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RESEARCH PAPER

Maastrichtian tectono-sedimentary evolution of the western Fars area (Zagros, SW Iran): insights into a foreland basin deposits

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Abstract
Late Cretaceous time interval as a turning point in the Zagros history is characterised by the obduction of oceanic sedimentary cover of the Neotethys over the NE-tilted Arabian Platform. This event was associated with tectono-sedimentary loading and creating a foreland basin along the NE margin of the Arabian plate resulting in huge thickness and facies variations. For stepping the events and showing the foreland basin evolution during the Maastrichtian time, a SW-NE trending regional transect of several outcrop and well sections is constructed and interpreted in a high resolution sequence stratigraphic framework (six depositional sequences). In general, three phases of foreland basin evolution could be determined along the transect: tilting and backstepping of the platform, foredeep basin development and SW prograding of the subsiding platform during the Santonian, Campanian and Maastrichtian sequences respectively. The Tarbur Formation with shallow water carbonates is the main lithostratigraphic unit of the Maastrichtian, which laterally grades to the pelagic marls of the Gurpi Formation to the SW and onlaps onto the obducted radiolarite and ophiolitic complex to the NE Fars area. Temporal and spatial developments of platform carbonates of the Tarbur Formation and its equivalent basinal marls of the upper part of the Gurpi Formations is an indication to show how foreland basin migrated during this time interval. The Maastrichtian shallowing up cycles are composed of various shallow-water carbonate and pelagic facies and radiolarite and siliciclastic petrofacies deposited from tidal flat to basinal depositional environments. Initiation and re-activation of the basement faults are one of the most important controlling factors in accommodation spaces which overprinted locally by the holokinetic movements.

Keywords: Fars area, Maastrichtian, Foreland basin, sequence stratigraphy, holokinetic movement, basement faults, obduction.

Introduction

The Zagros mountain range is a segment of the Alpine–Himalayan system formed along the Arabia–Eurasia collision zone (e.g. Berberian & King 1981; Golonka 2004; Saura et al., 2011). This convergence, which is attributed to subduction of the NE margin of Neotethys beneath central Iran, led to the emplacement of radiolarite and ophiolitic complex onto the northern edge of the Arabian plate in the Late Cretaceous time interval (Alavi 2004; Sherkati & Letouzey 2004; Piryaei et al. 2010, 2011). Although its precise timing and character have been addressed only recently (Fakhari et al., 2003; Sherkati et al. 2006; Blanc et al. 2008; Homke et al. 2009; Allahyari et al., 2010; Moghadam & Stern, 2015). The Fars area is located in the middle part of the Zagros belt, bounded by the Kazerun Fault to NW and Zendan Fault to the SE Zagros. The area is mostly marked by emergent Hormuz salt diapirs and east-west structural trends.

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This area is divided into the imbricated zone, interior, sub-coastal and coastal parts from the northeast to the southward (Stocklin, 1968; Falcon, 1974; Berberian & King, 1981; Alavi, 1994). The Fars area as the NE part of the Arabian Plate margin was marked by significant tectono-sedimentary events occurred during the Late Cretaceous time interval. These events are related to the development of a foreland basin setting in the NE Arabian Platform. During the collision and shortening of the Zagros the foredeep depocenter and attached platformal settings were migrated SW-wards (Alavi 2007; van Buchem et al 2006; Piryaei et al. 2010, 2011). This process could be due to stack thrusting and subsequent tectono-sedimentary loading in the northern side of the foreland basin.

In addition to the regional plate-scale tectonism, local basement fault and holokinetic movements could be considered as other important factors controlling the sedimentary systems of the Fars area (e. g. Ricou, 1971; Falcon 1974; Berberian & King, 1981; Sepehr & Cosgrove, 2005; Sherkati et al., 2006; Jahani et al., 2009; Piryaei 2010, 2011; Bigi et al., 2018; Aldega et al., 2018). The regional tectonics events may have triggered salt movements in the outer Fars area and Persian Gulf where the depocenter of Hormuz evaporitic series is located (Kent, 1979; Berberian & King, 1981; Piryaei et al., 2011; Motamedi et al., 2011; Perotti et al., 2011; Ezati Asl. et al., 2019). These holokinetic events can be traced from the opening of the Neotethys in the Permo-Triassic to the Late Cretaceous times. These local structural elements caused variable structural styles and subsequent thickness and facies variations in the study area. As a result of withdrawal and doming of the salt, localised mini basins and salt rooted isolated platforms have been developed in the study area (Jahani et al., 2009; Jackson et al., 2010; Peel, 2014; Jahani et al., 2017; Motamedi & Gharabeigli 2019). The main objective of this study is to recognise sedimentary features and integrate them in a reliable sequence stratigraphic framework. This will help for better understanding of the Late Cretaceous basin evolution with more focusing on the Maastrichtian interval. The basin evolution was associated with huge variations in subsidence and uplifting rates and subsequent accommodation spaces. Presence of time equivalent deep water to tidal flat sediments in the Maastrichtian Gurpi, Tarbur, Amiran and Sachun formations which are organised in a shallowing-upward and prograding trend is the best reasons to show this basin evolution.

Geological setting

The study area is located in the western part of the Fars area between Kazerun Fault to the NW, Zagros Main Thrust Fault to the NE, Razak lineament to the SE and Persian Gulf to the SW (Fig. 1). This area has been affected by three main factors including Basement faults, salt diapirs and late Cretaceous convergent tectonics. The N-S trending Kazerun Fault is one of the major basement faults which controlled sedimentation, subsidence and hydrocarbon system of the central part of the Zagros since the Early Cambrian (Sepehr & Cosgrove, 2005; Hasanlou & Hashemi, 2016). This fault system which is interpreted to have controlled the NW development of the Cambrian Hormuz, was reactivated in the Cretaceous and resulted in major sedimentary thickness and facies variations (Bahroudi & Koyi, 2003; Sherkati & Letouzey, 2004; Allen & Talebian, 2011; Burberry et al., 2011). The Kazerun Fault zone is also considered as northwest-facing Fars platform margin bordering the Dezful Embayment intrashelf basin during the Jurassic and much of the Cretaceous times (Sepehr & Cosgrove, 2005; Sherkati & Letouzey, 2004; Mobasher, 2007; Burberry 2015). Presence of salt diapirs in the eastern side of the Kazerun Fault and around South Fars Paleohigh indicate that thick Hormuz evaporitic units deposited across the deep-seated extensional faults (Talbot & Alavi, 1996; Bahroudi & Koyi, 2003; Letouzey & Sherkati, 2004; Sherkati et al., 2005; Sepehr & Cosgrove, 2005, 2007; Jahani et al., 2005, 2009; Callot et al., 2012; Jahani et al., 2017).

Interior part of the Fars area is the site of huge amounts of radiolarite and ophiolitic complexes (i.e. Neyriz ophiolites) along with thrusted para-autochthonous and allochthonous older units (Piryaei et al., 2010, 2011). These stacked units were inverted during the late cretaceous compressional tectonic and provided tectonic loading and foreland basin development. This event was marked by huge facies and thickness variations containing in situ platformal and basinal sediments interrupted frequently by shedding lower Cretaceous blocks (Fournier et al., 2006; Homke et al., 2009; Piryaei et al., 2010, 2011; Saura et al., 2011; Agard et al., 2011; Bayet-Goll et al., 2014). The main litho-stratigraphic units of the studied interval are the Tarbur Formation with shallow-water platform carbonate and its time equivalent Gurpi Formation with basinal pelagic marls (Fig. 2).

