>
<td>11.66</td>
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<tr>
<td></td>
<td></td>
<td>Ave.</td>
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<td>61.7</td>
<td>16.3</td>
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<td></td>
<td>Max.</td>
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<td>5.81</td>
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<tr>
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<td>Min.</td>
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<td>0.1</td>
<td>0.7</td>
<td>0.32</td>
</tr>
<tr>
<td></td>
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<td>Ave.</td>
<td>2.31</td>
<td>2.96</td>
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<td>2.66</td>
</tr>
<tr>
<td></td>
<td>GR</td>
<td>Max.</td>
<td>6.7</td>
<td>6.23</td>
<td>2.9</td>
<td>5.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min.</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ave.</td>
<td>3.35</td>
<td>3.11</td>
<td>1.45</td>
<td>2.64</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max.</td>
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<td>1.86</td>
<td>0.5</td>
<td>1.35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min.</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ave.</td>
<td>0.85</td>
<td>0.93</td>
<td>0.25</td>
<td>0.68</td>
</tr>
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<td></td>
<td></td>
<td>Max.</td>
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<td>22.1</td>
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</tr>
<tr>
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<td></td>
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<td>11.2</td>
<td>5.48</td>
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</tr>
<tr>
<td></td>
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</tr>
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<td>0.99</td>
<td>0.7</td>
<td>0.80</td>
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<td></td>
<td>Ave.</td>
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<td>2.89</td>
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<td>2.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max.</td>
<td>2.1</td>
<td>2.47</td>
<td>1.7</td>
<td>2.09</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ave.</td>
<td>10.5</td>
<td>1.23</td>
<td>0.85</td>
<td>1.05</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Max.</td>
<td>0.3</td>
<td>0.44</td>
<td>0.4</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Min.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ave.</td>
<td>0.15</td>
<td>0.22</td>
<td>0.20</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Table 7.2: Summary data of the radioactive elements measured from different formations/member in the studied outcrops, Zagros FTB.
7.3.3 Genow section (Fig. 7.6)

This logged section covers the uppermost 10 m of the Fahliyan Formation, followed by the Chahoo Formation which has a thickness of around 135 m. The natural radioactive elements were measured at 481 points along this section. This sequence mostly includes pure carbonates with rare intervals of argillaceous limestone.

7.3.3.1 Total gamma-ray

The Fahliyan Formation shows high values for both total GR (from 8.7 to 31 nGy/h) as well as for U content (from 1.2 to 5.2 ppm). This thin interval of pure carbonate is quite comparable with the equivalent unit in the previous sections (thickness of 350 m in the Fahliyan section and of 220 m in the Gadvan section). As already mentioned, this carbonate unit with particular radioactive elemental properties can be used as a benchmark for regional correlation across the platform.

The Chahoo Formation starts with an abrupt drop in the total GR (12.62 nGy/h). Then values increase gradually until the middle part of this formation which lithologically comprises marly intercalations, showing the highest values for total GR (27.19 nGy/h).

Upward, the total GR values decrease progressively toward the middle part of the formation, characterized by the presence of pure carbonates, and finally increases upward to reach 34.56 nGy/h.

7.3.3.2 Uranium (U)

As already mentioned, a value of 1.2 to 5.2 ppm is recorded for the Fahliyan Formation in this section. Then, this element decreases at the boundary of the Fahliyan and Chahoo formations, showing a value of 2.1 ppm. The highest value for U content is recorded within the upper part of the Chahoo Formation and reaches 5.81 ppm.

7.3.3.3 Thorium (Th)

The Fahliyan Formation in this outcrop shows very low values for Th, ranging between 0 and 1.4 ppm, an evidence for no siliciclastic fraction. The Th concentration shows the highest values in the marly limestone beds in the middle part of the Chahoo Formation, reaching up to 2.9 ppm. This element decreases upward, where there is no record (0 ppm) in the clean carbonate beds in the middle part of the formation.

7.3.3.4 Potassium (K)

The K concentration shows exactly the main trend as Th in this section, with a range of 0 to 0.4 % in the Fahliyan Formation, a highest value (0.5 %) in the lower part of the Chahoo Formation, and the lowest value in the middle part of this formation (0 %).

Finally, the pure carbonates in the upper part of this formation generally record a slight increasing trend in the radioactive elements to the top of the section, ranging from 2.9 to 35 nGy/h for total GR, 0.5 to 5.8 ppm for U, 0.2 to 2.2 ppm for Th and 0 to 0.4 % for K.
7.4 Discussion

7.4.1 Total Gamma-Ray (GR) versus U, Th and K

As already mentioned, a portable gamma spectrometer measures the radioactivity of sediments from three main contributions (U, Th and K). In order to evaluate the role of these three elements on the total GR response, the distribution of measured elements on the studied was outcrops plotted in Figs. 7.7-7.9.

The correlation matrices for total GR values and the three radioactive elements measured in outcrops are shown in Tables 7.3-7.5. These data reveal that the total GR values are dominated by the U content which shows the strongest correlation coefficient ($r = 0.87-0.93$). By contrast, Th is still significant but shows a lower correlation index ($r = 0.35-0.55$). The last element, K, has the less correlation with the GR value, represented by the lowest correlation coefficient ($r = 0.30-0.51$).

Th and K have good correlations with one another ($r = 0.55-0.79$). These elements are good indicators for clay influx and the siliciclastic fraction in marine sediments (Wignall and Myers, 1988; Raddadi et al., 2005).

This study shows that although there is a good correlation between Th and K, the regression lines drawn on thorium and potassium cross-plots commonly have a positive intercept on the thorium axis (Figs. 7.7-7.9). This interpretation is in agreement with the opinion of Quinif et al. (1982) that there is an excess of thorium which is not associated with potassium. Regarding U, this study shows that there is no clear relationship between the U values and Th and K, as the correlation index is very low (mostly $r = 0.02-0.04$, and rarely $0.17-0.22$).
Table 7.3: Correlation matrix for radioactive elements determined by gamma-ray spectrometry in the Fahliyan outcrop. Aggregated values are obtained from measurements made in different lithostratigraphic formations (Fig. 7.4).

<table>
<thead>
<tr>
<th>r</th>
<th>U</th>
<th>Th</th>
<th>K</th>
<th>Total GR</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Th</td>
<td>0.02</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>0.02</td>
<td>0.79</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Total GR</td>
<td>0.87</td>
<td>0.45</td>
<td>0.49</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 7.4: Correlation matrix for radioactive elements determined by gamma-ray spectrometry in the Gadvan outcrop. Aggregated values are obtained from measurements made in different lithostratigraphic formations (Fig. 7.5).

<table>
<thead>
<tr>
<th>r</th>
<th>U</th>
<th>Th</th>
<th>K</th>
<th>Total GR</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Th</td>
<td>0.25</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>0.17</td>
<td>0.70</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Total GR</td>
<td>0.93</td>
<td>0.55</td>
<td>0.51</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 7.5: Correlation matrix for radioactive elements determined by gamma-ray spectrometry in the Genow outcrop. Aggregated values are obtained from measurements made in different lithostratigraphic formations (Fig. 7.6).

<table>
<thead>
<tr>
<th>r</th>
<th>U</th>
<th>Th</th>
<th>K</th>
<th>Total GR</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Th</td>
<td>0.01</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>0.04</td>
<td>0.55</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Total GR</td>
<td>0.92</td>
<td>0.35</td>
<td>0.30</td>
<td>1</td>
</tr>
</tbody>
</table>

Therefore, the total gamma-ray signal is strongly influenced by U rather than by the clay content and/or the siliciclastic fraction. This interpretation also proves that there is no direct relationship between the U values and the total organic matter (see chapter 8). Therefore, it can be concluded that:

- The highest gamma-ray recording does not necessarily correspond with the maximum abundance of clay, siliciclastic input, or organic matter. This is in contradiction with the previous statements of Fiet and Gorin (2000); Lüning and Kolonic (2003) and Correia et al. (2012).
- In the studied outcrops, the highest values of U correspond with the lowest values in Th, K and organic matter, suggesting that the U content can be influenced by fractal phenomena in the basin, such as perturbation in the carbon cycle.
Fig. 7.7: Cross-plots of radioactive elemental ratios from the gamma-ray spectrometry on the Fahliyan outcrop.
Fig. 7.8: Cross-plots of radioactive elemental ratios from the gamma-ray spectrometry on the Gadvan outcrop.
Fig. 7.9: Cross-plots of radioactive-elemental ratios from the gamma-ray spectrometry on the Genow outcrop.
7.4.2 Lithology and log response

According to the literature, detrital Th is usually absent from pure carbonates, since it is insoluble and normally locked in the lattice structure of minerals which are entirely derived from continents through eolian and riverine pathways (Serra, 1988). Therefore, the low Th concentration indicates a small input of terrigenous material.

The K signal appears as a very good indicator of the clay content (Fiet and Gorin, 2000; Raddadi et al., 2005). By contrast, the concentration of U in a basin is probably controlled by the nature of sediments and by the depositional environment rather than by the amount of influx of uranium (Harris, 1996). We suggested that the U enrichment can be affected by perturbations in the carbon cycle on a global scale due to the climate change.

The Th/U value is used for interpreting sedimentary processes, when this ratio is more than 3, it reveals oxidized continental deposits or a higher siliciclastic input, while in most marine deposits precipitated under reducing environments, this ratio is less than 3 (Wignall and Myers, 1988; Wignall, 1994). This investigation shows that the Fahliyan and Sar Bisheh formations contain a small siliciclastic fraction in the Fahliyan outcrop (see Fig. 7.4). Toward the east, this formation shows several intervals of siliciclastic input in the Gadvan outcrop (see Fig. 7.5). Instead, the Ghari and Gadvan formations contain detrital fraction in all studied outcrops, as this ratio reaches to around 25 in the Fahliyan outcrop. But in the higher part of the platform, in the Bandar Abbas Hinterland, the Gadvan Formation does not record any siliciclastic influx and clay content in the Genow outcrop.

It is believed that most carbonate rocks that have been deposited under oxidizing environments contain very little U (detrital U) which is insoluble (Serra, 1988). Whereas, carbonate rocks which contain considerable organic matter and clay fraction, can absorb uranium ions (Harris, 1996). The presence of organic matter can increase the amount of U by a factor of 10,000 over that of surface runoff or ground water supplying U to the basin (Schmidt-Collerus, 1979). The main interpretations of carbonate rocks based on the data of spectral gamma-ray proposed by Serra (1988) are summarized in Table 7.6.

<table>
<thead>
<tr>
<th>Rock type</th>
<th>K</th>
<th>Th</th>
<th>U</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure carbonate, no organic matter</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Pure carbonate, with organic matter</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Shaly carbonate, no organic matter, oxidizing environm</td>
<td>High</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Shaly carbonate, with organic matter, reducing environm</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Glauconitic carbonate, no organic matter, oxidizing environm</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>Algal carbonate, with organic matter, reducing environm</td>
<td>High</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

Table 7.6: Interpretation of spectral gamma-ray data on carbonate rocks (modified from Serra, 1988).

This study reveals that the abundance curves of Th and K are very similar in all studied sections. Maximum values occur in marls and minimum values in pure carbonates. Instead, there is only a poor correlation between the U values and clay content (K) or siliciclastic fraction (Th), proving that the U values are not directly linked to the lithology, or at least that it is not controlled by the occurrence detrital deposits. Such intervals with maximum clay content and siliciclastics correspond to the lowest U value (see Ghari and Gadvan formations in the Fahliyan outcrop).

As already mentioned, there is an excellent match between the total gamma-ray curve and the U values. It can thus be concluded that the total GR curve cannot be used as an indicator for distinguishing shaly carbonates, clay content and/or siliciclastic input, and the idea that units with lowest GR, U, Th and K correspond necessarily to the highest carbonate content should be revised.
This study shows that the total gamma-ray values are highest in the Ghari and Gadvan formations, which lithologically comprise intercalations of marl and marly limestone. On the other hand, the lesser values belong to the pure carbonates of the Fahliyan Formation and the Khalij Member in all studied outcrops (Fig. 7.10).

We also analyzed in details the radioactive elements (U, Th, K) for each formation/member through the studied outcrops (Fig. 7.11). It reveals that:

- The highest U content occurs in the Fahliyan-Sar Bisheh formations. Instead, the lowest values are recorded in the Khalij Member. Therefore, although all these units lithologically comprise pure carbonates, their U content is quite different.
- The Th and K values are highest in the Ghari and Gadvan formations which lithologically include intercalations of marls and marly limestones.
- Th/U ratio, a factor to distinguish the amount siliciclastic deposits, is highest in the Gadvan Formation (which comprises of more marly intervals) and then in the Ghari Formation. The pure carbonates of the Fahliyan as well as the Khalij Member have no significant signature for a siliciclastic fraction.

**Fig. 7.10:** Maximum, minimum and average values of the total gamma-ray (nGy/h) for each formation/member measured on the studied outcrops.

**Fig. 7.11:** U, Th and K average contents for each formation/member measured on the studied outcrops.
We analyzed also the shape of gamma-ray logs of the different studied lithologies (Fig. 7.12) and the results suggest that:

- massive pure limestones show always large serrate to teeth-like spikes.
- intercalations of well-bedded marly limestones and pure limestones are characterized by irregular pulses of notches and teeth-like shape, representing more marly bedding partings.
- marls with intercalations of pure limestone beds show small serrate shapes with some needle-like spikes and small notch shapes.
- marly intervals show small serrate shapes.

Consequently, a quantitative analysis should be carried out by measuring the radiometric signatures corresponding to the lithologies found in all studied outcrops (Table 7.7). As the used portable gamma-ray spectrometer measures the characters of approximately 30 cm$^3$ of rock, data obtained for thin beds of marls
(in marl-limestone alternation) is affected (probably depleted) by the nearby limestone beds containing different amounts of radioactive elements.

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Total GR (nGy/h)</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>K (%)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure limestone</td>
<td>5 - 32</td>
<td>0 - 5.4</td>
<td>0 - 2</td>
<td>0 - 0.3</td>
<td>300</td>
</tr>
<tr>
<td>Marly limestone</td>
<td>14 - 40</td>
<td>1.7 – 6.5</td>
<td>0 – 2.3</td>
<td>0 – 0.5</td>
<td>170</td>
</tr>
<tr>
<td>Marls</td>
<td>8.5 - 31</td>
<td>0.15 - 3.6</td>
<td>0.15 - 4.7</td>
<td>0 - 0.5</td>
<td>116</td>
</tr>
</tbody>
</table>

Table 7.7: Relationship between lithology and the amounts of radioactive elements obtained through field gamma-ray spectrometry (this work). As a result, neither the total GR nor the U contents can be used to characterize a lithology. Instead, Th and K content become more abundant in marls and marly limestones, indicating a siliciclastic fraction and clay content. (n= number of reading values).

7.4.3 Implications in sequence stratigraphy and correlation with subsurface well logs

A correlation scheme between the surface GR logs and three subsurface well logs is illustrated in Fig. 7.13.

The aim of this chapter is to recognize key surfaces by using the measurements of natural radioactivity. Basically, major sequence boundaries, maximum flooding surfaces as well as shallowing-upward parasequences are recognized based on the microfacies and sedimentary patterns in the field.

Regarding the gamma-ray log, the main trend of the surface curve is well correlated with subsurface logs in separating transgressive-regressive phases. Transgressive phases correspond to gradual increase in the gamma-ray values and regressive phases are marked by a decreasing trend.

This study reveals that maximum flooding surfaces (mfs) usually correspond to high gamma-ray values. It is also concluded that mfs coincide with clay-rich intervals (medium to high values in K and Th). It probably indicates a decrease in the energy of the depositional environment (Catuneanu, 2006), linked to a deepening-upward phase and maximum condensation.

In contrast, sequence boundaries are recognized either by high values in gamma-ray peaks (such as at the top of the Sar Bisheh Formation in the Fahliyan outcrop, Seh Qanat well-1, Nargesi well-8, Fig. 7.13) or the low gamma-ray recording (such as at the top of the Ghari Formation and the Khalij Member shown in all curves in Fig. 7.13).

Therefore, using only the shape and trend of the gamma-ray curve for distinguishing sequence boundaries can be risky and it must be calibrated with microfacies. Because total gamma-ray value follows the main trend of the U content, and because these parameters (GR and U) indicate anoxia, they are not necessarily linked to sea-level change or condensation (Correia et al., 2012).

Similar to the total gamma-ray value, the U content shows the same behavior with respect to key surfaces in sequence stratigraphy: i.e., high values at sequence boundaries or maximum flooding surfaces. The same result has also been reported from the western Alps (France), where there is a good correlation between the abundance of echinoderm fragments and high values in U content at the vicinity of maximum flooding surfaces (Raddadi et al., 2005).
Fig. 7.13: Comparison of the total gamma-ray values with the T-R sequences distinguished on the Fahliyan outcrop with the subsurface well logs (Seh Qanat-1, Nargesi-8, Ahmadi-1), Zagros FTB.
The total gamma-ray signatures can also be used to determine the position of particular sections along a carbonate platform (Fig. 7.14). For instance, the Barremian Gadvan Formation comprises deposits of a mixed siliciclastic-carbonate platform in the studied area. In the deeper part of the platform (NW), where carbonates are interbedded with marls, transgressive-regressive cycles are spectacularly reflected in the gamma-ray logs that show several fining-upward cycles interpreted as genetic sequences (sensu Galloway, 1989), with the maximum gamma-ray intensity corresponding to maximum flooding surfaces (Fig. 7.14 a). In contrast, toward the southeast, in the shallower part of the platform which corresponds to lagoonal and tidal flat depositional environments that contain no marl, the progradational and retrogradational arrangements do not show up on the gamma-ray log or at least, the cyclicity is not obvious (Fig. 7.14 b).

Fig. 7.14: Typical gamma-ray signatures of outcrops located in deep and shallow platform areas, showing pronounced cyclicity in the deeper part. Examples from the Gadvan Formation in the Fahliyan (a) and Genow (b) outcrops. Brown arrows show trend of fining-upward cycles interpreted as genetic sequences.

7.4.4 Distribution of U in shallow-carbonate platform

The U can be preserved in the detrital clay fraction of marine sediments (detrital U) or precipitated under reducing conditions as authigenic (nondetrital) U (Wignall and Myers, 1988; Wignall, 1994).

As the quantification of the U content is important for interpreting sedimentary processes, the amount of authigenic U is computed based on the formula proposed by Wignall and Myers (1988) and Wignall (1994) as:

$$U_{authigenic} = U_{total} - \frac{Th}{3}$$

Therefore, the minimum Th/U ratio of normal marine deposits where uranium is assumed to be entirely detrital is 3.

The U is fixed in sediments in three different ways: (1) chemical precipitation in acidic or reducing environments, (2) adsorption by organic matter, plants (algal mats), plankton and shells, and (3) absorption by phosphates (Serra et al., 1980).
Outcrop Gamma-Ray Spectrometry

Fig. 7.15 Comparison of Total GR, total U, authigenic U, K, Th, Th/U and TOC, performed on the Fayliyan outcrop, representing the values of authigenic U and relationship with the siliciclastic fraction.
Unlike the K that is chemically combined in the molecules of minerals, U is quite independent, resulting in a heterogeneous sedimentary distribution (Serra, 1984). On the other hand, because of the high solubility of U, it is sensitive to leaching and re-deposition, this representing another reason for an irregular distribution in sediments (Serra, 1984). Therefore, the U can migrate during the diagenesis.

