



Tectonic and Eustatic Signatures in Depositional Sequences of a Foreland Basin: Example from the Oligo-Miocene Asmari Formation of Southwest Iran

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Abstract

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The Oligo-Miocene Asmari Formation (up to 500 m) and its time-equivalents in the Persian Gulf foreland basin are one of the world's most important petroleum reservoirs in southwest Iran. It is unconformably underlain by the basinal deposits of the Eocene-Oligocene Pabdeh Formation and is unconformably overlain by the continental deposits of the Middle Miocene Gachsaran Formation. Field and petrographic investigations of 10 outcrop and subsurface sections of the Asmari Formation in the northwest of the basin led to recognition of dominantly shallow marine carbonate, siliciclastic and evaporate facies. These are arranged into 7 depositional sequences that are correlated with the Oligo-Miocene eustatic sea-level cycles. In the southwest distal sections, the lower and middle Asmari sequences (Chattian-Aquitania) consist of mixed carbonate and siliciclastic facies, which change laterally to pure carbonate or carbonate and evaporate facies in the proximal area to the northeast. These sequences are absent towards the Zagros thrust belt, where the dominantly carbonate facies of the upper Asmari (Burdigalian) unconformably overlies the Eocene Shahbazan Formation.

Both eustatic sea-level changes and regional tectonics were responsible in controlling lateral and vertical facies variations of the Asmari succession. The predominantly carbonate facies and correlation of Asmari sequences with global sea-level cycles suggest a strong eustatic control during deposition. Siliciclastic intervals in the mixed siliciclastic-carbonate deposits are interpreted to represent forebulge uplift as a result of tectonic loading of the thrust sheets. The shallow marine pure carbonate/carbonate-evaporate intervals that cover the proximal foredeep or the entire foreland basin appear to be the consequence of both eustatic sea-level changes and tectonic quiescence.

Introduction

The Oligo-Miocene Asmari Formation and its time-equivalents in the Persian Gulf region are one of the world's most important petroleum reservoirs, estimated to hold more than 90% of the recoverable hydrocarbons of Iran and Iraq (Ghazban, 2009), Kirkuk Group. In recent years, several geologists have studied the facies, depositional environment and sequences of the Asmari Formation. They have proposed ramp platform for depositional environment and identified 1 (Seyrafian, 2000) 3 (Allahkarampour Dill et al., 2010), 4 (Vaziri-Moghaddam et al., 2005), 6 (van Buchem et al., 2010) and 8 (Ehrenberg et al., 2007) 3rd-

order sequence/sequences for the entire Asmari deposits. Most of these researchers assumed the Rupelian-Chattian, Chattian-Aquitainian, Aquitainian-Burdigalian, and Late Burdigalian boundaries are conformable. Amin-Rasouli (2008) is recognized seven 3rd-order depositional sequences and stated the Asmari deposits are formed at least in two platform types in complete sections.

The main purpose of this paper is to identify of facies, depositional environments and sequences of the Asmari Formation. Such studies will lead to a better understanding of sedimentary basin evolution, lateral and vertical changes of facies and thus to reconstruct the palaeogeography existing at the time the Asmari deposits were formed. These findings can help to recognize new reservoir rocks, and stratigraphic trap, too.

Methods and study areas

Ten (10) sections of the Asmari Formation were measured and studied in order to interpret facies, and their lateral and vertical variations, depositional environment and sequences stratigraphy. These sections include five outcrop (Gachsaran, Kuh-Asmari, Shahzadeh-Abdollah, Malavi, and Abdanan) and 5 subsurface (Gachsaran well no.31/GS31 and Agha-Jari well nos. 30, 60, 61 plus 66/ Agha-Jari) sections (Figure: 1a). The Asmari Formation in the study areas includes carbonate, evaporate and terrigenous deposits. A total of more than 5000 thin sections representative facies were studied to provide petrographic details to enhance the field and log descriptions.

The carbonate facies descriptions use the nomenclature defined by Dunham (1962), as modified by Embry and Klovan (1971) for describing constructed reefal facies. The classification for anhydrite texture is based on Meyers (2005) and Lucia (2007). Siliciclastic rocks are classified according to the Folk (1980) and Pettijohn et al. (1987) systems. In both carbonate and siliciclastic rocks, the upper size limit for matrix was considered to be 0.06 mm.

Depositional models were suggested based on vertical and lateral changes of facies (Middleton, 1973) and compared with ancient and present day depositional environments (e.g., Tucker and Wright, 1990; Flugel, 2004). The recognition of 3rd-order depositional sequences follows the definition provided by van Wagoner et al. (1988, 1990), Vail et al. (1991), Plint and Nummedal (2000), and Catuneanu et al. (2011).

Geological setting

The Late Cretaceous continental collision between Iranian and Arabian plates resulted in the formation of the Zagros Fold–Thrust belt and its associated the Persian Gulf foreland basin (e.g., Alavi, 2004). The timing of collision has been highly controversial, ranging from Late Cretaceous (Berberian and King, 1981), late Middle Eocene (Baziany, 2014; Mohammad et al., 2014) to Miocene (Berberian and Berberian, 1981) or uppermost Pliocene (Stocklin, 1964). The Persian Gulf foreland basin is the site of favorable condition of hydrocarbon generation, migration, and accumulation. Based on the lateral facies variations from SE to NW, the Zagros provenance has been subdivided into seven zones namely Izeh zone, Lurestan zone, Abadan Plain, Thrust zone, Dezful Embayment, Complex Structure with Metamorphic rocks, and Fars (Motiei, 1995). The study areas are located in Lurestan zone, Dezful Embayment and Izeh zone (Figure: 1b).

Regional stratigraphy

The name Asmari Formation is derived from Mount Asmari in southwest of Masjed Soleyman, northwest Haftgel in the Zagros Fold belt (Thomas, 1948). It is generally divided into lower- (Oligocene), middle- (Aquitainian) and upper- Asmari (Burdigalian) parts (Thomas, 1950). The Asmari Formation is up to 500 m thick and consists predominantly of carbonate rocks. Siliciclastic deposits and evaporates are present in the Ahwaz and Kalhur members, respectively. At the type section there is no indications of the presence of the lower part of Asmari Formation. Here, the Transitional zone (TZ-the equivalent of the lower Asmari) is developed (Motiei, 1993). It is conformably underlain by the Basal anhydrite. Some geologists (e.g., James and Wynd, 1965) believed the Transitional zone and the Basal anhydrite belong to the Pabdeh Formation. Amin-Rasouli et al. (2012) have proposed Basal anhydrite and Transitional zone as the parts of the Asmari Formation based on the presence of the unconformity below the Basal anhydrite and its correlative with the unconformity between the Asmari and Pabdeh formations in other sections.

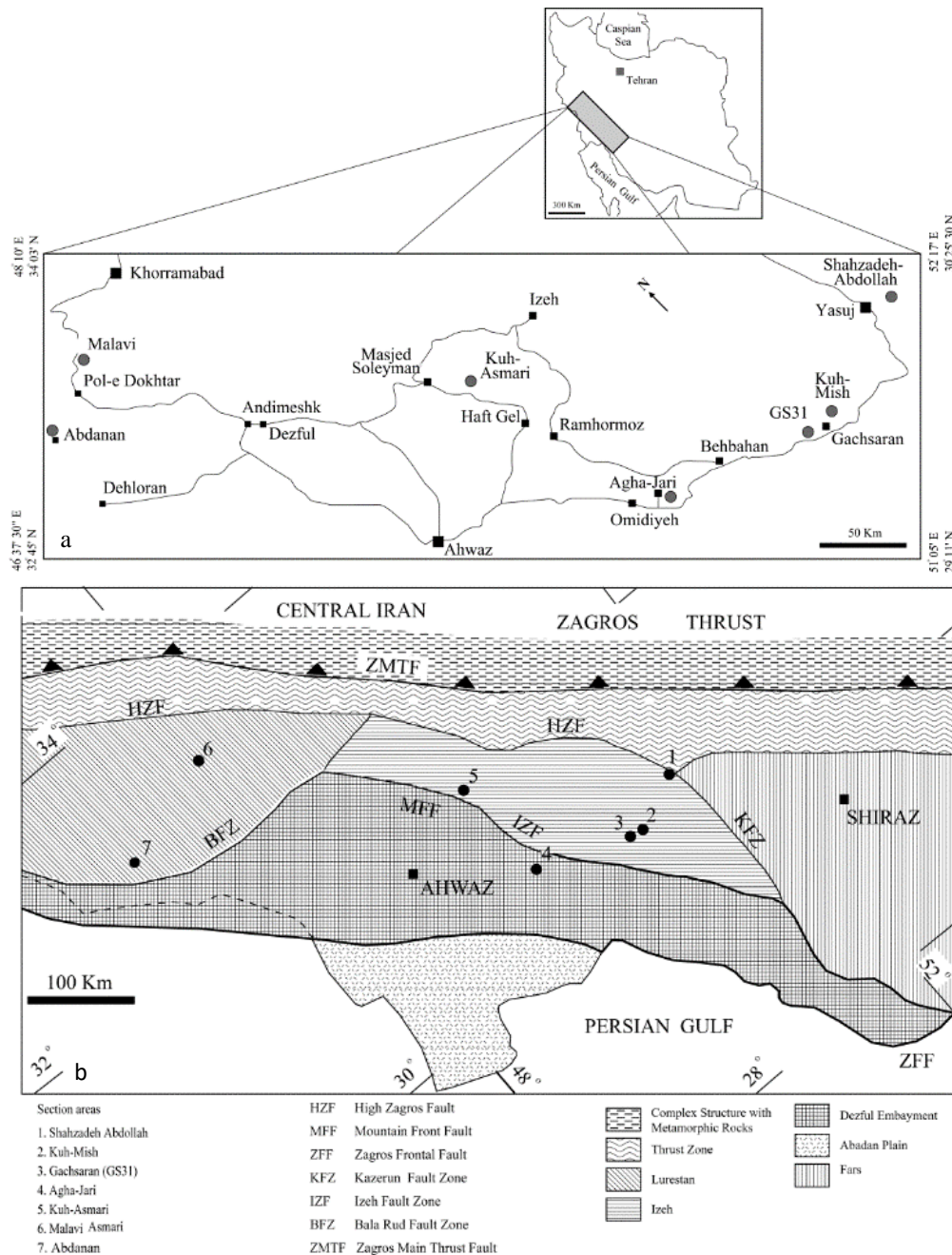


Figure-1: (a) Location map of the study areas are shown by filled circles. (b) Structural setting of the Zagros fold–thrust belt showing the major fault zones, and the basins/sub-basins mentioned in the text. Locations of the study sections are shown by filled circles and numbers (Motiei, 1995).

In the study areas, the Asmari Formation, in a northwest-southeast direction, varies in thickness from 60 m in the Abdanan section to 470 m in the Kuh-Mish section. It is unconformably overlain by the Upper Miocene Gachsaran/Razak continental deposits and is unconformably underlain by the Eocene Shahbazan Limestone or the Lower Oligocene Pabdeh Formation (Figure: 2a- e).

Facies and Depositional Environments

The Asmari Formation and Transitional zone in the study areas include carbonate, evaporate and terrigenous deposits.

Carbonate Facies Belts

Detailed petrographic, core data and log analysis of the carbonate sediments of the Asmari Formation led to recognition of several facies arranged into 5 palaeo-environment belts. These are tidal flat (A), lagoonal (B), reef flat (C), barrier island (D) and open marine (E) facies belts.

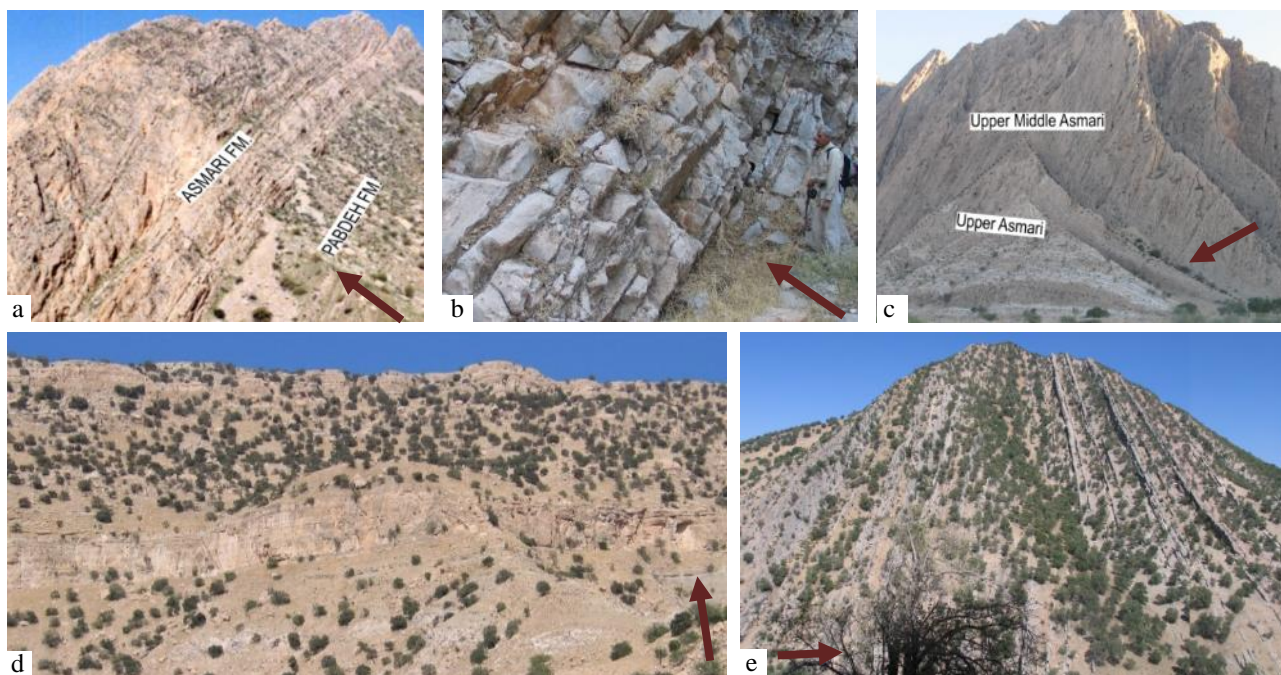


Figure-2: (a- c) Kuh-Mish section (a) Field photograph view to the west of the Pabdeh and Asmari formations. (b) Field photograph view to the west of the lower part of the lower Asmari. (c) Field photograph view to the northwest of the upper middle- and upper- Asmari. (d) Field photograph view to the northeast of the Asmari Formation, Kuh-Asmari. (e) Field photograph view to the north of the Asmari Formation, Shahzadeh-Abdollah (arrows towards stratigraphic top).

Open marine facies belt (E)

The open marine deposits include the deep (E1) and shallow (E2) open marine facies. The deep open marine consists of four facies: (E1-1) very dark gray marl/shale, (E1-2) the open marine bioclast mudstone/wackestone includes phosphate and glauconite grains, iron encrusting plus heavily bioturbated, (E1-3) thin calciturbidites, with the skeletal and non-skeletal grains originating from the slope, mainly, and (E1-4) shaly sponge spicule lime mudstone with boring, iron-encrusted, silicification and glauconite grains. The fauna of deep open marine facies include pelagic foraminifera, thin-shelled pelagic bivalves, sponge spicules, echinoderm, ditropa and *Operculina*. Occasionally the deep open marine facies is heavily bioturbated and contains some fecal pellet. The deep open marine facies is thin in the Asmari Formation, but it forms the bulk of the Transitional zone (Figure: 3a- i).

The shallow open marine deposits consists: (E2-1) the open marine wackestone/packstone including brozoans, *Lepidocyclina*, *Nummulites*, *Heterostegina*, *Operculina*, *Spiroclypeus*, *Miogypsinoides*, *Sphaerogypsina*, bivalve fragments, *Amphistegina*, echinoderm, red algae, and minor amounts of pelagic fauna, (E2-2) coral rudstone, and (E2-3) patch reefs mainly composed of red algae (Figure: 4a- f).