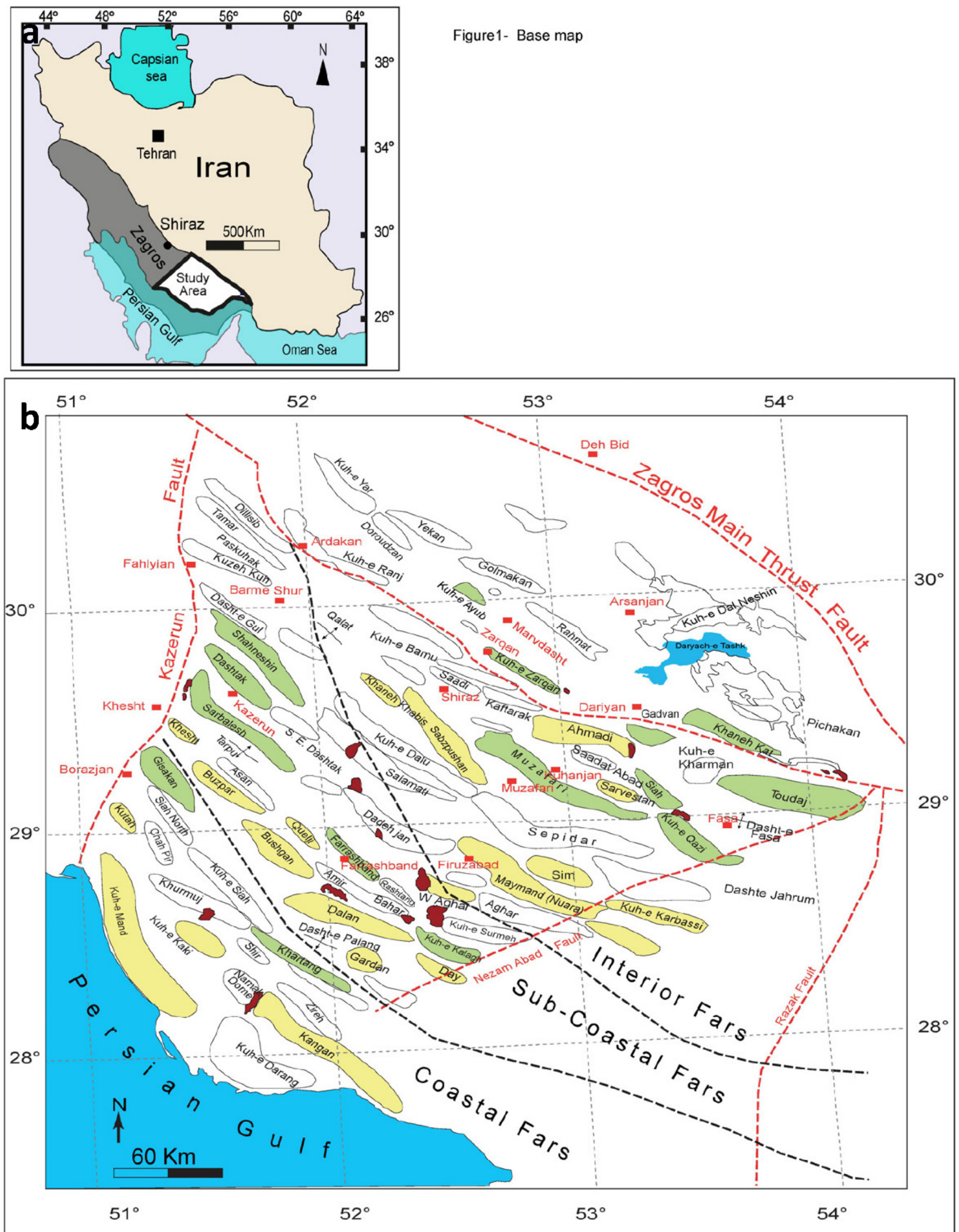

Figure 1. a) Location map of Iran, including Zagros region and study area, b) a close up view of the study area located in the western part of the Fars area, bounded by Kazerun Fault to the NW, Razak Fault to the SE, Main Thrust Fault to the NE and Persian Gulf to the SW

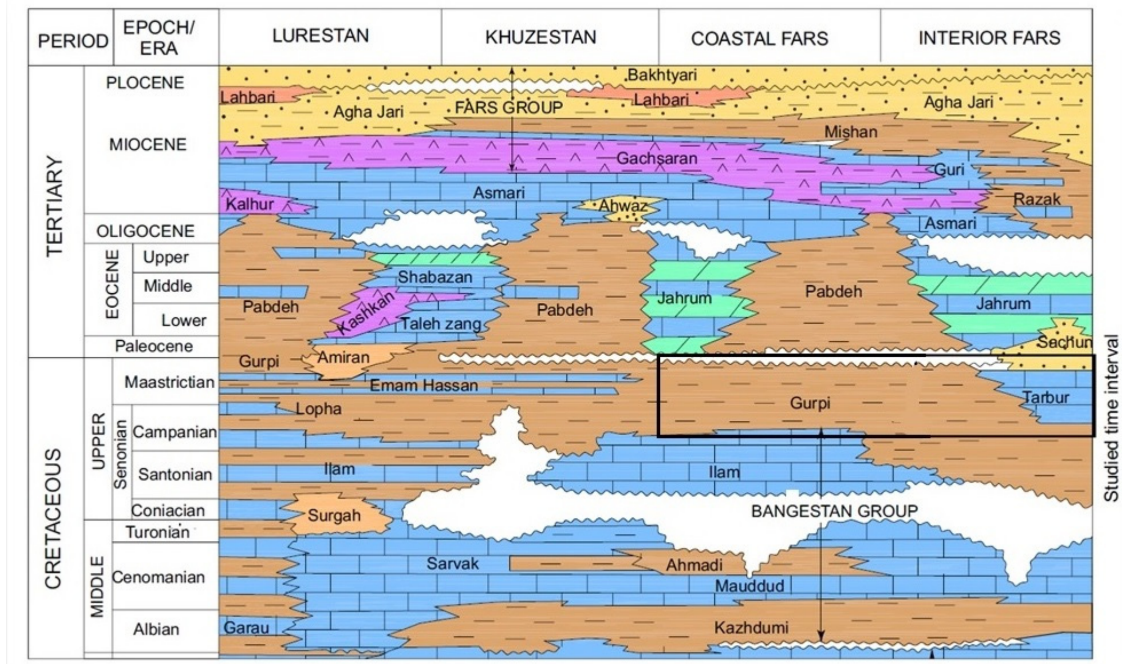

Figure 2. Litho-stratigraphic chart of Zagros (after Ghavidel-Syooki et al. 2003). The study interval is marked by a black rectangle

These units onlapped against SW-moving ophiolitic/radiolaritic nappe during the Campanian-Maastrichtian time interval (Koop & Stoneley, 1982; Sherkati & Letouzey, 2004; Piryaei, 2010; 2011; Bigi et al., 2018).

Methods and Materials

The study is based on two kinds of dataset including NIOC's achieved outcrops and well sections and field observations which have been carried out during the current study. The used well data includes the gamma ray, sonic, paleontological and lithological logs. The depositional facies and environments are interpreted based on the thin sections from cutting samples calibrated by other well data. In addition to the microscopic results, bedding geometries and patterns and sequence stratigraphic surfaces are investigated in the field. Integration between surfaces and subsurface data led to propose a sequence stratigraphic framework as a result of which the paleogeographic and evolution of the basin are analysed. In order to create sequence-stratigraphic model of foreland basin, key sections are organised along a regional transects perpendicular to the Zagros trend (former foreland basin). Finally, a high resolution sequence stratigraphic correlation chart has been prepared for the Maastrichtian interval in the west of Fars area.

Although depositional sequences in the foreland basin is dominantly controlled by tectonic processes rather than global sea level fluctuations, MFS K180 of Sharland et al. (2001) can be traced in the studied sections throughout the area as a time control. Above this sequence stratigraphic surface, the Tarbur Formation in the Zagros and its time equivalents Simsima and Tayarat formations in the other parts of the Arabian Plate are developed and can be correlated (van Bellent et al., 1959; James & Wynd, 1965; Sadooni. 2004).

Stratigraphy of the Santonian to Maastrichtian interval

The Santonian to Maastrichtian Gurpi Formation is dominated by thin-bedded pelagic marls and shales which are grading laterally and vertically to shallow-water carbonates of the Tarbur Formation. The Gurpi Formation is subdivided into biozones 32, 33, 33a, 39 by Wynd (1965) (Fig. 5). The planktonic foraminifera' assemblage includes *Gansserina gansseri, Contusotruncana contusa, Globotruncanita stuartiformis, Rugoglobigerina rugosa, Heterohelix sp. Globotruncanita stuarti Contusotruncana fornicata,* Hedbergella and Heterohelix in the basinal setting (Figs. 3).