Several authors suggest that the precipitation of authigenic U occurs when oxygen-depleted conditions prevail during sedimentation (Wignall and Myers, 1988; Wignall, 1994; Lüning and Kolonic, 2003; Bodin et al., 2011; Correia et al., 2012). Therefore, sediments with high concentration in authigenic U tend to be deposited under anoxic conditions that further allow large amounts of organic matter to accumulate (Wignall and Myers, 1988). Based on these suggestions, it has been proposed that the U content can be used as a proxy for total organic carbon content in pelagic sediments and black basinal shales (Fiet and Gorin, 2000; Lüning and Kolonic, 2003; Correia et al., 2012).

Our investigations show that authigenic U is the main component of the total U content in the studied shallow-platform carbonates (Fig. 7.15). It reveals that the Fahliyan Formation contains a very small siliciclastic fraction in the Khuzestan area, whereas, toward the east, in the Fars area, this formation includes several siliciclastic intervals where the Th/U ratio reaches to more than 25 (see Gadvan outcrop). In the contrary, the Ghari and Gadvan formations have a consistent siliciclastic fraction in both studied surface sections. Toward the east, in the Bandar Abbas Hinterland, the Fahliyan and Gadvan formations record no siliciclastic input with very low values (less than 2.35) in Th/U ratio.

In order to understand the relationship between the U content and total organic matter in shallow-platform setting, we analyzed some samples from the Fahliyan and Gadvan surface sections for organic matter, using Rock-Eval™ 6 device (details in chapter 8). The data showed that in both outcrops, very low values in total organic matter (Fig. 7.15) are recorded (less than 0.1 wt %). In addition, the U/TOC ratios are very low (Fig. 7.16) in both studied sections (poor correlation with r = 0.26 for the Fahliyan outcrop and 0.10 for the Gadvan outcrop). These results differ from those reported by different authors (Lüning and Kolonic, 2003; Bodin et al., 2011; Correia et al., 2012) from pelagic sediments with black basinal shales.

Therefore, in carbonate-dominated systems, the U content cannot be used as proxy for total organic matter, although anoxic conditions prevailed at some levels. As an example, in the 350 m-thick Fahliyan section, the authigenic U content records the highest value (8.7 ppm) in the interval containing the least amounts of total organic matter (0.03 wt.%).

The low preservation of organic matter in the studied samples can also result from the thermal maturation of marly limestones (T_max = 415 - 445 °C), while the U content is commonly less affected by diagenetic process.
7.5 Conclusions

The most important conclusions derived from this work can be summarized as:

1- The portable gamma-ray spectrometer is a quick, simple and low-cost technique with multiple applications to collect data that have a great importance in all correlations (lithological characterization, sequence stratigraphy).

2- The results confirm that Th and K values are associated with the siliciclastic fraction and clay content.

3- The U content does not follow the lithology; there is no significant correlation between the U values with Th and K contents.

4- The total gamma-ray values show an excellent match with the U content, and other contributions (Th, K) have subordinate roles.

5- High values in total gamma-ray correspond either to maximum flooding surfaces or sequence boundaries. This implies that using only the main trend of total gamma-ray curve for sequential interpretation is risky.

6- The outcrop gamma-ray technique is a powerful method to integrate subsurface and surface geology, and an important tool for hydrocarbon exploration, particularly when detecting time-lines in the subsurface logs is not difficult.

7- In the studied shallow-platform carbonates, a very low value for the U/TOC ratio is recorded, revealing that the total and authigenic U are not in agreement with the total organic carbon.

8- Total gamma-ray signatures can be used to determine the position of particular sections along a carbonate platform in terms of cyclicity and arrangements of progradational-retrogradational phases.
References:


8.1 Introduction

Table carbon and oxygen records measured on whole-rock carbonates provide a very valuable insight into
temporal changes in the global carbon cycle and paleo-environmental conditions (temperature, salinity) in
general. The Early Cretaceous comprises some significant oceanographic events recognized by a series of
short-lived anoxic conditions (OAEs) and identified by using the carbon isotope records of bulk carbonate
($\delta^{13}C_{\text{carb}}$) and organic matter ($\delta^{13}C_{\text{org}}$). Examples from these events linked to environmental changes are: the
Weissert Event close to the Early-Late Valanginian boundary and the Faraoni event at the Hauterivian-
Barremian boundary which have been reported by several authors from the Boreal realm and the northern and
western Tethys (Lini et al., 1992; Föllmi et al., 1994; Weissert et al., 1998; van de Schootbrugge et al., 2000;
Bartolini, 2003; Erba and Tremolada, 2004; Föllmi et al., 2006; Duchamp-Alphonse et al., 2007; McArthur et
al., 2007; Bodin et al., 2009; Gréselle et al., 2011; Kujau, 2012). Most of these researches report on marine
hemipelagic to pelagic deposits link the productivity and preservation of organic matter with the occurrence of
black basinal shales (see references here).

Dated from the late Early Valanginian-early Late Valanginian (ca. 135 Ma), the Weissert Event appears to
be related to a series of events including (1) a rise of CO$_2$ in the atmosphere-ocean system, (2) a subsequent
enhanced primary production and biocalcification crisis, (3) an increase in the amount and preservation of
buried organic carbon and (4) the growth of extensive photozoan carbonate platforms which operated as a sink
for dissolved inorganic carbon of continental origin. Its closing stages coincide with a cooling event recorded
by fish tooth and belemnite $\delta^{18}O$ (Puceat et al., 2003; McArthur et al., 2007; Barbarin et al., 2012).

In this work, we report, for the first time, the occurrence of a positive, Late Valanginian $\delta^{13}C$ excursion from
sediments deposited on the southern margin of the NeoTethys and discuss its possible origin.

The Valanginian climate change is similar to the present-day environmental change, especially with respect
to the limitation of anoxic conditions to marginal seas rather than to oceanic basins. Therefore, analyses of the
Valanginian event provide fossil analogues to the present-day global climate change (Westermann et al.,
2010) which is associated with the disappearance of tropical and subtropical reefs (Hughes et al., 2003).

We provide here new data regarding carbon and oxygen isotope variations in a shallow- platform setting of
the southern Tethyan realm to improve the time constraints on episodes of temperature variation and carbon
cycling. Therefore, we investigated two shallow-platform sections (Fahlivan and Gadvan), in order to
precisely determine the $\delta^{13}C$ and $\delta^{18}O$ records around the Weissert event and possibly the Faraoni level. This
study also tries to explain the link between the $\delta^{13}C$ excursion with dysoxic and/or anoxic conditions in a
neritic setting of the Tethyan realm. The obtained data are then correlated with published data from other
localities to get a more global view on the Valanginian climate change.

8.2 Previous works

Few studies have been performed on the Lower Cretaceous shallow-platform deposits of the Zagros FTB for
stable isotope analysis. The Fahliyan Formation (sensu James and Wynd, 1965) was studied at the type
locality for stable isotopes by Adabi et al. (2010). Another study was performed on the Gadvan Formation at
the type locality by Parvaneh Nejad Shirazi et al. (2008). These authors used the obtained data of stable
isotope analyses only for discriminating carbonates, and differentiating diagenetic environments and
carbonate systems.
8.3 Materials and Methods

Two sections, the Fahliyan and Gadvan outcrops, were selected for stable isotope and geochemical analysis (Fig. 8.1). The location of collected samples has been plotted on the field logs (Figs. 8.2-8.3). Detailed descriptions of the lithology and the micropaleontological content have been presented in chapters 2 and 4. Lithologically, the selected samples comprise limestone (micrite-dominated) to marly limestone. The selected samples belong to the Late Berriasian up to the Hauterivian (pro parte) in order to cover sediments older and younger than the Late Valanginian δ¹³C shift (see Figs. 8.2-8.3).

Fig. 8.1: Location of the studied sections (Fahliyan and Gadvan), Zagros FTB.

8.3.1 Carbon and oxygen isotope analysis

Measurements of the stable carbon and oxygen isotopes of sedimentary carbonates were made on 200-300 µg of 70 powdered bulk samples derived only from the sediment matrix. In order to avoid detrital and diagenetic-related effects, rock specimens were cut into thin slabs and inspected for calcite veins and obvious detrital material and/or secondary diagenetic crystals. These were removed from the sections and the subsequent sample was washed several times with water and distilled water and then dried at 110 °C in an oven. The selected material was then crushed and homogenized in an agate mortar.

The samples were analysed at the stable isotope laboratory of the University of Lausanne, Switzerland, following a method adapted after Spötl and Vennemann (2003). Samples were run on a Thermo Fisher Scientific Gas Bench II preparation device interfaced with a Thermo Fisher Scientific Delta plus XL continued flow isotope-ratio mass spectrometer (IRMS). Carbon dioxide was extracted at 70 °C. Values of carbon and oxygen isotopes are reported in the conventional delta (δ) notation relative to the Pee Dee Formation belemnite international standard calibrated by the IAEA in Vienna (VPDB), in per mil (‰). Replicate analyses have demonstrated an analytical reproducibility of the international calcite standard NBS-19 and of the internal laboratory standard Carrara Marble of better than ± 0.05 ‰ for δ¹³C and ±0.1 ‰ for δ¹⁸O values.

8.3.2 Rock-Eval pyrolysis

A number of 30 samples were analyzed for total organic carbon (TOC) on a Rock-Eval™ 6 in the geochemical laboratory of the University of Lausanne, Switzerland, following the standard procedure of Espitalié et al. (1985), with an instrumental error of <2%. Approximately 70 mg of powdered bulk sample was first pyrolyzed and subsequently completely oxidized. The amount of hydrocarbon released during pyrolysis
was measured by a FID detector, whereas the amount of CO₂ and CO released during both steps was measured by infrared absorbance. According to the standard method, pyrolysis started isothermally at 300 °C for three minutes (S1: hydrocarbons released during the isothermal phase). The sample was then heated to 650 °C (S2: hydrocarbons released between 300 and 650 °C). The oxidation step started isothermally at 400 °C for three minutes (S3: CO₂ released) and subsequently, the sample was heated up to 850 °C. The obtained TOC contents are expressed in weight % (wt. %). The hydrogen and oxygen record as: HI = S2/TOC × 100 in mg hydrocarbons per g TOC and OI = S3/TOC × 100 in mg CO₂ per g TOC. Moreover, the standard IFP 160000 was applied to calibrate the measurements. The error relative is 0.77, 0.25 and 1.5 % for TOC, HI and OI, respectively.

8.4 Results

8.4.1 Carbon and oxygen isotopic composition

Recorded values of δ¹³C and δ¹⁸O from both studied outcrops are given in Tables 8.1 and 8.2, and also plotted against the stratigraphy (Figs. 8.2-8.3) with precise biostratigraphical data from this study.

8.4.1.1 Fahliyan section

The carbon isotope curve obtained for the Fahliyan section shows a decreasing trend during the Berriasian from 1.72 ‰ to - 0.04 ‰. The Valanginian interval is characterised by several positive-negative peaks, ranging from - 0.64 to 2.25 ‰. In the upper part of the measured section, the δ¹³C curve shows a slight decreasing trend, values ranging from - 1.06 ‰ to 1.82 ‰. Thereafter, the positive gradient in δ¹³C curve becomes steeper, and reaches to a positive shift around 2.25 ‰ in the interval which is considered as an equivalent of the Weissert level.

![Fig. 8.2: δ¹³C and δ¹⁸O curves obtained from whole-rock carbonate samples (n = 46) of the Fahliyan outcrop. Age determination is based on this work (details in chapter 4).](image)

![Table 8.1: Results of stable isotope analyses performed on some samples from the Fahliyan outcrop.](table)
Thus, in the Fahliyan outcrop, the $\delta^{13}C$ mean value shows five main phases including I: almost stable pre-exursion values at about 0.2 ‰ during the Berriasian to Early Valanginian, II: a 2.25 ‰ increase that forms the major positive peak in the late Early Valanginian that continuous in the Late Valanginian, III: a decreasing trend at the Valanginian-Hauterivian boundary that reaches to about 0.5 ‰ within the Early Hauterivian, IV: another increase in values which reach to 1.31 ‰ as the second small positive peak in the Late Hauterivian, V: and finally a long term decrease in the trend of $\delta^{13}C$ to pre-exursion values during the Barremian (Table 8.1, Fig. 8.2).

The $\delta^{18}O$ curve shows rather stable values in the general trend, ranging from – 3.34 ‰ to - 5.90 ‰. A sharp negative peak, from - 3.74 ‰ to - 7.82 ‰ is recorded near the top of the Early Valanginian interval. The boundary of the Early and Late Valanginian is marked by a decrease to the lowest value, - 4.99 ‰ (Table 8.1, Fig. 8.2).

8.4.1.2 Gadvan section

In this section, there is a sharp negative peak at the boundary of the Berriasian (1.72 ‰) and the Valanginian (0.34 ‰) for the carbon isotope curve, then the $\delta^{13}C$ trend shows comparatively stable values (around 1.41‰), indicating no severe changes in the isotopic ratio of sea water during the Early Valanginian. The late Early Valanginian is marked by small positive-negative pulses, and finally the highest positive peak (2.15‰) occurred in the early Late Valanginian that is assumed as an equivalent of the Weissert level. During the Hauterivian, the main trend of $\delta^{13}C$ shows similar records as pre-exursion values, ranging between 1.88-1.27 ‰ (Table 8.2, Fig. 8.3).

The $\delta^{18}O$ curve shows a heavy value at the boundary of the Berriasian and the Valanginian (from - 5.57 ‰ to - 4.01‰). Upward, from the base of the Valanginian toward the top of this interval, $\delta^{18}O$ values record a general trend from heavier to lighter values, approximately - 4.01‰ to - 6.92 ‰. The boundary of the Early and Late Valanginian is marked by a trend from lighter (- 6.78 ‰) to heavier (- 4.93 ‰) values. The Hauterivian interval is characterised by slightly stable values in the $\delta^{18}O$, ranging from - 6.38 ‰ to - 4.73 ‰ (Table 8.2, Fig. 8.3).

Table 8.2: Results of stable isotope analyses performed on some samples from the Gadvan outcrop.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>$\delta^{13}C$ (‰ VPDB)</th>
<th>$\delta^{18}O$ (‰ VPDB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMR 6144</td>
<td>1.72</td>
<td>-5.57</td>
</tr>
<tr>
<td>AMR 6146</td>
<td>0.34</td>
<td>-4.01</td>
</tr>
<tr>
<td>AMR 6150</td>
<td>1.29</td>
<td>-5.76</td>
</tr>
<tr>
<td>AMR 6153</td>
<td>1.28</td>
<td>-6.51</td>
</tr>
<tr>
<td>AMR 6157</td>
<td>1.43</td>
<td>-6.14</td>
</tr>
<tr>
<td>AMR 6160</td>
<td>1.37</td>
<td>-7.22</td>
</tr>
<tr>
<td>AMR 6165</td>
<td>1.45</td>
<td>-7.16</td>
</tr>
<tr>
<td>AMR 6170</td>
<td>1.45</td>
<td>-6.71</td>
</tr>
<tr>
<td>AMR 6173</td>
<td>1.48</td>
<td>-6.92</td>
</tr>
<tr>
<td>AMR 6175</td>
<td>1.52</td>
<td>-6.57</td>
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<tr>
<td>AMR 6178</td>
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<tr>
<td>AMR 6180</td>
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<tr>
<td>AMR 6182</td>
<td>1.18</td>
<td>-4.39</td>
</tr>
<tr>
<td>AMR 6184</td>
<td>1.52</td>
<td>-7.08</td>
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<td>1.59</td>
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<tr>
<td>AMR 6198</td>
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<tr>
<td>AMR 6200</td>
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<td>AMR 6202</td>
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<td>AMR 6208</td>
<td>1.18</td>
<td>-4.92</td>
</tr>
<tr>
<td>AMR 6212</td>
<td>1.27</td>
<td>-6.38</td>
</tr>
</tbody>
</table>

Fig. 8.3: $\delta^{13}C$ and $\delta^{18}O$ curves obtained from whole-rock carbonate samples (n = 25) of the Gadvan outcrop. Age determination is based on this work (details in chapter 4).
8.4.2 Organic matter analysis

8.4.2.1 Fahliyan section

In the Fahliyan section, the TOC records range from 0.03 to 0.09 %, and the maximum values are recorded below the carbon isotope excursion (Table 8.3). The hydrogen index (HI) and oxygen index (OI) range between 65 to 462 mg HC/g TOC and 237 to 617 mg CO2/g TOC respectively, representing mostly Type Π organic matter which is based on the standard statistical evaluation of results in a van Krevelen diagram (Espitalié et al., 1985). The temperature of maximum hydrocarbon generation ranges from 343 to 478 °C with the average value of 445 °C (n=16) for samples of this outcrop (Figs. 8.9-8.10).

<table>
<thead>
<tr>
<th>Sample (MANA)</th>
<th>TOC</th>
<th>HI</th>
<th>OI</th>
<th>Tmax</th>
</tr>
</thead>
<tbody>
<tr>
<td>214</td>
<td>0.03</td>
<td>65</td>
<td>323</td>
<td>461</td>
</tr>
<tr>
<td>215</td>
<td>0.03</td>
<td>91</td>
<td>355</td>
<td>456</td>
</tr>
<tr>
<td>216</td>
<td>0.05</td>
<td>130</td>
<td>313</td>
<td>449</td>
</tr>
<tr>
<td>218</td>
<td>0.09</td>
<td>167</td>
<td>392</td>
<td>478</td>
</tr>
<tr>
<td>220</td>
<td>0.06</td>
<td>124</td>
<td>337</td>
<td>440</td>
</tr>
<tr>
<td>223</td>
<td>0.04</td>
<td>131</td>
<td>237</td>
<td>477</td>
</tr>
<tr>
<td>225</td>
<td>0.04</td>
<td>98</td>
<td>311</td>
<td>476</td>
</tr>
<tr>
<td>228</td>
<td>0.04</td>
<td>140</td>
<td>293</td>
<td>476</td>
</tr>
<tr>
<td>230</td>
<td>0.04</td>
<td>181</td>
<td>353</td>
<td>486</td>
</tr>
<tr>
<td>233</td>
<td>0.04</td>
<td>237</td>
<td>327</td>
<td>463</td>
</tr>
<tr>
<td>234</td>
<td>0.04</td>
<td>181</td>
<td>643</td>
<td>369</td>
</tr>
<tr>
<td>235</td>
<td>0.04</td>
<td>387</td>
<td>436</td>
<td>381</td>
</tr>
<tr>
<td>236</td>
<td>0.04</td>
<td>14196</td>
<td>456</td>
<td>373</td>
</tr>
<tr>
<td>237</td>
<td>0.04</td>
<td>462</td>
<td>455</td>
<td>476</td>
</tr>
<tr>
<td>240</td>
<td>0.04</td>
<td>343</td>
<td>415</td>
<td>343</td>
</tr>
</tbody>
</table>

Table 8.3: Results of organic matter analyses on some samples from the Fahliyan outcrop.