Interpretation: The abundance of well-preserved planktonic foraminifera, the very dark color of the thin bedded and laminated lime mudstone, and associated marl/shale with calciturbidites are interpreted to represent deposition in a reducing condition of deep open marine environment (e.g., Blomeier and Reijmer, 2002). Lasemi (1995) has suggested analog the facies E1-4 as a hardground and it is resulted due to starvation of basin after drowning of the platform. The presence of large flat *Lepidocyclina* and *Nummulites* foraminifera, in facies E2-1, indicate that sedimentation took place in proximal open marine.

Barrier island facies belt (D)

This facies belt includes grainstone (D1) and boundstone (D2) facies. The grainstone facies show large-scale cross-stratification in the surface sections and contain diverse normal-marine fauna, including (D1-1) echinoderm, bryozoan, *Miogypsina*, *Lepidosyclina*, *Hetrostegina*, *Amphistegina*, red algae and coral and non-skeletal grains such as ooid (D1-2), and pellet (D1-3). In the Shahzadeh-Abdollah section, as well as these facies, exists a facies namely (D1-4) sandy *Nummulites* grainstone. The sandy *Nummulites* grainstone is characterized by large *Nummulites* and 10 to 50% siliciclastic grains (Figure: 5a- e). The boundstone facies

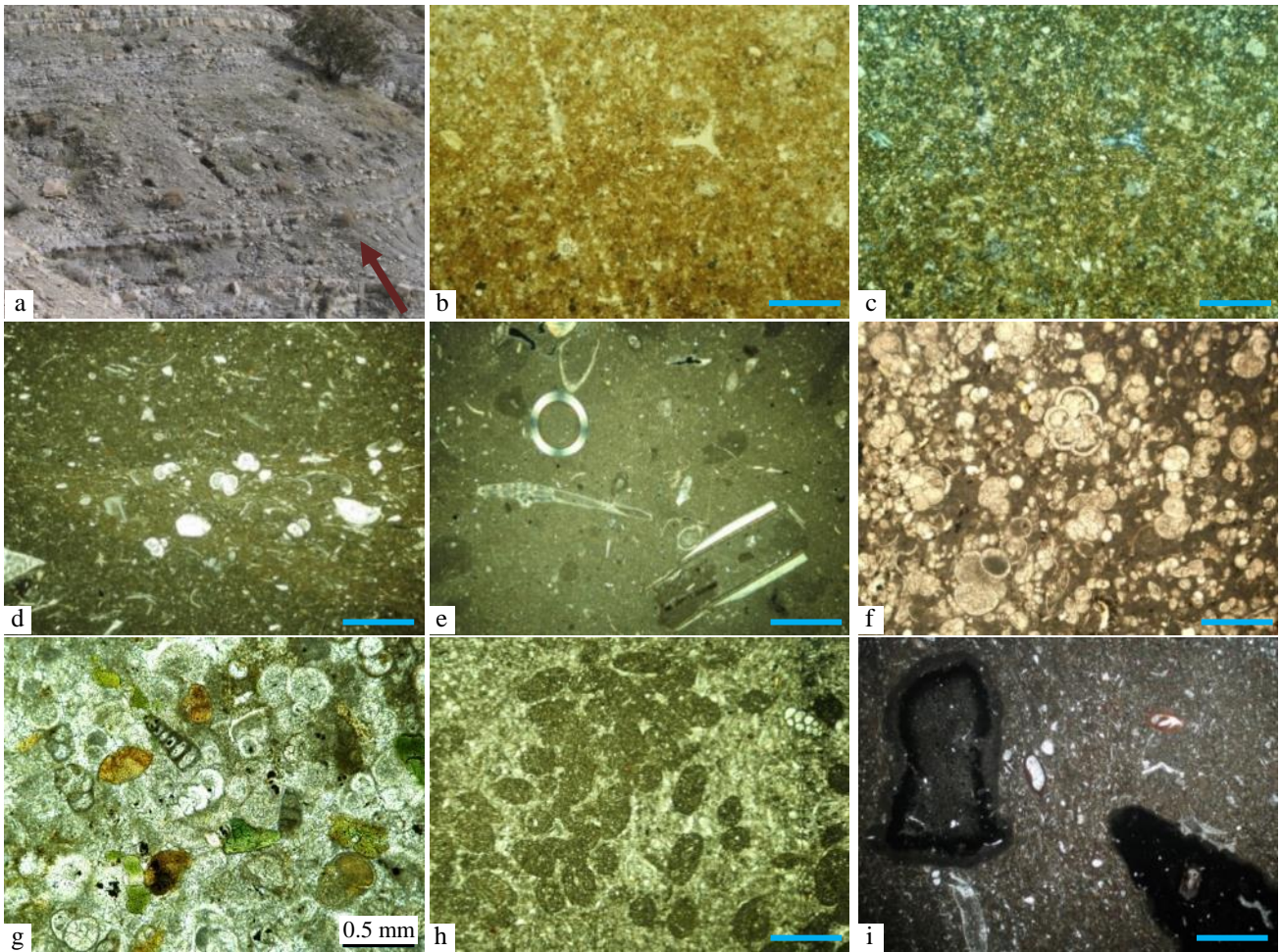


Figure-3: Deep open marine facies. (a) Field photograph view to the south of the Transitional zone of the Pabdeh and Asmari formations in the type section (arrow towards stratigraphic top). (b, c) Shaly sponge lime mudstone containing silicified sponge spicules (b) ppl, and (c) xpl. (d) Planktonic foraminifera mud-/ wacke-stone, ppl. (e) *Ditropa* bioclast mud-/wacke-stone, xpl. (f) Planktonic foraminifera packstone, ppl. (g) Planktonic foraminifera packstone with phosphates and glauconite grains, xpl. (h) Bioclast pellet wackestone, ppl. (i) Intraclast wackestone with iron oxide coated fragments, ppl (blue scale bar 0.5 mm long).

includes (D2-1) coral framestone, (D2-2) red algae bindstone and (D2-3) microbial *Numulites* bindstone. The coral framestone is characterized by the dominance of corals which represent primary framework builders. The dominant growth form is massive-globular, ranging in size from 0.60 to 1.2 m in diameter and 1 to 2 m in height. They are commonly encrusted by red algae. The coral framestone and red algae bindstone in the lower Asmari occur as patch reefs and are surrounded by grainstone facies of barrier island environment. The patch reefs and association facies show 5 stages, same as patch reef in Great Barrier Reef (e.g., Tucker and Wright, 1990), namely initial growth as isolated knobs (stage 1), vertical growth (stage 2), differentiation of the reef structure, lateral growth and bindstone cap (stage 3). The stages 4 and 5 have formed in reef flat facies belt. The microbial *Numulites* bindstone occurs in the Shahzadeh-Abdollah section contains, mainly, *Nummulites* and microbial filaments as binders (Figure: 5f- h).

Interpretation: Grains abundance and the mud free, sorted and cross-bedded nature of this facies indicate a high energy condition, barrier island environments. The patch reefs are developed windward zone of platform, based on the 5 stages of reef growth. The growth style changes from being a mainly vertical one to lateral accretion in the leeward direction (Tucker and Wright, 1990). These deposits have been accumulated near the wave-agitated shelf margin as a semi-continuous to continuous rim, which restricted circulation and wave action to form a reef flat or a low-energy lagoonal belts (e.g., Read, 1985).

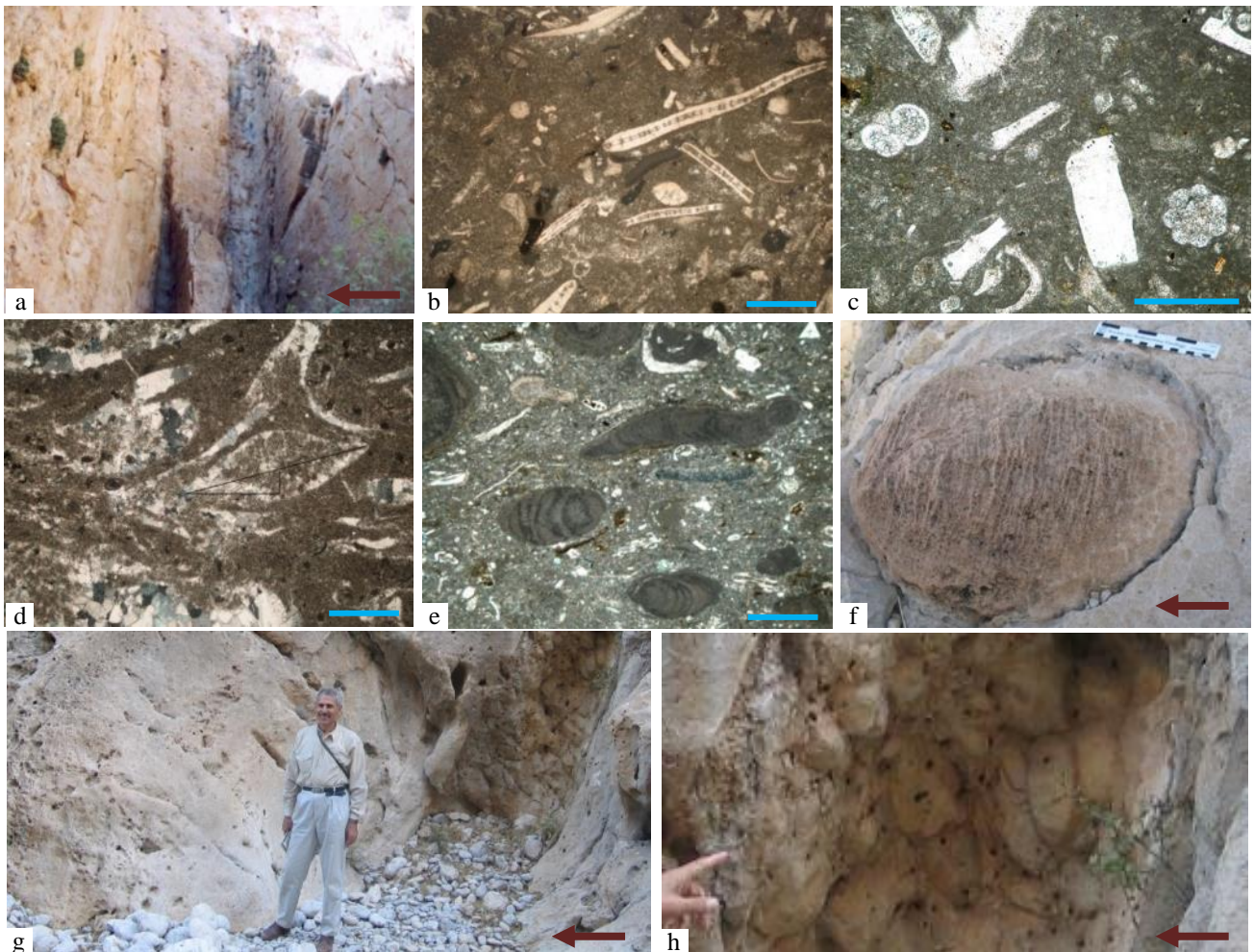


Figure-4: Shallow open-marine facies. (a) Field photograph view to the west of dark grey marl and thick bedded shallow open marine of the lower Asmari, Kuh-Mish section. (b) *Operculina* bioclast wackestone, ppl. (c) Echinoderm planktonic foraminifera wackestone, ppl. (d) Bivalve packstone, ppl. (e) Bioclast red algae floatstone, ppl. (f) Field photograph of red algae bindstone, Kuh-Mish section (blue scale bar 1 mm long). (g, h) Field photographs of forereef facies, Kuh-Mish (arrows towards stratigraphic top).

Reef flat facies belt (C)

Behind and partially protected by the reef crest is the reef-flat belt. The reef flat consists of 4 facies namely (C1) *Rotalia* grainstone, (C2) red algae rudstone/floatstone, (C3) patch reef, and (C4) pellet cyanobacteria bindstone. The reef flat facies belt shows dissolution and precipitation related to meteoric diagenesis. It is overlain by subaerial exposure/paleosol bearing *Microcodium* (Košir, 2004). The red algae floatstone to rudstone is crudely stratified and consists of red algae, mainly, *Rotalia*, large coral fragments, bryozoan, small *Lepidocyclina*, *Hetrosteigina*, green algae, pellet and intraclast. The red algae and bryozoans occur as crusts and nodules types and locally bioclast fragments are encrusted by them forming oncoids. Pellet cyanobacteria bindstone facies consist of microbial filaments/blue-green algae, pellets, porcelainous foraminifera, echinoderm and gastropods. Patch reef types are bindstone, with sparse coral framestone (Figure: 5i- 1).

Interpretation: Reef flat with coarse rampart (stage 4), and beach rocks (stage 5) include rudstone and grainstone with meteoric diagenesis due to relative sea-level fall. The relative sea-level fall also caused subaerial exposure of the reef crest and formed *Microcodium*. The co-existence of corallines and cyanobacteria in this belt are interpreted to represent the changes of chemistry of sea-water during sea-level rise.

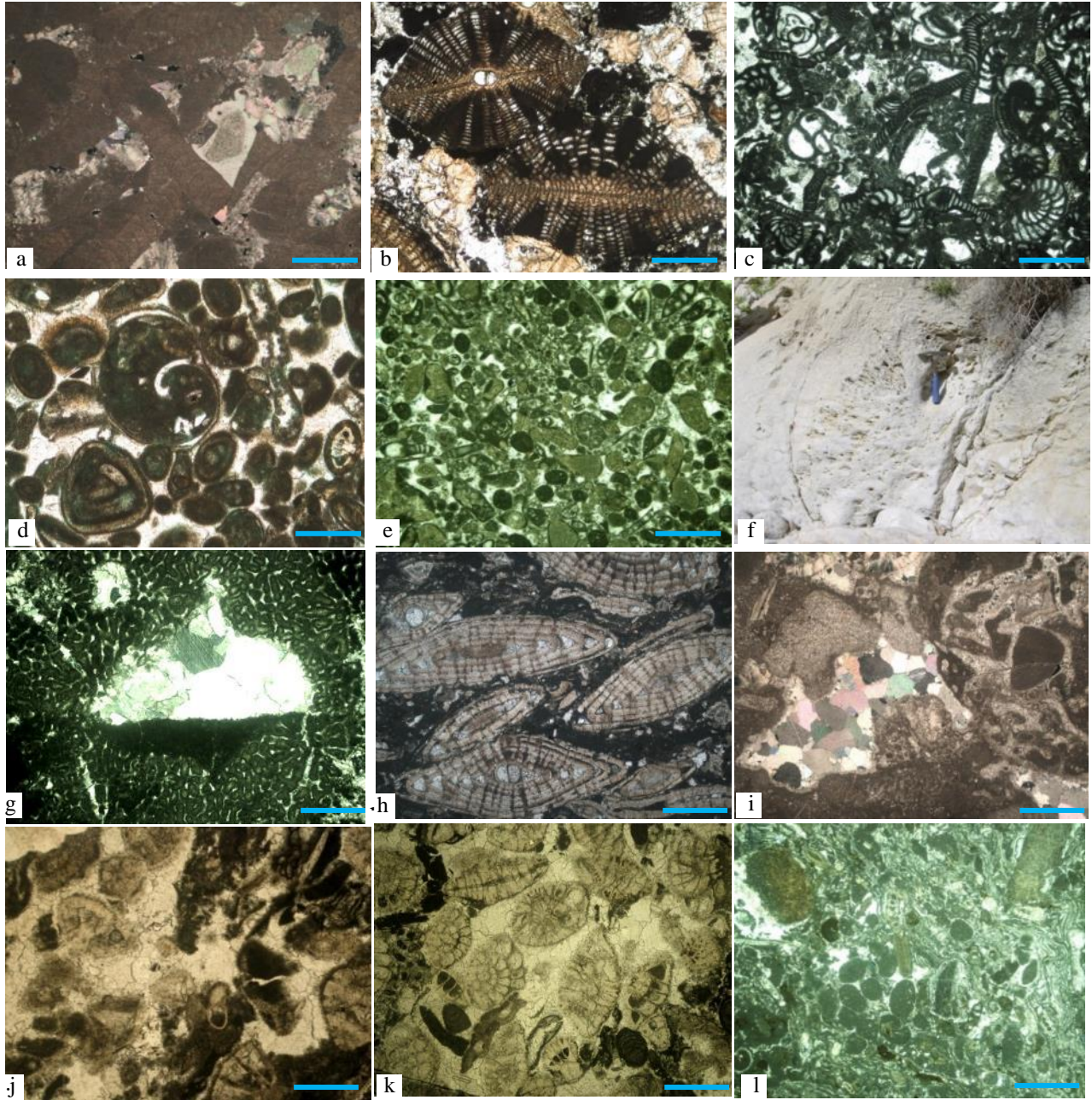


Figure-5: Barrier island grainstone. (a) Red algae grainstone, xpl. (b) Bioclast *Neorotalia Lepidocyclus* grainstone, ppl. (c) *Penroplis* grainstone, ppl. (d) Bioclast ooid grainstone, ppl. (e) *Faverina* pellet grainstone, ppl. Barrier island patch reef facies, Kuh-Mish section, (f) Field photograph of coral patch reef framestone. (g) Photomicrograph of coral framestone with geopetally filled internal sediment, ppl. (h) Microbial *Numulites* bindstone, ppl. Reef flat facies (i- k). (i) Red algae coral rudstone with evidence of dissolution and precipitation, xpl. (j, k) *Rotalia* grainstone, note the facies shows dissolution and precipitation, ppl. (l) Pellet cyanobacteria bindstone, ppl (blue scale bar 1 mm long).