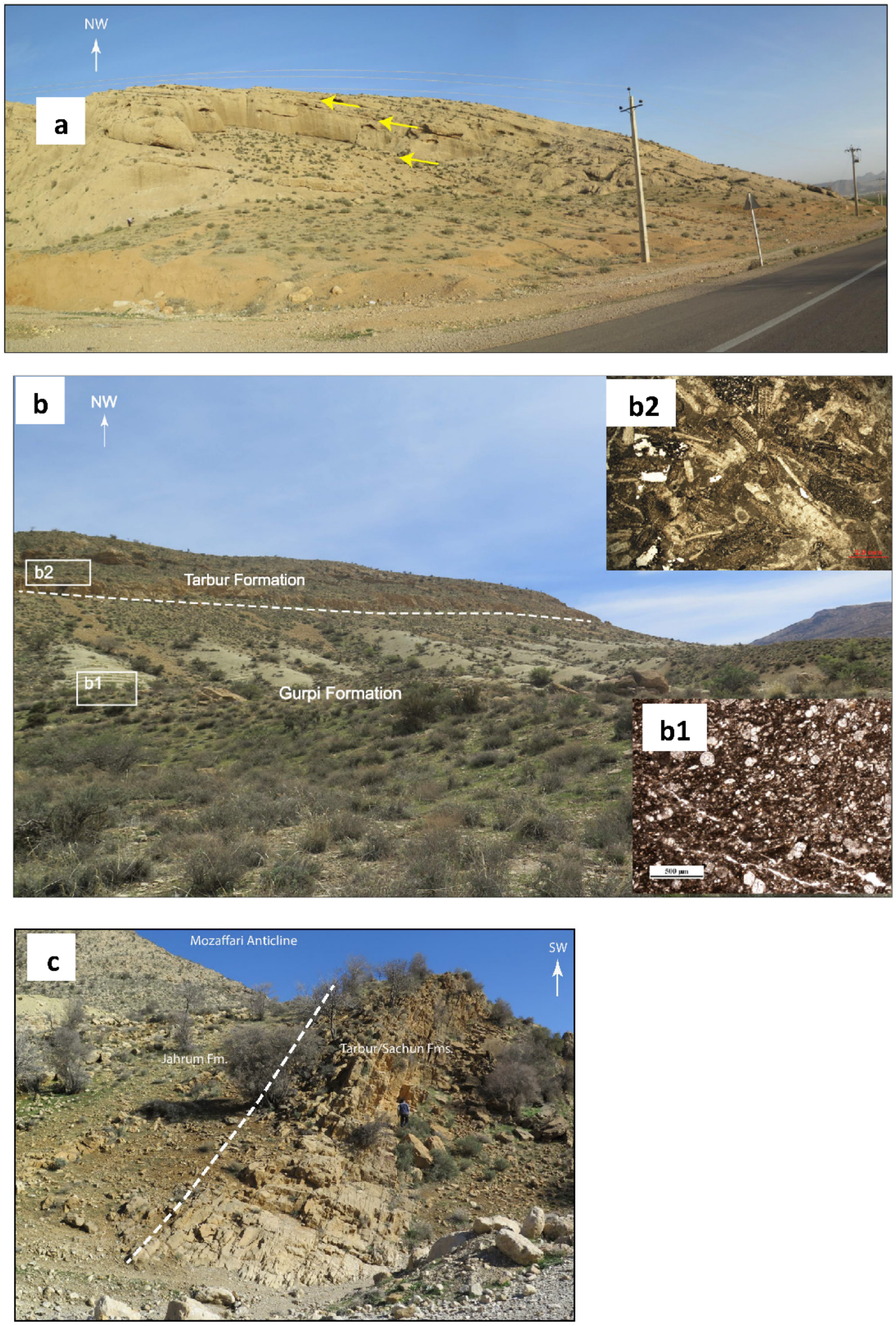

Figure 3. a) prograding wedge of the Tarbur Formation, in Gadvan section, showing a transition from normal to forced regression (yellow arrows). b) Shallowing-up cycle of the Gurpi-Tarbur formations from grey pelagic marls to rudstones of the platform carbonates. b1) Planktonic foraminifera' packstone microfacies in the Gurpi Formation. b2) Bioclast rudist rudstone, Tarbur Formation. c) Contact between Tarbur/Sachun Fms. and Jahrum Fm

The basinal sediments of the Gurpi Formation were onlapped on the Albian to Santonian (Bangestan Group) unconformity (Fig. 3 and 5). Depending on the tectono-sedimentary setting, thickness of the Gurpi Formation varies from a few metres over the paleohighs to more than 600 metres (e.g. at Saadat Abad#1) in the foredeep setting (Fig. 6). The marly facies of the Gurpi Formation is developed in most parts of the Zagros and interfingers to the shallow-water carbonates of the Maastrichtian Tarbur Formation towards the platformal setting (Saadat Abad well#1) (Fig. 3b, Fig.7).

The Maastrichtian Tarbur is characterised by thick bedded to massive carbonates that are dominated by rudist facies contain an Monolepidorbis -Orbitoides and Omphalocyclus-Loftusia assemblage zone (Fig. 5) (biozone 36 and 37 of Wynd, 1965 and *Omphalocyclus macroporus* and *Loftusia minor* assemblage zone of Afghah, 2016) fauna on the platformal setting. Tarbur Formation in all studied outcrops are characterised by cream to brownish grey limestone, which is occasionally argillaceous or arenaceous (Fig. 3, to 6), and very rich of large foraminifera (*Loftusia* sp., *Omphalocyclus* sp., *Antalyna korayi, Sirtina orbitoidiformis Monolepidorbis* sp., *Orbitoides* sp.), especially pelecypods between them rudist. Large echinoderms, gastropods, coral and dasycladacean algae, are also common. Slumped block (up to a few metres) and reef taluses are normally can be found around the Tarbur platform margin as syn-sedimentary calciturbidites. In the Fars area, particularly in the Bandar Abbas region where the salt diapirs created isolated platforms collapsing of the platform margin is more common (Piryaei et al., 2010). Thickness of the Tarbur Formation increases from southwest to northeast along the studied transect varies from 160 m in Kuh-e Mozaffari to 325 m in Saadat Abad well#1 and 523 m in Gadvan section (Fig.7).

The Maastrichtian-Paleocene Amiran Formation is composed of turbiditic mudstone-siltstone, medium- to coarse-grained sandstone, with lenticular channel bodies. Sandstones contain ultramafic rocks minerals including detrital grains of serpentinite, serpentinized, olivines and altered feldspar. Iron oxides, glauconite, chlorite, other clay minerals, and chert (possible radiolarian cherts) and carbonate rock fragments are also common. These facies are originated from the stack thrusting units, especially in the imbricated zone. In Mozaffari section, the Amiran Facies observed in some locations.

The upper Maastrichtian-lower Paleocene Sachun Formation comprises a variety of lithologies including intercalation of dolomite and evaporite, shale, marl, and siliciclastics (Fig. 3).