8.4.2.2 Gadvan section

In the Gadvan section, TOC values are also quite low, varying from 0.04 to 0.1% (Table 8.4), and the maximum TOC value (0.1 %) corresponds with the highest carbon-isotope shift. HI and OI show ranges between 0 to 395 mg HC/g TOC and 312 to 730 mg CO2/g TOC respectively. The plotted parameters always reveal Type Π organic matter, except for one sample which plots in Type III and has no record for HI (0) which shows an altered signature for the preserved organic matter. The Tmax values have ranges from 373 to 498 °C and the mean value for the measured samples of this section is 415 °C (n=14) (Table 8.4; Figs. 8.9-8.10).

<table>
<thead>
<tr>
<th>Sample (AMR)</th>
<th>TOC</th>
<th>HI</th>
<th>OI</th>
<th>Tmax</th>
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<tbody>
<tr>
<td>6175</td>
<td>0.05</td>
<td>395</td>
<td>389</td>
<td>381</td>
</tr>
<tr>
<td>6178</td>
<td>0.04</td>
<td>277</td>
<td>469</td>
<td>382</td>
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<tr>
<td>6180</td>
<td>0.04</td>
<td>160</td>
<td>496</td>
<td>437</td>
</tr>
<tr>
<td>6182</td>
<td>0.06</td>
<td>178</td>
<td>730</td>
<td>388</td>
</tr>
<tr>
<td>6184</td>
<td>0.06</td>
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<td>479</td>
<td>375</td>
</tr>
<tr>
<td>6186</td>
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<td>458</td>
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<tr>
<td>6188</td>
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<td>457</td>
</tr>
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<td>6190</td>
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<td>389</td>
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<tr>
<td>6197</td>
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<td>460</td>
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<tr>
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<td>249</td>
<td>325</td>
<td>373</td>
</tr>
<tr>
<td>6202</td>
<td></td>
<td></td>
<td>553</td>
<td></td>
</tr>
</tbody>
</table>

Table 8.4: Results of organic matter analyses on some samples from the Gadvan outcrop.

8.5 Discussion

8.5.1 Stable isotopes and diagenesis

The carbon isotope records are normally rather robust and only affected during the later stages of diagenesis (van de Schootbrugge et al., 2000). The reason is that the amount of dissolved carbon in diagenetic fluids is very low by comparison to the carbon present in the carbonates. In the contrary, the oxygen isotope is much more sensitive to diagenetic processes during burial. Several diagenetic phenomena can include changes in δ13C and δ18O signals, such as subaerial exposure, water in the vadose, fresh-water phreatic, mixing and finally the marine phreatic zone, all of which have positive and/or negative influence on stable isotopes (see Swart, 2011). A strong covariance between δ13C and δ18O is evidence of diagenetic alteration due to the influx.
of meteoric water in the mixing zone (Allan and Mathews, 1982) or of progressively decreasing alteration within the freshwater phreatic zone (Swart, 2011).

In this study, the scatter plots of $\delta^{13}C$ and $\delta^{18}O$ ratios show a very low correlation index ($r = 0.09$ and $0.13$ respectively for the Fahliyan and Gadvan outcrops) (Fig. 8.4), indicating none or very weak diagenetic effects. Although it reveals that samples were not affected by diagenesis, some features clearly show a probable difference in the tectonic history of these two studied sections. For example, the mean value for oxygen isotope composition in the Fahliyan outcrop is about -5.00‰, while in the Gadvan outcrop it is around -6.00‰ (see Tables. 8.1-8.2). This is possibly related to the burial history of these sections, because the Gadvan section is closer to the High Zagros Thrust Fault and was probably exposed to higher burial temperature during the Zagros deformation.

![Fig. 8.4](image)

**Fig. 8.4:** Cross-plots of $\delta^{18}O$ vs. $\delta^{13}C$ for the studied outcrops, show very low covariance ($r = 0.09 - 0.13$) between these variables, suggesting low diagenetic effects on the analysed samples.

### 8.5.2 The Valanginian positive carbon-isotope excursion: global correlations

The Valanginian positive excursion in $\delta^{13}C$, which is interpreted as the "Weissert Event", is a global event present in the Atlantic, Pacific, Southern and Northern Tethyan margins (Lini, 1994). Based on the initial definition, the Valanginian $\delta^{13}C$ shift starts at $1 \pm 0.5$‰ (in the late Early Valanginian) and has constant amplitude of 1.5‰. The maximum value is $2.5 \pm 0.5$‰ which it reached in the early Late Valanginian. Pre-excursion values are reached again in the Late Hauterivian (Lini et al., 1992).

In the Tethyan realm, this significant positive excursion in $\delta^{13}C$ was calibrated with biostratigraphy (ammonite zones) during the Valanginian (Fig. 8.5) and corresponds with the *Campylotoxus-Verrucosum* ammonite zones (Channel et al., 1993; Weissert et al., 1998; Hennig et al., 1999; Erba et al., 2004; Weissert and Erba, 2004). Generally, the amplitude of both negative and positive excursions in $\delta^{13}C$ is greater in deep marine and terrestrial deposits than in carbonates (Jenkyns, 2010).

A positive shift in $\delta^{13}C$ (up to 2.03‰) is recorded in the studied platform deposits in the Zagros FTB. It is reported for the first time from the Southern Tethyan realm and corresponds to a global perturbation in the carbon cycle. It is interpreted as the "Weissert Event", and dated from late Early Valanginian-early Late Valanginian (~135 Ma).

This main trend and mean values of the $\delta^{13}C$ excursion are relatively similar (in the long term) to the Tethyan reference curve (Weissert et al., 1998), as well as to the records from the other parts of the Tethyan realm, Pacific and Atlantic oceans (Fig. 8.5, curves 13-14). Although some distinct differences are observed at a smaller scale, they can be due to the difference in carbonate sources (platform vs. pelagic). Another difference may be due to the local oceanographic conditions (Royer et al., 2001) or even to terrestrial input that can change the values of the carbon isotope composition. We propose a duration of around 450 Kyr for the stratigraphic interval which covers the Weissert event in this shallow platform setting (around 15-16 m thickness, see Figs. 8.2, 8.3).
Therefore, a composite curve can be established based on the main trend of the $\delta^{13}C$. It shows two positive excursions separated by a negative shift during the Weissert event in this shallow platform setting. This trend quite corresponds with the standard model for OAEs linked to geochemical processes during volcanism, which shows a positive $\delta^{13}C$ excursion interrupted by a negative excursion. The latter is produced by the input of isotopically negative methane (an abrupt release of marine methane into the active carbon cycle where CH$_4$ has light isotope values of $\sim -60$‰) and its oxidation products carbon dioxide (Weissert, 2000; Jenkyns, 2010).

**Fig. 8.5:** Chemostratigraphic correlation of $\delta^{13}C$ (this study) with some sections recorded from the Tethyan realm, Western Atlantic and Pacific Ocean. The “Weissert Event” is shown in light brown colour. 1: Tethyan ammonite zones and reference curve on carbon isotope (Channell et al., 1993; Weissert et al., 1998; Henning et al., 1999; Erba et al., 2004), 2: Hole 1149 B, Nadezhda Basin (Bartolini, 2003), 3: DSDP hole 534 A (Bornemann and Mutterlose, 2008), 4: Angles, France (Duchamp-Alphonse et al., 2007), 5: Vergol, France (Kujau, 2012), 6a-c: Vocontian Trough, France (6a van de Schootbrugge et al., 2000; 6b Ducham-Alphonse, 2006 and 6c Emmanuel & Renard, 1993), 7: Vocontian Trough, France (Föllmi et al., 2006), 8: Vergol and La Charce, France (Henning et al., 1999; Gréselle et al., 2011), 9: Alvier, Switzerland (Föllmi et al., 1994), 10: Breggia, Switzerland (Bersezio et al., 2002), 11: Capriolo, Italy (Lini et al., 1992), 12: Lombardy Basin, Italy (Erba and Tremolada, 2004), 13-14: Zagros fold-thrust belt (13: Fahlitian section, 14: Gadvan section).

8.5.3 Is there a Late Valanginian greenhouse event?

According to recent studies, the greenhouse hypothesis for the Early Cretaceous proposed by Lini et al. (1992) is questionable (Gröcke et al., 2005). Recent records of $\delta^{18}O$ obtained from Valanginian-Hauterivian belemnites and nannofossils suggest that climate became cooler during the end of the Valanginian (Pucéat et al., 2003; Price and Mutterlose, 2004; Gröcke et al., 2005; McArthur et al., 2007; Brassell, 2009).

In this study, the $\delta^{18}O$ record has also been determined on fine-grained whole-rock sediments. Generally, the O-isotope composition of bulk carbonate samples is not reliable as a paleo-temperature or paleo-salinity proxy, because the calcite cement precipitated during deep burial shifts the bulk O-isotope curve towards lighter values and shows burial temperature instead of the past sea-surface temperature (Schrag et al., 1995; Weissert and Erba, 2004). Paleo-temperature calculations here are based on the proposed equation by Anderson and McArthur (1983), as:

$$T = 16 - 4.14(\delta^{18}O_c - \delta^{18}O_w) + 0.13(\delta^{18}O_c - \delta^{18}O_w)^2$$

Where:
- $T$ = Temperature (°C).
- $\delta^{18}O_c$ = Oxygen isotopic composition of samples measured by the Mass Spectrometer.
- $\delta^{18}O_w$ = Oxygen isotopic composition of sea water according to the SMOW (Standard Mean Ocean Water).

The $\delta^{18}O$ value for the Cretaceous seawater is assumed to be -1‰ SMOW (Shackelton and Kennet, 1975; Baron, 1983; Gröcke et al., 2003; McArthur et al., 2004).
Although the $\delta^{18}$O values show the effect of diageneric processes and/or the signature of post-depositional thermal alteration (according to the high $T_{\text{max}}$), the main trend of the O-isotope curve is considerable and shows a warming episode during the Weissert Event (at the boundary of the Early and Late Valanginian). It records a temperature of around 32 °C before the excursion, of 37 °C within the interval of the Weissert Event, and finally of 33 °C at the end of excursion in the Fahliyan outcrop. In the Gadvan section, the values are of 31.5 °C, 40 °C and 32 °C, respectively. Therefore, this trend matches the main trend of the Tethyan curve (Lini, 1994; Erbacher 1994; Jenkyns et al., 1994; Menegatti et al., 1998; Weissert et al., 1998; Erba et al., 1999; Herrle, 2002; Erba, 2004) and those recorded from the Northern and Central Tethys (Emmanuel and Renard, 1993; van de Schootbrugge et al., 2000; Weissert and Erba 2004; Duchamp-Alphonse, 2006; Godet et al., 2006; McArthur et al., 2007; Bodin et al., 2009; Főzy et al., 2010) (Fig. 8.6).

As every global warming is negatively affecting the dissolved oxygen content of the ocean and because naturally occurring oceanic oxygen minimum zone are expanding into shallow- water environments (Keeling and Garcia, 2002; Helly and Levin, 2004), this event can be interpreted as a phase of temporary hypoxic or even anoxic conditions in the studied area. This hypothesis is confirmed with the biotic crisis as well as the enrichment and precipitation of authigenic U (see chapter 7) which coincides with a major perturbation in $\delta^{13}$C. Such an expanding of the oxygen minimum zone is responsible for the preservation of the organic matter from oxidation, although the amount of TOC is very low within the studied pure carbonates.

![Fig. 8.6: Chemostratigraphic correlation of $\delta^{18}$O (this study) with some Tethyan sections, representing the "Weissert Event" in light brown colour. Tethyan ammonite zones after: Channell et al., 1993; Weissert et al., 1998; Hennig et al., 1999; Erba et al., 2004. 1: Simplified $\delta^{18}$O curve for Tethyan realm (Lini, 1994; Erbacher, 1994; Jenkyns et al., 1994; Menegatti et al., 1998; Weissert et al., 1998; Erba et al. 1999; Herrle, 2002; Erba, 2004), 2-3: Se France and SE Spain, 2 Belemnite calcite and 3 Sea water (McArthur et al., 2007), 4 a-b: Vocontian Trough, France, Belemnite samples; 4a (Bodin et al., 2009), 4b (van de Schootbrugge et al., 2000; McArthur et al., 2007), 5 a-d: Vocontian Trough, France, Bulk samples; 5a (Godet et al., 2006; Wissier et al., 2004), 5b (van de Schootbrugge et al., 2000), 5c (Duchamp-Alphonse, 2006), 5d (Emmanuel and Renard, 1993), 6: Bakony Mountains, Hungary (Főzy et al., 2010), 7-8 Zagros fold-thrust belt (7: Fahliyan outcrop, 8: Gadvan outcrop).](image)

8.5.4 Connection of the Weissert Event and faunal changes

Although the Weissert Event is not quite associated with a mass extinction in the studied area, the onset of the carbon positive excursion coincides with important environmental changes that influenced the biota. For example, algal mats and all calcareous green algae almost became extinct. At the same stratigraphic level, other photozoan communities, including benthic foraminifera record a significant decrease in diversity and frequency, resulting in a crisis of carbonate production. This event is similar to the main decrease in bryozoan fauna that has been recorded from the shallow-platform carbonates in Jura Mountains, and this crisis includes the coldest period of the Valanginian time in that area (Walter, 1989). In other localities, this event coincides with a significant environmental changes leading to the disappearance of calpionellids and a major turnover in belemnites in the Harskut section in Hungary (Főzy et al., 2010). There are many other localities where the Weissert Event is accompanied with an onset of extinction in calpionellids (see Erba et al., 2004).
In the Zagros FTB, a sequence of community changes is represented by temporal variations in the environment through time. This palaeo-community replacement can be compared with the pattern of successional stages in modern ecosystems affected by anoxia, where four stages for benthic community structure along a gradient of oxygen decline has been recognized in marine ecosystems (Diaz and Rosenberg, 2008). These stages include: undisturbed communities in normally oxygenated conditions (stage III), transitional communities with periodic hypoxia conditions (stage II), disturbed communities in hypoxia conditions (stage I) and finally the system moves from hypoxia to anoxia conditions where all the microfauna disappears (stage 0) (Diaz and Rosenberg, 2008). Equivalents of these four stages (Fig. 8.7) can be recognised in this study as:

(Stage III): The lower part of the section, during the Berriasian, is represented by an undisturbed community, including a well-diversified assemblage of benthic foraminifera and dasycladalean algae, indicating normoxia conditions.

(Stage II): There is a reduction in the diversity index of benthic communities, marked by a 15% decrease of benthic foraminifera and dasycladalean algae, probably as a result of a decrease in oxygen level. This stage covers the early Lower Valanginian.

(Stage I): Around 40% of the benthic foraminifera and 50% of the dasycladalean algae have disappeared in this stage, which probably indicates the shift from hypoxia to anoxia conditions that occurred in the late Lower Valanginian.

(Stage 0): In the latest Lower Valanginian to earliest Upper Valanginian, a grossly disturbed community and mass mortality occurred. 50% of benthic foraminifera and 75% of dasycladalean algae have disappeared, and probably an anoxic condition occurred. This stage is located in the interval corresponding with the Weissert Event. The average size of some dasycladalean algae, such as Salpingoporella annulata (Fig. 8.8) and Iranella inopinata, was affected by anoxia. Regionally, specimens from the Berriasian and Early Valanginian are large, whereas those from the Late Valanginian and Early Hauterivian are dwarfed (Hosseini et al., 2013). The same is true for benthic foraminifera: only low spiral and basal-inflated trocholinids (Coscinococcus chouberti, C. alpinus) are present within this interval. After the Weissert Event, as oxygen levels normalized, the benthic fauna started to recover during the Hauterivian, with an increasing diversity index for benthic communities observed regionally in the studied sections.
**Salpingoporella annulata**

d: 97-250  
D: 160-650  
d/D: 30-50%  
(after: Carras et al., 2006)

<table>
<thead>
<tr>
<th>d (µm)</th>
<th>D (µm)</th>
<th>d/D (%)</th>
<th>Age</th>
<th>Marine ecosystem</th>
</tr>
</thead>
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<tr>
<td>210-215</td>
<td>564-615</td>
<td>34-38</td>
<td>Late Hauterivian</td>
<td>Normoxia</td>
</tr>
<tr>
<td>105</td>
<td>282</td>
<td>37</td>
<td>early Late Valanginian to Early Hauterivian</td>
<td>Dwarfed samples</td>
</tr>
<tr>
<td>142</td>
<td>410</td>
<td>35</td>
<td>late Early Valanginian</td>
<td>Hypoxia - ? Anoxia</td>
</tr>
<tr>
<td>200-230</td>
<td>589-600</td>
<td>33-39</td>
<td>early Early Valanginian</td>
<td>Normoxia</td>
</tr>
<tr>
<td>200-260</td>
<td>500-643</td>
<td>36-40</td>
<td>Berriasian</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 8.8:** *Salpingoporella annulata*, analysis of the average size through time: before, within and after the interval assigned to the Weissert Event regionally in the Zagros FTB. Dwarfed samples within the interval assigned to the Weissert Event are possibly affected by anoxia, and respond to the marine ecosystem.
8.5.5 Organic matter analysis

Rock-Eval pyrolysis was used to determine the type and thermal maturity of sediment samples from the studied outcrops. For both studied outcrops, very low values in TOC (between 0.03 to 0.1 %) were recorded. The interpretation of HI, OI and \(T_{\text{max}}\) is difficult when the TOC value is less than 0.3wt. % (Espitalié et al., 1985).

Our data show that preserved organic matter is always of marine origin with variable terrestrial mixtures shown in HI/OI and HI/\(T_{\text{max}}\) on van Krevelen-type diagrams (Espitalié et al., 1985) (Figs. 8.9-8.10). This type of organic matter preservation is typical of a well-oxygenated marine setting with intermittent inputs of continental organic matter. The higher values in OI in the Gadvan outcrop can be related to the location of this section which is positioned in the proximal part of the basin.

At a global scale, a similar marine origin with intermittent terrestrial inputs, has been reported for organic matter deposited in oxygenated waters from the Atlantic Ocean, the Morocco Basin, the western Tethys (sections of Mallevial, Vergol and Angles in eastern France, Alvier in eastern Switzerland, Breggia in southern Switzerland and Capriolo in northern Italy), the Wawal section in Poland and the Shatsky Rise section in northwestern Pacific (Westermann et al., 2010). In contrast, in the marginal seas of the North Atlantic, the Pacific and the Weddell Sea, organic matter is of marine origin, but the TOC values reach up to 18 % in the Weddell Sea and indicate dysaerobic to anaerobic conditions during the Valanginian (Westermann et al., 2010).