Lagoonal facies belt (B)

The lagoonal facies are characterized by: (B1) bioclast packstone of mixed lagoonal (mainly miliolid) and open marine (rotaliid, red-algae and echinoids) biota, (B2) bioturbated lime mudstone/wackestone to packstone composed mainly of peloid, intraclast and skeletal grains, including gastropods, ostracods, porcelaneous foraminifera and calcareous green algae; and (B3) lime mudstone composed of abundant calcite pseudomorphs after gypsum/anhydrite and silt size quartz with no evidence of subaerial exposure (Figure: 6a- c).

Interpretation: Rocks of the lagoonal facies were deposited in an extensive, open to restricted lagoon landward of reef flat/barrier island facies. The subtidal origin is supported by the lack of subaerial exposure features and by the fact that the lagoonal facies normally underlies the tidal flat facies with a gradational contact. The mixed fauna/normal marine with lagoonal biota packstone suggests higher-energy conditions in an open shallow subtidal setting. The abundance skeletal components of restricted biota such as ostracod, benthic foraminifera, or gastropod assemblages and lack of normal-marine biota represent restricted condition. The bioturbated and pelleted lime mudstone/wackestone indicates a protected shelf interior. The possible analogs for the semi-restricted facies are the shallow subtidal lagoonal facies of the Persian Gulf, Florida and Bahamian platforms (Shinn, 1986). Lime mudstones with abundant evaporate minerals and no evidence of subaerial exposure is interpreted hypersaline conditions in the lagoon.

Tidal flat facies belt (A)

The carbonate tidalites of the Asmari Formation comprise: (A1) miliolid grainstone bearing keystone, (A2) wavy or flat laminated stromatolite bindstone, (A3) fenestral dolomudstone, dolomudstone bearing evaporate cast (chickenwire) and anhydrite layer, and (A4) mud-cracked laminated lime mudstone (Figure: 6d- g).

Interpretation: The fenestral miliolid grainstone is interpreted to have been deposited in a high-energy lower intertidal sub-environment. Dunham (1970) considered similar facies as representative of high energy beach (lowest intertidal) environment, where trapped air between the grains of irregular shape leads to the development of birdseyes. The laminated lime mudstone has been interpreted as supratidal deposits (e.g., Lasemi, 1995; Lasemi et al., 2012). The tidal flat environment of the Asmari Formation is analogous to the extensive intertidal-supratidal environments of the Persian Gulf (Shinn, 1986; Lasemi et al., 2012).

Basal anhydrite deposits (EV)

The uppermost layers of the Pabdeh Formation, in Kuh-Asmari section consist of microbial (tufa and stromatolite) and paleosol. These deposits are unconformably overlain by the Basal anhydrite/the tongue of Kalhur member and Transitional zone of the Asmari and Pabdeh formations. The Basal anhydrite with a thickness about 6 m is composed of monotonous and non-porous white anhydrite (Figure: 6h, i). In Kirkuk Oil Field and its surrounding, the equivalent of Basal anhydrite can locally seal oil columns in the Hamrin Formation (Aqrabi et al., 2010).

Interpretation: The Basal anhydrite interpreted to have been formed subaqueously in a low-energy restricted intrashelf basin/ isolated saline basin /the shallow water deep basin model (Schmalz, 1969). This idea is supported by existence of tufa, microbial facies, exposure surface and deep open marine facies in the lower and upper deposits (Amin-Rasouli et al., 2012).

Sepehr and Cosgrove (2004) have interpreted Kalhur basin formation due to reactivation of Bala-rud Fault. This activity has resulted to broken foreland basin into smaller-scale sub-basins. In these sub-basins have been deposited evaporate and shale/marl facies during sea-level fall and rise, respectively. This event is similar to Messinian event in Mediterranean that has resulted forebulge migration toward thrust wedge. Intrashelf basins could be associated with giant fields, because they contain source beds that are in close proximity to reservoir carbonates.

Terrigenous Facies (T)

The terrigenous deposits exist in the Agha-Jari and Shahzadeh-Abdollah sections. The Asmari Formation includes Ahwaz sandstone member in the Agha-Jari Oil Field. This member consists of 5 units, known as unit I to unit V from top to base. To study the Ahwaz sandstone member, core, cutting and log data provide the foundation on which our geologic observations, interpretations, and conclusions are based. The terrigenous deposits are related to cut and filled valleys, shallow open marine, barrier island, tidal flat, beach, elongate and lobate deltas, and fluvial environments. The terrigenous deposits include only one facies (TY) in the Shahzadeh-Abdollah section. Distinguishing sedimentologic and stratigraphic characteristics of each terrigenous facies and facies association, as well as the contacts separating them, are described and interpreted in the following.

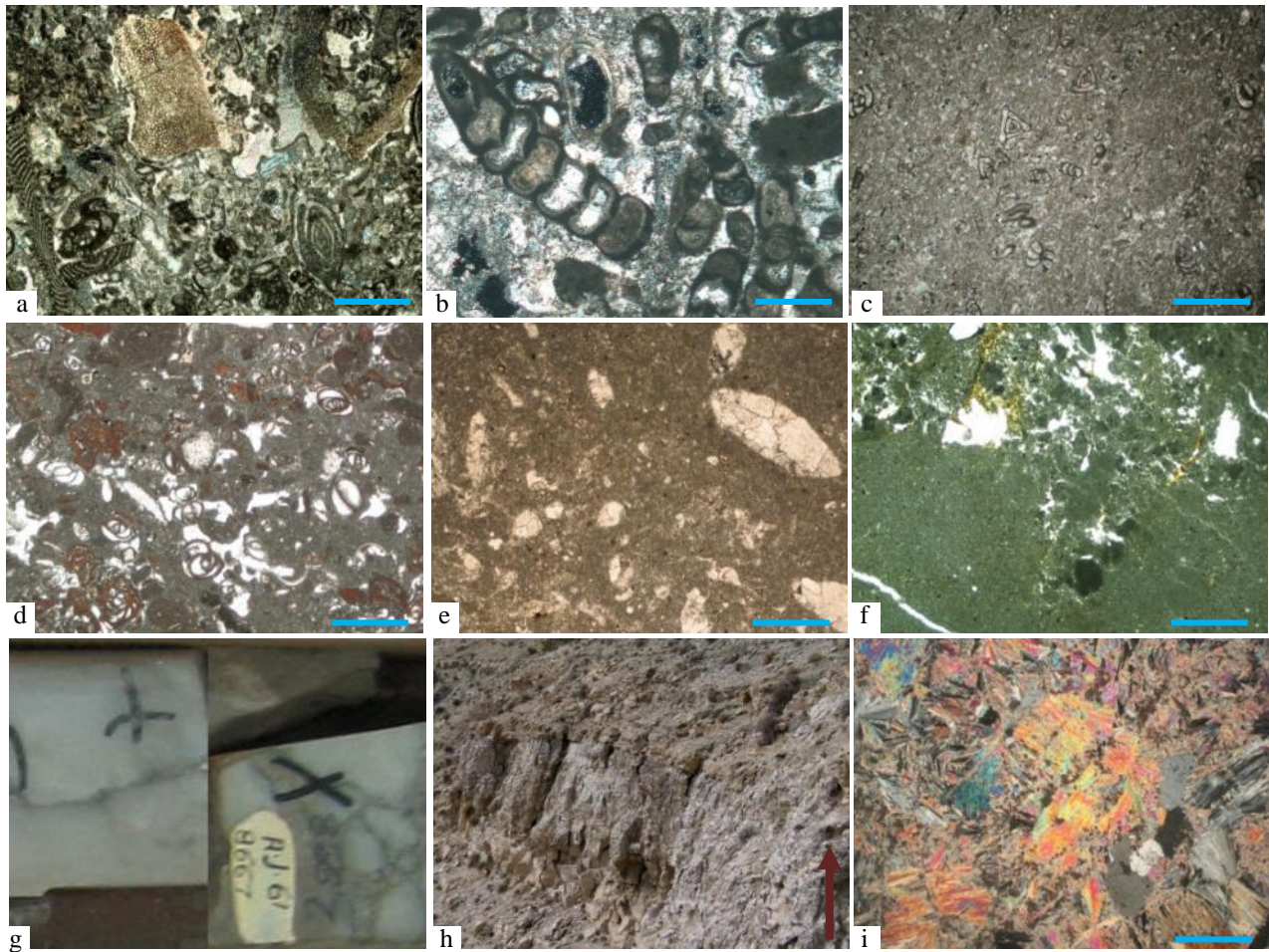


Figure-6: Lagoonal facies (a- e). (a) Echinod foraminifera packstone, xpl. (b) *Dendritina* packstone, ppl. (c) Foraminifera wackestone, ppl. Tidal flat facies (d- g). (d) Keystone miliolid grainstone, ppl. (e) Lime mudstone with evaporate casts, mesh texture, ppl. (f) Lime mudstone with mud crack, ppl. (g) Lime mudstone with anhydrite, chickenwire texture. (h) Field photograph of Basal anhydrite, Kuh-Asmari. (i) Photomicrograph of anhydrite, xpl (blue scale bar 1 mm long).

Cut and filled valley facies (TV)

This facies is located on the basal part of the unit V of the Ahwaz sandstone member in Agha-Jari Oil Field. The lower contact is erosional and very sharp with the Pabdeh Formation and the upper contact is sharp and consists of shale. The gamma-ray (GR) log of this facies shows cylinder shape. The facies consists of coarse sandstone with quartz (<75%), and terrigenous carbonate (>25%) grains (Figure: 7a, b).

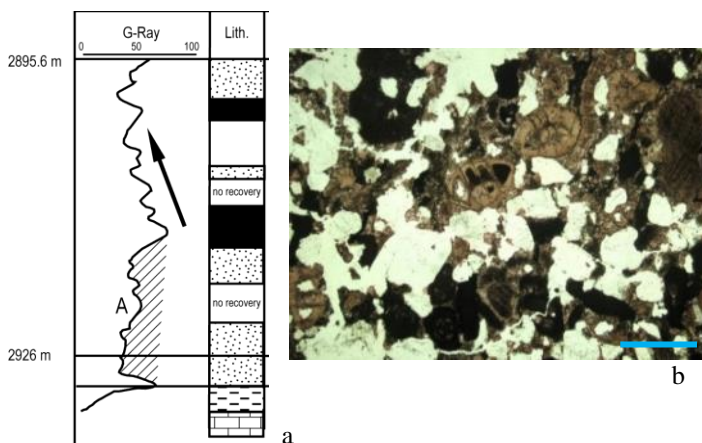


Figure-7: (a) Gamma ray log of the subsurface Agha-Jari. The gamma ray log pattern is showing cylinder-shaped (A) that is interpreted to be cut and filled incised valley deposits. Arrow shows coarsening-upward trend. (b) Photomicrograph of filled valley deposits, showing calcilithite, ppl (blue scale bar 1 mm long).

Interpretation: This facies is calcilithite and interpreted to have been deposited in incised valley depositional environment. The incised valley was generated during sea-level fall and bypassing sediment to the basin, where it accumulated as submarine fans. This is supported by the gamma ray log shape (Serra, 1985) and sharp-based sandstones. The ensuing rise of relative sea-level led to the deposition of the sandstones and filled incised valley. Therefore, the unit V of the Ahwaz sandstone member includes two parts (submarine fans and filled valley deposits). Finally, during period of rapid sea-level rise, the shale facies was deposited (e.g., Miall, 2000).

Shallow open marine sandstone facies (TO)

This facies is occurred between the open marine bioclast packstone below normal wave base, with lower and upper erosional contacts. The shallow open marine facies includes mixed siliciclastic-terrigenous and non-terrigenous carbonates grains. The siliciclastic grains are medium sorted, fine sand sized, vary from angular to rounded, and consist of quartz (80%), feldspar (8-12%) and heavy minerals. Towards up, the abundance, sorting and size of siliciclastic grains are increased (Figure: 8a-e).

Interpretation: This facies is bioclast subarkose and is interpreted as proximal open marine deposits due to the occurrence between shallow open marine carbonate facies (E2). They have formed during sea-level fall (e.g., Plint and Nummedal, 2000). This interpretation is based on increasing grain size of the sandstone towards up and its situation. Increasing grain size and sorting of sandstones upward indicate an increasing in the energy of the depositional environment due to reducing the depth.

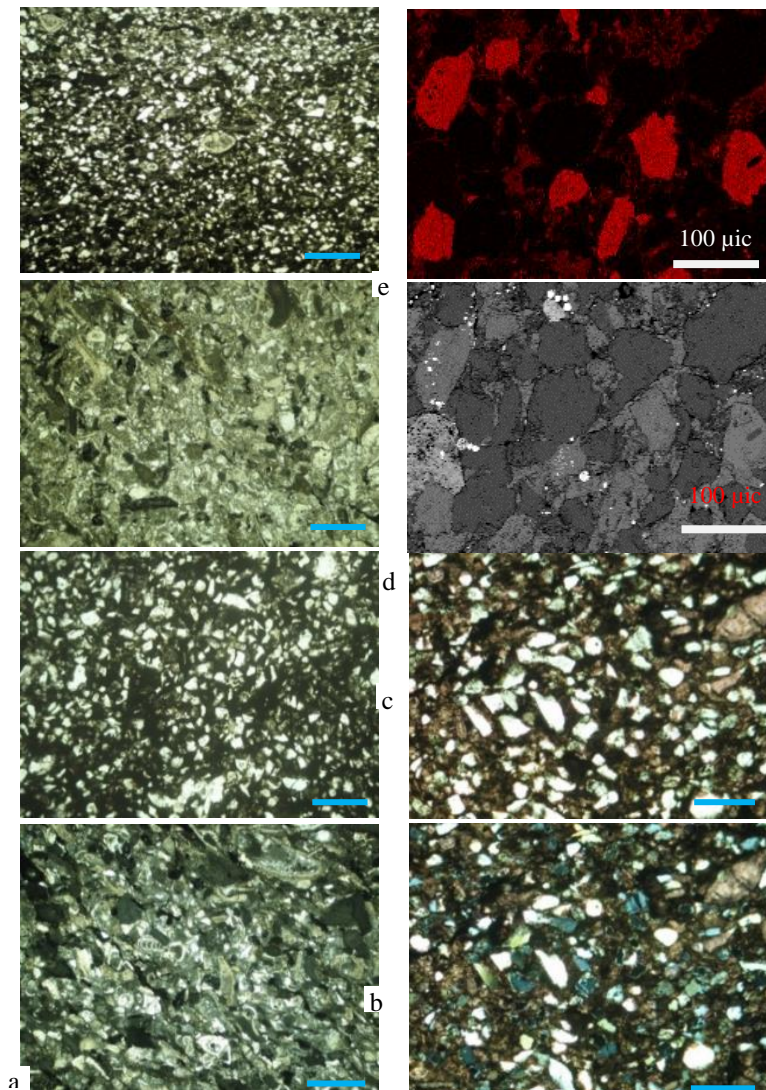


Figure-8: (a) Interbedded shallow open marine bioclast packstone and bioclastic subarkose facies, ppl. (b, c) Bioclastic subarkose facies includes quartz, feldspar and bioclast debris, ppl (b) and xpl (c) (blue scale bar 1 mm long). (d) Backscatter image from subarkose facies, white grains are feldspars. (e) Potassium map of subarkose facies, red grains are K-feldspar.