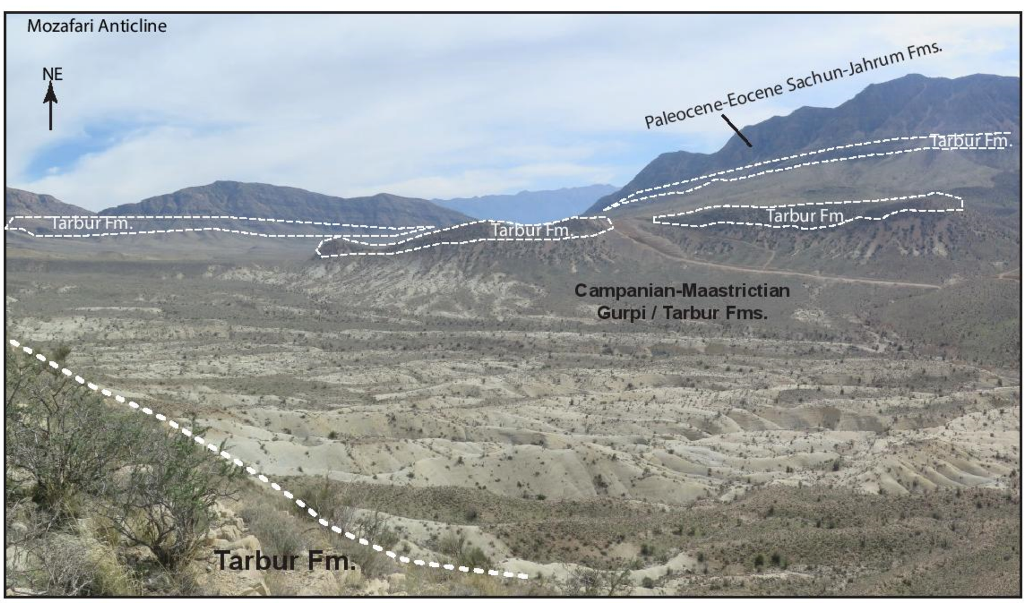

Figure 4. View of Campanian-Maastrichtian sediments in the Mozaffari section

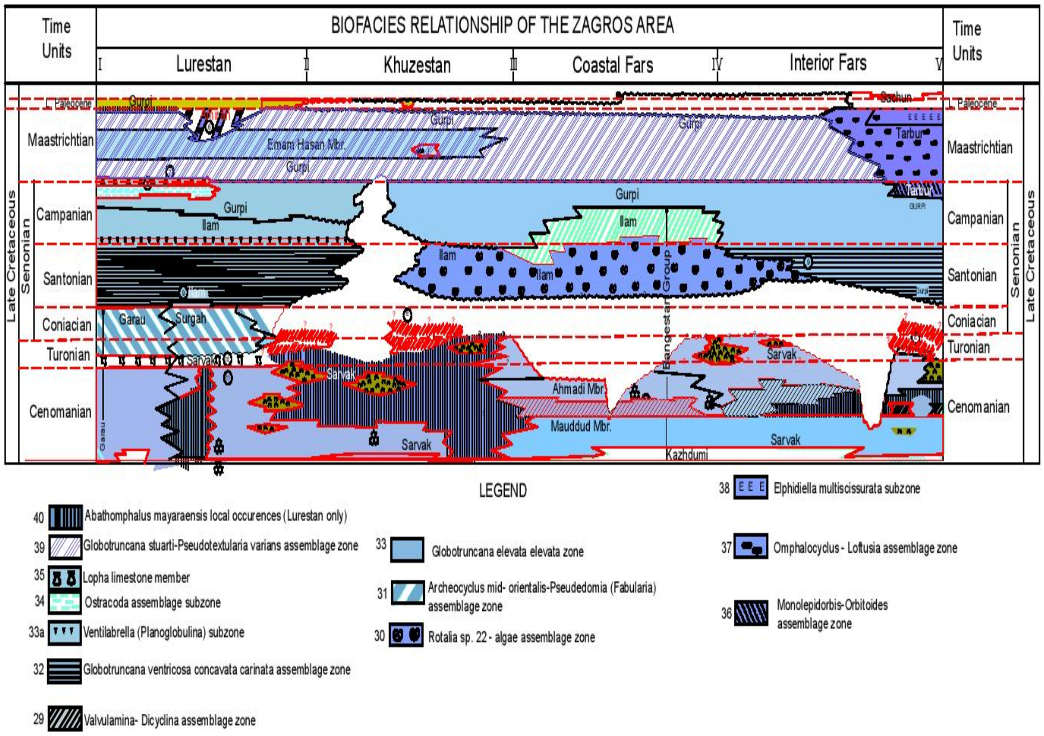

Figure 5. Biozonation of Khuzestan, Lurestan and Fars area by Wynd 1965

The Sachun Formation is deposited in the restricted lagoonal setting of the Tarbur platform in the interior Fars (Fig. 5). The thickness of this formation increased from southwest to southeast; actually it seems the Mountain Front Fault is a boundary of the Sachun Formation in south. The Sachun Formation is introduced by subzone 38 *Elphidiella multiscissurata* range subzone Wynd (1965) (Fig. 5). Toward southwest, the Amiran Formation changes to the Gurpi and Pabdeh Formation. In the northern part of the Fars area (Mozaffari section), the Sachun Formation is subdivided into the Qurban limestone and Sarvestan members (Motiei, 1993). The Sachun Formation is deposited in the restricted lagoonal setting of the Tarbur platform in the interior Fars. The thickness of this formation increased from southwest to southeast; actually it seems the Mountain Front Fault is a boundary of the Sachun Formation in south. The Sachun Formation is introduced by subzone 38 *Elphidiella multiscissurata* range subzone Wynd (1965).

Ophiolite-Radiolarite Series

Regional tectonics event that took place mostly in the Santonian and Maastrichtian-Paleocene times (e.g. Ricou, 1971; Ravaut et al., 1997; Babaei et al., 2005), led to the obduction of ophiolite and radiolarite tectonics units along the NE Arabian passive margin, from Oman to SE turkey (Ricou, 1977). The emplacement of ophiolites onto the northern edge of the Arabian plate at the Turonian–Coniacian boundary (Sherkati & Letouzey 2004; Piryaei et al. 2010) resulted in tilting and development of a foreland basin setting along the NE margin (Stoneley 1981). Finally, the shallow water reefal carbonates of the Maastrichtian Tarbur platform carbonates transgressively onlapped the exhumed ophiolites to the NE and downlapping over the Gurpi marls of the foredeep location to the SW Fars area. The ophiolites as large blocks are limited in the central and eastern part of the Dalneshin, while their components are transferred to the foredeep setting further to the SW as radiolaritic-ophiolitic nappes or siliciclastic turbidites (Piryaei et al., 2010).

Depositional facies and interpretation

In the Maastrichtian deposits of the studied interval a variety of carbonates, evaporites and terrigenous facies have been identified (Table 1) which are described in the following.

Basinal facies

The main microfacies of this group are planktonic foraminifera packstone (A1) and Oligosteginid bioclast packstone/ wackestone (A2). Allochems of this microfacies are dominated by *Oligostegina* sp., and other planktonic *Globotruncana* sp., *Globigerina* sp., (10%), sponge spicule (3%), *Radiolaria* sp., and echinoderm (15%) (Fig. 6a, b). *Heterohelix* sp., *Hedbergella* sp., together with drifted sponge spicules. Shallower water conditions are indicated by echinoid debris, red algae and rudist debris which fines away from build-ups. This microfacies is equivalent to SMF 1 of Flügel (2010). The oligosteginids biota and depositional textures indicate that the facies was probably deposited in moderate water depths ("deeper shelf": perhaps 100 to 200m according to Adams et al., 1967), during maximum flooding to early highstand conditions.

Outer platform facies

This group of facies can be divided into two kinds of microfacies: B1- Benthic foraminiferal dominated facies which are organised mostly in packstone texture. The bioclast components include *Omphalocyclus macroporous*, *Loftusia* sp., *Siderolites calcitrapoides*, *Orbitoides* sp. as well as rudist, echinoderm, and bivalve debris associated with non-skeletal grain like peloids (Fig. 6c). Omphalocyclus are index fossils of Tethyan realm (Ozcan, 2007) and lived in the upper part of photic zone and mostly observed in the upper part of shallowing upward cycles (Hottinger 1983; Moro et al., 2002; Abramovich & Keller, 2002). B2- Calciturbidites consist of mixed planktonic and benthic foraminifera. This microfacies is characterised by the presence of large intraclasts in basinal microfacies (fine grained bioclast packstone). Intraclasts contain bioclasts of shallower parts including bioclasts of *Siderolites calcitrapoides* and *Rotalia* sp. (Fig. 6d).

Table 1. Microfacies and petrofacies identified in the Maastrichtian deposits in the studied area

Facies Code	Facies	Facies Association	
A1	Planktonic foraminifera packstone/ wackestone	Basin (A)	
A2	Oligosteginid bioclast packstone/ wackestone		
B1	*Omphalocyclus/Siderolites/orbitoides/Lepidorbitoides* wackestone/packstone	Outer platform (B)	
B2	Calciturbite		
C1	Rudist boundstone	Main body reef	
C2	Rudist bioclast (Siderolites/Omphalocyclus/Loftusia) packstone/grainstone/floatstone/rudstone	Fore- reef	Reef (C)
C3	Pelloidal benthic foraminifer rudist packstone/grainstone//floatstone/rudstone	Back-reef	
D1	Peloid benthic foraminifera bioclast packstone/ wackestone	Open lagoon (D)	
E1	Algal pelloidal bioclast wackestone/packstone	Restricted lagoon (E)	
F1	Dolomudstone	Tidal flat (F)	
F2	Anhydrite		
M1	Conglomerate	Terrigenous petrofacies (M)	
M2	Sandstone		
M3	Hybrid sandstone		
M4	Mudstone and shale		