Moreover, according to the Rock-Eval analysis, the average value of \(T_{\text{max}}\) in the Fahliyan outcrop is around 445 \(^\circ\)C (n=16) and it is about 415 \(^\circ\)C (n=14) in the Gadvan outcrop. For type II organic matter, \(T_{\text{max}}\) values between 435 \(^\circ\)C to 465 \(^\circ\)C indicate a high degree of maturation and correspond to the oil window (Espitalié et al., 1985) (see Fig. 8.9). Higher values in \(T_{\text{max}}\) (more than 465 \(^\circ\)C) suggest that organic matter experienced a higher degree of burial or a matrix/diagenetic effect. These high \(T_{\text{max}}\), low value in HI and high value in OI, suggest the presence of post-depositional thermal alteration in the studied sections.
Fig. 8.10: HI/OI diagrams indicating the type and values of organic matter of the studied outcrops. Type Π and rarely Type Ω organic matter are observed in the studied sections.

We also compared the sedimentation rates with the values of TOC during the interval assigned to the $\delta^{13}$C positive excursion in order to distinguish oxic from anoxic depositional environments according to the model introduced by Langrock and Stein (2004). According to the drawn TOC/SR diagram for both studied sections, none of the samples plots in the area of anoxic conditions (Fig. 8.11). These points imply that, in the southern Tethyan domain, preserved organic matter shows questionable hypoxia or anoxia conditions based on the geochemical analyses.

Fig. 8.11: Sedimentation rate versus total organic carbon in the studied outcrops. All of samples plot in the normal marine environments, as proof of well-oxygenated conditions. (modified from Langrock and Stein, 2004).
8.5.6 Possible mechanisms for the Valanginian Weissert Event driving the evolution of $\delta^{13}C$ in the studied area

There are several possible causes for the Weissert Event and the global perturbation of the carbon cycle, such as: increasing of $pCO_2$ into the atmosphere due to volcanic activity or continental weathering of igneous basaltic rocks. These events could be related to the Paraná-Entendeka continental flood basalts and/or to increased rates of oceanic crust production during the Gondwana breakup (Lini et al., 1992; Föllmi et al., 1994; Weissert and Erba, 2004; Erba et al., 2004). When volcanic activity increases the amount of CO$_2$ in the atmosphere-ocean system, it decreases the pH of the water and has effects on carbonate ion concentration of surface waters (Weissert and Erba, 2004).

The very low values in organic matter (TOC= 0.0-0.1 %) in the studied platform deposits are not sufficient to account for the positive excursion in $\delta^{13}C$. Therefore, the mechanism proposed by Weissert et al. (1998) is not confirmed as a possible mechanism for changing the carbon isotopic composition in this part of the Tethyan realm.

In addition, there is no evidence for enhanced storage of organic matter on the continent neither in the Zagros basin nor in the Arabian Plate during the Early Cretaceous. As most of the coal deposition in the southern part of the Eurasian Plate occurred in the Triassic and Early-Middle Jurassic as recorded in the central parts of Iran (Kerman area), the alternative scenario suggested by Weissert et al. (1998) and Westermann et al. (2010) that shallow-water platforms can operate as a sink for dissolved inorganic carbon of continental origin is not confirmed here. This disagreement coincides with the type of organic matter obtained from this study, which is always of marine origin (Type II).

Consequently, in addition to the suggested global mechanism (Paraná-Entendeka volcanism and continental flood basalts, Large Igneous Province), an alternative local mechanism is proposed for this part of the Tethyan margin. The Zagros FTB was located at the southern margin of the Neo-Tethys Ocean during the Early Cretaceous, and the oceanic crust of the Neo-Tethys, which began to be subducted beneath the Eurasian Plate (Iranian Microplate) from the Late Triassic, became more active during the Early Cretaceous. The subduction was associated with local volcanic activity (composed of tholeiitic, calc-alkaline, and K-rich alkaline intrusive and extrusive rocks) along the Urumieh-Dokhtar Magmatic Arc zone which is parallel to the main trend of the Zagros region (Takin, 1972; Berberian and King, 1981; Alavi, 1994, 2007). Therefore, this volcanic activity may have been responsible for the increase of $pCO_2$ in the atmosphere-ocean system, perturbation in the carbon cycle and finally reversing greenhouse mode during the Late Valanginian in this part of southern Tethyan realm.

8.5.7 Signals for an equivalent of the Faraoni level in the studied area

The Faraoni level is defined as an anoxic event by Baudin et al. (2002) and Baudin (2005). The difference between this anoxic event with other Cretaceous OAEs is that the positive excursion in the carbon isotope record in the Faraoni level is marked by a very small shift, around 0.5 ‰ (Erba et al., 1999; van de Schootbrugge et al., 2000; Bodin et al., 2006; Godet et al., 2006). According to Baudin et al. (2002), the main mechanism for the onset of the anoxic conditions during the Faraoni level is the increased nutrient delivery and primary productivity during the main second-order maximum transgressive phase that occurred in the Late Hauterivian (Ha 6 sequence of Haq et al., 1987; Hardenbol et al., 1998). This transgression led to the connection between the Tethyan and the Boreal realms as shown by belemnite migration (Mutterlose and Bornemann, 2000) and the presence of boreal nannoplankton in the Vocontian Trough (Godet et al., 2006). This bathymetric change may have led to the increased influx of colder and more nutrient-rich waters into the Tethys (van de Schootbrugge et al., 2003).

In the studied area, a positive shift in the $\delta^{13}C$ value is recorded within the Late Hauterivian interval in the Fahliyan section (see Fig. 8.2). This positive peak is tentatively considered as an equivalent of the Faraoni level. As this level is positioned at the vicinity of the maximum flooding surface of the main large-scale sequence of the Hauterivian in this section, it corresponds with the proposed model for the Tethyan realm (Haq et al., 1987; Hardenbol et al., 1998). In the same interval, the total organic carbon is around 0.05 %, indicating no organic matter preservation in this part of the Tethyan realm.
8.6 Conclusions

The carbon and oxygen stable-isotope record from selected sections of the shallow-platform carbonates in the Zagros FTB gives a reliable image of paleo-environmental changes in the Valanginian. The Early-Late Valanginian boundary is characterized by a significant positive excursion in carbonate carbon isotope that is considered as the Weissert Event and is reported for the first time from a neritic setting in the Arabian Plate. Our results correlate well with those reported from other locations in the Tethys, Atlantic and Pacific realms.

Results of organic matter analysis indicate very low rates of accumulation and preservation of buried organic matter, which is not sufficient to explain the positive excursion in δ13C. Moreover, preserved organic matter is always of marine origin, typical of a rather well-oxygenated marine environment. This result is in contradiction with the biotic crisis that regionally occurred in the same interval, which corresponds almost to a mass extinction. Indeed, the change in the size and geometry of some benthic foraminifera and dasycladalean algae are indicative of anoxic conditions. Moreover, as it is shown in the δ18O records, this event was accompanied by a period of relative climate stability with a tendency toward warm conditions, associated with an anoxic event.

In the classical scenario, the Valanginian Weissert Event is related to the magmatic activity of the Paraná-Etendeka large igneous province and to the increased rate of oceanic crust production during the Gondwana breakup (see Erba et al., 2004 and references here). We also propose a local origin for this change in the carbon cycle that is probably linked to volcanism or weathering of andesitic rocks from the Uromieh-Dokhtar Magmatic Arc zone at the southern part of the Eurasian continent. This was possibly responsible for increasing pCO2 in the atmosphere-ocean system and making a perturbation in the carbon cycle and finally a reversal of the greenhouse mode in this part of southern Tethyan realm during the Late Valanginian.

Moreover, we detected evidence of the Faraoni Level, which corresponds to a maximum transgressive phase in the Late Hauterivian, and is related to the increased availability of nutrients during the sea-level rise in this part of the southern Tethys.

References


9.1 Introduction

Sr-isotope stratigraphy is used with a reasonable confidence to date the deposits and correlate marine sedimentary rocks. This method is marked by three main principles. It is assumed that: (1) the $^{87}\text{Sr} / ^{86}\text{Sr}$ ratio is always homogenous throughout the oceans, (2) this ratio has varied significantly through time due to the input of Sr from continental crust and mantle sources, and finally (3) this isotopic ratio is precisely recorded by calcium-bearing minerals precipitated from sea water (Burke et al., 1982; Elderfield, 1986; Jenkyns et al., 1995; McArthur et al., 2012). The isotopic composition of sea water is controlled by the relative influx of $^{87}\text{Sr}$ from a continental origin and $^{86}\text{Sr}$ from mid-ocean ridge, and these variables quantified through time with much certainty (McArthur et al., 2001).

The most common deposits used for Sr-isotope stratigraphy are carbonates, provided that diagenetic alteration must be minimal to record the accurate original $^{87}\text{Sr} / ^{86}\text{Sr}$ ratio (Burke et al., 1982; Elderfield, 1986; Mearon et al., 2003).

In Cretaceous time, there are several intervals which have no magnetic reversal and biostratigraphic zones may span several million years. Sr-isotope stratigraphy thus provides a high resolution in dating sediments and for stratigraphic correlations (Bralower et al., 1995; Mearon et al., 2003). This technique is particularly useful in shallow-water carbonates with sparse benthic fauna with limited stratigraphic resolution.

According to the details of the LOWESS version 4 (Howarth and McArthur, 2004), the $^{87}\text{Sr} / ^{86}\text{Sr}$ curve for the Early Cretaceous (especially for the Berriasian up to the Hauterivian) shows a sufficient slope to be useful for dating (Fig. 9.1).

In this study, the Lower Cretaceous shallow-platform deposits from the Zagros FTB have been investigated for the first time for Sr-isotope stratigraphy. The aims of this study are to: (1) obtain a relative age for critical stratigraphic intervals which lack accurate biostratigraphic data, (2) define a numerical age for the top and the base of introduced biozones and also at stratigraphic boundaries, and finally (3) estimate the net deposition rates across the platform.

![Variations of the $^{87}\text{Sr} / ^{86}\text{Sr}$ ratio through time according to the data of LOWESS version 4 (modified from McArthur et al., 2012).](image-url)
9.2 Sample selection

In order to obtain an accurate numerical age based on $^{87}\text{Sr}/^{86}\text{Sr}$ values, selected samples must have four characteristics: (1) absence of contaminant material having $^{87}\text{Sr}/^{86}\text{Sr}$, (2) small amount of $^{87}\text{Rb}$, (3) low diagenetic alteration, and finally (4) no exchange of Sr from other minerals or interstitial waters during burial (Elderfield, 1986; Mearon et al., 2003).

The best samples for Sr-isotope analysis are made of well-preserved biogenic calcite (Ehrenberg et al., 2007). Basically, brachiopod and bivalve shells resist very well to diagenesis and are the most useful materials for Sr-isotope analysis (McArthur et al., 2012).

As the studied shallow-water deposits contain few shells, most of the selected samples are micrite-dominated carbonates. We selected samples with less impurities and lack of diagenetic alteration. We analyzed 13 samples, collected from stratigraphically important intervals from 6 outcrops in the studied area (Fig. 9.2). These samples belong to the Fahliyan, Sar Bisheh, Ghari and Gadvan formations (Berriasian up to Barremian).

![Fig. 9.2: Location map of the selected samples used for Sr-isotope analysis.](image)

9.3 Methods and errors

All samples were cleaned thoroughly to remove any possible detritus and vein-sparite. Then samples were washed with deionized water by using ultrasonic treatment for at least 20 min. After drying, samples were crushed to fine powders with mortar and pestle. Sufficient material (about 50 mg) from the dried sample powders was weighed out.

Sr-isotope measurements were performed at the geochemical laboratory from the University of Geneva (Switzerland), using the TRITON Thermo Finnigan Thermal Ionization Mass Spectrometer (TIMS). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio were measured on Faraday cups in static mode by using a virtual amplifier mode to reduce uncertainty in the amplifier cross-calibration. All $^{87}\text{Sr}/^{86}\text{Sr}$ ratios have been internally corrected for fractionation by normalizing to a standard value of 0.1194 for $^{86}\text{Sr}/^{88}\text{Sr}$. This procedure is used to make corrections for the large isotopic fractionations between $^{84}\text{Sr}$, $^{86}\text{Sr}$, $^{87}\text{Sr}$ and $^{88}\text{Sr}$ that happen during mass-spectrometric measurement, and coincidentally remove natural fractionations. Subsequently, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio was renormalized to the value of the SRM987 standard by a value of 0.710248 for $^{87}\text{Sr}/^{86}\text{Sr}$ by applying a +0.03 ‰ per a.m.u (isotopic mass) correction factor based on more than 100 measurements of the SRM987 standard. This long-term (>100 measurements) external reproducibility (1 σ) of the SRM987 standard is less than 7 ppm. The uncertainty of recorded ages includes the uncertainty of the global Sr sea-water curve, the measurements (1 sigma), tools and any isotopic heterogeneity.
9.4 Results

The reference curve for the $^{87}\text{Sr} / ^{86}\text{Sr}$ ratio was updated based on a new database (LOWESS version 4) according to the GST 2012 (Howarth and McArthur, 2004; McArthur et al., 2012). For the Early Cretaceous, the $^{87}\text{Sr} / ^{86}\text{Sr}$ reference curve shows a sharp rise from the base of the Berriasian toward the top of the Valanginian (Fig. 9.3). It further shows that the Hauterivian and Barremian intervals are poorly defined, as indicated by overlap values in the $^{87}\text{Sr} / ^{86}\text{Sr}$ ratio, and would barely give resolution to the level of these stages.

As it is shown on Fig. 9.4, the $^{87}\text{Sr} / ^{86}\text{Sr}$ ratio declines from the Middle Barremian toward the Late Barremian (from the value of 0.707492 to 0.707427). Therefore, for measurements may be in error or suggesting more than one possible numerical age, the results of the Sr-isotopes should be calibrated by the biostratigraphy. According to the reference curve, the $^{87}\text{Sr} / ^{86}\text{Sr}$ values range from 0.707173 to 0.707492, for the Berriasian to Barremian interval. Moreover, the studied stages are marked by the following values for the $^{87}\text{Sr} / ^{86}\text{Sr}$ (Fig. 9.4):

- Berriasian = 0.707173 – 0.707316, (139.8 – 145.0 Ma)
- Valanginian = 0.707316 – 0.707442, (132.9-139.8 Ma)
- Hauterivian = 0.707442 – 0.707478, (129.4 – 132.9 Ma)
- Barremian = 0.707427 – 0.707492, (125.0 – 129.4 Ma)
The numerical ages of selected samples were identified by plotting the results of measured \(^{87}\text{Sr} / ^{86}\text{Sr}\) values on the LOWESS (LOcally WEighted Scatterplot Smoothing) reference curve proposed by Howarth and McArthur (2004). The results of this work are presented into two separate groups according to the geological regions where these samples were selected: Khuzestan and Fars areas.

9.4.1 Khuzestan region

Eleven samples from five outcrop sections in the Khuzestan region (Fahliyan, Kuzeh Kuh, Mish, Anneh and Lar) were analyzed. The obtained results are presented here.

9.4.1.1 Fahliyan section

Sr-isotope dating was performed on 6 samples from the Fahliyan, Sar Bisheh, Ghari and Gadvan formations in the Fahliyan section (details of the lithostratigraphy and biostratigraphy in chapters 2 and 4). These selected samples belong to the Fahliyan (MANA 150), the Sar Bisheh (MANA 187, 233), the Ghari (MANA 258), and the Gadvan (MANA 278, 301) formations. The obtained results of the \(^{87}\text{Sr} / ^{86}\text{Sr}\) ratios of these samples are presented in Table 9.1, and Fig. 9.5.

<table>
<thead>
<tr>
<th>Outcrop</th>
<th>Sample</th>
<th>Ratio</th>
<th>Error</th>
<th>Ratio+error</th>
<th>Ratio-error</th>
<th>Min.-age</th>
<th>Age (Ave.)</th>
<th>Max.-age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fahliyan</td>
<td>MANA 301</td>
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<td>0.707448</td>
<td>0.707442</td>
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</tr>
<tr>
<td></td>
<td>MANA 278</td>
<td>0.707417</td>
<td>0.000004</td>
<td>0.707421</td>
<td>0.707413</td>
<td>133.87</td>
<td>134.21</td>
<td>134.55</td>
</tr>
<tr>
<td></td>
<td>MANA 258</td>
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<td>0.000003</td>
<td>0.707396</td>
<td>0.707390</td>
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<td>135.58</td>
<td>135.90</td>
</tr>
<tr>
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<td>MANA 233</td>
<td>0.707404</td>
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<td>0.707408</td>
<td>0.707400</td>
<td>134.56</td>
<td>134.94</td>
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</tr>
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<tr>
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<td>MANA 150</td>
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<td>0.707289</td>
<td>0.707281</td>
<td>140.39</td>
<td>140.60</td>
<td>140.80</td>
</tr>
</tbody>
</table>

Table 9.1: Results of the measured \(^{87}\text{Sr} / ^{86}\text{Sr}\) ratios on some samples from the Fahliyan outcrop.

**Fig. 9.5:** Sr-isotope dating of some samples from the Fahliyan outcrop plotted on the LOWESS curve. Green circles show results that are in agreement with the biostratigraphy and pink circles those that are not confirmed by the biostratigraphy (more details in the next sub-section).
9.4.1.2 Kuzeh Kuh section

Two samples were selected from the Kuzeh Kuh outcrop, MAK 4888 and 5034, respectively from the Berriasian (Fahliyan Fm.) and Hauterivian (Ghari Fm.). The values of Sr-isotope measurements are shown here (Table 9.2, Fig. 9.6).

<table>
<thead>
<tr>
<th>Outcrop</th>
<th>Sample</th>
<th>Ratio</th>
<th>Error</th>
<th>Ratio+error</th>
<th>Ratio-error</th>
<th>Min.-age</th>
<th>Age (Ave.)</th>
<th>Max.-age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kuzeh Kuh</td>
<td>MAK 5034</td>
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<td>0.000004</td>
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<td>126.12</td>
</tr>
<tr>
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<td>MAK 4888</td>
<td>0.707220</td>
<td>0.000004</td>
<td>0.707224</td>
<td>0.707216</td>
<td>142.51</td>
<td>142.95</td>
<td>143.38</td>
</tr>
</tbody>
</table>

Table 9.2: Results of the measured $^{87}\text{Sr} / ^{86}\text{Sr}$ ratios on two samples from the Kuzeh Kuh outcrop.

![Sr-isotope dating of two samples from the Kuzeh Kuh outcrop plotted on the LOWESS curve. Green circles show results that are in agreement with the biostratigraphy and pink circle that is not confirmed by the biostratigraphy (more details in the next sub-section).](image)

9.4.1.3 Mish section

Only one sample, AFA 42 was analyzed for Sr content from the Hauterivian interval (Ghari Fm.) in the Mish outcrop section (Table 9.3, Fig. 9.7).

<table>
<thead>
<tr>
<th>Outcrop</th>
<th>Sample</th>
<th>Ratio</th>
<th>Error</th>
<th>Ratio+error</th>
<th>Ratio-error</th>
<th>Min.-age</th>
<th>Age (Ave.)</th>
<th>Max.-age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mish</td>
<td>AFA 42</td>
<td>0.707463</td>
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<td>0.707466</td>
<td>0.707460</td>
<td>126.04</td>
<td>126.15</td>
<td>126.25</td>
</tr>
</tbody>
</table>

Table 9.3: Results of the measured $^{87}\text{Sr} / ^{86}\text{Sr}$ ratios on one sample from the Mish outcrop.
Fig. 9.7: Sr-isotope dating on a sample from the Mish outcrop plotted on the LOWESS curve. It suggests two possible numerical ages: green circle shows result that is in agreement with the biostratigraphy and pink circle that is not confirmed by the biostratigraphy (more details in the next sub-section).