Delta facies (TD)

Based on thickness two delta types have been distinguished: (1) large-scale size deltas which are formed due to delta switching and delta-lobe shifting; and (2) smaller ones that built between interdistributary deposits.

Large-scale size deltas

These deltas are divided according to dominant process into delta plain, delta front and prodelta. They usually occur in either of two forms. One type, known as elongate, is represented most clearly by the modern bird-foot delta of the Mississippi river. The other, called lobate, is exemplified by the older Holocene deltas of the Mississippi river system. Both of these high-constructive types have a large sediment supply relative to the marine processes that tend to disperse sediment along the shoreline.

Prodelta facies (TD-1)

This facies is located at the base of the coarsening-upward succession. It is containing thick, sharply based, medium to dark grey laminated, marine shale and grades upwards into siltstone and sandstone. Shale facies are recognized by their distinctive indentation in the gamma-ray, where the core non-recovered (Figure: 7a).

Interpretation: Thick accumulations of marine shale are indicative of long periods of low-energy deposition, as is common in offshore environments, below storm wave base. The presence of this fine-grained lithology in the base of coarsening-upward succession is interpreted here as prodelta deposits. The well laminated facies indicates anoxic condition (Sageman et al., 1996).

Delta front facies (TD-2)

This facies is composed of several coarsening- and thickening-upward cycles. Deposits are muddy sandstone, cross-bedded sandstone and bioclastic sandstone. Muddy sandstone is composed mainly of mud (20 to 45%), quartz (50 to 70%), feldspar (6 to 10%) and bioclast (less than 5%). The sandstone is dominated by quartz (80 to 94%), feldspar (6 to 10%). The bioclastic sandstone type contains of quartz (50 to 85%), feldspar (5 to 7%) and bioclast (10 to 40%). Bioclasts include *Rotalia*, echinoderm and ditropha. Mud/matrix includes terrigenous and carbonate particles. These deposits belong to unit V and show lenticular form in the isopach map of sandstone (Figure: 9a- c).

Interpretation: These deposits are composed of quartz- to feldspathic-wacke, subarkose and bioclast subarkose facies. The upward coarsening- and thickening-produced cycles indicate an increase in energy of environment and representing deposition during general upward increasing in the current and wave activities as a result of the gradual progradation of fluvial channel. The abundant main fluvial channel and its switching have been resulted to form a new delta as a lenticular form far away from the previous delta. This indicates that such lenticular sandstones are diachronous. The high thickness of the strata, isolated sand body, lenticular form, and absence of thick interdistributary deposits indicate that these deposits are formed on the lobate delta, similar to ancient Mississippi delta.

Delta plain facies (TD-3)

Delta plain deposits include distributary channel, interdistributary, crevasse splay, and exposure sub-environments. It includes arenite and wacke sandstones.

Distributary channel facies (TD-3a)

This facies comprises cross-laminated sandstone with fining-upward cycles that each cycle starting with a lower erosional base. The grains have poorly-sorted, sub-angular to rounded and fine to medium sand sized. Sandstone is composed mainly of quartz (60 to 80%), feldspar (8 to 20%), terrigenous carbonates (5 to 30%) and rarely heavy minerals such as rutile, zircon and tourmaline (Figure: 9d- e).

Interpretation: Sandstones of this sub-environment are arkose, subarkose and calcilithite. Fining-upward cycles, cross-laminated, erosional base and interbedded with interdistributary deposits are thought to represent distributary channel deposits.

Interdistributary facies (TD-3b)

The interdistributary/bay deposits are composed of sand (25-75%), bioclast (5-30%) and mud (>15%). Mud includes terrigenous and carbonate types. Grains are siliciclastic, terrigenous carbonates and non-

terrigenous carbonates. The non-terrigenous carbonate grains are oyster, bryozoan, gastropod, pelecypod, *Miogypsina*, echinoderm and fecal pellet. Some samples have bioclasts up to 30% and the abundance of terrigenous sands is between 10 to 35%. The siliciclastic grains contain quartz (70-97%), feldspar (4 to 8%), angular to sub-angular, unsorted and fine sand sized. The terrigenous carbonate grains (20 to 45%) contain reworked pisoids and fossils with evidence of exposure, iron oxide stained. These deposits are overlain by black carbonate pebbles, anhydrite nodules, and evaporate casts filled with limey mud (Figure: 9f- i).

Interpretation: This deposits include quartz wacke, feldspathic wacke and lithic wacke which their characteristics indicate that they have been formed in a low-energy environment (Shinn, 1983), such as interdistributary environment. The change of grains and the abundance of bioclasts may be due to river flooding (high abundance of terrigenous grains due to high precipitation and climate change (Wright and Hine, 2005), and relative sea-level change (change in abundance of allochems, rate of restricted), and depositional setting relative to main channel. Pisoid and grains with iron oxide stained indicate the paleosol is formed in the exposure platform that reworked during the subsequent flooding (e.g., Tropeano and Sabato, 2005). The black carbonate pebbles, anhydrite nodules, and evaporate casts filled with limey mud are characterized of paleosol, too (e.g., Mack et al., 2003). The presence of pisoids and evaporate minerals reflect a semi-arid to arid condition in the region (Lasemi et al., 2012). Bay deposits are much more abundant in the upper Ahwaz sandstone member. This indicates, there has been river- dominated elongate-type delta. Elongate-type delta is formed in microtidal areas on the homoclinal ramp, similar to recent Mississippi delta.

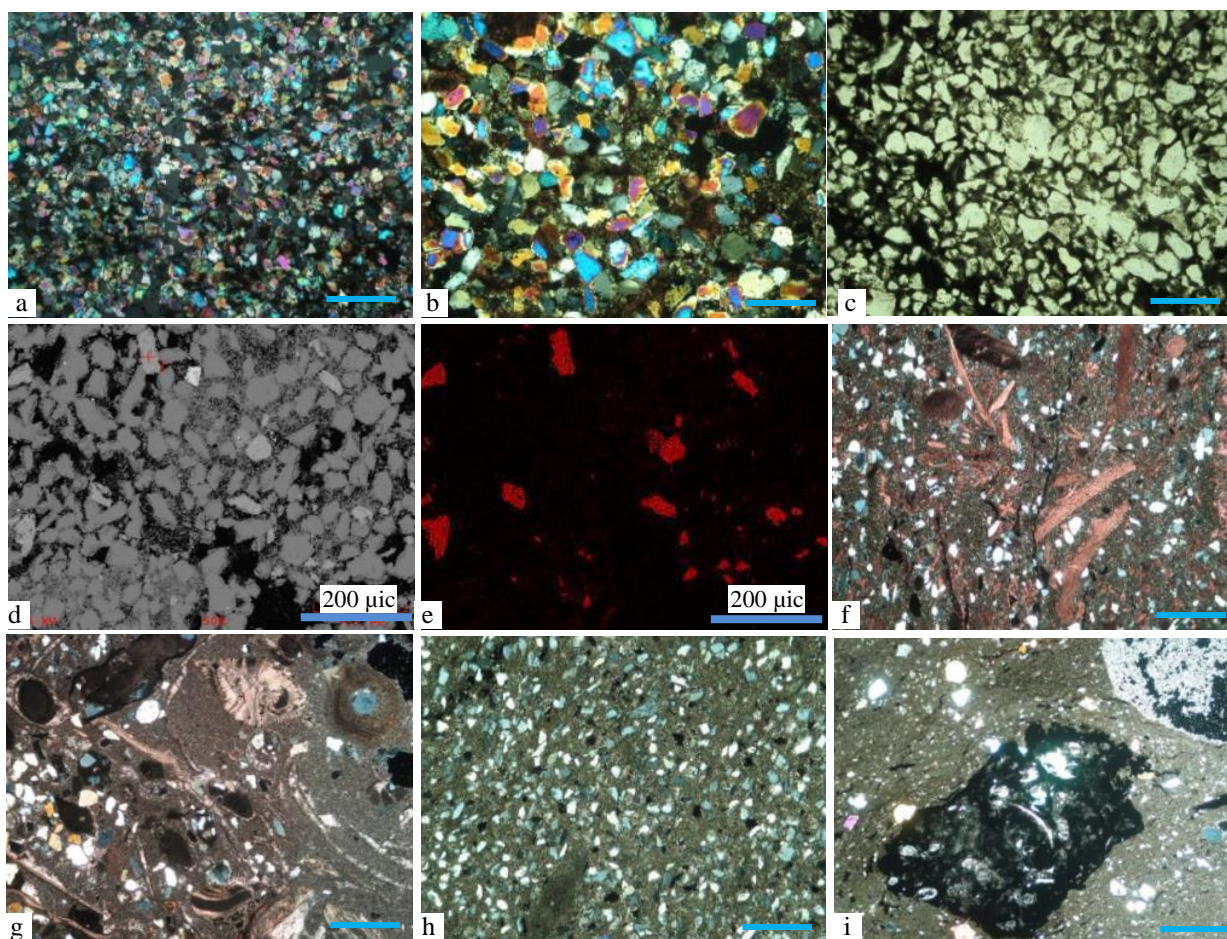


Figure-9: Delta facies (a- e). (a, b) Delta-front deposits, (a) feldspathic wacke, in the lower part of a coarsening-upward cycle and (b) subarkose, after 5 feet above sample 9a, ppl. (c) Subarkose facies which filled distributary channel, ppl. (d) Backscatter image of figure c. (e) Potassium map of sample d, red grains are K-feldspar. Interdistributary/bay facies (f-h). (f) Oyster bioclastic quartz wacke, xpl. (g) Lithic wacke includes reworked pisoid and bioclast with evidence of exposure, xpl. (h) Feldspathic wacke, xpl. (i) Pebbly mudstone bearing casts filled with limey mud, note black pebble has evidence of exposure, ppl (blue scale bar 1 mm long).

Crevasse delta facies (TD-3c)

There is a coarsening-upward thin deposit between interdistributary deposits with lag deposits at the base. These deposits grade upward from siltstone to sandstone with increasing sorting and roundness of grains. Sand grains are quartz (80-90%), feldspar (6-12%) and rock fragments (4-7%) (Figure: 10).

Interpretation: Sandstones of this succession are subarkose. The lag deposits are formed during flooding, and its coarsening-upward trend indicates restricted interdistributary environment that is filled by progradational sediments. Similar facies are interpreted as crevasse delta (e.g., Helland-Hansen, 2010)/small delta size.

Barrier island facies (TBi)

This facies is composed of coarsening- and thickening-upward, clean sandstone including sandstone and sandstone bearing bioclast. Grains include terrigenous and bioclasts. Its bioclasts are *Rotalia*, mainly, echinoderm and ditropha. The abundances of bioclasts are increased upward. The terrigenous sand sized includes quartz (90-97%) and feldspar (3-10%), with moderately well sorted and medium- to coarse-grained. The intergrains are completely filled by calcite cement (Figure: 11a, b).

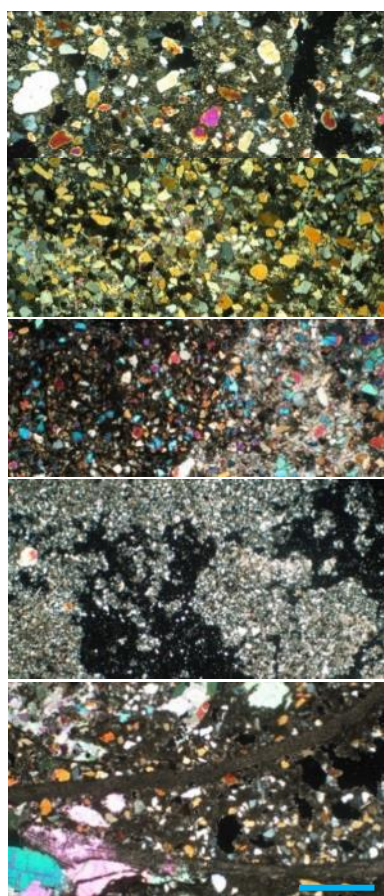


Figure-10. Sharp-based coarsening-upward (from shale to medium sized sandstone) crevasse deposits with basal erosional surface and lag deposits, xpl (scale bar 1 mm long).

Interpretation: The sandstones in this facies are dominantly subarkose/quartz arenite to bioclast quartz arenite. The coarsening- and thickening-upward, high maturity and the absence of mud are resulted from deposition in a high energy environment. This condition has been created by abandoned delta and retrogradation of river.

Lagoonal facies (TL)

This facies is characterized by muddy bioclastic sandstone to dark grey sandy bioclastic mudstone. Bioclasts include *Hetrosteigina*, ditropha, porecelaneous foraminifera, gastropod, and rarely echinoderm. The terrigenous grains, mainly quartz and feldspar, are angular to subangular silt to coarse sand sized (Figure: 11c, d).

Interpretation: The characteristics of this facies indicate a low-energy protected lagoonal environment, in which accumulation took place. The fining-upward deposits with sharp-based are interpreted as tempestite.

Beach facies (TB)

Beach facies contains of sub-rounded to rounded, coarse sand, mainly quartz, and terrigenous carbonate grains (>25%). It shows evidence of meteoric diagenesis such as dissolution and precipitation (Figure: 11e).

Interpretation: Facies TB is calcilithite and it is interpreted as beach deposits. It is formed by wave, after being inactive delta, most probably due to a rapid rise in sea level. Its poor compositional maturity indicates that this facies is affected by marine currents during a short period. This is a characteristic of river-dominated delta (Wright and Coleman, 1973).

Tidal flat facies (TF)

Deposits comprise of cross-laminated silt-sized quartz and peloids, sharp-based fining-upward cycles that overlain with limey mudstone and lime mudstone bearing tidal bounding and carbonate nodules (Figure: 11f).

Interpretation: This facies is interpreted to have been deposited on a tidal flat environment as suggested by the sedimentary characteristics (e.g., Lasemi et al., 2012).

Fluvial facies (TR)

There are some fining-upward cycles of sharp-based cross-bedded pebbly sandstones. Pebbles are shale particles, and sand grains are medium to coarse size, mainly of quartz (85 to 92%), and feldspar (<5%) with moderately sorting and rounded. Most of the intergrain spaces are filled by sparite and matrix (Figure: 11g).

Interpretation: This facies is pebbly subarkose and interpreted to have been deposited in a fluvial channel environment. The upward fining cycles is thought to be related to lateral channel migration. This is caused to erosion of the flood plain, in active side, and created pebbly shale. Some matrix is produced by squeezing of shale particles.