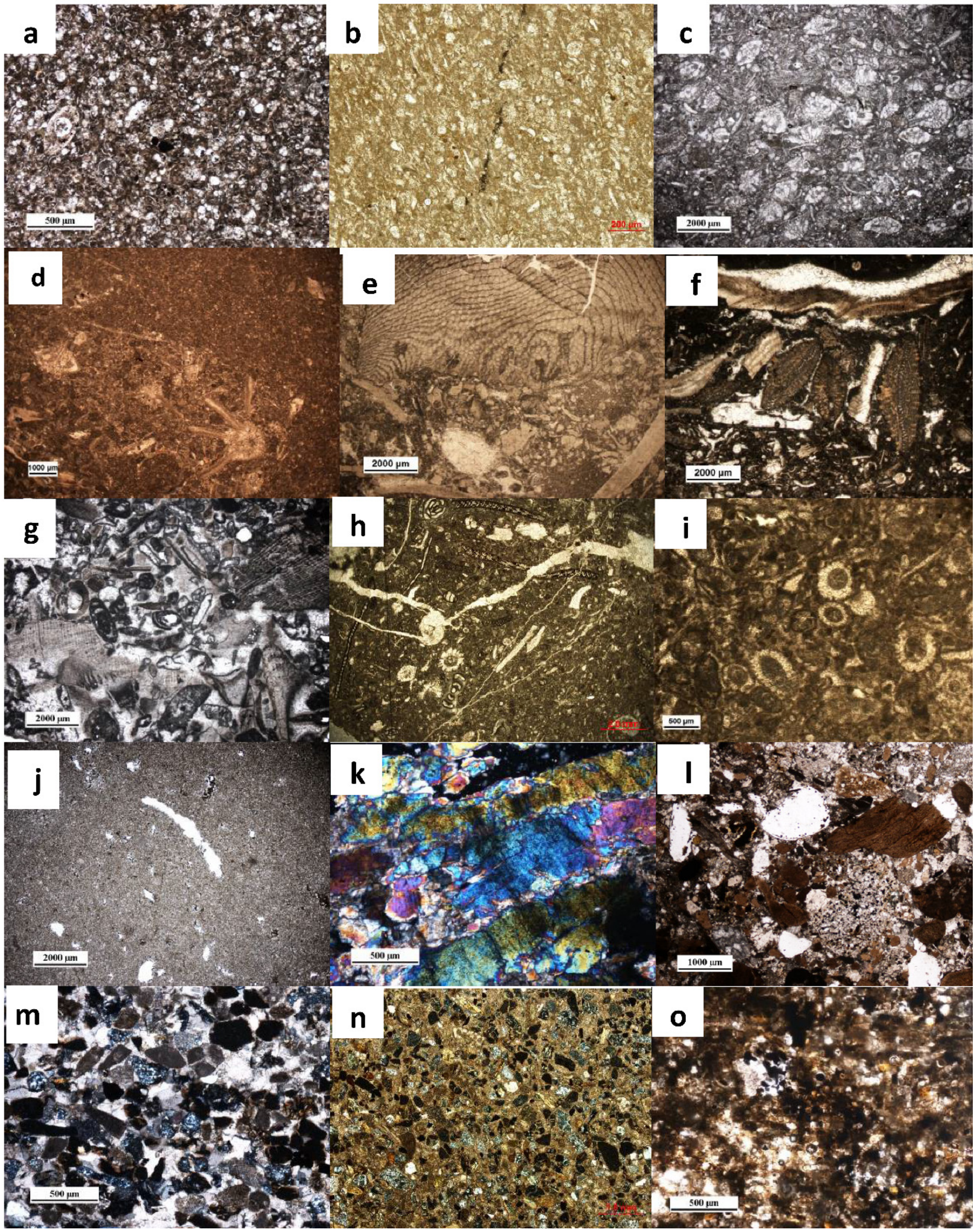

Figure 6. a- Oligosteginid planktonic foraminifera packstone related to basin (A1), Gurpi Formation, Mozaffari section, ppl. b- Bioclast oligosteginids packstone (A2), Mozaffari section, ppl. c- Siderolites packstone (B1), outer shelf, Gadvan section, ppl. d- Calciturbite (B2), intraclast of bioclast Siderolites packstone in mudstone, outer mid shelf, Gadvan section, ppl. e- Rudist boundstone, main reef body, mid platform, the Gadvan section, ppl. f- Orbitoides rudist grainstone, fore-reef, mid shelf, Gadvan section, ppl. g- Bioclast rudist rudstone, back-reef, mid shelf, Gadvan section, ppl. h- Benthic foraminifera bioclast packstone/ wackestone, open lagoon (D1), Gadvan outcrop section, ppl. i- Dasyclad bioclast packstone (E1), restricted lagoon, inner shelf, Gadvan outcrop section, ppl. j- Dolomudstone (F1), tidal flat, inner shelf, Gadvan section, ppl. k- Anhydrite (F2), tidal flat, inner shelf, Gadvan section, ppl. l- Conglomerate, polymictite(M1), Mozaffari section, ppl. m- Sandstone (chert arenite), Mozaffari section, xpl. N- Hybride sandstone (calclithite), Mozaffari section, xpl. O- Shale, Mozaffari section, ppl. (See Fig. 1 for the locations)

Loftusia in Mozaffari section shows its chaotic orientation. Fabric of rudstones with reworked bioclasts indicates deposition far from the shoreline in offshore settings, just below the storm wave base, with a long-term high-energy current or wave activity (Fig. 6I).

Reefal facies

Reef-building organisms in the Tarbur Formation consist of rudists, with minor amount of corals and red algae. During the Cretaceous, rudists were important constructors of shelf mounds and shelf margins throughout Arabian plate (Wilson, 1975), and also occur principally in the Shuaiba and Mauddud and the Mishrif formations (Alsharhan & Nairn, 1997). The dominant rudists of the Tarbur Formation in the Fars area are radiolitidae and rarely hiporitidae types and their amount reach to 10–50%. Reefal facies includes: C1 to C5 (Table 1); Rudistic facies which are organised in packstone, grainstone, floatstone, rudstone, and boundstone textures. It recorded rudist biostromes in the form of boundstone texture (Fig. 6e) in all of section intervals in the middle part of the shelf as main reef body. Gaddo (1971) noted that rudist colonies within the succession tend to increase in size upwards; small reefs and banks pass up into larger biostromes. Gaddo (1971) and Alkersan (1975) suggested that rudists were dismantled by bio-erosion and wave or current activity. Rudist shells were reworked over a broad area (Sadooni, 2005). Large, unsorted, angular rudist fragments were assumed to have been deposited in water depths of>10m. The reef build-ups probably did not form continuous complexes, unlike modern reefs. Similar rudist-dominated Albian-Cenomanian platform margin complexes are exposed in the Sierra Madre Oriental, Mexico, at Sierra de El Abra (Scott, 1990).

Rudists are commonly associated with red algae, Loftusia, Siderolites, Omphalocyclus and Orbitoides large benthic foraminifera especially in fore-reef in mid shelf (Fig. 6f). Rudist debris occasionally accompanied by some pelagic elements in outer shelf that indicated reworked from fore-reef environment. In some cases, rudist fragment are together with shallow-water benthic foraminifera such as *Cuneolina* sp., *Nezzazata* sp., *Minouxia* sp., *Dicyclina shlumbergeri*, Miliolide, *Valvulina* sp., *Sirtina* sp., *Coskinolina* sp., *Nezzazatinella* sp., and *Dictyoconous* sp., which are attributed to back-reef depositional setting (Fig. 6g). This microfacies is equivalent to SMF 7 of Flügel (2010).

Open lagoon facies

This group of facies is mainly packstone and wackestone in texture dominated by benthic foraminifers such as *Cuneolina* sp., *Nezzazata* sp., *Minouxia* sp., *Dicyclina shlumbergeri*, *Rotalia* sp., *Valvulina* sp., *Sirtina* sp., *Coskinolina* sp., *Nezzazatinella* sp., *Dictyoconous* sp., *Loftusia* sp, and *Omphalocyclus* sp. in combination with gastropods, ostracod, coral, rudist and dacyclad, as well as echinoderm and bivalve debris (Fig. 6h). Peloids (0–40%) are the main non-skeletal allochems of this microfacies. Micritization and bioturbation are common. High diversity benthic foraminifera indicate the normal salinity of the sea water and abundant microfauna indicates prolific conditions (Purser, 1973; Palma et al. 2007; Jamalian et al., 2010).

Restricted lagoon facies

It was into a subtidal sub-facies dominated by smaller benthic foraminifera in packstone/wackestone texture, and a finer-grained intertidal-supratidal sub-facies with unusual allochem assemblages. Allochems in the subtidal packstone-wackestones include smaller agglutinated foraminifera e.g. miliolids, textulariids, Nezzazata, rotaliids, dascycladacean algae, ostracods that particularly were common in energetically different parts of the inner platform (Flügel, 2010). Bioclasts are rarely sorted and usually unabraded. One microfacies have been identified in this facies belt: E1- Algal pelloidal bioclast wackestone/packstone with micritized bioclasts (20–40%) and common bioturbation. (Fig. 6i). This microfacies is completely dolomitized. It is equivalent to SMF 18 of Flügel (2010). The presence of miliolids shows a very shallow water environment, with subsaline-to-hypersaline conditions. They live preferably in low-turbulence water, where abundant sediment fines occur (Hottinger 1997, 2007; Geel 2000). The presence of porcelaneous benthic foraminifera such as miliolids and textularids in a muddy background, low diversity of benthic foraminifera, and the presence of dacyclad green algae, pervasive dolomitization, and association with tidal flat microfacies in vertical interval indicate that E1 and E2 were deposited in the restricted lagoon (Flügel 2010). Green algae are abundant in the upper Cretaceous deposits of the Zagros successions and representing shallow warm water with relatively high salinity (Riding 1991; Mosadegh & Shirazi 2009; Mehrabi et al. 2015).

Tidal flat facies

Tidal flat facies are mainly distributed in the northern part of the study area (Gadvan and Saadat Abad well), where open platform Tarbur bioclasts dominated facies are turning to restricted and marginal facies of the evaporitic Sachun. These facies include: F1- Dolomudstone, which consist of fine dolomite crystals (2-16 microns) (Fig. 6j) and is equivalent to SMF 25 of Flügel (2010); and F2- Anhydrite (Fig. 6k), which is deposited in upper intertidal to supratidal environments. Well-preserved gypsum and anhydrite can be distinguished in thin sections by their crystal morphology (Schreiber et al., 1982). Anhydrites indicate extreme restricted and drawdown.

Terrigenous petrofacies

Terrigenous sediments of the Maastrichtian succession of the Fars area can be subdivided into four facies associations; (M1) conglomerates with the thickness reaching to a few tens of metres (Fig. 6l), (M2) sandstone-dominated petrofacies (Fig. 6m), (M3) hybrid sandstone (Calclithite) (Fig. 6n) and (M4) mudstone and shale (Fig. 6o). The mixed carbonate-terrigenous facies are alternated with thin laminated pelagic mudstone facies (Fig. 3). Towards the top of this succession, the shale bed decreases both in thickness and rate of repetition and is replaced by marl or silty marl capping the rhythmic cycles of a predominantly siliciclastics sequence. The sedimentary evidences of the Amiran Formation siliciclastic deposits related to submarine fan environment that spilled over in the narrow Neotethys onto the passive continental margin in Zagros (Homke et al., 2009; Saura et al., 2011).

Depositional Environments

Six facies and microfacies zones have been identified based on the types and percentage of allochems, vertical change of microfacies, and comparison to the standard microfacies of the Wilson (1975) and Flügel (2010). The Maastrichtian deposits consist of large variety of skeletal and non-skeletal grains. Skeletal components include mainly rudists, *Omphalocyclus macroporus*, *Loftusia* sp., echinoids, *Siderolites calcitrapoides, Orbitoides* sp., sponge spicule and planktonic foraminifera such as *Globotruncana* sp., *Globotruncana stuarti*, *Heterohelix* sp. and green and red algae. Non-skeletal grains mainly consist of peloids and intraclasts. The propagation of fauna and facies of the Maastrichtian time shows seven facies belts. Intertidal to lagoonal environments, the carbonate reefs and its associated environments were deposited in a carbonate platform bordering the open sea to the northwest, outer shelf to basinal environments, and flysch facies that developed within the north of Fars area and high Zagros as turbidites derived from uplifted thrust sheets.