9.4.1.4 Anneh section

One sample (ARP 235) from this outcrop was selected from the Ghari Formation (Hauterivian) for Sr-isotope analysis. The results are presented here (Table 9.4, Fig. 9.8).

Table 9.4: Results of the measured $^{87}$Sr / $^{86}$Sr ratios on one sample from the Anneh outcrop.

<table>
<thead>
<tr>
<th>Outcrop</th>
<th>Sample</th>
<th>Ratio</th>
<th>Error</th>
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<th>Ratio-error</th>
<th>Min.-age</th>
<th>Age (Ave.)</th>
<th>Max.-age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anneh</td>
<td>ARP 235</td>
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<td>0.000004</td>
<td>0.707486</td>
<td>0.707478</td>
<td>127.04</td>
<td>127.00</td>
<td>126.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>128.28</td>
<td>129.10</td>
<td>129.91</td>
</tr>
</tbody>
</table>

Fig. 9.8: Sr-isotope dating of one sample from the Anneh outcrop plotted on the LOWESS curve, suggesting two possible numerical ages: green circle shows result that is in agreement with the biostratigraphy and pink circle that is not confirmed by the biostratigraphy (more details in the next sub-section).

9.4.1.5 Lar section

Sr-isotope analysis was performed on one sample, ARP 960, from the Ghari Formation (Hauterivian) in the Lar outcrop. Results are shown in Table 9.5 and Fig. 9.9.

<table>
<thead>
<tr>
<th>Outcrop</th>
<th>Sample</th>
<th>Ratio</th>
<th>Error</th>
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<th>Ratio-error</th>
<th>Min.-age</th>
<th>Age (Ave.)</th>
<th>Max.-age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anneh</td>
<td>ARP 235</td>
<td>0.707482</td>
<td>0.000004</td>
<td>0.707486</td>
<td>0.707478</td>
<td>127.04</td>
<td>127.00</td>
<td>126.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td>128.28</td>
<td>129.10</td>
<td>129.91</td>
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</tbody>
</table>
Strontium Isotope Stratigraphy

<table>
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<th>Ratio</th>
<th>Error</th>
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<th>Ratio-error</th>
<th>Min.-age</th>
<th>Age (Ave.)</th>
<th>Max.-age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lar</td>
<td>ARP 960</td>
<td>0.707440</td>
<td>0.000004</td>
<td>0.707444</td>
<td>0.707436</td>
<td>125.37</td>
<td>125.42</td>
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<tr>
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<td>132.63</td>
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</table>

Table 9.5: Results of the measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios on one sample from the Lar outcrop.

![Sr-isotope dating of one sample from the Lar outcrop plotted on the LOWESS curve. It suggests two numerical ages: green circle shows result that is in agreement with the biostratigraphy and pink circle that is not confirmed by the biostratigraphy (more details in the next sub-section).](image)

8.4.2 Fars region, Gadvan section

From the Fars area, one outcrop section (Gadvan) was selected for measuring the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. Two samples (AMR 6182, 6208), were analyzed and the obtained results are presented here (Table 9.6, Fig. 9.10).

<table>
<thead>
<tr>
<th>Outcrop</th>
<th>Sample</th>
<th>Ratio</th>
<th>Error</th>
<th>Ratio+error</th>
<th>Ratio-error</th>
<th>Min.-age</th>
<th>Age (Ave.)</th>
<th>Max.-age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gadvan</td>
<td>AMR 6208</td>
<td>0.707417</td>
<td>0.000004</td>
<td>0.707421</td>
<td>0.707413</td>
<td>133.87</td>
<td>134.21</td>
<td>134.55</td>
</tr>
<tr>
<td></td>
<td>AMR 6182</td>
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<td>0.000002</td>
<td>0.707330</td>
<td>0.707326</td>
<td>139.28</td>
<td>139.47</td>
<td>139.65</td>
</tr>
</tbody>
</table>

Table 9.6: Results of the measured $^{87}\text{Sr}/^{86}\text{Sr}$ ratios on two samples from the Gadvan outcrop.

![Sr-isotope dating of two samples from the Gadvan outcrop plotted on the LOWESS curve. Green circle shows that the dating corresponds with the biostratigraphy and pink circle is not confirmed by the biostratigraphy.](image)
9.5 Discussion and interpretation of the $^{87}\text{Sr}/^{86}\text{Sr}$ measurements

9.5.1 Sr-age model

According to the reference curve based on the $^{87}\text{Sr}/^{86}\text{Sr}$ measurements (Howarth and McArthur, 2004; McArthur et al., 2012) during the Early to Middle Cretaceous, one recorded $^{87}\text{Sr}/^{86}\text{Sr}$ value provides more than one possible numerical age (Fig. 9.11). As it is shown, values for the Early Berriasian and Valanginian are equal to values in the Aptian, Albian, Cenomanian and Late Turonian. This problem is also observed for the Early Valanginian and the entire Hauterivian stages for which values correspond also to the Barremian stage. Therefore, the reliability of the chronostratigraphic data provided by the Sr-isotopes should be checked by the biostratigraphic results.

Fig. 9.11: Reference curve of the LOWESS version 4, and possible numerical ages for equal values of the $^{87}\text{Sr}/^{86}\text{Sr}$ during the Early-Middle Cretaceous (modified from Howarth and McArthur, 2004; McArthur et al., 2012).

9.5.2 Calibrating of the biostratigraphy and Sr-isotope dating

The biostratigraphic data used for calibrating Sr measurements are based on the biozones defined in this study (see chapter 4). These biozonation patterns are based on diagnostic benthic foraminifera and/or dasycladalean algae from shallow-water deposits and also on tintinnids from deeper deposits.

Most of the recorded $^{87}\text{Sr}/^{86}\text{Sr}$ values and suggested numerical ages are confirmed by the biostratigraphic results. The summary results of all studied outcrops are presented in Table 9.7 and Fig. 9.12.

9.5.2.1 Fahliyan section

In this section, one sample (MANA 150) was selected near to the top of the Berriasian interval (Fahliyan Fm.). The $^{87}\text{Sr}/^{86}\text{Sr}$ value of 0.707285 suggests an age of 140.6 Ma. This age is confirmed by the micropaleontological data (Fig. 9.12), based on the defined biozones such as: benthic foraminifera (Protopeneroplis ultragranulata - Mohlerina basilensis assemblage zone), dasycladalean algae (Salpingopolrella circassia, Zergabriella embergeri - Clypeina dragastani interval zone) and tintinnids (Calpionellopsis simplex/oblonga zone). As this sample was collected 30 m below the Berriasian-Valanginian boundary, this suggested age (140.6 Ma) is acceptable by comparison with the age assignment based on the standard time scale (GST 2012) which is around 139.8 Ma for this boundary.

Two samples selected from the Valanginian interval, MANA 187 from the base and MANA 233 very close to the top of this interval (see Appendix 2 for sample location). The $^{87}\text{Sr}/^{86}\text{Sr}$ measurements are 0.707310 and 0.707404, suggesting ages of 139.75 and 134.94 Ma respectively, indicating a Valanginian age according to
the standard time scale (GST 2012). This suggested age is supported by the biostratigraphic data, such as the biozones of: benthic foraminifera (*Paravalvulina arabica* / *Valdanchella miliani* - *Trocholina campanella* / *T. delphinensis* interval zone), dasycladalean algae (*Actinoporella jaffrezoi* - *Salpingoporella katzeri* interval zone), and tintinnids (*Calpionellites darderi* interval). This numerical age supports the range of *Actinoporella jaffrezoi* taxon-range zone as a marker for the Early Valanginian in this area.

<table>
<thead>
<tr>
<th>Outcrop</th>
<th>Sample</th>
<th>Ratio</th>
<th>Age (Ave.)</th>
<th>Suggested age (LOWESS)</th>
<th>Confirmed age (Biostratigraphy)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fahliyan</td>
<td>MANA 301</td>
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<td>125.57</td>
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<td>Barremian</td>
</tr>
<tr>
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<td>MANA 278</td>
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<td>Aptian</td>
<td>Valanginian</td>
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<tr>
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<tr>
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<td>Valanginian</td>
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<td>Hauterivian</td>
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<td>0.707417</td>
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<td>Valanginian</td>
<td>Hauterivian</td>
</tr>
<tr>
<td></td>
<td>AMR 6182</td>
<td>0.707328</td>
<td>139.47</td>
<td>Valanginian</td>
<td>Valanginian</td>
</tr>
</tbody>
</table>

**Note:** Table 9.7: Summary data of the recorded $^{87}$Sr / $^{86}$Sr values accompanied with the suggested numerical age, comparing with the biostratigraphic results performed on all studied outcrops.

Based on the data of the International Chronostratigraphic Chart (GTS 2012), the top of the Valanginian interval has an age of 132.9 Ma. By contrast, Sr-isotope measurements in the Fahliyan outcrop suggest an age of 134.94 Ma for the top of the Valanginian interval which corresponds to the top of the Sar Bisheh Formation in this area. Therefore, a stratigraphic hiatus of ~ 2 Ma is present at the top of the Valanginian interval in this outcrop. This significant gap is also confirmed by biostratigraphical data, where *Actinoporella jaffrezoi* taxon-range zone, a marker for the Early Valanginian age (Fig. 9.12) is present very close to the top of the Valanginian interval in this section (see appendix 2 for distribution range of fossils).
One sample (MANA 258) from the Hauterivian interval was analyzed for Sr. It records a value of 0.707393, suggesting two possible numerical ages, 135.58 Ma (Valanginian) and 124.65 Ma (Aptian). None of these suggested ages is confirmed by the biostratigraphy and this result is ignored in regional interpretations.

Two samples (MANA 278 and 301) were analyzed for Sr-isotope from the Barremian interval. The first sample (MANA 278) was selected from the lower part of the Gadvan Formation, close to the basal contact. The $^{87}$Sr / $^{86}$Sr value of this sample is 0.707417, provides two numerical ages, 134.21 Ma (Valanginian) and 124.65 (Aptian). Again, none of these numerical ages is confirmed by the biostratigraphy.

Another sample, MANA 301, the Sr analysis of which was performed on a bivalve shell, was selected from the upper part of the Gadvan Formation (above the Khalij Member). The $^{87}$Sr / $^{86}$Sr measurement is thus very reliable. It records a value of 0.707445, suggesting ages of 132.72 Ma (Hauterivian) and 125.57 Ma (Latest Barremian). According to the biostratigraphical data, the Hauterivian age (132.72 Ma) can be rejected without any doubt. By contrast, the other suggested age (125.57 Ma, Latest Barremian) is definitely confirmed by biostratigraphy. The sample was selected from above the Khalij Member, and as this clean carbonate lithology contains many orbitolinids, characterized by the co-occurrence of *Eoparalbitolina transiens* - *Palorbitolina lenticularis*, the Late Barremian age can be confirmed (Fig. 9.12).

### 9.5.2.2 Kuzeh Kuh section

Two samples were analyzed for Sr-isotope in this section. Sample MAK 4888 was selected from the basal part of the Fahlivan Formation (very close to the Jurassic/Cretaceous boundary). The measured value in the $^{87}$Sr / $^{86}$Sr is 0.707220, suggesting an age of 142.95 Ma. This age is confirmed by the biostratigraphic data, which is marked by defined biozones such as: benthic foraminifera (*Protopeneroplis ultragranulata - Mohlerina basiliensis* assemblage zone) and dasycladalean algae (*Salpingopolrella circassa, Zergabriella embergeri - Clypeina dragastani* interval zone) (Fig. 9.12).

According to the standard geological time scale (GTS 2012), the base of the Berriasian is characterized by an age of ~ 145 Ma. By contrast, this boundary is marked by an age of ~ 143 Ma in the Kuzeh Kuh section. Therefore, it reveals that in the Khuzestan area, there is a significant stratigraphic gap between the Jurassic and the Cretaceous, representing non-deposition conditions. This duration of stratigraphic gap is estimated at around 2 Ma. It is worth mentioning that in the Khuzestan and Fars areas, this stratigraphic gap had not been detected by the biostratigraphical data, because the stratigraphic range of the taxa cannot separate Early, Middle and Late Berriasian intervals. But toward the east in the Bandar Abbas Hinterland, the duration of this stratigraphic gap increases. The Early and early Middle Berriasian are missing, which has identified by tintinnids (details in chapter 4 and Appendix 2).

Another sample, MAK 5034, selected from the Hauterivian interval (Ghari Fm.), yielded a value of 0.707460 for the $^{87}$Sr / $^{86}$Sr ratio, suggesting two numerical ages, 131.62 Ma (Hauterivian) and 126.05 Ma (Late Barremian). Based on the fossil content of this interval and also on regional correlations in terms of sequence stratigraphy, the Late Barremian age is not confirmed for this interval, indicating that the Ghari Formation belongs to the Hauterivian.

### 9.5.2.3 Mish, Anneh and Lar sections

From each of these sections, one sample was selected from the Ghari Formation for Sr-isotope analysis. The analyzed samples (AFA 42, ARP 235 and ARP 960) gave values of 0.707463, 0.707482 and 0.707440, for the Mish, Anneh and Lar outcrops respectively. These recorded values provide two numerical ages: Hauterivian and Late Barremian. According to the biostratigraphic data and also sequence interpretation, the Late Barremian age cannot be confirmed without any dispute. Therefore, the Hauterivian age is suggested for the Ghari Formation which is in accordance with the micropaleontological data of benthic foraminifera and dasycladalean algae (see appendix 2, distribution range charts of Mish, Anneh and Lar sections).

### 9.5.2.4 Gadvan section

From the Fars area, two samples from the Gadvan outcrop were analyzed for Sr-isotopes. One sample (AMR 6182) collected from the upper part of the Valanginian interval of the Sar Bisheh Formation, gave one value of 0.707328, suggesting a numerical age of ~139 Ma, indicating an Early Valanginian age. This age is confirmed by the biostratigraphy data, both by benthic foraminifera and dasycladalean algae (Fig. 9.12).
As this sample was gathered close to the top of the Valanginian interval (close to top of the Sar Bishe Formation), it reveals that, in the Fars area, there is a large stratigraphic gap at the top of the Valanginian, where the entire Late Valanginian is missing (a hiatus of ~ 3 Ma). This stratigraphic gap is also confirmed by the biostratigraphic data, because the Actinoporella jaffrezoi total range zone, a marker for the Early Valanginian continues upward to top of the Valanginian interval (see Appendix 2, distribution fossil range chart of the Gadvan section). Therefore, this regional stratigraphic gap at top of the Valanginian interval increases from the west toward the east, and the largest missing time occurs in the Fars area.

One sample (AMR 6208) selected from the Ghari Formation (Hauterivian interval), gave a value of 0.707417, suggesting a numerical age of 134.21 Ma, indicating a Valanginian age. This age is in accordance neither with the micropaleontological data of benthic foraminifera and dasycladalean algae nor with the sequence interpretation in regional transects.

### Fig. 9.12: Comparison between the age determinations of the studied stratigraphic intervals based on the biostratigraphic data and Sr-isotope results. Values in the 87Sr / 86Sr and proposed numerical ages represented in red colors are not confirmed by biostratigraphic data. Lithostratigraphy nomenclature and biozones are based on this study.

#### 9.5.3 Depositional rates and estimation of stratigraphic levels

By combining the Sr-isotope data and biostratigraphic results, the position of stage boundaries are well documented in the studied shallow-platform carbonates. The results of this combined analysis are reflected in reconstructing regional patterns on all litho- biostratigraphic as well as sequence stratigraphic data.

The Sr ages allow to calculating the depositional rates in the Khuzestan and Fars areas. The role of basement subsidence or additional effects of eustatic rises in sea-level and/or local tectonic loading on the sediment thickness was discussed in chapter 3. Here, we calculate the rate of sediment accumulation for the Berriasian and Valanginian intervals to make a link between the stratigraphic gaps detected by biostratigraphy and the results of Sr-isotope dating.

#### 9.5.3.1 Berriasian

In order to evaluate the deposition rate for the Berriasian interval, we used the Sr-isotope data from the Kuzeh Kuh outcrop (for the base of the Berriasian) and the Fahllyan outcrop (for top of the Berriasian interval). The mean value in the sediment thickness in Lar, Mish, Anneh, Fahllyan and Kuzeh Kuh outcrops (these sections are very close to each other) is about 200 m (see appendices 1 and 2 for stratigraphical columns). Based on the obtained Sr-isotope data (a duration of around 3 Ma for the Berriasian), a rate of 0.067 mm/yr or 67 m/Ma is estimated for the Berriasian interval in the Khuzestan area. This rate of accumulation is in accordance with typical values for the Cretaceous carbonate platforms (Schlager, 1981, 1999).
As the sediment thickness increases from the Kuzeh Kuh toward the Lar to the west, it appears that the base of the Berriasian should be positioned at around 144 Ma in the Lar, Mish and Anneh sections, implying that the sedimentary gap decreases from the east toward the west in this part of the Zagros FTB (Fig. 9.13).

Concerning the Fars area, and assuming a consistent sedimentary rate and considering the thickness of the Berriasian sediments in the Gadvan section (138 m), the base of the Berriasian will be positioned at around 142 Ma., proving that the sedimentary gap increases toward the east (Fars area) (Fig. 9.13).

![Fig. 9.13: Sr-isotope dating of the Berriasian sediments throughout some outcrops in the studied area. Definite (numerical) and relative (estimated) ages are shown and the estimated amount of the stratigraphic gap at the base of the Berriasian represented by vertical hatches. The abbreviations are: Ber.: Berriasian, Val.: Valanginian, Hau.: Hauterivian, Bar.: Barremian.](image)

### 9.5.3.2 Valanginian

The best example for calculating the rate of sediment accumulation with a high resolution is given in the Fahliyan section in the Khuzestan area, where the Valanginian interval is marked by the Sr-isotope data at the base (MANA 187) and close to the top of the interval (MANA 233). Based on these data (about 93 m thickness for a duration of about 5 Ma), a rate of 18.6 mm/yr or 18.6 m/Ma is suggested for sediment accumulation.

As we detected a regional stratigraphic gap at top of the Valanginian interval across the platform (according to biostratigraphy and Sr-isotope data), the thickness variations toward the west in the Lar and Anneh sections suggest that the amount of this stratigraphic gap decreases westward in the Khuzestan area. This suggestion is supported by the biostratigraphical data, where the LO of the index marker of the Early Valanginian (*Actinoporella jaffrezoi* taxon-range zone) occurs in the middle part of the Valanginian interval in these outcrops (see appendix 2, fossil distribution range charts of Lar, Mish and Anneh sections). By contrast, in the Fars area, a reliable Sr-isotope age was recorded in the Gadvan section, indicating that the stratigraphic gap increases in this area and that the entire Late Valanginian is missing, which is also confirmed by the biostratigraphy (Fig. 9.14).
Strontium Isotope Stratigraphy

9.6 Conclusions

This study shows that Sr-isotope dating is possible within the shallow-platform deposits (Fahliyan, Sar Bisheh, Ghari and Gadvan formations) in the Zagros FTB. It reveals that Sr-isotope stratigraphy offers a comparable resolution to that achieved by the biostratigraphical methods, and a combination of these two methodologies enables to separate stratigraphic levels with a higher resolution and also to estimate the depositional rates.