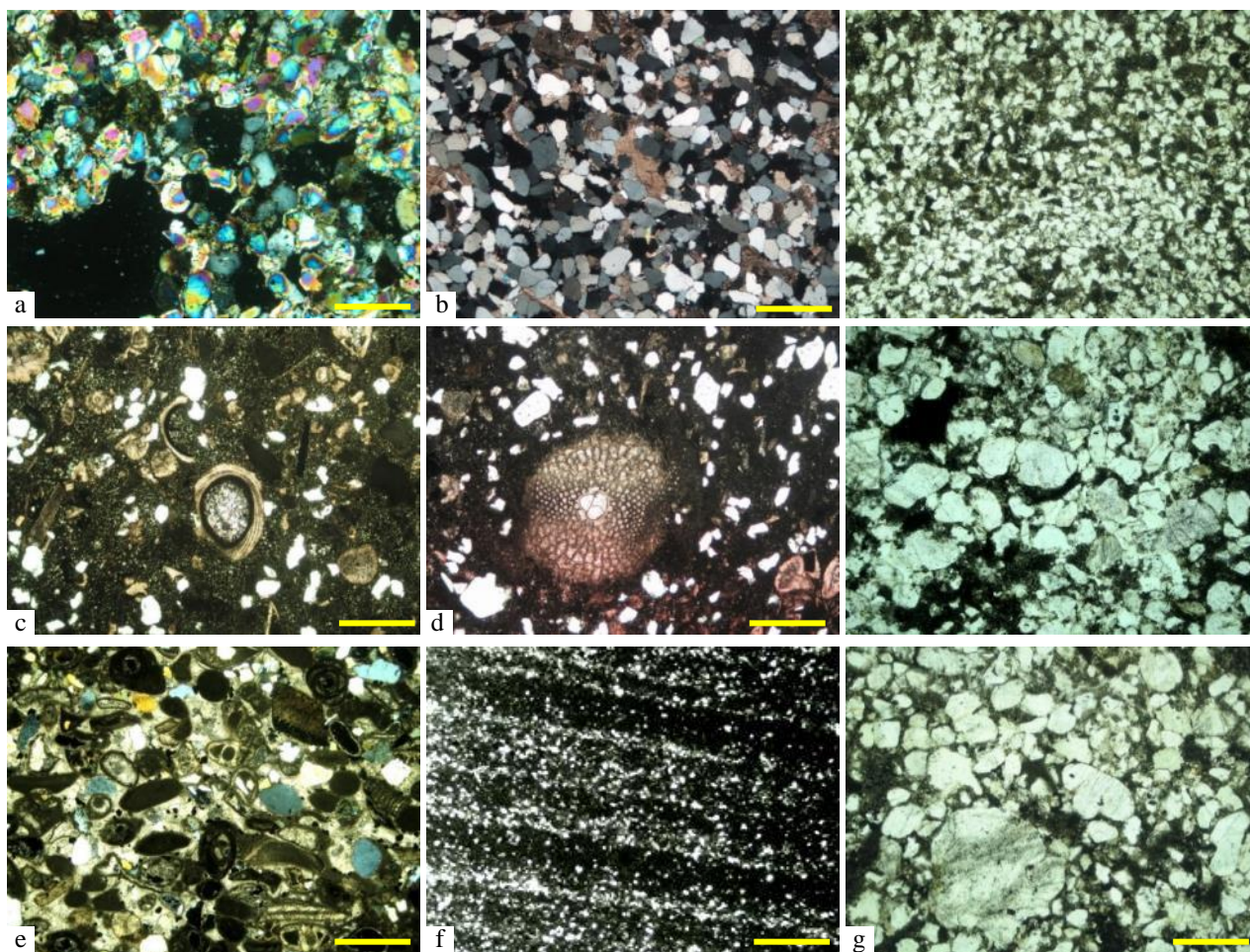


Figure-11: Barrier island facies (a). Quartz arenite, xpl. (b) Bioclastic quartz arenite, xpl. Lagoonal facies. (c, d). (c) Sandy *Ditropa* bioclastic mudstone, ppl. (d) *Hetrosteigina* bioclastic mudstone, ppl. (e) Beach facies/calclithite, xpl. (f) Tidal flat facies/cross-laminated siltstone, ppl. (g) Fining-upward deposits belong to fluvial channel, ppl (yellow scale bar 1 mm long).

Terrigenous facies in Shahzadeh-Abdollah section

The Asmari Formation in the Shahzadeh-Abdollah section contains the following terrigenous facies:

Channel chert arenite facies (TY)

This facies represents fining upwards with an erosional and sharp-based. It is located between bank deposits and incised channel deposits with trough cross-bedded. The sediments include terrigenous carbonate and siliciclastics grains. Grains are angular, pebble- to sand-sized, poor sorting and include chert, quartz and carbonate particles belong to bank with evidence of exposure (Figure: 12a- c).

Interpretion: This facies is interpreted to be filled channels deposits on fringing banks (e.g., Read, 1985). The trough cross-bedded belongs to prograding shoreline and indicates it forms above normal wave base, during sea-level fall. The Amiran Formation is the source for siliciclastic grains, and increase in thickness and abundance of siliciclastic beds in Kuh-Khami section, toward thrust zone.

Storm Facies

Numerous samples consist of normal grading (from grain-supported to mud-supported textures), sharp/erosive basal contacts, bioclasts debris, and mixed fauna, open marine-lagoonal fauna, are present throughout the Asmari Formation in the study sections (Figure: 12d, e).

Interpretion: These deposits according to Aigner (1985) are interpreted as storm-generated deposits/tempestite.

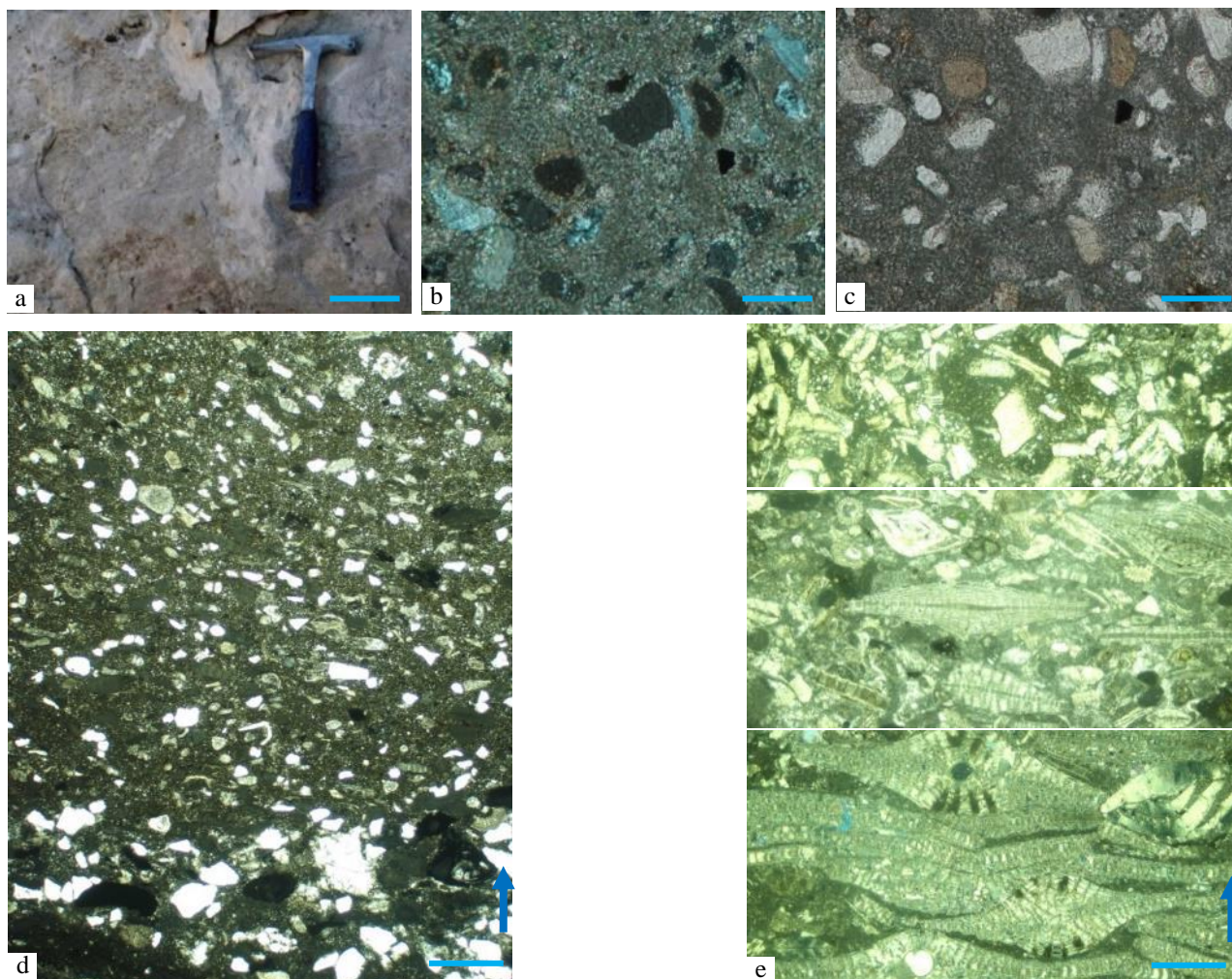


Figure-12: Terrigenous facies in Shahzadeh-Abdollah (a- c). (a) Trough cross-bedded. (b, c) Chert arenite, (b) in xpl and (c) in ppl. (d, e) Fining upward storm deposits, (d) Kuh-Asmari, (e) Kuh-Mish (blue scale bar 1 mm long and arrows towards top of thin section).

Depositional models

The present study indicates that the Asmari Formation is deposited in different platform. In Kuh-Mish section, the Asmari Formation is composed of deep and shallow open marine, barrier island (grainstone-boundstone), reef flat, lagoon and tidal flat deposits. The abrupt contact of the basinal succession of the Pabdeh Formation with the shallow marine Asmari Formation suggests break in slope in deeper water settings due to reactivation of the substrate fault gives rise to the model of a distally steepened ramp (e.g., Read, 1985), same as Mississippian deposits in Illonoies basin (Lasemi et al., 2003). The distally steepened ramp is supported by calciturbidites with components originating from the slope. The high rate of carbonates production is resulted to platform prograde onto the earlier distally steepened ramp, and transition it to the reef-rimmed platform (e.g., Read, 1985). In this section, the presence of numerous calciturbidites beds that are interbedded with pelagic facies, the absence of siliciclastic components, and existence of high energy facies, in the lower Asmari, indicate the existence a windward isolated-platform margin, similar to the Bahamian Platform, during their deposition. The isolated platform windward margins are ideal reservoir

facies. Siliciclastic grains are present in carbonate facies of the middle to upper Asmari which indicate of platform growth, gradual filling of the basinal setting and development of a homoclinal ramp type platform (similar to present day Persian Gulf) (Figure: 13a- c).

The facies E1-4 (shaly sponge spicule lime mudstone) in the GS31 indicates a starvation of platform during onset of lower Asmari deposits. The development of hardgrounds and related glauconitic- phosphate crusts in the GS31 area may be attributed to starved basin due to drowning platform. Stacking pattern of facies and existence of thin calciturbidites with bioclasts belong to slope, and good preservation of fossils in the upper part of slope environment reflects deposition is occurred in distally steepened ramp. The absence of barrier reef facies and abundance of lagoonal facies indicate a lee ward margin for the craton ward GS31, similar to the western margin of the Great Bahama Bank (Figure: 13a). Production and progradation of carbonate deposits were resulted to change platform to homoclinal ramp (Figure: 13c).

In the Shahzadeh-Abdollah four major depositional environments were identified in the Asmari Formation. These include tidal flat, lagoon, barrier island, shallow- and deep- open marine environmental settings. Here, the lower Asmari is composed of abundant of large *Nummulites* that mixing with variable amounts of quartz sand and miliolids. These features as well as existence channel on fringing bank indicate that there was no lagoonal environment between tidal flat and bank (e.g., Pomar, 2001). Therefore, these deposits were formed on flat-topped fringing bank in a high energy area, similar to fringing seagrass banks, Shark Bay (e.g., Read, 1985). Later, in the middle and upper Asmari, the fringing bank evolved into a ramp platform including shallow open marine, barrier island, lagoonal and tidal flat facies belts (Figure: 13d, e).

In the Asmari type section (Kuh-Asmari), the lower Asmari consists of evaporate facies with deep marine facies in its middle part suggesting deposition in an intra-shelf basin/barred basin, which was sealed off from the open sea during evaporate deposition. Shallow to deep open marine carbonate facies in the rest of the Asmari Formation in this section, records open marine conditions in a ramp setting. Only the upper middle and upper part of upper Asmari deposits in the Malavi, and upper part of upper Asmari deposits in the Abdanan sections are present (Figure: 13f, a), that they have been deposited in a homoclinal ramp..

The Asmari Formation in the Agha-Jari section includes various carbonate and terrigenous facies related to different depositional systems. The carbonates have been deposited on open marine, barrier island, lagoon and tidal flat facies belts. The terrigenous deposits, known as Ahwaz sandstone member, are related to shallow open marine, cut and filled valleys, barrier island, lagoon, tidal flat, beach, elongate and lobate deltas and fluvial environments (Figure: 13g, h).

Generally, these sandstones are divided into 5 (I to V from top to base) units. The units V and IV are formed large lenses and they are equivalent to the lower Asmari. The units I to III of Ahwaz sandstone member are equivalent to middle and upper Asmari carbonate sediments. Based on delta types in this study, the units V and IV were formed on mixed carbonate-terrigenous distally steepened ramp, but the units III to I, on the other hand, were formed on a homoclinal ramp (Figure: 14a- e).

Sequence stratigraphy

Sequence stratigraphy is methodology for the analysis of genetically related packages of sedimentary strata that was initially developed in the 1970's by researchers at Exxon. Seven 3rd-order depositional sequences are identified from stacking patterns and sequence boundary features in the study areas, except in Malavi (includes sequences 5, 7) and Abdanan (just includes sequence 7) sections.

Sequence 1: The lower boundary of sequence 1 conformity equivalent of unconformity in the GS31, and sequence boundary type 1 (SB1), paleosol/erosional surface, in other sections. In the Kuh-Mish section, sequence boundary is overlain by facies bearing reworked *Microcodiums* and large clasts. These facies are formed by erosion of exposure platform (Figure: 15a- d).