Sequence stratigraphy Analysis

In order to study Maastrichtian tectono-sedimentary evolution of the western Fars, it is necessary to establish a stratigraphic sequences framework for the reconstruction of the time and place of the sedimentary basin.

To stepping the tectono-sedimentary events through the Maastrichtian, a sequence stratigraphic approach has been used to explain the distribution of depositional facies, diagenetic features, thickness variation, and bedding pattern in the both local and regional scales through the time and space. In terms of dating, age of the Maastrichtian is based either on the presence of fore-reef assemblage zone in the shallow-water carbonate (Tarbur Formation) or on the presence of *Globotruncana stuarti–Pseudotextularia varians* assemblage zone [zone 39 of Wynd (1965)] in the basinal setting (Gurpi Formation). This dating is not precise enough for the high-resolution sequence stratigraphy in the Maastrichtian scale. In addition, many parts of the sections are barren and Maastrichtian interval cannot be easily defined. Therefore, the prepared sequence stratigraphic framework is mainly based on regional correlation.

Obduction of the Neotethys oceanic crust with its sedimentary cover on the Arabian platform took place from the Cenomanian to the end of Cretaceous which was associated by foreland basin creation. Foreland basin continued migrating SW-wards until the end of the Pliocene. The peak of obduction occurred in Santonian and Campanian time interval, which evidenced by huge shedding amounts of ophiolites and Neo-Tethyan sedimentary cover into foreland basin. However, in some locations such as Kuh-e Khush in the southeast of the Zagros, ophiolites emplace between the Maastrichtian pelagic marls of the Gurpi Formation. These ophiolites are interpreted to be originating from Oman Mountain (Piryaei et al., 2012). Six third order depositional sequences with averages 3My duration have been identified in the studied succession from Santonian to end Cretaceous:

Santonian (Sant.)

In this time interval, local uplift occurred in the more internal parts of the Arabian plate as a result of the development of a foreland basin flexural bulge (Murris 1980; Robertson 1987; Piryaei et al., 2010). Tilting of the Arabian plate during Cenomanian to Coniacian times was followed by emergence in vast area of the Arabian Plate resulting in a highly diachronous unconformity. By the Santonian transgression, the platformal setting was stepping back to the SW uplifted areas. Therefore, the lower part of the Santonian sequence was deposited in the depression (location of Saadat Abad well; Fig. 7). In the late Santonian, this sequence contained mainly by pelagic marls of the lower Gurpi Formation grading to the platform carbonate towards the high areas/ foreland bulge (e.g. Well Dalan-1 and Farashband outcrop section; Fig.7). Southwestwards in the depressed back bulge setting this part of the sequence dominates by pelagic sediment again (e.g. Kuh-e Kaki and Mond wells; Fig.7). The thickness of Santonian sediments reaches to 280 m in the Saadat Abad well (Fig.7) and 150m in the Mozafari outcrop section (Figs. 3 and 7). The Assemblage zone of 30; which containing rudist, algae, mollusks, echinoids, and benthic foraminifera such as Rotalia, (Rotalia species Skourensis) defined in the Ilam Formation (Fig. 7). The Santonian sediments which filled the underlying depressions contains planktonic fauna such as Heterohelix, Oligosteginids of the Gurpi Formation (biozone 32) while the shallow-water environments are majored mainly by and biozone 31. Santonian can be divided into Santonian1 and 2 sequences but for simplifying it is considered as one single sequence.

Campanian (Camp.)

The Campanian sequence is formed while the basin was in the main stages of foreland creation, meanwhile; subsidence continued in the foredeep. During this sequence almost all parts of the Zagros were deep enough for deposition of pelagic marls. The thickest Campanian sediments are related to Saadat Abad#1 with 420 metres, and the thinnest to the Dalan 1 with 21-metres. Again, in this sequence, due to the subsidence caused by sedimentation and bending in the foreland basin, the greatest thickness is related to Saadat Abad #1 and Mozaffari section in foredeep. Because of subduction of Arabian plate, the bulge is migrated from NE to SW. This bulge setting to be in Farrashband to Dalan well#1. Then during the Campanian, the location of this bulge was in the Farrashband section and Dalan 1 so in these area the boundary of Santonian-Campania is also discontinuously and erosive. The first sequence of the Campanian begins with the lithology of argillaceous limestone and contains pelagic foraminifera. This sequence is deposited in the deep part of the basin. Its HST part is shale and argillaceous limestone in all sections exception in the Mand 2 well, which it contains limestone lithology. Its upper boundary is also continuous and of SB2 type, which is characterised by the reduction of gamma log, extinction of some pelagic species and the presence of glauconite, especially in Kuh-e Kaki well 1 (Fig. 7).

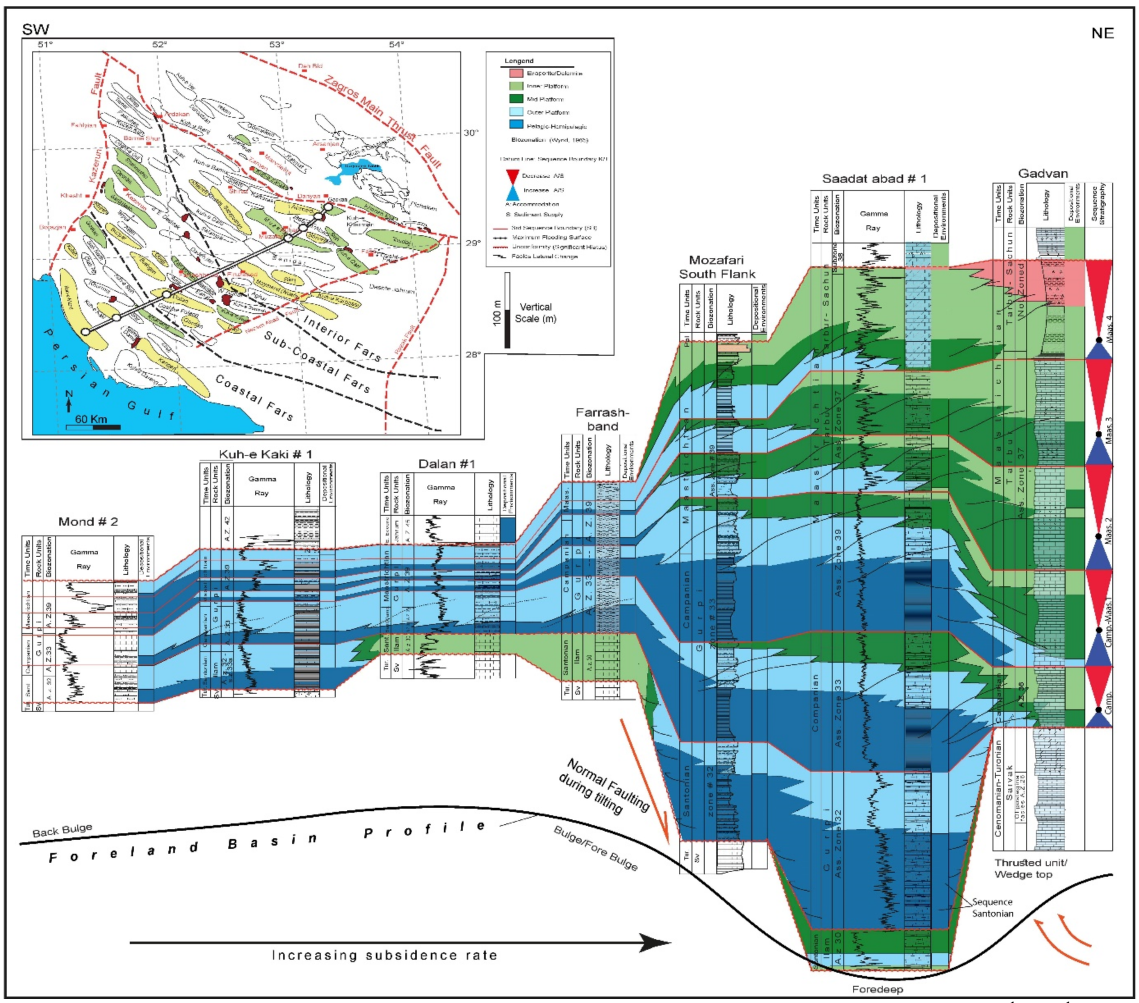

Figure 7. SW-NE trending regional transect connecting the Outer and Inner Fars area. Six 3rd to 4th order sequences are interpreted along the transect representing a migrating foreland basin perpendicular Zagros trend. Prograding shallower units (Tarbur and Sachun formations) on the deep unit (Gurpi Formation). Wedge shape geometry and prograding facies indicated typical sediments of foreland basin. Bulge migrated from NE to SW whereas Arabian plate was proceeding opposite direction (SW to NE)

Campanian -Maastrichtian 1 (Camp. -Maas. -1)

Sedimentation of Sequence No. 1 Late Campanian-Maastrichtian begins when Gurpi Formation has been deposited uniformly along the entire basin during the Campanian. Transgressive systems tract (TST) deposits of this sequence are recorded in the same interval zone and the increase in water depth is recognised by the increased clay content in the marls (increasing rate of gamma log), and the abundance and diversity of the microfossil assemblages. The TST containing the Headbergla, Heterohelix, and Globotruncana pelagic foraminifera that deposited in outer facies platform that correspond biozone 33 Wynd (1965).