According to the obtained data, the base of the Cretaceous (Berriasian) has an age of ~144 Ma in the western part of the Khuzestan area (Lar, Mish and Anneh), but towards the east, this level becomes younger (~143 Ma in Fahliyan and Kuzeh Kuh), and finally toward the Fars area, it becomes even younger (~141.5 Ma). Thus, there is a regional stratigraphic gap at the base of the Berriasian in the shallow-platform setting of the Zagros FTB. The amount of missing time increases from west to east, and the largest amount is recorded in the Bandar Abbas Hinterland, which is confirmed by the biostratigraphic data (tintinnids), showing that the Early to early Middle Berriasian is missing.

The Sr-isotope data confirm the presence of another regional discontinuity at top of the Valanginian that was also detected by the biostratigraphy. It reveals that the amount of this stratigraphic gap increases from the west (Khuzestan) towards the east (Fars), where most parts of the Late Valanginian is missing in the Fars area (such as: Kalagh, Surmeh and Khartang), which is confirmed by the micropaleontological data. Moreover, Sr-isotope dating supports the range of Actinoporella jaffrezoi taxon-range zone as a marker for the Early Valanginian in this area.

This study also provides a precise dating for the Ghari Formation (former Upper Fahliyan Formation sensu Wynd, 1965), also confirmed by the biostratigraphy, indicating an Hauterivian age, which is not in accordance with previous statements (Wynd, 1965). This Sr-isotope dating also confirms that the Gadvan Formation does not reach the Aptian age in the Zagros FTB, which is confirmed by the biostratigraphy.
References


Conclusions and Future Perspectives

10.1 Conclusions

In this study, the stratigraphic framework of the Berriasian - Barremian interval from the Zagros FTB is revised by using several approaches. They led to produce a higher resolution scheme based on an integrated stratigraphy (lithostratigraphy, biostratigraphy, sequence stratigraphy and isotope stratigraphy) of shallow-platform deposits. This work contains new information such as: a time-rock synopsis based on the re-defined and/or established new lithostratigraphic units, a new regional biostratigraphical pattern, regional correlations with a new sequence stratigraphic framework, identification of global climate changes, calibration between biostratigraphy and Sr-isotopic dating, and finally outcrop gamma-ray spectrometry.

According to regional facies variation and the recognition of relatively elevated structures (paleo-highs), we propose some locations as possible prospects for exploration of stratigraphic traps. The studied area covers the eastern part of Khuzestan, entire Fars, Bandar Abbas Hinterland and offshore area. The most important results of this study can be summarized as follows:

10.1.1 Lithostratigraphic subdivisions

A revision of the Lower Cretaceous lithostratigraphy of the studied shallow-platform succession led to describe three new formations. We consider that the well-bedded upper part of the former Lower Fahliyan Formation (sensu Wynd 1965) does not resemble to the lower part neither by the lithological composition nor by the physical properties and bedding patterns. Moreover, the former Upper Fahliyan (sensu Wynd 1965) is bounded by two significant hardgrounds. The lower contact corresponds with a regional stratigraphic gap and the upper boundary shows at least a short pause in sedimentation (diastem). Therefore, according to the regulations of the International Commission on Stratigraphy (chapter 3, part B and chapter 5, part D: Murphy and Salvador, 1999), we proposed:

i) The Fahliyan Formation (re-defined), includes grey to brown color, thick to massive-bedded, oolitic to peloidal limestones. A prominent erosional hiatus exists between the Fahliyan Formation and the underlying Upper Jurassic Hith Formation (brown brecciated dolomite). The top of the Fahliyan Formation coincides with an abrupt break in sedimentation from very shallow-water carbonates below to rubbly limestones with intercalations of marl above (Sar Bisheh Formation).

ii) The Sar Bisheh Formation has a thickness of 73 m (at the type section). It consists of very well bedded (thin to thick), dark gray argillaceous limestone and gray nodular limestones with some intercalations of green marl, denoting a global sea-level rise and recording an increase of clay supply and siliciclastic input. The lower boundary of this unit coincides with top of the first large-scale (second-order) sequence of the underlying Fahliyan Formation and the upper boundary corresponds to the post-Valanginian unconformity.

iii) The Ghari Formation is 43 m thick at the type section. It is characterized by an alternation of carbonate beds and marly intervals. Bedding pattern of limestone intervals varies from thin to thick. This unit corresponds to a period of significant clay supply and siliciclastic input from the southeast and is marked by high values of Th and K recorded by the natural gamma ray logs. The lower boundary of this formation corresponds to the pre-Hauterivian unconformity and the upper boundary corresponds to the top of the former Fahliyan Formation (sensu James and Wynd, 1965), marked by a very well-developed hardground surface with abundant iron nodules, indicating a short break in sedimentation (diastem).

iv) The Chahoo Formation has a thickness of 135 m in its type section, very well-bedded, bedding pattern of which varies from thin to thick, including limestones of cream to light gray color. Both the lower and upper contacts of this new lithostratigraphic unit are unconformable: the Upper Valanginian and all of the Hauterivian are missing on top of the underlying Fahliyan Formation and on top of the Chahoo Formation, the Kazhdumi Formation is believed to be Albian in age, indicating a hiatus corresponding...
to the Late Aptian. This formation has been defined based on lateral changes in the lithologic composition (example for the Ghari, Gadvan and Dariyan formations), where these units are merged.

10.1.2 Biostratigraphical schemes and time-control

We revised the old biozonation of Wynd (1965) and proposed a new pattern including 12 biozones for the Berriasian - Barremian interval. The suggested pattern is based on stratigraphically important taxa of benthic foraminifera, dasycladalean algae and tintinnids, allowing to separate the studied stages (Berriasian, Valanginian, Hauterivian and Barremian). This dating was calibrated with the Sr-isotope analysis performed on bivalve shells and bulk-rocks carbonates from critical intervals at several localities throughout the studied area.

According to biostratigraphic and Sr-isotope data, two regional stratigraphic gaps are reported: an important time gap (non-deposition conditions/ exposure) exists at the base of the Berriasian across the platform, and a regional exposure and erosion (2-5 Ma missing) was detected at top of the Valanginian. Time equivalents of this stratigraphic gap are found in several localities on the Arabian Plate.

10.1.3 Depositional models and platform configuration

Sedimentary systems are represented by inner to mid-platform settings during the Berriasian and Valanginian, except for the Bandar Abbas Hinterland and offshore area which are covered by basinal deposits containing tintinnids and radiolarians. The system is marked by a mid-platform to slope depositional environment with temporary basinal seaways during the Hauterivian and Barremian. This time coincides with significant siliciclastic input from the west.

Four evolutionary stages were observed in the platform growth: rimmed platform (Early - Middle Berriasian), isolated rimmed platform (Middle Berriasian - earliest Valanginian), non-rimmed open platform to ramp (Valanginian), and finally a mixed siliciclastic-carbonate platform to ramp (Hauterivian - Barremian).

Detailed paleofacies maps led to distinguish the role of tectonic and eustasy on sedimentation patterns, to interpret relative rates of subsidence, and finally to recognize possible paleo-highs with low subsidence and condensed sections. Such paleo-highs are suggested in several locations in the Fars area, such as: Kalagh, Surmeh, Khartang, Khormuj and Assaluyeh during the Late Valanginian and Hauterivian.

10.1.4 Regional sequence stratigraphy

We proposed five large-scale sequences (? 2nd-order) in the studied area for the Berriasian - Early Aptian interval. These sequences are well dated, respectively Berriasian - earliest Valanginian, Valanginian, Hauterivian, Early - Late Barremian and finally latest Barremian - Early Aptian.

This sequence framework compares well with the models proposed for the Arabian Plate (Sharland et al., 2004; Haq and Al Qahtani, 2005; Simmons et al., 2007), representing a good match in number, position and relative age of flooding surfaces (K20, K30, K40, K50 and K60) which are:

- K60 (latest Barremian, ~126 Ma)
- K50 (Early Barremian, ~128 Ma)
- K40 (Late Hauterivian, ~131 Ma)
- K30 (Early Valanginian, ~138 Ma)
- K20 (Late Berriasian, ~142 Ma)

Moreover, we identified seventeen small-scale sequences (? 3rd-order) used for establishing regional correlations and finding geometries that can be interpreted as lowstand systems tract.

10.1.5 Outcrop gamma-ray spectrometry

A portable gamma-ray spectrometer was used as a tool for quantitative measurements of uranium (U), thorium (Th) and potassium (K) in sediments. It is now concluded that:

i) Th and K values are associated with the siliciclastic fraction and clay content.
Conclusions and Future Perspectives

ii) U peaks do not necessarily correspond to pulses of siliciclastics or clays and cannot be used as a proxy for organic matter in shallow-platform carbonates.

iii) The U content does not follow the lithology; there is no significant correlation between U values and Th and K contents.

iv) The total gamma-ray values show an excellent match with the U content, and other contributions (Th, K) show lower correlation indices.

v) High values in total gamma-ray correspond either with maximum flooding surfaces or sequence boundaries.

10.1.6 Chemostratigraphy ($\delta^{13}$C, $\delta^{18}$O)

Carbon and oxygen stable isotope ($\delta^{13}$C, $\delta^{18}$O) analyses were applied to evaluate temporal changes in the carbon cycle and paleo-environmental conditions during the Valanginian. We detected a distinct positive carbon isotope excursion (>2.03 ‰) at the Early - Late Valanginian boundary, interpreted as the Weissert Event which is reported for the first time from a neritic setting on the Arabian Plate.

According to the $\delta^{18}$O records and considering the biotic crisis that occurred in the interval assigned to the Weissert Event, this event was probably accompanied by an anoxic condition in this area.

Beside the classical scenario for the origin of the Valanginian Weissert Event (magmatic activity of the Paraná-Etendeka Large Igneous Province), we also proposed an alternative local mechanism for this event in this area. It is suggested that this change in the carbon cycle is probably linked to volcanism or weathering of andesitic rocks from the Uromieh-Dokhtar Magmatic Arc zone at the southern part of the Eurasian continent. This was possibly responsible for an increasing $pCO_2$ in the atmosphere-ocean system, a perturbation in the carbon cycle and finally a reversal of the greenhouse mode in this part of southern Tethyan realm during the Late Valanginian.

Moreover, we detected evidence of the Faraoni Level, corresponding to the maximum transgressive phase in the Late Hauterivian, which is related to the increased availability of nutrients during the sea-level rise in this part of the southern Tethys.

10.1.7 Sr-isotope dating

This study reveals that Sr-isotope dating offers a comparable resolution to that achieved by the biostratigraphical methods performed on the shallow-platform deposits (Fahliyan, Sar Bisheh, Ghari and Gadvan formations) in the Zagros FTB.

This study shows that there are two stratigraphic gaps in the studied interval: one at the base of the Cretaceous (Berriasian) which becomes younger from the west (Khuzestan) towards the east (Fars and Bandar Abbas). Another hiatus is present at top of the Valanginian interval which becomes older from the west towards the east.

This study also provides a precise age for the Ghari Formation (former Upper Fahliyan Formation sensu Wynd, 1965), also confirmed by the biostratigraphy, indicating an Hauterivian age, which is not in accordance with previous statements.

10.1.8 Potential stratigraphic traps

A detailed sequence stratigraphic analysis which was constructed by facies interpretation and biostratigraphic results provided a good understanding of the geological setting of the studied shallow-platform deposits. This study lets us to interpret facies variations and recognize some relatively high structures with onlap and pinch-out geometries onto the flanks of these structures during the subsequent flooding. Such paleo-highs are recognized in the Fars area: Kalagh, Surmeh, Assaluyeh, Khurmoj and Khartang (Fig. 10.1), which were in the non-deposition/erosion conditions during the Late Valanginian and Hauterivian.

In the Zagros FTB, the thick to massive carbonates of the Fahliyan Formation are one of the major oil-producing reservoirs in the Khuzestan and Fras areas. On the other hand, marl-dominated deposits of the Gadvan Formation are the most effective source rock in the Zagros FTB, where the total organic carbon

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**Chapter 10**

**Post-depositional erosion / exposure**

**Depositional regime**

- Gradational facies change from shale / marl to pure limestone (such as: Lower Gadvan Fm.)
- Lateral facies change from oolitic limestone to argillaceous marly limestone (such as: Fahliyan Fm.)
- Lateral facies change from oolitic limestone to argillaceous marly limestone on both flanks of the platform (such as: Fahliyan Fm.)

**Erosional and depositional regime**

- Onlap pinch-out onto erosional surface and flanks of a relative high structure

**Fig. 10.1:** High-resolution stratigraphy imaging of the studied stratigraphic intervals and the suggested stratigraphic traps with trapping mechanisms for the studies shallow-platform deposits of the Zagros FTB. Suggested intervals which are capable for stratigraphic traps are shown by red and blue circles.
(TOC) ranges between 0.42-4.33 %, with always type Π kerogen (Bordenave and Huc, 1995; Rabbani and Bagheri Tirtashi, 2010).

As the Gadvan Formation shows a strong lateral facies change from marl-dominated deposits at the west (Khuzestan) to the pure carbonates at the east (Bandar Abbas Hinterland), this facies variation makes a capacity for establishing stratigraphic traps.

According to the high-resolution imaging of the stratigraphy in this work, we propose two types of stratigraphic traps in the studied area (Fig. 10.1) that are all distributed in the Fars area. The approximate locations of these traps which can be assumed as prospects for exploration are shown here (Fig. 10.2). The suggested stratigraphic traps are separated based on the controlling mechanisms, as: (1) the lateral facies change is controlled by the depositional regime, and (2) the onlap pinch-out onto erosional surface and flanks of a relative high area (structure) is controlled by a mixed erosional and depositional regime. Therefore, in terms of hydrocarbon migration / entrapment, post-depositional erosion / exposure events may provide exploration targets if (1) the sedimentary record is porous and/or, (2) they match syn-sedimentary growth.

**Fig. 10.2:** Location map of the studied area and the suggested locations of possible prospects (stratigraphic traps) for exploration. Abbreviations: HZTF: High Zagros Thrust Fault, KZF: Kazerun Fault, ZMFF: Zagros Mountain Front Fault, NZF: Nezamabad Fault, RZF: Razak Fault, HDF: Hendurabi Fault, BSF: Bastak Fault (Basement faults map from Bahroudi and Talbot, 2003, with modification).

**10.2 Future perspectives**

The important future works proposed are:

*Regional stratigraphic architecture*

This work provided basic information in terms of biostratigraphy and time control, accompanied with facies interpretation and sequence stratigraphy in the Fahliyan platform. By adding more control points, biostratigraphic zones, paleofacies and isopach maps will be improved and the location of the suggested prospects as possible stratigraphic traps will be more precisely defined.

In addition, in terms of regional implications, using 3D seismic data and correlating with regional transects on outcrops will provide more details for interpreting geometries and relative high structures.

*Triggers for the Valanginian isotope excursion*
This study was the first step for understanding the nature of the Valanginian Weissert Event in this part of the Tethyan realm. In order to evaluate the main triggers for this event and understand the role of marine or terrestrial causes, further investigations are needed on the platform deposits in this area.

Moreover, in the Zagros FTB, the time equivalent of the shallow platform deposits is the basinal black shales with pelagic facies (Garau Fm.) in the Lurestan Basin. It is suggested to use other methodologies to estimate the source of carbon in the ocean and assess paleoenvironmental and climate change analysis. These methodologies are: total phosphorus analysis and redox-sensitive trace elements accompanied by detailed organic matter analysis and stable isotopes (carbon and oxygen). These will provide more information for a better assessment of the Lower Cretaceous episodes of anoxic conditions, such as: the Weissert event (Early-Late Valanginian boundary), the Faraoni level (Late Hauterivian) and the Selli level (Early Aptian) in this part of the Tethyan realm.

References


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### Lithology and Bedding

- **Genow (Tang-e Asboo)**
- **LET P**
- **Suru well -1**
- **Nargesi well -8**
- **ARP Anneh**

### Depth and Lithology

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### Appendix 1

#### Datum

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<td></td>
</tr>
<tr>
<td><strong>LET P</strong></td>
<td>0 50 100 150 200 250 300 350 400 450</td>
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<tr>
<td><strong>4950</strong></td>
<td>4960 4970 4980 4990 5000 5010 5020 5030 5040 5050</td>
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#### Thickness (m.)