In GS31, the drowning platform is resulted to form shaly sponge spicule lime mudstone. In the Agha-Jari filled incised valley, Shahzadeh-Abdollah sandy carbonate, and in the Kuh-Asmari lag deposits (Figure: 15e) and the Basal anhydrite are covered paleosol and tufa facies (Figure: 15f) that all of them represent the

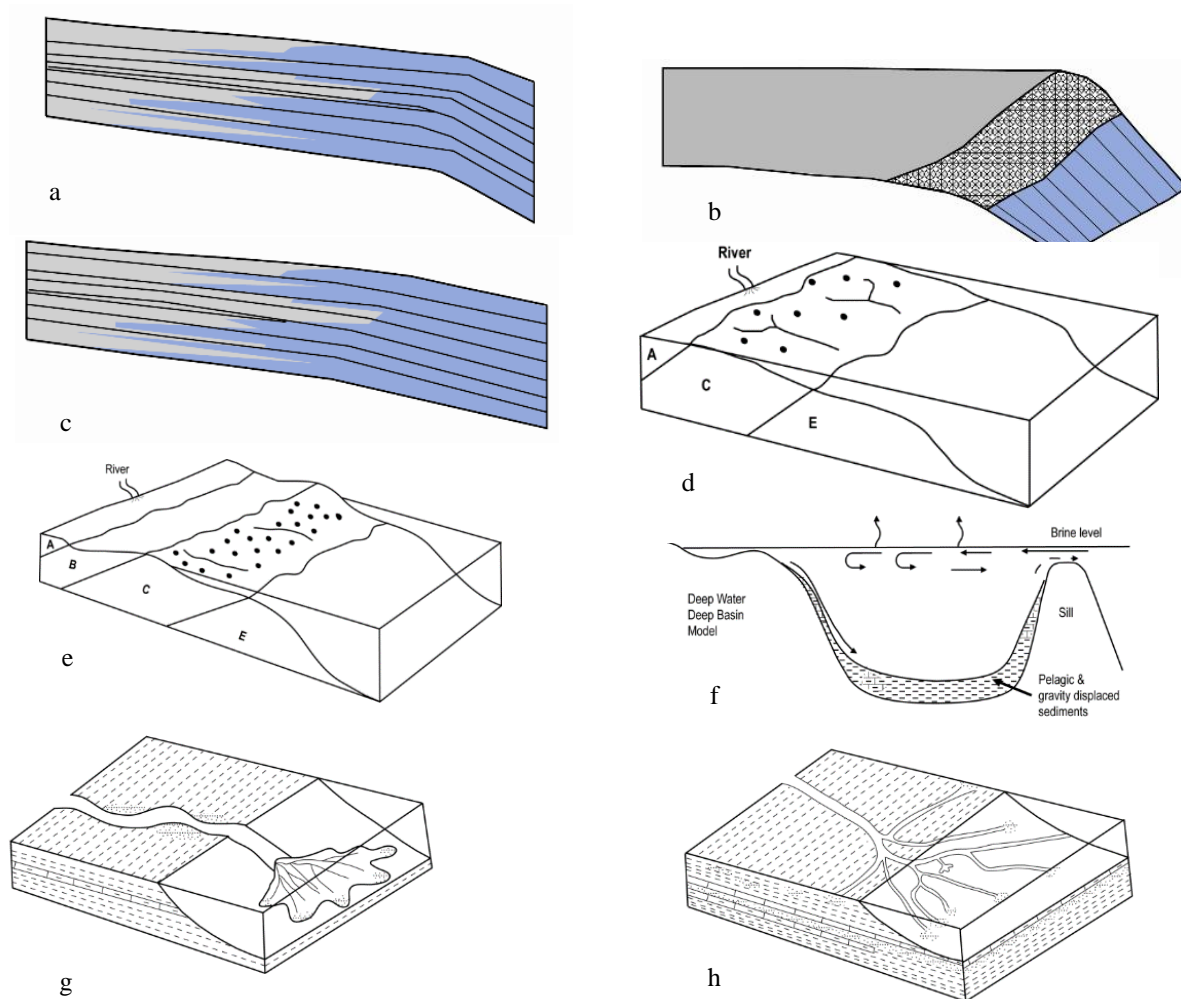


Figure-13: Depositional model for the Asmari Formation in the study areas. (a) Distally steepened ramp. (b) Shelf margin and (c) ramp platform, Kuh-Mish. Shahzadeh-Abdollah section (d, e). (d) Fringing bank and (e) Barrier bank complexes. (f) Barred basin, Kuh-Asmari. Agha-Jari (g, h). (g) Lobate delta and (h) elongate delta (after Amin-Rasouli, 2008).

lowstand systems tract (LST). The equivalents of these facies are sandstones deposits in the Tang-Sorgh and Rag- Sefid.

The transgressive systems tract (TST) is marked by deepening-upward cycles with the shallow open marine and barrier island facies in Kuh-Mish, fringing bank deposits in Shahzadeh-Abdollah, shallow and deep open marine facies in GS31, shale/prodelta facies (TD-1) in Agha-Jari and deep open marine facies in Kuh-Asmari sections. The maximum flooding surface (mfs) is characterized by shallow open marine bioclast wackestone in Kuh-Mish and Shahzadeh-Abdollah, marl/shale and planktonic foraminifera lime mudstone in Kuh-Asmari, and *Lepidocyclina* packstone in Agha-Jari sections.

The highstand systems tracts (HST) are composed of cycles of thickening-upward bioclast packstone and grainstone in Kuh-Mish and Shahzadeh-Abdollah, planktonic foraminifera lime mudstone and thin calciturbidites in Kuh-Asmari and GS31 (Figure: 15g), and bioclast packstone/grainstone in Agha-Jari sections. The fall in sea-level caused to occur interbedded of carbonate-terrigenous deposits with sharp and erosional contacts (Figure: 8a) in the Agha-Jari (e.g., Plint and Nummedal, 2000), reduce in thickness of layers and formed barrier islands facies bearing dissolution vuggy in the Kuh-Mish (Figure: 16a), restrict the platform and formed facies with evaporate casts in GS31 (Figure: 16b), sandy facies belongs to bank and lagoon in the Shahzadeh-Abdollah, restrict the sub-basins and formed carbonate deposits bearing siliciclastic grains in the Kuh-Asmari sections. The upper contact of sequence 1 is SB2.

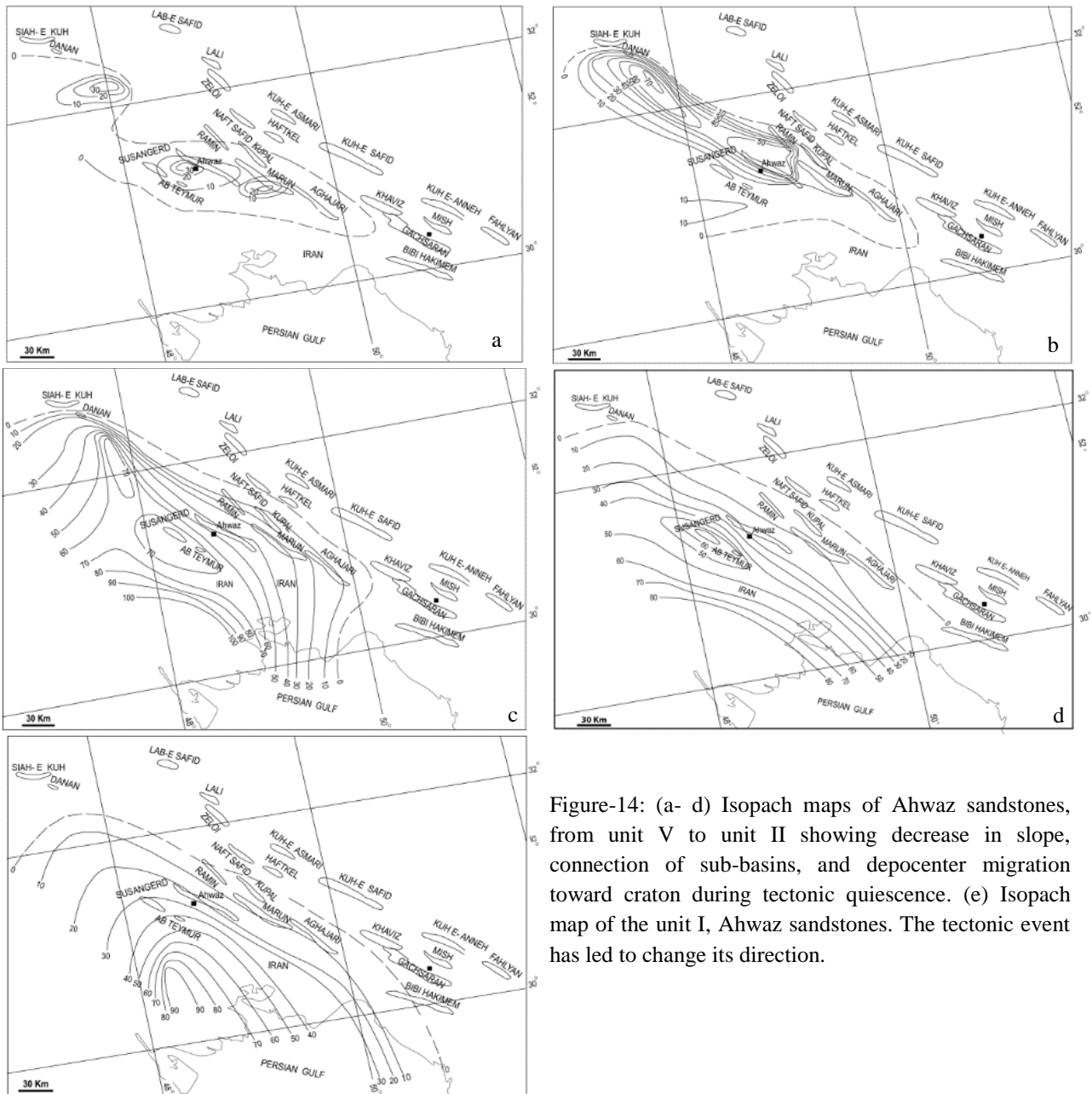


Figure-14: (a- d) Isopach maps of Ahwaz sandstones, from unit V to unit II showing decrease in slope, connection of sub-basins, and depocenter migration toward craton during tectonic quiescence. (e) Isopach map of the unit I, Ahwaz sandstones. The tectonic event has led to change its direction.

Sequence 2: The TST of sequence 2 starts with shallow open marine bioclast packstone in the Kuh-Mish and GS31, mixed *Nummolites*-miliolid and miliolid grainstone in the Shahzadeh-Abdollah, *Rotalia* packstone, coral rudstone and barrier island facies, bioclast packstone/grainstone, in Agha-Jari, and bivalve packstone and after that planktonic foraminifera lime mudstone in Kuh-Asmari sections.

The mfs consists of deep open marine lime mudstone in the Kuh-Asmari, and shallow open marine wackestone in the other sections. The HST is marked by shallowing-upward trend with shallow open marine wackestone/packstone in Kuh-Asmari, and thick grainstone (Figure: 16c)/reef and forereef facies in the other sections. During falling stage systems tract (FSST), lagoonal facies, with development of porosity, dolomitization, anhydritization and presence of quartz grains (Figure: 16d) in the Kuh-Mish, Shahzadeh-Abdollah and GS31, red-algae bounstone with evidence of exposure and development paleosol and facies change in the Agha-Jari (Figure: 16e, f), and sandy bioclast bearing echinoderm and planktonic foraminifera in the Kuh-Asmari sections are formed. The upper contact of this sequence is SB2 in entire sections.

Sequence 3: Sequence 3 starts with TST cycles. It consists of shallow open marine packstone in Kuh-Mish and GS31, lagoonal wackestone/packstone facies in the Shahzadeh-Abdollah, shallow open marine packstone to barrier island grainstone in the Agha-Jari, and wackestone/packstone belongs to shallow open

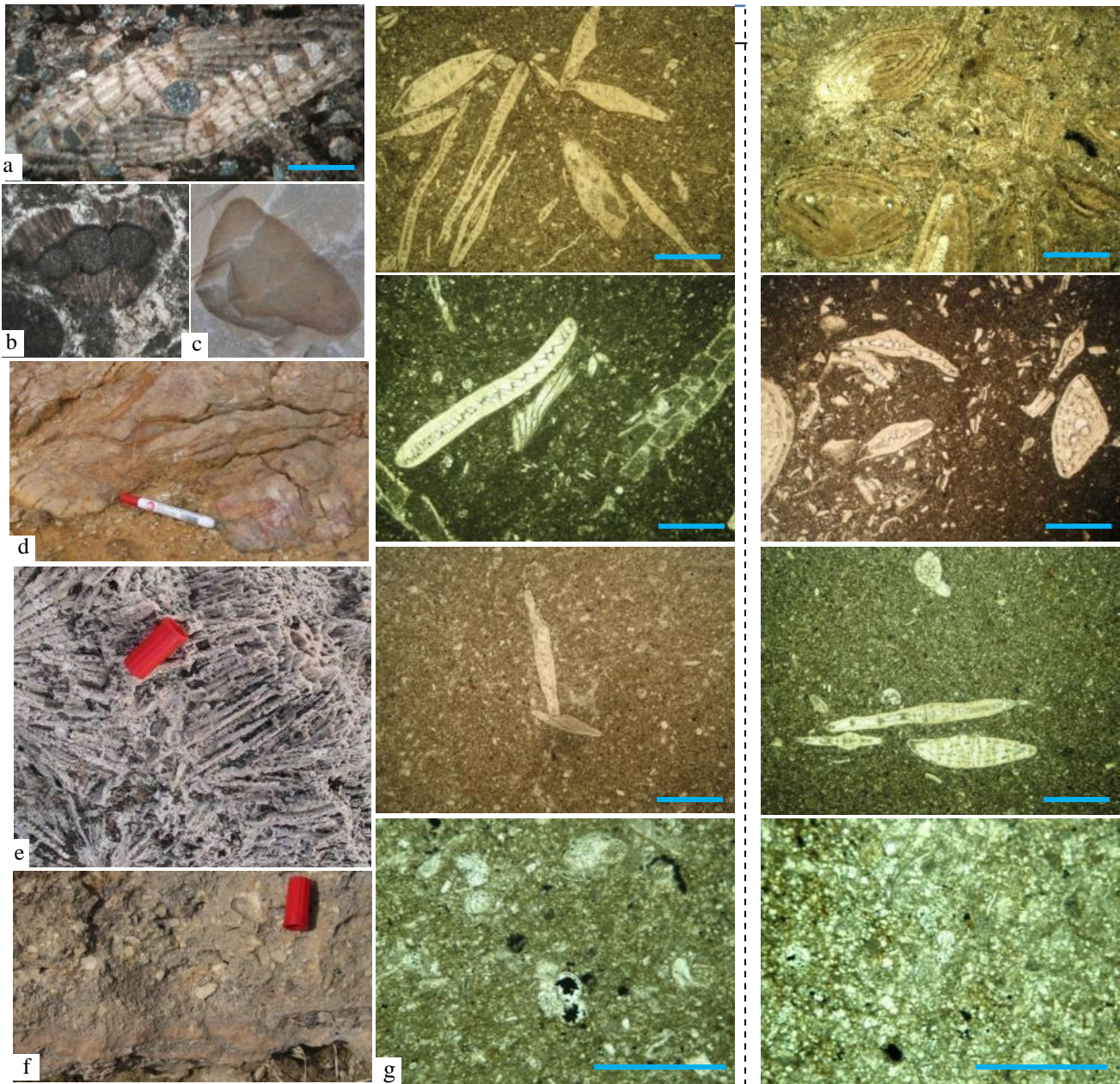


Figure-15: (a) Lag deposits at the base of *Nummolites* grainstone/ calclithite facies (xpl), Shahzadeh-Abdollah. (b, c) Reworked *Microcodium* (b) and fragments (c), at the base of the sequence 1, Kuh-Mish section. (d) Paleosol horizon above Pabdeh Formation, Kuh-Asmari section. (e) Tufa facies, Kuh-Asmari. (f) Lag deposits on the base of the sequence 1, Kuh-Asmari section. (g) Shallowing-upward cycles within sequence 1 in the GS31. The first cycle consists of planktonic foraminifera mudstone at the base, and *Operculina* bioclast wackestone at the top, ppl. The base of cycle 2 has been formed in the more shallow depth than cycle 1. These are characteristics of progradational system tracts LHST (blue scale bar 1 mm long).

marine in the Kuh-Asmari sections. The mfs includes *Operculina* wackestone in Kuh-Mish and GS31, red algae packstone in Shahzadeh-Abdollah, *Lepidosyclina* packstone in the Agha-Jari, and bioclast wackestone in the Kuh-Asmari. The HST is indicated by forereef, reef and barrier island bioclast grainstone in the Kuh-Mish and GS31, porcelaneous foraminifera packstone to grainstone in the Shahzadeh-Abdollah and Agha-Jari, and pellet bioclast (bryozoan, echinoderm and ditropa) wackestone in the Kuh-Asmari.

The falling of sea-level resulted to restricted sub-basins and formed pellet grainstone and paleosol in the Kuh-Mish, Shahzadeh-Abdollah and Kuh-Asmari, lagoonal packstone with vuggy pores in the GS31, and interbedded sandstone with thin fenestral limestone bearing evaporate cast in the Agha-Jari (Figure: 16g, h). The upper contact of this sequence is SB1 (in entire sections except Malavi and Abdanan sections) and coincides with the lower-middle Asmari boundary.