The HST of this sequence is characterised by a decrease in pelagic and hemiplagic facies related to the outer and basin environments. Foraminifera such as Globotruncana, Rogoglobigrina, Hedbergella, and Heterohelix are present, while the progradation of the sequences has led to the formation of a shallow platform carbonate at the Gadvan sections with limestone and Omphalocyclus limestones. These limestones contain rudist facies hippurites and foraminifers such as Omphalocyclus, Orbitoides, as well as Miliolid, Dicyclina, Ostracods and Gastropods (Fig. 7 and 8).

The MFS is often only recognised by a change in the relative abundance and diversity of planktonic foraminifera. Light gray to cream marls with carbonate planktonic foraminifera wackestone contain abundant oxidized minerals, suggesting deposition during low sea level within outer neritic to upper slope. This MFS is equivalent to MFS K180 of Sharland et al. (2001, 2004) which is traceable in the most Arabian Plate (Fig. 7).

The lower and upper sequence boundaries in all outcrops and wells are type 2, which lie in the Gurpi Formation. It is characterised by gamma, sonic logs and the extinction of some fossil species. The gamma ray log at the boundary of the sequences shows a high peak due to the entry of detrital materials, shale or clay.

Maastrichtian 2 (Maas. -2)

TST of this sequence in the shallow parts of the platform begins with the facies related to the middle part of the platform, while in the deep parts of the basin it comprises the pelagic facies of the outer part of the platform. In Saadat Abad well#1 (interfingering of pelagic and shallow marine facies), in Mozaffari section, Globotruncana marls (Biozone 39) and also in Farrashband the shale and marl containing pelagic fossils. The Maastrichtian sediments in Gadvan section starts with the Tarbur Formation, containing thick-bedded to massive limestones, predominantly bioclastic packstone which locally grades to grainstone and reefal facies that deposited in outer platform setting. The TST in this section contain small benthic foraminifers, rudist debris, shell fragments and some planktonic foraminifers. Non-skeletal grains such as pelloids and intraclasts are also common. Large dolomitized rudists are present just below the interval where the Tarbur Formation conformably overlies the Gurpi Formation (Fig 7 and 8).

The HST of this sequence in the carbonate shallow platform with the presence of benthic fossils such as Milliolide, Dicyclina, Textularia, and the expansion of reef facies in the form of boundstone and rudstone is further determined in the sections of foredeep (Mozaffari) section. In the bulge situation (Farrashband section and Dalan #1) and back bulge (Mand well#2) in the form of argillaceous limestone with pelagic facies. The thickest sequence is in the Saadat Abad well#1, which was located in the foredeep. While the thinnest is related to the deep part of the basin Dalan and Mand wells.

Reefal facies in northeast (Gadvan section and Saadatabad well#1) graded into basinal facies of the Gurpi Formation near the Mozaffari outcrop (Fig. 8). At that time, the water depth reached a level where the oxygen minimum zone almost covered the area and permitted the preservation of organic matter. Other minor sea-level falls thought to have occurred at this time, are, however, not evidenced by the presence of corresponding shallow-water benthic foraminifera. The palaeoenvironmental evidence indicates open marine outer shelf and basin conditions.

Maastrichtian 3 (Maas. -3)

The TST of the platform begins with the shallow carbonate platform facies containing *Omphalocyclus* and *Loftusia*, *Siderolites*, the outer part of the platform containing the fossils of *Orbitoides*, *Pseudocyclammina* and Oligosteginid. In Farrashband, Dalan#1, Kuh-e Kaki#1 and Mand#2 of the lithology including argillaceous limestone and marl while in the Gadvan section includes limestone (Fig 7 and 8). This is followed by shales accompanied by an increased abundance and greater diversity of planktonic foraminifera that represent the TST.

This sequence comprises of open marine facies in TST that increasing Bryozoan, *Omphalocyclus*, Orbitoides and Siderolites that continued to reef environment and back reef with rudist facies and fauna which developed in reef and back reef environment such as benthic foraminifer and green algae. The MFS is placed where the black shale represented. This sequence in another area involves reefal sediments of Tarbur Formation. The HST comprises shale and marl, as well as the limestone, which contain benthic foraminifera.

The HST of this sequence in the shallow parts of the platform starts as calcareous facies containing benthic foraminifera and with the expansion of reef facies as in the previous sequence. Thick reef facies with rudstone, packstone and grainstone textures accompanied by Milliolid, Rotalia and Algae.

Maastrichtian 4 (Maas. -4)

The sequence is lies in the uppermost part of the Maastrichtian and the maximum progradation towards the basin and development of the Platform and shallow-water carbonates (Fig.7). In the proximal platform where the lagoonal setting becomes more restricted the sequence are composed mainly of gypsiferous carbonate and marls (e.g. Gadvan Section; Fig.7) The sequences started with the outer and middle part of the platform that continued in Saadat Abad#1 with the of outer shelf, and at the Mozaffari section represents the outer shelf and mid shelf facies belts. In other sections, this sequence is related to outer and basinal parts of platform.

The TST of this sequence is characterised by limestone lithology with packstone and grainstone texture containing *Omphalocyclus*, *Siderolites* in the section of Gadvan and Saadat Abad well#1 and well, the limestone section in Mozaffari section and the shale and lime section in Kuh-e Kaki and clay limestone in Dalan. It can be seen that the facies are pelagic in all sections (Fig.7 and 8).

The HST of this sequence is marked in the Gadvan, Saadat Abad#1 and Mozaffari sections with reefal facies limestone, as well as the presence of benthic foraminifers such as milliolide, *Dicyclina*, *Loftusia* and green algae. In Mozaffari section, these reefal facies are transported in the form of rudstone and floatstones textures containing rudist fragments, *Loftusia, Siderolites* and *Omphalocyclus*, which are probably due to carriers have reached this area on the slope of the basin.

The upper sequence boundary coincides with the regional unconformity at the top of Cretaceous (K/Pg boundary) which locally may have truncated the upper most of the Sequence Maas-4.

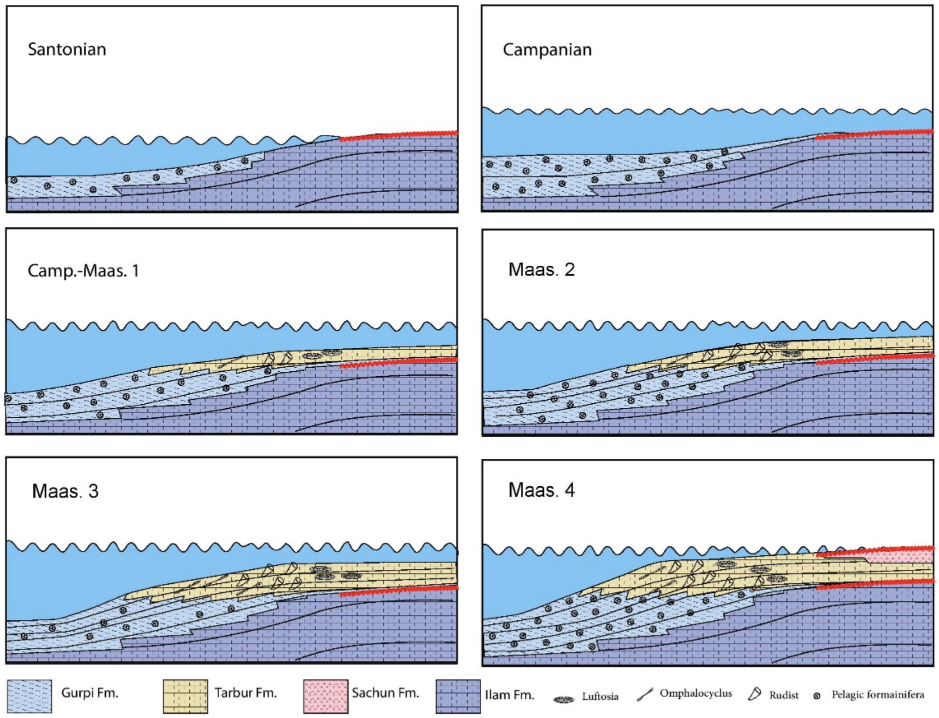

Figure 8. A sequence stratigraphic and sedimentary scheme models, which illustrate the characteristics of the Maastrichtian geometries across studied Transect

Tectono-sedimentary model for the foreland-basin evolution

Sediments, thickness and geometry of the sequences were deposited in the studied interval were influenced from a combination of tectonics, climate, and sea level factors in which the role of tectonics is much more than the two others. Flexure of the continental lithosphere in continental collision zones gives rise to foreland basin systems. Flexure of the lower or subducting plate generates proforeland basins (Naylor & Sinclair 2008). Foreland basins are therefore emphatically syn-orogenic. Increased loading in the orogen during an orogenic pulse was predicted to result in the subsidence of the proximal part of the foreland basin and a contemporaneous uplift distally to form a forebulge. Separating orogenic pulses were times of orogenic quiescence (Beaumont et al., 1993), during which erosional off-loading in the orogen was modeled as resulting in uplift of the proximal sector and subsidence of the forebulge region or distal sector (Catuneanu et al. 1997, 1999; Catuneanu, 2006).