<table>
<thead>
<tr>
<th><strong>Sample No.</strong></th>
<th><strong>Genow (Tang-e Chahoo)</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>E: 56°12'40.49&quot;, N: 27°24'21.48&quot;</strong></td>
<td>0 50 100 150 200 250 300 350 400 450</td>
</tr>
<tr>
<td><strong>1670</strong></td>
<td>1680 1690 1700 1710 1720 1730 1740 1750 1760 1770</td>
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<tr>
<td><strong>Qeshm well-1</strong></td>
<td>0 50 100 150 200 250 300 350 400 450</td>
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<tr>
<td><strong>E: 56°2'25.20&quot;, N: 27°9'50.77&quot;</strong></td>
<td>0 50 100 150 200 250 300 350 400 450</td>
</tr>
<tr>
<td><strong>103</strong></td>
<td>104 105 106 107 108 109 110 111 112 113</td>
</tr>
<tr>
<td><strong>Suru well-1</strong></td>
<td>0 50 100 150 200 250 300 350 400 450</td>
</tr>
<tr>
<td><strong>E: 56°13'59.65&quot;, N: 27°23'56.80&quot;</strong></td>
<td>0 50 100 150 200 250 300 350 400 450</td>
</tr>
<tr>
<td><strong>195</strong></td>
<td>196 197 198 199 200 201 202 203 204 205</td>
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#### Lithology

Fahliyan Gadvan Khalij Mbr. Rock unit Surmeh / Hith Gadvan Dariyan Valanginian Time unit Late Jurassic Barremian Hauterivian Aptian Barriasian

#### Gamma Data

<table>
<thead>
<tr>
<th><strong>Sample No.</strong></th>
<th><strong>Total GR (nGy/h)</strong></th>
<th><strong>0 100</strong></th>
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<tbody>
<tr>
<td><strong>Laterite</strong></td>
<td><strong>0 100</strong></td>
<td><strong>10 -10</strong></td>
</tr>
<tr>
<td><strong>MRN</strong></td>
<td><strong>Graphic Log (Lithology &amp; Bedding)</strong></td>
<td><strong>0 100</strong></td>
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<tr>
<td><strong>0 20</strong></td>
<td><strong>-2 2</strong></td>
<td><strong>10 -10</strong></td>
</tr>
<tr>
<td><strong>10 -10</strong></td>
<td><strong>765 780 800 820 840</strong></td>
<td><strong>10 -10</strong></td>
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</tbody>
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#### Schlumberger logs

<table>
<thead>
<tr>
<th><strong>Depth (m.)</strong></th>
<th><strong>Lithology</strong></th>
<th><strong>Sonic</strong></th>
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</thead>
<tbody>
<tr>
<td><strong>Qeshm well-4</strong></td>
<td><strong>Sonic</strong></td>
<td><strong>40140</strong></td>
</tr>
<tr>
<td><strong>40140</strong></td>
<td><strong>Gamma ray</strong></td>
<td><strong>0 100</strong></td>
</tr>
<tr>
<td><strong>Schlumberger logs</strong></td>
<td><strong>Depth (m.)</strong></td>
<td><strong>Lithology</strong></td>
</tr>
<tr>
<td><strong>E: 55°34'57.79&quot;, N: 26°40'5.59&quot;</strong></td>
<td><strong>E: 56°13'59.65&quot;, N: 27°23'56.80&quot;</strong></td>
<td></td>
</tr>
<tr>
<td><strong>3300 3350 3400 3450 3500 3550 3600</strong></td>
<td><strong>Genow</strong></td>
<td><strong>Gadvan Kharis</strong></td>
</tr>
</tbody>
</table>

#### Schlumberger logs

<table>
<thead>
<tr>
<th><strong>Depth (m.)</strong></th>
<th><strong>Lithology</strong></th>
<th><strong>Sonic</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Qeshm well-4</strong></td>
<td><strong>Sonic</strong></td>
<td><strong>40140</strong></td>
</tr>
<tr>
<td><strong>40140</strong></td>
<td><strong>Gamma ray</strong></td>
<td><strong>0 100</strong></td>
</tr>
<tr>
<td><strong>Schlumberger logs</strong></td>
<td><strong>Depth (m.)</strong></td>
<td><strong>Lithology</strong></td>
</tr>
<tr>
<td><strong>E: 55°34'57.79&quot;, N: 26°40'5.59&quot;</strong></td>
<td><strong>E: 56°13'59.65&quot;, N: 27°23'56.80&quot;</strong></td>
<td></td>
</tr>
<tr>
<td><strong>3300 3350 3400 3450 3500 3550 3600</strong></td>
<td><strong>Genow</strong></td>
<td><strong>Gadvan Kharis</strong></td>
</tr>
</tbody>
</table>
### Appendix 2 - Fossil distribution range charts

<table>
<thead>
<tr>
<th>Depth (m.)</th>
<th>Dasyridales</th>
<th>Benthic foraminifera</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>2400</td>
<td>S. annulata</td>
<td>C. palasiensis</td>
<td></td>
</tr>
<tr>
<td>2450</td>
<td>S. steihauseri</td>
<td>K. jurassica</td>
<td></td>
</tr>
<tr>
<td>2500</td>
<td>S. pygmaea</td>
<td>Ps. lituus</td>
<td></td>
</tr>
<tr>
<td>2550</td>
<td>I. inopinata</td>
<td>Ch. decipiens</td>
<td></td>
</tr>
<tr>
<td>2600</td>
<td>S. circassa</td>
<td>P. lenticularis</td>
<td></td>
</tr>
<tr>
<td>2650</td>
<td>S. piriniae</td>
<td>echinoids</td>
<td></td>
</tr>
<tr>
<td>2700</td>
<td>S. hispanica</td>
<td>sponge spicules</td>
<td></td>
</tr>
<tr>
<td>2750</td>
<td>A. podolica</td>
<td>S. katzeri</td>
<td></td>
</tr>
<tr>
<td>2800</td>
<td>A. jaffrezoi</td>
<td>C. alpinus</td>
<td></td>
</tr>
<tr>
<td>2850</td>
<td>L. annulata</td>
<td>P. reticulata</td>
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</tr>
<tr>
<td>2900</td>
<td>B. formosa</td>
<td>Ch. algae</td>
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</tr>
<tr>
<td>2950</td>
<td>B. foraminifer</td>
<td>B. cereiforme</td>
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</tbody>
</table>

#### Schlumberger logs

<table>
<thead>
<tr>
<th>Time unit</th>
<th>Rock unit</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jurassic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liasian</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carboniferous</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Permian</td>
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</table>

#### Geologic Log

<table>
<thead>
<tr>
<th>Depth (m.)</th>
<th>Schlumberger logs</th>
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</thead>
<tbody>
<tr>
<td>2400</td>
<td>Green</td>
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<tr>
<td>2450</td>
<td>Orange</td>
</tr>
<tr>
<td>2500</td>
<td>Yellow</td>
</tr>
<tr>
<td>2550</td>
<td>Pink</td>
</tr>
<tr>
<td>2600</td>
<td>Black</td>
</tr>
<tr>
<td>2650</td>
<td>Brown</td>
</tr>
<tr>
<td>2700</td>
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<tr>
<td>2750</td>
<td>Blue</td>
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<tr>
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<td>Red</td>
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<tr>
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<td>Pink</td>
</tr>
<tr>
<td>2900</td>
<td>Green</td>
</tr>
<tr>
<td>2950</td>
<td>Yellow</td>
</tr>
</tbody>
</table>

#### Geologic Time Scale

- Barremian
- Hauterivian
- Valanginian
- Berriasian
- Late Jurassic
- Surmeh / Hith Gadvan
- Garhi
- Sar Bisheh
- Fahliyan Gadvan
- Khalij Mbr.
## Fossil Distribution Range Charts

### Assaluyeh

<table>
<thead>
<tr>
<th>Rock Unit</th>
<th>Time Unit</th>
<th>Thickness (m.)</th>
<th>Sample No.</th>
<th>Lithology &amp; Bedding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assaluyeh</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

### Dasycladales

- C. elongatus
- C. alpinus
- P. lituus
- O. lemmensis
- S. dinarica
- R. bartelli
- K. texana
- C. mollesus
- L. maculatus
- M. zagarthica
- C. cherchiae
- Z. embergeri
- M. arabica
- A. podolica
- C. sulcata (jurassica)
- C. delphinensis
- P. lenticularis
- R. lugeoni
- D. hahounerensis
- Ch. decipiens
- P. lenticularis

### Benthic foraminifera

- R. Appio
- P. ultingenulae
- C. albus
- C. macrotroum
- C. delphinus
- C. cherchiae
- C. elongatus
- P. rupestris
- M. arbus
- M. ultingenulae
- M. ultingenulae
- M. ultingenulae
- M. ultingenulae
<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Lithology &amp; Bedding</th>
<th>Thickness (m.)</th>
<th>Rock unit</th>
<th>Time unit</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMS 54°26'55.87&quot; E, 27°28'15.83&quot; N</td>
<td>Burkh Chahoo Barremian - Early Aptian Valanginian Haut. Barremian - Early Aptian</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Fossil distribution range charts

Rock unit
Surmeh / Hith Fahliyan
Ghari Gadvan
Khalij

Time unit
Barremian
Hauterivian
Valanginian
Berriasian
Late Jurassic

Fahliyan
51°26'41.75" E, 30°11'30.49" N

Gamma Data

Sample No. (MANA, MAK)

Thickness (m.)

Total GR (nGy/h)

Th (ppm)

U (ppm)

K (%)

-2 2

10 -10

Lithology & Bedding

Dasycladales

Benthic foraminifera

Others

Dasycladales

Benthic foraminifera

Others

S. annulata

S. istriana

S. granieri

S. pygmaea

I. inopinata

Dariyan

Aptian

Sar Bisheh

Dasycladales

Benthic foraminifera

Others

Dasycladales

Benthic foraminifera

Others

C. sulcata (jurassica)

S. circassa

S. piriniae

C. solkani

A. podolica

S. hispanica

S. neocomiensis

O. lemmensis

A. jaffrezoi

Terquemella sp.

S. dinarica

Lithocodium / Bacinella

Stromatopores (Clado. spp.)

K. jurassica

N. oolithica

R. lugeoni

C. alpinus

Ps. lituus

C. delphinensis

C. elongatus

T. peneropliformis

M. basiliensis

P. ultragranulata

V. miliani

C. sagittarius

H. joukowski

P. arabica

C. cherchiae

C. molestus

C. campanellus

C. chouberti

D. hahounerensis

V. laurenti

Ch. decipiens

N. simplex

var. germanica

C. odukpaniensis

Ch. arcana

P. lenticularis

M. arabica

E. transiens

H. sigali

Th. parvovesiculifera

Permocalculus sp.

echinoids

ostracod shells

bivalves

sponge spicules

Hedbergella spp.

Globigerinelloides spp.
### Rock unit

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Thickness (m.)</th>
<th>Total GR (nGy/h)</th>
<th>Th (ppm)</th>
<th>U (ppm)</th>
<th>K(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0100</td>
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</tr>
</tbody>
</table>

### Lithology

- Surmeh
- Hith Fahliyan
- Gadvan

### Bedding

- Gadvan Dariyan

### Time unit

- A. jaffrezoi
- I. inopinata
- Terquemella sp.
- O. lemmensis
- S. dinarica
- C. alpinus
- Ps. lituus
- C. sagittarius
- C. elongatus
- R. lugeoni
- V. laurenti
- Orbitolinids
- Ch. decipiens
- P. lenticularis
- E. transiens
- Echinoids
- A. podolica
- S. pygmaea
- S. annulata
- S. katzeri
- C. solkani
- S. piriniae
- C. dragastani
- S. circassa
- M. zagarthica n. sp.
- S. pygmaea
- S. achatina
- S. oblonga
- S. latia
- S. steinhauseri
- S. hispanica
- Z. embergeri
- S. hispanica
- Stromatopores
- P. ultragranulata
- C. cherchiae
- H. joukowskyi
- C. campanellus
- C. molestus
- Ch. arcana
- Brachiopods
- Dicirratulina / Bacinella
- Brachiopods

### Diagram

- Lithocodium / Bacinella
- Other brachiopods
- Foraminifera
- Benthic foraminifera
- Others
- Sponge spicules
- Other
Fossil distribution range charts

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Thickness (m.)</th>
<th>Lithology &amp; Bedding</th>
</tr>
</thead>
<tbody>
<tr>
<td>JHT</td>
<td>2090</td>
<td>Dasycladales Benthic foraminifera Others</td>
</tr>
<tr>
<td>Kalagh</td>
<td>2080</td>
<td>Dasycladales Benthic foraminifera Others</td>
</tr>
</tbody>
</table>

- Genow (Chahoo) 56°12'40.49" E, 27°24'21.48" N
- Kalagh 52°28'7.28" E, 28°25'26.55" N

<table>
<thead>
<tr>
<th>Time unit</th>
<th>Rock unit</th>
<th>Sample No.</th>
<th>Lithology &amp; Bedding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fah.</td>
<td>Barremian</td>
<td>JHT</td>
<td>Dasycladales Benthic foraminifera Others</td>
</tr>
<tr>
<td></td>
<td>Valanginian</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Haut. Aptian</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>Late Jurassic</td>
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</tr>
</tbody>
</table>

- Genow (Chahoo) 56°12'40.49" E, 27°24'21.48" N
- Kalagh 52°28'7.28" E, 28°25'26.55" N
## Appendix 2

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Thickness (m.)</th>
<th>Lithology &amp; Bedding</th>
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</thead>
<tbody>
<tr>
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<td>Gadvan</td>
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</table>

### Rock Unit

<table>
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<th>Lithology &amp; Bedding</th>
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</thead>
<tbody>
<tr>
<td>Berriasian</td>
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<td>Benthic foraminifera</td>
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<td></td>
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<td>10</td>
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<tr>
<td></td>
<td>0</td>
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</table>

### Sample No.

- A. podolica
- C. dagastani
- S. annulata
- O. lemmensis
- C. solani
- S. neocomensis
- I. inopinata
- S. cincasa
- Z. embergeri
- S. granieri
- A. jaffrezoi
- S. pygmea
- S. piriniæ
- S. kateri
- M. lagarthica n. sp.
- S. hasi
- S. dinarica

### Lithology

<table>
<thead>
<tr>
<th>Lithology</th>
<th>Bedding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dasycladales</td>
<td>Benthic foraminifera</td>
</tr>
</tbody>
</table>

### Diagram

[Diagram showing stratigraphic columns and fossil distributions across Berriasian, Valanginian, and Barremian time units.]

- Berriasian
- Valanginian
- Barremian

- Dasycladales
- Benthic foraminifera
Appendix 2

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Lithology &amp; Bedding</th>
<th>Rock unit</th>
<th>Time unit</th>
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</thead>
<tbody>
<tr>
<td>GAJ</td>
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<td>Sample No</td>
<td>Sample No</td>
</tr>
<tr>
<td>Khush</td>
<td></td>
<td>Sample No</td>
<td>Sample No</td>
</tr>
</tbody>
</table>

**Lithology & Bedding**

- Dasycladales Benthic foraminifera
- Others
- S. annulata
- A. podolica
- S. pygmaea
- S. katzeri
- C. solkani
- S. piriniae
- I. inopinata
- S. hispanica
- S. dinarica

**Lithology & Bedding**

- Bacinella
- Stomatopores (Clado. spp.)
- K. jurassica
- Pe. jaccardi
- C. campanellus
- C. delphinensis
- Ps. latus
- R. lugeoni
- Ch. decipiens
- C. elongatus
- C. sagittarius
- Echinoids
- Ps. jaccardi
- Paleodictyoconus sp.
- N. germanica
- D. hahounerensis
- P. lenticulea
- E. transiens
- M. arabica

**Lithology & Bedding**

- Echinoids
- Sponge spicules
- Radiolarians
- Others
- Condylactis
- C. elliptica
- R. campathica
- T. carpathica
- C. oblonga
- T. longa
- C. dardeli

**Lithology & Bedding**

- Condylactis
- C. elliptica
- R. campathica
- T. carpathica
- C. oblonga
- T. longa
- C. dardeli

**Lithology & Bedding**

- Radiolarians
- Sponge spicules
- Echinoids
- Others
- Condylactis
- C. elliptica
- R. campathica
- T. carpathica
- C. oblonga
- T. longa
- C. dardeli

**Lithology & Bedding**

- Radiolarians
- Sponge spicules
- Echinoids
- Others
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- R. campathica
- T. carpathica
- C. oblonga
- T. longa
- C. dardeli

**Lithology & Bedding**

- Radiolarians
- Sponge spicules
- Echinoids
- Others
- Condylactis
- C. elliptica
- R. campathica
- T. carpathica
- C. oblonga
- T. longa
- C. dardeli

**Lithology & Bedding**

- Radiolarians
- Sponge spicules
- Echinoids
- Others
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- R. campathica
- T. carpathica
- C. oblonga
- T. longa
- C. dardeli

**Lithology & Bedding**

- Radiolarians
- Sponge spicules
- Echinoids
- Others
- Condylactis
- C. elliptica
- R. campathica
- T. carpathica
- C. oblonga
- T. longa
- C. dardeli

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- Others
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- C. elliptica
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- T. carpathica
- C. oblonga
- T. longa
- C. dardeli

**Lithology & Bedding**

- Radiolarians
- Sponge spicules
- Echinoids
- Others
- Condylactis
- C. elliptica
- R. campathica
- T. carpathica
- C. oblonga
- T. longa
- C. dardeli
<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Lithology &amp; Bedding</th>
<th>Thickness (m.)</th>
<th>Time unit</th>
<th>Rock unit</th>
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</thead>
<tbody>
<tr>
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**Kuzeh Kuh**

- **Fahliyan**
- **Sar Bisheh**
- **Giran**
- **Gadvan**

**Stratigraphy & Biostratigraphy**

- **Berriasian**
- **Valanginian**
- **Hauterivian**

**Location**

- 51°36'10.96" E, 30°12'42.24" N

**Lithology**

- **S. annulata**
- **S. granieri**
- **S. pygmaea**
- **I. inopinata**
- **S. circassa**
- **S. piriniae**
- **C. solkanii**
- **S. lemmensis**
- **C. podolca**
- **S. cirassia**
- **M. zaghi.thio n. sp.**
- **S. phiniae**
- **I. inopinata**
- **S. pygmaea**
- **A. jaffezi**
- **Terquemella sp.**
- **S. dinarica**

**Foraminifera**

- **S. dinarica**
- **Lithocodium / Bacinella**
- **Dasycladales**
- **Benthic foraminifera**

**Forams**

- **C. solkanii**
- **S. annulata**
- **S. granieri**
- **S. lemmensis**
- **C. podolca**
- **S. cirassia**
- **M. zaghi.thio n. sp.**
- **S. phiniae**
- **I. inopinata**
- **S. pygmaea**
- **A. jaffezi**
- **Terquemella sp.**
- **S. dinarica**
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### Nargesi - 8

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#### Time unit

- Barremian
- Hauterivian
- Valanginian
- Sen Bieneh
- Bajocian
- Bathonian

#### Rock unit

- Mbr.
- Gadvan
- Garbi

#### Lithology

- Dasycladales
- Benthic foraminifera
- Others

#### Schlumberger logs

- Lithocodium / Bacinella
- Stromatopores (Clado. spp.)
- Permocalculus
- echinoids
- small planktonics

#### Stratigraphic Column

- A. podoca
- S. dinarica
- S. katzeri
- C. solkani
- C. cherchiae
- D. hahounerensis
- P. lenticularis
- D. lugeoni
- C. alpinus
- Ps. lituus
- C. delphinensis
- C. elongatus
- M. basiliensis
- C. sagittarius
- P. arabica
- C. cherchiae
- Ch. decipiens
- P. lenticularis
- Permocalculus
- sp.