Sequence 4: Sea level rise starts with a pellet cyanobacteria bindstone and *Archaias* packstone/grainstone belongs to reef-flat in the Kuh-Mish, sandy *Archaias* miliolid packstone of lagoonal facies in the Shahzadeh-Abdollah, lag deposits and lagoonal wackestone/packstone to grainstone belongs to barrier island in the GS31, lagoonal facies with sandy quartz grains at the base and increased a variety of fossils and decreased sand grains towards up in the Agha-Jari, and lagoonal facies in the Kuh-Asmari sections. The mfs begins with shallow open marine bioclast packstone in the Kuh-Mish, Shahzadeh-Abdollah, Agha-Jari, GS31, and shallow open marine bioclast wackestone in the Kuh-Asmari sections. The HST facies are characterized by coral boundstone and miliolid grainstone in the Kuh-Asmari, and in the other sections with thick bedded porcelaneous foraminifera grainstone.

The FSST package consists of lagoonal facies bearing miliolid, *Astrolina*, ostracod, quartz grains in the Kuh-Mish and Shahzadeh-Abdollah, *Microcodium* and root cast in the GS31, quartz grains and lag deposits in the Agha-Jari, and lagoonal deposits bearing bioclast casts in the Kuh-Asmari sections (Figure: 16i- k). The upper contact of the sequence 4 is characterized by SB2 in all sections.

Sequence 5: This sequence exists in all sections except in Abdanan section. Its TST consists of sandy restricted lagoonal facies in the Kuh-Mish, Kuh-Asmari, Malavi and GS31, lag deposits and fining-upward cycles from pebbles to coarse sands with trough structure belongs to channel (Figure: 16l) and peritidal deposits bearing keystone in the Shahzadeh-Abdollah, and sandy bioclast packstone to grainstone in the lower part, and bioclast grainstone belongs to barrier island in the upper part in the Agha-Jari. In the mfs shallow open marine packstone, and during the HST porcelaneous foraminifera grainstone cycles with aggradational trend are formed in the all sections.

The FSST are characterized by bioclast packstone of restricted low energy lagoon, increased dolomitization and quartz grains, and exist red paleosol in the Kuh-Mish, Shahzadeh-Abdollah and GS31, peritidal cycles capped by sabkha and paleosol with honeycombed structure in the Agha-Jari (Figure: 17a, b), and lagoonal facies bearing quartz grains and evidence of meteoric diagenesis in the Kuh-Asmari sections (Figure: 18a- d). The Malavi section includes a small part of the sequence 5 that is capped by *Microcodium* horizon (Figure: 18e, f). The upper contact of sequences 5 is a SB1, in all sections except in Abdanan section.

Sequence 6: The lower boundary of this sequence coincides with the middle-upper Asmari boundary. The onset of sequence 6 is characterized by sea-level rise in all sections (except Malavi and Abdanan sections) (Figure: 18g). Shallow open marine facies include red algae patch reef/*Lepidocyclina* packstone (Figure: 18h) in the Kuh-Mish, lagoonal facies bearing siliciclastic grains in the Shahzadeh-Abdollah, peritidal facies in the Kuh-Asmari, and red algae packstone and thin bedded sandstone in the Agha-Jari sections. Thickness and grain sizes of the sandstone deposits are decreased towards up. The pelagic facies in the Dehdez, Tang-Ban and Tang-Pabdeh sections (e.g., Seyrafian, 2000) are equivalent time of these deposits.

The mfs are marked by shallow open marine bioclast packstone, in all sections. The bioclasts are *Miogypsina* in the Kuh-Mish and Shahzadeh-Abdollah, *Lepidocyclina* in the Agha-Jari, and *Hetrosteigina* and *Operculina* in the Kuh-Asmari. During HST are formed thick bedded ooid grainstone in Kuh- Mish and Agha-Jari, red algae/ porcelaneous foraminifera packstone-grainstone in the Shahzadeh-Abdollah and Kuh-Asmari sections. These facies are absent in the GS31, may be due to faulting. Sea-level fall is marked by restricted lagoonal and tidal flat facies with quartz grains and evidence of exposure in Kuh-Mish, Shahzadeh-Abdollah and Kuh-Asmari, and interbedded sandstone and carbonate with sharp contacts belong to lagoonal environment and delta system in the Agha-Jari sections. The upper boundary of sequence 6 is SB2.

Sequence 7: This sequence starts with lag deposits and dolomite bearing moldic porosity in the Kuh-Mish and Kuh-Asmari sections, respectively. They are capped by lagoonal wackestone-packstone cycles. In the Shahzadeh-Abdollah and Agha-Jari sections, the TST facies are marked by lagoonal facies include quartz grains in lower part. There is a transgressive conglomerate in the lower part of this sequence, above the upper contact of sequence 5, in the Malavi section. In the Abdanan section, the upper part of upper Asmari deposits

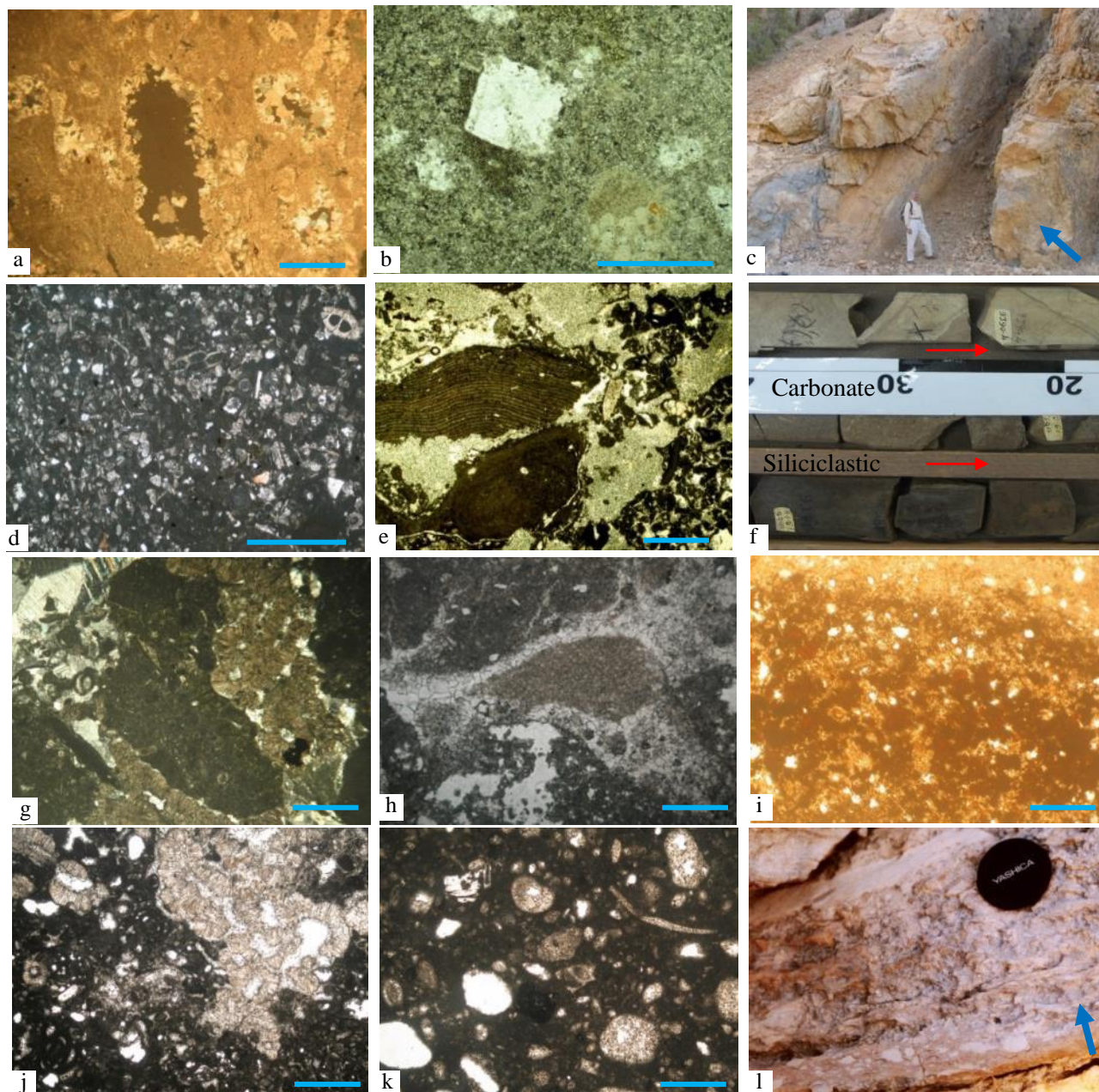


Figure-16: (a) Evidence of dissolution in the uppermost sequence 1, Kuh-Mish section. (b) Halite cast on the upper part of the sequence 1, GS31 section. (c) The aggradational normal-marine packstone/grainstone facies, HST of sequence 2 in the Shahzadeh-Abdollah section. (d) Mixed siliciclastic-carbonate deposits in the sequences 2 and 3 boundary, Shahzadeh-Abdollah section. (e) Red algae bearing evidence of soil formation, Agha-Jari. (f) Facies changes close to sequences 2 and 3 boundary, Agha-Jari. (g) *Microcodium* between sequences 3 and 4, Kuh-Mish section. (h) Lagoonal facies shows dissolution and precipitation in the sequences 3 and 4 boundary, Shahzadeh-Abdollah section. (i) Tidal flat facies, the appearance of fine quartz on the top of sequence 4, Kuh-Mish section. (j) Lagoonal facies containing *Microcodium* in the sequences 4 and 5 boundary, GS31. (k) Lagoonal facies containing root cast between sequences 4 and 5, GS31. (l) Fining-upward channel deposits, starting with conglomerate at the base (lag deposit) of sequence 5, Shahzadeh-Abdollah section (photomicrographs in ppl and arrows towards stratigraphic top).

are underlain by Pabdeh Formation with sharp contact. These deposits are capped by lagoonal and barrier island facies. In the study sections (except GS31), mfs is marked by echinoderm wackestone. This facies exist in other Gachsaran wells and all study sections. The absence of this facies and low thickness of the Asmari Formation in GS31 have been resulted, most probably, from elimination of deposits by fault. The upper part deposits of sequence 7 are not exposure in the Kuh-Mish and Kuh-Asmari. In the other sections, the FSST facies are marked by restricted lagoonal and tidal flat facies and they are unconformably (SB1) overlain by the Upper Miocene Gachsaran continental deposits (Figure: 18i).

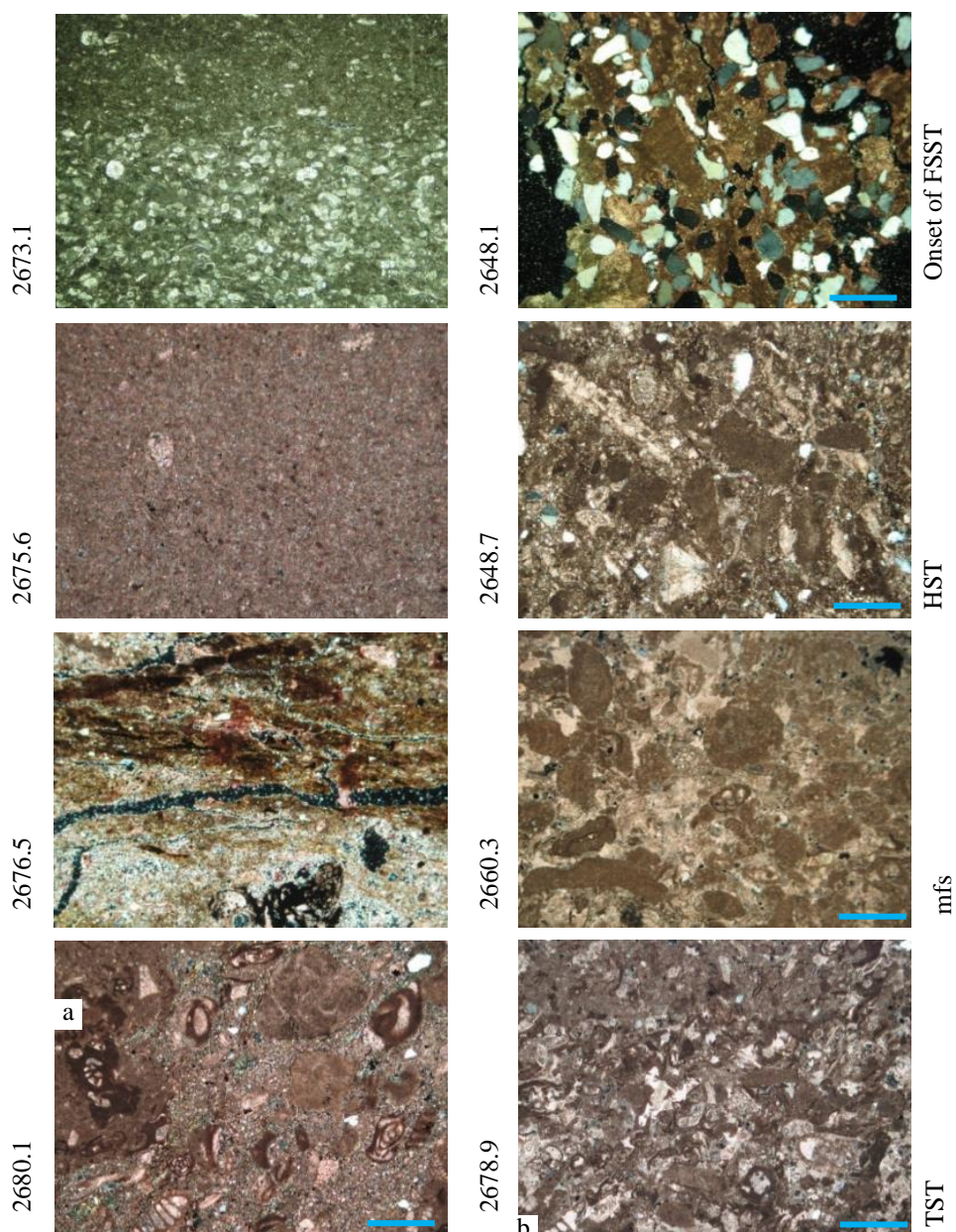


Figure-17: (a) Facies changes at the base of lagoonal cycles within TST of sequences 5. The sea level rise is caused to increase depth of lagoon and formed anoxic condition. Foraminifera planktonic have been entered into lagoon during upwelling current. (b) Change in characteristics of shallow open marine facies in different systems tracts of sequence 5, photomicrograph in ppl and numbers are depth in meter.

Tectonic events

Investigation of the Asmari Formation in different study sections represent the lower Asmari includes various facies in the different sections, e.g., change from the open basin to barred basin, existence megabreccia and turbidities facies in the upper part of the Pabdeh Formation, and appearance of Ahwaz sandstone. These changes show that the lower Asmari are deposited in various sub-basins with intervening highs. These different topographies have been occurred as a result of the reactivation of pre-existing basement faults and slope failure due to over-thrust loading related to the Zagros orogeny. The middle Asmari has similar facies in the study areas. This indicates presence of a basin-wide extensive platform. Such basins are formed as a result of erosion of highs and gradual infilling of the sub-basins during tectonic quiescence.