The divergent tectonics of the Neotethys that was started from the Perom-Triassic time continued with, development of the passive margin up to the early Cretaceous. The convergent tectonics regime is marked by the emplacement of the ophiolites along the tilted NE margin of the Arabian plate. This was accompanied by creation of a foreland basin perpendicular to the actual Zagros trend. Tilting and backstepping of the platform during the Santonian was followed by the deepest foredeep in the Campanian during which the entire area was under deposition of pelagic sediments (Piryaei et al. 2010). The Maastrichtian successions in the foreland system of Zagros were deposited during a series of regional third-order transgressions and regressions, locally modulated by fourth- and lower-order cycles. The major change in the sedimentation patterns on the Arabian plate took place during the Turonian to Campanian, when the sedimentary system showed a series of major tectono-sedimentary events affecting both continental and margin settings. The continental plate was tilted more towards the NE (Murris 1980; Robertson 1987), during the Santonian thus creating a foreland basin between the Arabian and Iranian plates. In the study area, this phenomenon was accompanied by the channeling and slumping of the Santonian platform carbonate deposits from the SW. Field examples allowed us to refine the existent theoretical models and to relate the observed facies changes to stages and phases of tectonics evolution recorded within the foreland basin. Eventually forebulge migration occurred from High Zagros (NE) toward Mountain front fault (SW) (Fig. 7 and 8). In the Fars area the basement faults acted in two forms, the belt parallel Mountain Front and High Zagros Fault, the N–S trending, Nezam Abad and E–W trending Sarvestan, Mengharak and Sabzpoushan fault zones are defined as the master structural elements of the west Fars basin.

By the Campanian- Maastrichtian time, the Zagros fold-thrust belt had returned to the uniform sedimentation of the Gurpi Formation, which covered nearly the entire Zagros. The thickness of the Gurpi Formation increases dramatically towards the northeast and its maximum thickening is along the major Mozaffari and Saadat Abad depocenter. This formation covered most of the post-Turonian horsts but it appears that highs received less sedimentation.

During the Santonian, the bulge was located in the Farrashband and Dalan well#1 while, it moved to the southwest in Campanian Farrashband, Dalan#1 and Kuh-e Kaki#1 to be bulge setting. At the beginning of Campanian, the transgression is occurred on the Arabian Plate that according K160 (Sharland et al., 2001). Sedimentation in shallow carbonate platform has been developed in bulge, forebulge to backbulge setting. Nevertheless, a seaway was presented in the foredeep area, the deep marine facies (Gurpi Fm.) developed on the distal side., in the most proximal areas of the basin the thickness of sediments was increased indicating sedimentation rates usually exceed the subsidence rates.

The shelf breaks also moved to the southwest during the Santonian to Maastrichtian. However, during the Campanian, with the sea level rise, retrogradation occurred in the entire southwestern Fars basin, inferred from sedimentation of the pelagic facies. Shelf break and shorelines have been tendency prograding under the influence of high rate carbonate sedimentation along the shelf and shelf edge, then the shelf-derived sediments have been reached to the slope and deep parts of the basin such as Maastrichtian Tarbur facies in Mozaffari section (Fig. 3). Considering the thick to very thick carbonate sediments (Tarbur Formation) which deposited in bulge and forebulge area is compatible with subsidence in proximal region and uplift of distal (bulge and backbulge areas) (Figs. 7 to 9).

In Santonian flexural uplift is more than dynamic loading then bulge constrain subaerial exposure bring to erosion sediments at Santonian and Campanian boundary (Dalan#1 and Farrashband section). While in Campanian dynamic loading be more than flexural uplift then thick to very thick sediments accommodated in foredeep setting (Saadat Abad#1 and Mozaffari section) (Fig. 7). At the end of Maastrichtian again the flexural uplift be more than dynamic loading. In the late of Maastrichtian, a general regression created a major Cretaceous–Cenozoic unconformity throughout the Zagros (James & Wynd 1965; Setudehnia 1978), closure of basin.

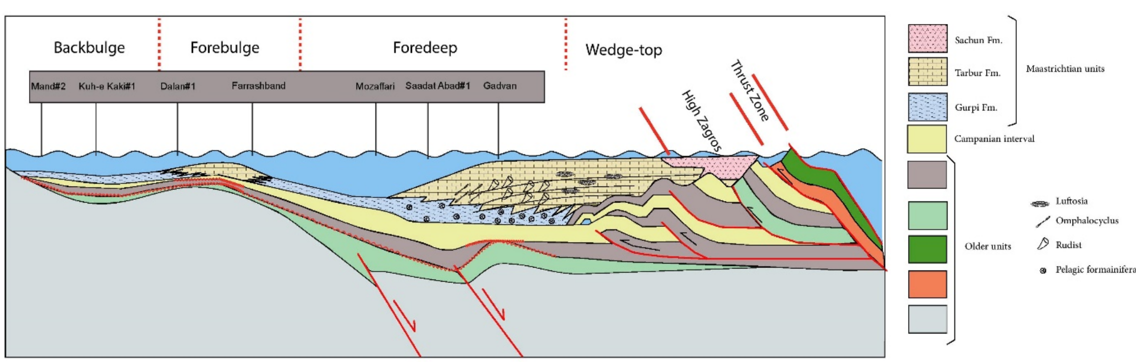

Figure 9. Tectono-sedimentary conceptual model during the Maastrichtian constructed for the western part of Fars area

The distribution of "sabkha" units restricted to the proximal region, away from the main sediment source, as a result, a gradual steepening of the topographical profile occurs together with the fall in base level and destruction of accommodation space, the pelagic and hemipelagic sediments being the equivalent of a marine "transgressive event" deposited in backbulge setting (Fig. 9).

In the Fars area from Jurassic reveal the stable platform which is continued to Maastrichtian and bounded by E-W and N-S trending lineaments. The Sabzpoushan E-W fault acted as the depositional (Sepehr, 2001; Mouthereau et al., 2007) boundary zone that controlled distribution of Tarbur Formation and more so in the end of Cretaceous bounded the Sachun Formation in the west and southwest of Fars area. Normal and transfer basement fault increased subsidence in foredeep setting whiles thrusting in wedge top increased tectonics loading. In addition, basement system faults such as Sarvestan and Sabzpoushan increasing subsidence in foredeep depozone (Saadat Abad#1 and Mozaffari section). In wedge top zone some thrusted fault (High Zagros Fault) occurred thrusting the pre Campanian intervals in Gadvan section developed discontinuity in the base of Campanian.

Subduction process had been moved and pushed the plate in direction toward NE was created dynamic subsidence in foredeep setting whereas flexural tectonics was caused bulge in response to orogenic loading (in wedge top setting). The subsidence rates generally increased in a proximal direction (foredeep) as a result crated diverge time lines whiles in the same direction in bulge and back bulge setting they closer and converge. Comparing with the latest chart of global sea level changes (Haq, 2014) related to the Maastrichtian sequences, shown different from global sea level change. Because of especially the tectonics effected on active margins and foreland basins.

Conclusions

The late Cretaceous interval is a period of time during which a variety of events such as radiolarite-ophiolite emplacement and foreland basin development occurred in the NE Arabian Platform. These event are well documented in the Fars area by using subsurface and surface sections and field observations. Among this time interval the Maastrichtian succession marked the maximum changes in accommodation spaces, strong lateral and vertical facies and thickness variation and more evidences of the foreland basin migration. Variable sediment supplies along a SW-NE trending regional transect has created general wedge shaped geometry for the Maastrichtian interval. Maastrichtian sedimentary succession is introduced by pelagic marls of the Gurpi Formation, carbonates of the Tarbur, and evaporates of the Sachun formations along with obducted radiolaritic and ophiolitic complexes. Three main tectono-stratigraphic phases could be interpreted in the late Cretaceous succession; Northeast tilting of the Arabian plate and SW backstepping of the carbonate platform during the Santonian sequence, maximum development of the foreland basin and shedding of the allochthonous sediments into the basin during the Campanian sequence and the maximum SW migration of foreland basin which is associated with stacked prograding wedges during the Campanian to Maastrichtian sequences. The Gadvan section in the proximal platform seems to be located on the thrusted sheet and shows shallowest carbonate and evaporitic facies. Saadat Abad Well and Mozaffari section are located in the foredeep setting and show shallowing –up trends with progradation of the shallow water carbonate onto the basinal pelagic facies. Other section in the SW part of the transect are mainly composed of pelagic marls in both TST and HST of their depositional sequences. Configuration of the sequences Maas.1 to Maas. 4 represent an increasing rate in procreation terminating by a forced regression of the sea water at the end of Cretaceous (Mass. 4 sequence). In Sequence 4, the facies of the inner shelf environment consist of dolomitic and evaporitic deposits (Sachun Formation) in the Gadvan section prograded on deposits of the inner and middle shelf environments. Our studied illustrated bulge migration was continued from NE to SW. In addition, such basement and normal faults parallel the trend of the Zagros (probably Sarvestan Fault) increasing subsidence in foredeep depozone.

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