Chapter 2

The Geology of the Asmari Formation and Associated Units

2.1. Sequence Stratigraphy of the Zagros Fold-Thrust Belt

The latest Neoproterozoic through Phanerozoic stratigraphy of the Zagros fold-thrust belt has been revised in the light of recent investigations. The revised stratigraphy consists of four groups of rocks, each composed of a number of unconformity-bounded megasequences representing various tectonosedimentary settings. In the lowest group, ranging in age from latest Precambrian to Devonian (?), the uppermost Neoproterozoic to middle Cambrian rocks constitute a megasequence of evaporites, siliciclastic deposits, and interlayered carbonates, which were deposited in pull-apart basins that developed by the Najd strike-slip fault system (Alavi, 2004). This megasequence is overlain by a second one, Middle to Late Cambrian in age, which consists of shallow, marine siliciclastic and carbonate rocks representing deposition in an epicontinental platform (Alavi, 2004).

The overlying shales, siltstones, and partly volcanogenic sandstones of Ordovician, Silurian, and Devonian (?) age are local remnants of stratigraphic units that were extensively eroded during development of several major unconformities. The second group consists of two megasequences, one Permian and the other Triassic, composed of widespread, transgressive basal siliciclastic rocks and overlying evaporitic carbonates of an equatorial, epi-Pangean, very shallow platformal sea (Alavi, 2004). The third group is composed of four megasequences formed of shallow and deep-water carbonates with some siliciclastic and evaporite deposits, which accumulated on a Neo-Tethyan continental shelf during earliest Jurassic through late Turonian times. The fourth group comprises siliciclastic and carbonate deposits of a largely underfilled, northwest to southeast-trending, forward and backward migrating, late Cretaceous to Recent proforeland basin, which has evolved as an integral part of the Zagros orogen (Alavi, 2004).

This last group consists of three megasequences (IX, X, and XI) with distinctive lateral and vertical facies variations, which reflect specific tectonic events. Megasequence IX comprises uppermost Turonian to middle Maastrichtian prograding and retrograding siliciclastic and carbonate deposits, whose accumulations reflect emplacement (obduction) of ophiolite slivers and subsequent collisional events in the Zagros orogen (Alavi, 2004).
Megasequence X consists of uppermost Maastrichtian to upper Eocene siliciclastic and carbonate rocks, which deposited first progradationally in front of the Zagros orogenic wedge with reduced contractional tectonic activity, and then retrogradationally due to intensified thrust stacking in the interior parts of the orogen. Megasequence XI consists of Oligocene and lower Miocene carbonate strata deposited retrogradationally shortly after a period of intensified late Eocene thrust faulting in the deformational wedge, and an overlying succession of upward-coarsening, northeasterly-derived siliciclastic deposits of lower Miocene to Recent age which are composed of erosional by products of the southwest-vergent Zagros thrust sheets (Alavi, 2004).

2.1.1. Tectonic Setting

The Zagros orogen (Figure 2.1) is interpreted as the product of three major sequential geotectonic events: (1) subduction of the Neo-Tethyan oceanic plate beneath the Iranian lithospheric plates during Early to Late Cretaceous time, (2) emplacement (obduction) of a number of Neo-Tethyan oceanic slivers (ophiolites) over the Afro-Arabian passive continental margin in Late Cretaceous (Turonian to Campanian) time, and (3) collision of the Afro-Arabian continental lithosphere with the Iranian plates in Late Cretaceous and later times (Alavi and Mahdavi, 1994). The orogen is bounded to the northwest by the East Anatolian left-lateral strike-slip fault (EAF) and to the southeast by the Oman Line (OL)

(Falcon, 1969), which is here considered to be a transform fault inherited from the opening of Neo-Tethys. The orogen consists of three parallel belts:

(1) the Urumieh-Dokhtar magmatic assemblage (UDMA), which forms a subduction-related, distinctively linear and voluminous magmatic arc composed of tholeiitic calc-alkaline, and K-rich alkaline intrusive and extrusive rocks (with associated pyroclastic and volcaniclastic successions) along the active margin of the Iranian plates; (2) the Zagros imbricate zone (ZIZ) (the "Sanandaj-Sirjan Zone", as redefined by Alavi and Mahdavi (1994), after Stocklin, 1968a, 1977), which is a zone of thrust faults that have transported numerous slices of metamorphosed and non-metamorphosed Phanerozoic stratigraphic units of the Afro-Arabian passive continental margin, as well as its obducted ophiolites, from the collisional suture zone on the northeast toward interior parts of the Arabian Craton to the southwest; and (3) the Zagros fold-thrust belt (ZFTB),which forms the less strained external part of the orogen, and consists of a pile of folded and faulted rocks composed of 4 to 7 km of mainly Palaeozoic and Mesozoic successions overlain by 3 to 5 km of Cenozoic siliciclastic and carbonate rocks resting on highly metamorphosed Proterozoic Pan-African basement that was affected by the late Neoproterozoic–Cambrian Najd strike-slip faults (for example, Brown and Jackson, 1960; Moore, 1979; Agar, 1987; Husseini, 1988).

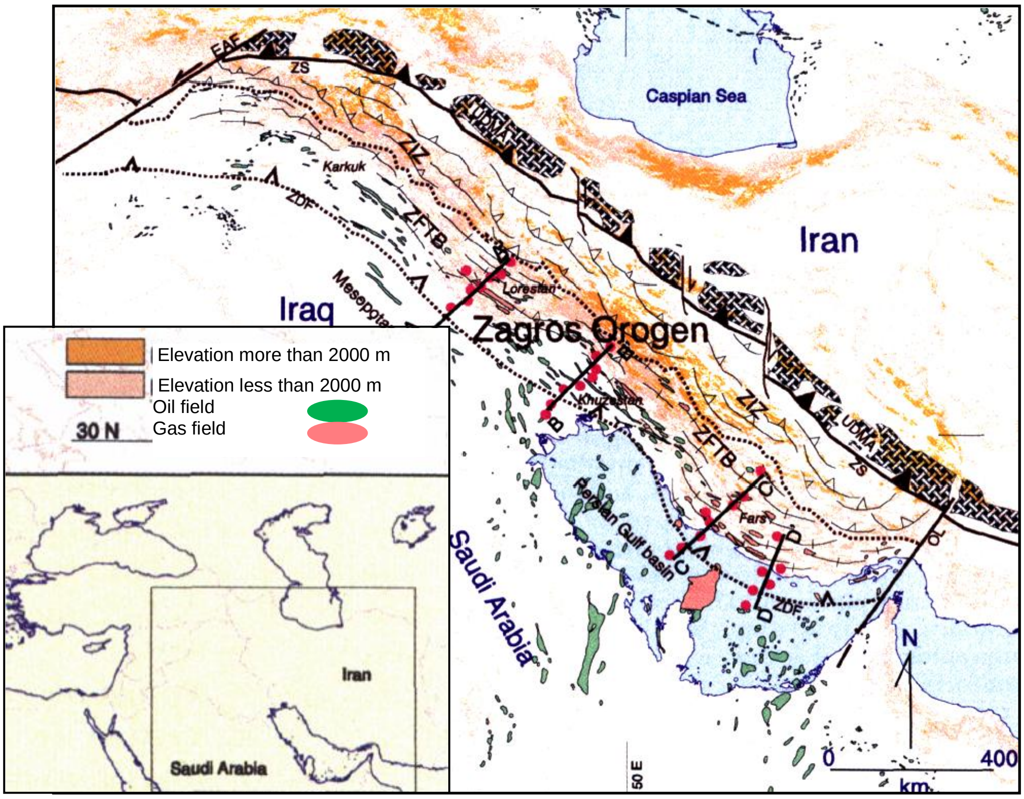


Figure 2.1. The Zagros orogenic belt and its subdivisions. Abbreviations; EAF – East Anatolian fault; OL- Oman line; UDMA – Urumieh-Dokhtar magmatic arc; ZDF – Zagros deformational front; ZFTB – Zagros fold-thrust belt; ZIZ – Zagros imbricate zone: ZS – Zagros suture; Red dots show location of the stratigraphic columns. Hydrocarbon fields of the region (oil in green and gas in pink) are also shown (after Alavi, 2004).