The lateral and vertical facies of upper Asmari, in study sections, show changes in distribution unit I of Ahwaz sandstone member (Figure: 14e), regression of the sea-level in the Malavi area and deposition of shallow open marine facies in other areas, except the Abdanan section. In the Dehdez, Tang-Ban and Tang-

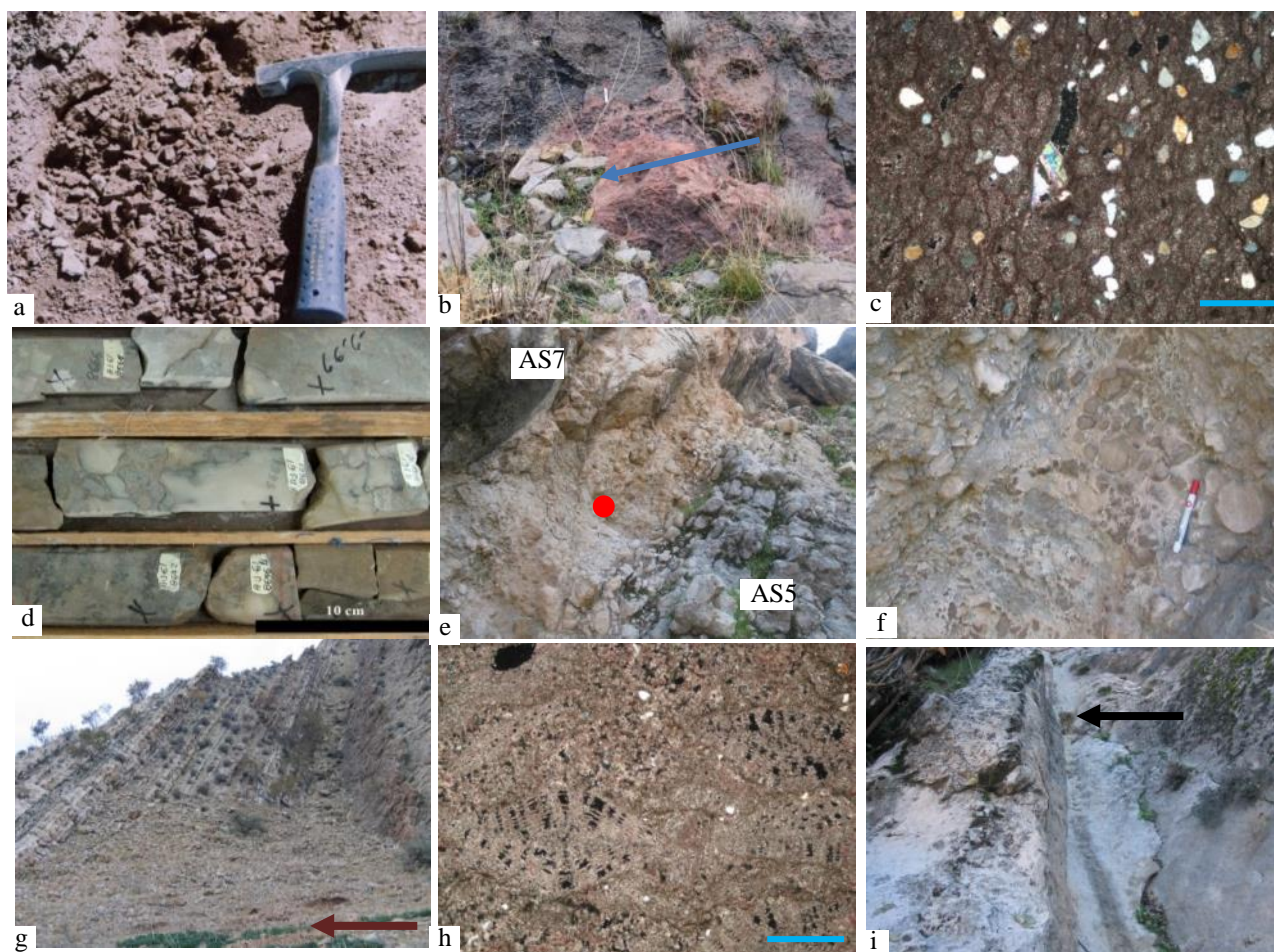


Figure-18: (a- d) Paleosol/red stein deposits between sequences 5 and 6. (a) Shahzadeh-Abdollah section. (b) Kuh-Mish section. (c) Paleosol with honeycombed structure (xpl), Agha-Jari. (d) A close up view from facies change close to the boundary, Agha-Jari. It shows abundance evaporate deposits, numbers indicate depth in meter. (e) Field photograph from sequences 5 and 7 boundary, Malavi section. Filled circle shows conglomerate at the top of sequence 5. (f) A close up view from conglomerate at the base of sequence 7, Malavi section. (g) Thinning-upward cycles/TST in the beginning of sequence 6, Kuh-Mish section. (h) *Lepidocyclina* packstone in the lower part of sequence 6 (ppl), Kuh-Mish section. (i) The uppermost Asmari Formation overlain by Gachsaran Formation, Malavi section view towards the east (arrows towards stratigraphic top).

Pabdeh areas have been deposited deep marine basinal facies during this time as a result of the foredeep migration due to over-thrust loading. The similarity of the upper Asmari sediments in the study areas indicate transgression of sea-level has occurred on the vast area of the Persian Gulf foreland basin, without reactivation basement faults, during early Burdigalian.

Age of identified sequences

Adams and Bourgeois (1967) and Zahedi-Nejad (1987) stated Upper Eocene age for the Ahwaz sandstone member. They have proposed Eocene to Miocene age for the lower deposits of Asmari Formation, and Upper Burdigalian age for the upper Asmari deposits. Several sedimentologists (e.g., Seyrafian, 2000; Vaziri-Moghaddam et al., 2005; Amirshahkarami et al., 2007; Mossadegh et al., 2009) have not been recognized the unconformities between Rupelian-Chatian, Chatian-Aquitania and Aquitania-Burdigalian. They stated these boundaries are conformity and identified 1 to 8 third-order sequences for entire Asmari Formation. In the study areas, there are paleosol horizons and significant unconformities in these boundaries.

To age determination of identified sequences of Asmari Formation have been used sequence stratigraphy, event stratigraphy, biozonation and compared them with global cycles of sea-level changes (Golonka and Kiessling, 2002). Thrust loading/tectonic activity during deposition of the Pabdeh Formation led to major changes in depositional environments and form lake deposits as indicated by tufa and microbialites in the Kuh-Asmari, drowning of platform in GS31 as indicated by hardground (E1-4), and incised valley and

submarine fans in the proximal and distal parts of the Ahwaz sandstone member, respectively. Such changes are occurred close to the 2nd-order sequence boundary and by considering the age of deposits (Oligo-Miocene) and their characteristics, they are interpreted to coinciding with high sea-level fall in late Rupelian. After that, sea-level rise and its transgressive resulted in the development of Basal anhydrite and upper sandstone of the unit V in the Kuh-Asmari and Agha-Jari sections, respectively. The existence of a Basal anhydrite as a tongue of the Kalhur member under Transitional zone, and a tongue of lower Asmari between the Kalhur member confirmed this mentioned. These observations, together with supporting Sr isotope dates (Ehrenberg et al., 2007; van Buchem et al., 2010), suggest that the age of the Basal anhydrite is latest Oligocene (e.g., Aqrabi et al., 2010). Tectonic activity and sea-level fall has been formed a significant sequence boundary in Iran, Italy, Newjersy of America and Brazil (Rouchy and Saint-Martin, 1992) during this time.

There is *Archaias* fossil above the lower contact of sequence 4. *Archaias* fossil age is Aquitanian, based on biozonation (Adams and Bourgeois, 1967) and Sr dating (Ehrenberg et al., 2007). Therefore, the unconformity on the base of the sequence 4 is Chattian-Aquitanian boundary. Also, thrust loading close to the boundary of sequences 5 and 6 was resulted to sea-level fall, lack of sequence 6 in the Malavi section, change in the distribution of the unit I of the Ahwaz sandstone member and deepening platform and formed deep open marine/basinal facies in the Dehdaz, Tang-Ban and Tang-Pabdeh, and shallow open marine in the other study sections. The sequence 6 includes *Borelis melo-curdica* and based on biozonation of Adams and Bourgeois (1967), this contact is Aquitanian-Burdigalian boundary. The unconformable contact of the upper Asmari with that of the Gachsaran Formation and the presence of 2 depositional sequences in the upper Asmari, in the Tang-Ban and Tang-Sapou sections (Mossadegh et al., 2009) and all study areas, except Malavi and Abdanan sections, that are equivalent to the Burdigalian global sea-level cycles suggest that the upper contact of the Asmari Formation coincides with the early - late Burdigalian boundary. So, the unconformities in the lower contact of the sequence 1, between sequences 3 and 4, between sequences 5 and 6, and in the upper contacts of sequence 7 are Rupelian-Chattian, Chattian-Aquitanian, Aquitanian-Burdigalian and late Burdigalian in age, respectively. The Chattian-Burdigalian sequences belong to second-order global cycles of the Upper Tejas I (UT I) and Upper Tejas II (UT II). Therefore the Asmari sequences (1-7) are correletable with UT I-1 to UT I-5 and UT II- 1 to UT II- 2 sequences (Golonka and Kiessling, 2002). Lasemi and Amin-Rasouli (2004) have recognized the same number (7 sequences) sequences for the Oligo-Miocene Qom Formation (back arc foreland basin) (Figure: 19).

Conclusions

(1) Facies analysis of the Asmari Formation has resulted in recognition of carbonate, terrigenous and evaporates facies. The carbonate deposits include deep and shallow open marine, barrier island, reef flat, lagoonal and tidal flat facies belts. The terrigenous facies related to shallow open marine, cut and filled valley, tidal flat, elongate and lobate deltas, barrier island, lagoon, tidal flat, beach and fluvial environments, and evaporate facies related to barred basin. This study indicates that the lower Asmari has various facies in different sections, due to deposition in the different topographies. In the middle and upper Asmari the variability of facies are decreased. Therefore, the facies/reservoir rocks in the lower Asmari have low laterally extensive and the identification of sub-basins help to recognition of new reservoirs. Also, the similarity facies of the middle and upper Asmari in the study sections indicate that they have been deposited on the extensive homoclinal ramp. Such deposits can typically form laterally extensive reservoir bodies.

(2) This study has led to recognition of two tectonic events. The first event, close to Rupelian-Chattian boundary, resulted in various facies reflecting over-thrust loading, forebulge migration towards the thrust zone and formation of various sub-basins with intervening highs. Continuous tectonic movement and craton-ward migration of the thrust belt formed a thicker and more rigid underlying crust leading to reduced subsidence rate and gradual infilling of the sub-basins. As a result of tectonic quiescence the forebulge and inter-basinal highs were eroded forming a basin-wide extensive ramp, during the Late Aquitanian time. The second tectonic event is occurred near Aquitanian-Burdigalian boundary, which resulted in over-thrust loading, regression of the sea in the Malavi area, deposition of deep open marine facies in the Dehdez and Tang-Pabdeh, and shallow open

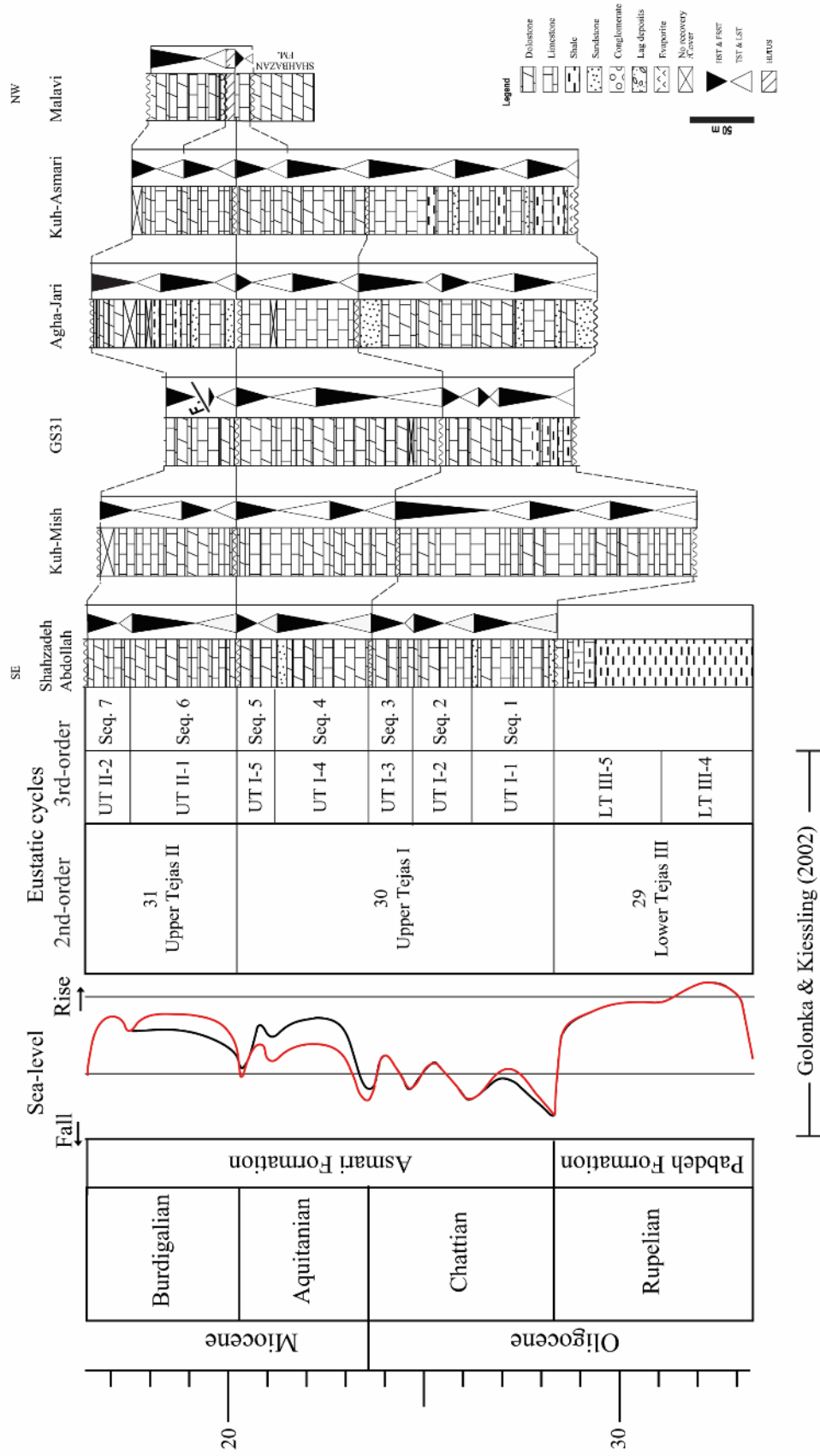


Figure-19: A correlation of the Asmari sequences recognized in the study areas with those from Golonka and Kiessling (2002).

marine facies in other areas, except Malavi and Abdanan sections. The similarity of the upper Asmari sediments in the study areas indicate transgression of sea-level has occurred on the vast area (without reactivation basement faults). These events have a significant role in development of the Ahwaz sandstone member. The similar tectonic events occur close to the boundary of second-order cycles.

(3) In the type section, the reactivation of basement faults, close to the Rupelian-Chattian boundary, has resulted in failure the slope, formed hinterland, deep basin, and changed the open basin to barred basin. Erosion of highland, most probably, has been caused to deposit megabreccia and turbidities facies in the upper part of the Pabdeh Formation.

(4) Sequence stratigraphy analysis has revealed the presence of two second-order sequences, which include 7 depositional sequences with both types 1 and 2 sequence boundaries in the all sections, except in the Malavi and Abdanan sections, that only 2 sequences (AS5 and AS7) and 1 sequence (AS7) have been recognized, respectively. This illustrates that, contrary to the previous suggestions, the Rupelian-Chattian (Pabdeh-Asmari), Chattian-Aquitania (lower-middle Asmari), Aquitania-Burdigalian (middle-upper Asmari) and Upper- Lower Burdigalian (Asmari-Gachsaran) boundaries are unconformable.

(5) The unit V of Ahwaz sandstone member includes submarine fan and cut and filled valley deposits that they were formed during FSST and LST, respectively. Therefore, based on mentioned above, the Rupelian-Chattian boundary (SB1) is located between the lower and upper part of unit V. So, the Asmari Formation in the distal part of Ahwaz sandstone member includes submarine fan deposits belongs to another sequence, uppermost Rupelian in age.

(6) In the study areas, thrusting and sea-level changes are not exactly synchronous; especially at the base of sequence 1 in the Kuh-Asmari and Agha-Jari sections. But, the Asmari sequences are well correlated with the global cycles of sea-level changes that have been suggested for passive margins and Qom Formation (back arc foreland basin). Therefore, in the formation of the Asmari depositional sequences, global sea-level changes have been more important than local/regional tectonic activity in the Persian Gulf foreland basin that is related to an active continental margin.

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