#### Fossil Species

- S. annulata
- M. zagarthica
- n. sp.
- S. granieri
- S. pygmaea
- I. inopinata
- S. circassa
- S. piriniae
- C. dragastani
- S. hispanica
- S. neocomiensis
- A. jaffrezoi
- Terquemella
- sp.
- S. dinarica
- S. katzeri
- D. lugeoni
- C. alpinus
- Ps. lituus
- C. delphinensis
- C. elongatus
- M. basiliensis
- C. sagittarius
- P. arabica
- C. cherchiae
- Ch. decipiens
- P. lenticularis
- Permocalculus
- sp.
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**Fossil distribution range charts**

- *S. annulata*
- *M. viennoti*
- *S. hasi*
- *S. pygmaea*
- *I. inopinata*
- *S. circassa*
- *S. piriniae*
- *C. solkani*
- *A. podolica*
- *S. hispanica*
- *S. neocomiensis*
- *K. blanchetti*
- *A. jaffrezoi*
- *Terquemella* sp.
- *S. dinarica*
- *Lithocodium / Bacinella Stromatopores (Clado. spp.)*
- *K. jurassica*
- *C. alpinus*
- *Ps. lituus*
- *C. delphinensis*
- *C. elongatus*
- *C. sagittarius*
- *P. arabica*
- *C. cherchiae*
- *C. campanellus*
- *Ch. decipiens*
- *P. lenticularis*
- *M. arabica*
- *C. alpina*
- *C. elliptica*
- *R. cadischiana*
- *T. longa*
- *C. simplex*
- *C. darderi*
- *C. oblonga*
- Dasycladales Benthic foraminifera
- Tintinnids

**Benthic foraminifera**

- *K. lehmani*
- *M. flapos
di*
- *C. canina*
- *C. chernetzi*
- *C. inopinata*
- *C. inopinata a*
- *C. inopinata b*
- *C. inopinata c*
- *C. inopinata d*
- *C. inopinata e*
- *C. inopinata f*
- *C. inopinata g*
- *C. inopinata h*
- *C. inopinata i*
- *C. inopinata j*
- *C. inopinata k*
- *C. inopinata l*
- *C. inopinata m*
- *C. inopinata n*
- *C. inopinata o*
- *C. inopinata p*
- *C. inopinata q*
- *C. inopinata r*
- *C. inopinata s*
- *C. inopinata t*
- *C. inopinata u*
- *C. inopinata v*
- *C. inopinata w*
- *C. inopinata x*
- *C. inopinata y*
- *C. inopinata z*
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- *C. inopinata H*
- *C. inopinata I*
- *C. inopinata J*
- *C. inopinata K*
- *C. inopinata L*
- *C. inopinata M*
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- *C. inopinata T*
- *C. inopinata U*
- *C. inopinata V*
- *C. inopinata W*
- *C. inopinata X*
- *C. inopinata Y*
- *C. inopinata Z*
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- *C. inopinata BB*
- *C. inopinata CC*
- *C. inopinata DD*
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- *C. inopinata LL*
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- *C. inopinata NN*
- *C. inopinata OO*
- *C. inopinata PP*
- *C. inopinata QQ*
- *C. inopinata RR*
- *C. inopinata SS*
- *C. inopinata TT*
- *C. inopinataUU*
- *C. inopinataVV*
- *C. inopinataWW*
- *C. inopinataXX*
- *C. inopinataYY*
- *C. inopinataZZ*
Appendix 3 – Plates of identified microfossils

PLATE 1

1-4 Coscinoconus alpinus


5-9 Coscinoconus elongatus

5: sample MAK 4955, Valanginian, Sar Bisheh Fm., Kuzeh Kuh outcrop; 6: sample MANA 203, Valanginian, Sar Bisheh Fm., Fahliyan outcrop; 7: sample MAK 5244, Valanginian, Sar Bisheh Fm., Fahliyan outcrop; 8: sample ARP 185, Valanginian, Sar Bisheh Fm., Anneh outcrop; 9: sample AFA 181, Valanginian, Fahliyan Fm., Khartang outcrop.

10-14 Coscinoconus cherchiae


15-18 Coscinoconus chouberti


19-22 Coscinoconus molestus


23-27 Coscinoconus sagittarius

23: sample MANA 184, Valanginian, Fahliyan Fm., Fahliyan outcrop; 24-26: samples ARP 114 (Valanginian, Fahliyan Fm.), 147 (Valanginian, Fahliyan Fm.) and 168 (Valanginian, Sar Bisheh Fm.), respectively, Anneh outcrop; 27: sample MAK 4917, Berriasian, Fahliyan Fm., Kuzeh Kuh outcrop.

Scale bars: 100 µm.
PLATE 2

1-4 *Pseudocyclammina lituus*

1: sample MANA 205, Valanginian, Sar Bisheh Fm., Fahliyan outcrop; 2-3: samples MAK 5247 and 5625 respectively, Valanginian, Sar Bisheh Fm., Fahliyan outcrop; 4: sample AFA 175, Valanginian, Fahliyan Fm., Khartang outcrop. Scale bars: 500 µm.

5-8 *Haplophragmoides joukowskyi*


9-12 *Redmondoides lugeoni*

9: sample ARP 123, Valanginian, Fahliyan Fm., Anneh outcrop; 10-12: samples MAK 5550, 5594 and 5609 respectively, Berriasian, Fahliyan Fm., Fahliyan outcrop. Scale bars: 200 µm.

13-16 *Debarina hahounerensis*

13: sample ASL 2541, Barremian, Gadvan Fm. (Khalij Mbr.), Assaluyeh outcrop; 14: sample ASL 2645, Hauterivian, Gadvan Fm., Gavbast outcrop; 15: sample ARP 257, Barremian, Gadvan Fm., Anneh outcrop; 16: sample MAK 5049, Barremian, Gadvan Fm., Kuzeh Kuh outcrop. Scale bars: 100 µm.

17-21 *Vercorsella camposaurii*

17-18: samples ARP 128 and 183, Valanginian, Fahliyan and Sar Bisheh formations respectively, Anneh outcrop; 19-21: samples MAK 4941 (Valanginian, Fahliyan Fm.), 5015 and 5034 (Hauterivian, Ghari Fm.), Kuzeh Kuh outcrop. Scale bars: 50 µm.

22-25 *Vercorsella scarsellai*

22-24: samples ARP 174 (Valanginian, Sar Bisheh Fm.), 212 (Valanginian, Sar Bisheh Fm.) and 227 (Hauterivian, Ghari Fm.), respectively, Anneh outcrop; 25: sample AFA 62, Barremian, Gadvan Fm. (Khalij Mbr.), Mish outcrop. Scale bars: 50 µm.

26-30 *Vercorsella laurenti*


31-32 *Vercorsella cf. Haleinensis*

31: sample MAK 4919, Berriasian, Fahliyan Fm., Kuzeh Kuh outcrop; 32: sample JHT 1317, Berriasian, Fahliyan Fm., Surmeh outcrop. Scale bars: 100 µm.
PLATE 3

1-20: *Salpingoporella circassa*

1: sample BHM 121, Valanginian, Fahliyan Fm., Gavbast outcrop; 2-8: samples AFA 154 (Berriasian, Fahliyan Fm.), 156 (Berriasian, Fahliyan Fm.), 163 (Valanginian, Fahliyan Fm.), 166, 166 (Valanginian, Fahliyan Fm.), 171 and 171 (Valanginian, Fahliyan Fm.), respectively, Khartang outcrop.; 9: sample GAJ 1704, Hauterivian, Chahoo Fm., Khush outcrop; 10-15: samples ARP 128 (Valanginian, Fahliyan Fm.), 166 (Valanginian, Fahliyan Fm.), 169 (Valanginian, Sar Bisheh Fm.), 169, 169 and 176 (Valanginian, Fahliyan Fm.), respectively, Anneh outcrop; 16: depth 2590-92 m., Valanginian, Sar Bisheh Fm., Ahmadi well-1; 17-19: samples MAK 5620, 5253 and 5245 respectively, all in Valanginian, Sar Bisheh Fm., Fahliyan outcrop; 20: depth 2472m, Berriasian, Fahliyan Fm., Seh Qanat well-1. Scale bars: 100 µm.
PLATE 4

1-8, 10-17: *Otternstella lemmensis*

9, 18: *Otternstella aff. lemmensis*

1: sample AFA 158, Berriasian, Fahliyan Fm., Khartang outcrop; 2-5: samples ARP 846 (Valanginian, Fahliyan Fm.), 893 (Valanginian, Sar Bisheh Fm.) and 898 (Valanginian, Sar Bisheh Fm.) respectively, Lar outcrop; 6: sample M1, Berriasian, Fahliyan Fm., Mangasht outcrop; 7-10: samples MAK 4936, 4925, 4944 and 4947 respectively, all Valanginian, Fahliyan Fm., Kuzeh Kuh outcrop; 11-12: samples DMS 317 and 319 respectively, Berriasian, Fahliyan Fm., Burkh outcrop; 13-14: samples AFA 160 and 160, Valanginian, Fahliyan Fm., Khartang outcrop; 15: sample ARP 159, Valanginian, Fahliyan Fm., Anneh outcrop; 16: sample MAK5587, Berriasian, Fahliyan Fm., Fahliyan outcrop; 17: sample MAK 4919, Berriasian, Fahliyan Fm., Kuzeh Kuh outcrop; 18: sample JHT 1328, Berriasian, Fahliyan Fm., Surmeh outcrop. Scale bars: 200 µm.
Appendix 3

PLATE 4
PLATE 5

1-20: *Salpingoporella piriniae*

1-2: samples JHT 2066 (Valanginian, Fahliyan Fm.) and 2079 (Berriasian, Fahliyan Fm.), Kalagh outcrop; 3-4: samples ARP 833 (Berriasian, Fahliyan Fm.) and 875 (Valanginian, Sar Bisheh Fm.), Lar outcrop; 5-6: samples RAP 14566 and 14566, Valanginian, Fahliyan Fm., Nakh outcrop; 7-8: sample M1, Berriasian, Fahliyan Fm., Mangasht outcrop; 9-13: samples MAK 4885 (Berriasian, Fahliyan Fm.), 4892 (Berriasian, Fahliyan Fm.), 4922, 4922 (Berriasian, Fahliyan Fm.) and 4933 (Valanginian, Fahliyan Fm.), Kuzeh Kuh outcrop; 14: sample AFA 166, Valanginian, Fahliyan Fm., Khartang outcrop; 15-20: samples RAP 42, 45, 45, 45 and 45, all in Berriasian, Fahliyan Fm., Darbast outcrop. Scale bars: 100 µm.
PLATE 5
PLATE 6

1-10: *Salpingoporella aff. katzeri*. sample M1, Berriasian, Fahliyan Fm., Mangasht outcrop.
Scale bars: 100 µm.
PLATE 7

1-16: *Salpingoporella pygmaea*

1: sample ARP 2212, Valanginian, Fahliyan Fm., Gavbast outcrop; 2: sample GAJ 1695, Valanginian, Fahliyan Fm., Khush outcrop; 3-4: samples AFA 163 and 175, Valanginian, Fahliyan Fm., Khartang outcrop; 5-6: samples ARP 878 and 882, Valanginian, Sar Bisheh Fm., Lar outcrop; 7: sample ARP 137, Valanginian, Fahliyan Fm., Anneh outcrop; 8: sample MAK 4922, Valanginian, Sar Bisheh Fm., Kuzeh Kuh outcrop; 9-10: samples DMS 324 and 327, Berriasian, Fahliyan Fm., Burkh outcrop; 11: sample AFA 174, Valanginian, Fahliyan Fm., Khartang outcrop; 12-13: samples LETP 5017 (Valanginian, Fahliyan Fm.) and 5021 (Barremian, Chahoo Fm.), Genow (Asboo) outcrop; 14-15: samples JHT 2061 (Hauterivian, Gadvan Fm.) and 2067 (Valanginian, Fahliyan Fm.), Kalagh outcrop; 16: sample M7, Valanginian, Sar Bisheh Fm., Mangasht outcrop. Scale bars: 100 µm.
PLATE 8

1-6: *Clupeina sulcata* (*jurassica*)

1-3: sample ASL 2480, Berriasian, Fahliyan Fm., Assaluyeh outcrop; 4: sample ARP 33, Late Jurassic, Surmeh Fm., Anneh outcrop; 5-6: sample ARP 764, Late Jurassic, Surmeh Fm., Lar outcrop.

7-9: *Salpingoporella istryana*

7: sample RAP 45, Berriasian, Fahliyan Fm., Darbast outcrop; 8: sample ARP 860, Valanginian, Fahliyan Fm., Lar outcrop; 9: sample DMS 334, Berriasian, Fahliyan Fm., Burkh outcrop.

10: *Salpingoporella* sp. cf. *S. parapiriniae*

sample RAP 23, Berriasian, Fahliyan Fm., Darbast outcrop.

11: *Holosporella arabica*

sample ARP 175, Valanginian, Sar Bisheh Fm., Anneh outcrop.

12: *Furcoporella* ? aff. *F. vasiliijesimici*

sample 14570, Berriasian, Fahliyan Fm., Nakh outcrop.

13-18: *Mizzia zagarthica* n. sp.

13: sample MAK 5663, Valanginian, Sar Bisheh Fm., Dasht-e Gul outcrop; 14: sample MAK 5591, Berriasian, Fahliyan Fm., Fahliyan outcrop; 15: sample JHT 2066, Valanginian, Fahliyan Fm., Kalagh outcrop; 16-17: samples MAK 4922 (Berriasian, Fahliyan Fm.) and 4932 (Valanginian, Fahliyan Fm.), Kuzeh Kuh outcrop; 18: sample JHT 1324, Berriasian, Fahliyan Fm., Surmeh outcrop.

Scale bars: 1-6: 200 µm., 7-16: 100 µm.
PLATE 9

1-23: *Actinoporella podolica*

1: sample JHT 2071, Valanginian, Fahliyan Fm., Kalagh outcrop; 2-3: samples ARP 2212 and BHM 98, Valanginian, Fahliyan Fm., Gavbast outcrop; 4-5: samples ASL 2507 and 2510, Berriasian, Fahliyan Fm., Assaluyeh outcrop; 6-7: samples MAK 5247 and 5621, Valanginian, Sar Bisheh Fm., Fahliyan outcrop; 8-11: samples ARP 163 (Valanginian, Fahliyan Fm.), 167 (Valanginian, Fahliyan Fm.), 169 (Valanginian, Sar Bisheh Fm.) and 176 (Valanginian, Sar Bisheh Fm.), Anneh outcrop; 12-13: samples MAK 4928 and 4932, Valanginian, Fahliyan Fm., Kuzeh Kuh outcrop; 14: depth 2330 m., Valanginian, Sar Bisheh Fm., Seh Qanat well-1; 15-16: depths 3673-75 m and 3727-29 m, Valanginian, Fahliyan Fm., Suru well-1; 17: sample RAP 46, Valanginian, Fahliyan Fm., Darbast outcrop; 18-22: samples JHT 1326, 1328, 1328, 1328, 1328 and 1319, all in Berriasian, Fahliyan Fm., Surmeh outcrop. Scale bars: 100 µm.
PLATE 9
PLATE 10

1-20: Salpingoporella annulata

1: sample ASL 2507, Berriasian, Fahliyan Fm., Assaluyeh outcrop; 2-3: samples MAK 5656 (Berriasian, Fahliyan Fm.) and 5662 (Valanginian, Sar Bisheh Fm.), Dasht-e Gul outcrop; 4: sample ARP 2212, Valanginian, Fahliyan Fm., Gavbast outcrop; 5: sample AFA 163, Valanginian, Fahliyan Fm., Khartang outcrop; 6-7: samples ARP 56 (Berriasian, Fahliyan Fm.) and 169 (Valanginian, Sar Bisheh Fm.), Anneh outcrop; 8-10: samples JHT 2061 (Hauterivian, Gadvan Fm.), 2067 (Valanginian, Fahliyan Fm.) and 2074 (Berriasian, Fahliyan Fm.), Kalagh outcrop; 11-12: samples ARP 775 (Berriasian, Fahliyan Fm.) and 843 (Valanginian, Fahliyan Fm.), Lar outcrop; 13-16: samples MAK 4887, 4888, 4888 and 4925, all Berriasian, Fahliyan Fm., Kuzeh Kuh outcrop; 17-18: depths 2398 m (Valanginian, Sar Bisheh Fm.) and 2472 m (Berriasian, Fahliyan Fm.), Seh Qanat well-1; 19-20: sample JHT 1324, Berriasian, Fahliyan Fm., Surmeh outcrop. Scale bars: 100 µm.
PLATE 10
PLATE 11

1-5: *Pseudoclypeina crnogorica*

Sample ASL 2509, Berriasian, Fahliyan Fm., Assaluyeh outcrop.

6-14: *Iranella inopinata*

6-8: Samples ASL 2647, 2647 and 2648, Hauterivian, Gadvan Fm., Gavbast outcrop; 9: Sample LETP 5033, Barremian, Chahoo Fm., Genow (Asboo) outcrop; 10: Sample ARP 235, Hauterivian, Ghari Fm., Anneh outcrop; 11: Sample AFA 42, Haurterivian, Ghari Fm., Mish outcrop; 12-14: Samples ASL 2508, 2508 and 2509, Berriasian, Fahliyan Fm., Assaluyeh outcrop.

15-18: *Salpingoporella dinarica*

15: Sample MRN 799, Barremian-Eraly Aptian, Chahoo Fm., Genow (Chahoo) outcrop; 16-17: Samples M 7 and M 8 respectively, Valanginian, Sar Bisheh Fm., Mangasht outcrop; 18: Sample RAP 14509, Barremian-Eraly Aptian, Chahoo Fm., Nakh outcrop.

Scale bars: 1-5: 500 µm, 6-9 and 15-18: 100 µm, 10-14: 200 µm.
Appendix 4 - Sequence patterns based on outcrops and subsurface sections

**Ahmadi - 1**

<table>
<thead>
<tr>
<th>Time unit</th>
<th>Rock unit</th>
<th>Schlumberger logs</th>
<th>Lithology</th>
<th>Texture &amp; Depositional environment</th>
<th>T-R sequence</th>
<th>Depth (m.)</th>
</tr>
</thead>
<tbody>
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**Anneh**

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**Ahmadi - 1**

- Location: 32°38'1.12" E, 29°24'51.63" N
- Rock unit: Anneh
- Time unit: Barremian
- Texture & Depositional environment:
  - Small-scale: Small-scale
  - Large-scale: Large-scale

**Anneh**

- Location: 51°18'26.07" E, 30°22'55.41" N
- Rock unit: Anneh
- Time unit: Barremian
- Texture & Depositional environment:
  - Small-scale: Small-scale
  - Large-scale: Large-scale

**Ahmadi - 1**

- Location: 32°38'1.12" E, 29°24'51.63" N
- Rock unit: Anneh
- Time unit: Barremian
- Texture & Depositional environment:
  - Small-scale: Small-scale
  - Large-scale: Large-scale

**Anneh**

- Location: 51°18'26.07" E, 30°22'55.41" N
- Rock unit: Anneh
- Time unit: Barremian
- Texture & Depositional environment:
  - Small-scale: Small-scale
  - Large-scale: Large-scale
Sequence patterns based on outcrops and subsurface sections

**Darbost**

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<th>Texture &amp; Depositional environment</th>
<th>T-R sequence</th>
<th>Thickness (m.)</th>
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</thead>
<tbody>
<tr>
<td>Barremian</td>
<td>Gadvan</td>
<td>53°37'15.50&quot; E, 28°23'32.00&quot; N</td>
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**Dasht-e Gul**

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<th>Thickness (m.)</th>
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<td>Gadvan</td>
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### Genow (Tang-e Chahoo)

56°12'40.49" E, 27°24'21.48" N

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<th>Stratigraphic &amp; Depositional environment</th>
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### Lithology & Bedding

- **Alb.**
- **Kazh.**
- **Chahoo**
- **Khalij Mtr.**
- **Chahoo**
- **Val.**
- **Fah.**
Sequence patterns based on outcrops and subsurface sections
### Khurmoj

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### Khush

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*Note: The diagrams show the stratigraphic columns with detailed lithology, bedding, texture, and depositional environment for each sample location.*
### Nakh

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<th>Rock unit</th>
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<th>Texture &amp; Depositional environment</th>
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### Nargesi - 8

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Appendix 4

Seh Qanat-1
51°5'28.49" E, 30°7'40.80" N

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<td>Valanginian</td>
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<td>Gamma ray</td>
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Surmeh
52°34'0.00" E, 28°32'0.00" N

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<td>Surmeh / Hith</td>
<td>Gamma ray</td>
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Sample No.
JHT
MW P G B F D
T-R sequence
T R T R R T T
Sequence patterns based on outcrops and subsurface sections