The southwestern boundary of the Zagros fold-thrust belt defines the present-day Zagros deformational front (ZDF), to the southwest of which deformation has not yet propagated (Alavi, 2004).

2.1.2. Stratigraphy

More than a hundred stratigraphic columns have been studied by Alavi and Mahdavi (1994) from both subcrop (well) and outcrop section in various parts of the Zagros belt. Based on this database and available published and unpublished stratigraphic, sedimentological, and petrographic information, as well as field and laboratory observations a description for each stratigraphic unit has been prepared (Alavi and Mahdavi, 1994).
The latest Neoproterozoic-Phanerozoic stratigraphy of the Zagros fold-thrust belt is represented by four major groups of rocks that are defined based on their tectonosedimentary features. Each group consists of a number of unconformity-bounded megasequences, each of which represents a discrete sedimentary cycle and consists of a number of lithostratigraphic units (Figures 2.2 and 2.3).

2.1.2.1. Lithostratigraphic Units of the Zagros Fold-Thrust Belt

2.1.2.1.1. Neoproterozoic to Devonian (?) Pull-apart Basin and Epicontinental Platform Deposits

Hormus (uppermost Proterozoic to Middle Cambrian): evaporites (mainly halite and anhydrite with subordinate gypsum near top), with interlayered volcanics in upperpart.
Barut (Lower Cambrian): gray stromatolitlitic dolomite (Alavi, 2004).
Zaigun (Lower Cambrian): red, purple, grey green nonmarin shale.
Lalun (upper Lower Cambrian): red and purple sandstones, siltstone, and shale with polymict pebble conglomerate near top.
Mila (Middle to lower Upper Cambrian): white orthoquartzite and quartzose sandstone, partly stromatolitic limestone and dolomitic (Alavi, 2004).
Ilbeyk (Upper Cambrian): grey to greenish grey, trilobite-bearing, micaceous marine shale.
Ordovician strata (including Lower to Middle Ordovician Zard Kuh): greenish gray trilobite-bearing and/or brachiopod-bearing, partly graptolitic shale.
Silurian strata (including ***Gahkum*** shales): unconformity-succession of dark gray to black, Orthoceras-bearing and graptolite-bearing, shale and thin sandstone. (Alavi, 2004).
***Devonian strata*:** unconformity-bounded succession of light gray, partly conglomeratic sandstone interbedded with siltstone and shale (Alavi, 2004).

2.1.2.1.2. Permian to Triassic Epi-Pangean Platform Deposits

Faraghan (Lower Permian): light gray polymict conglomerate overlain by cross-bedded quartzarenites, siltstone and red shale.
Dalan (Lower to Upper Permian); medium to thick-bedded oolitic to micritic dolomite, dolomitic limestone with intercalations of evaporites.
Kangan (Lower Triassic): gray Claraia-bearing and partly oolitic limestone and dolomitic limestone with intercalations of shale.
Khaneh Kat (Lower to lower Upper Triassic): thin bedded dark gray dolomite and dolomitic limestone.
Aghar (medial Triassic): thin interval (~50 m thick) of brown shale and silty argillite with thin intercalations of dolomite, anhydrite, and siltstone (Alavi, 2004).
Dashtak (Middle to Upper Triassic): massive to thick-bedded, dolomite, dolomitic limestone interbedded with evaporites (Alavi, 2004).

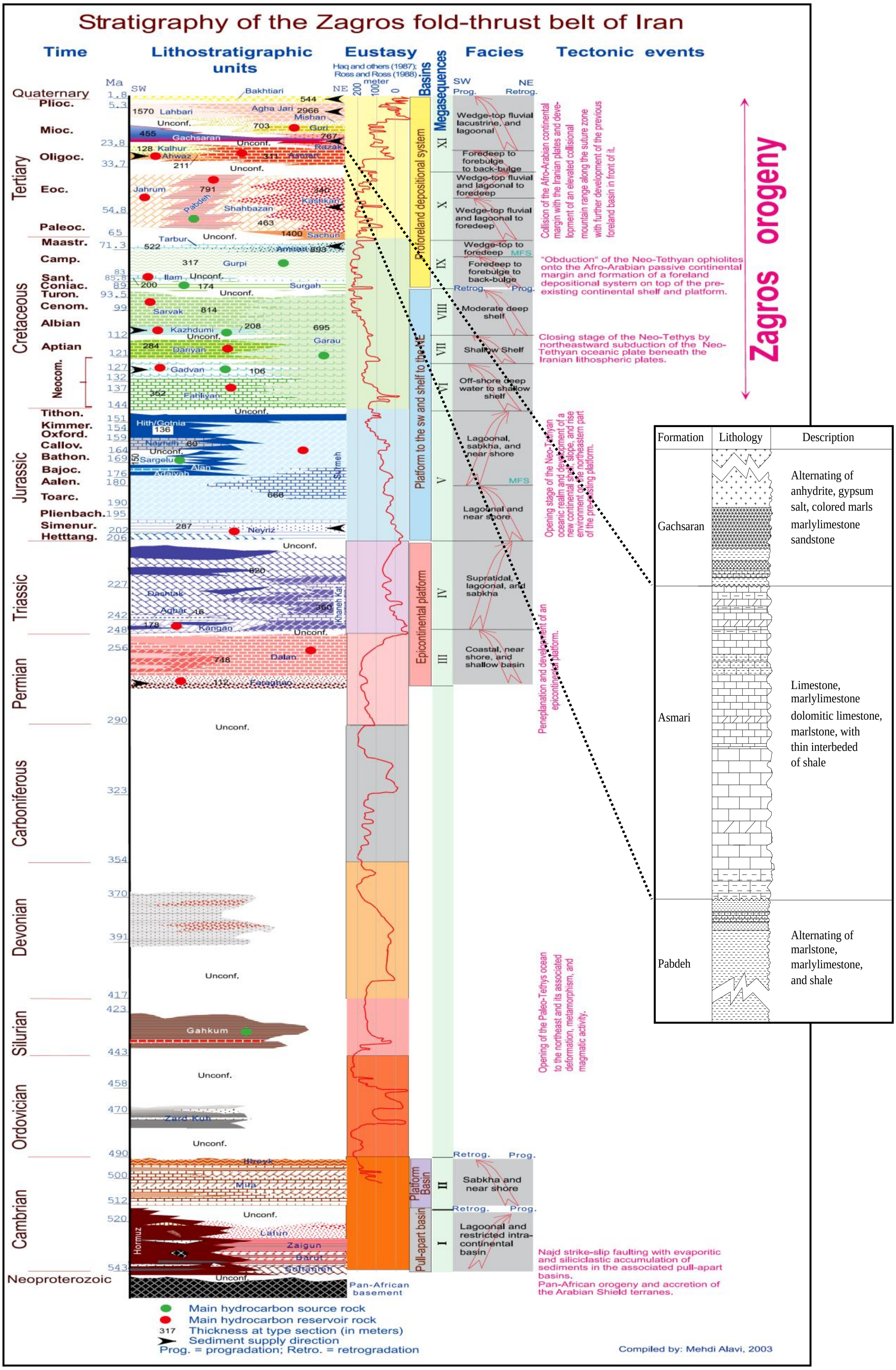


Figure 2.2. Stratigraphy column of the Zagros fold-thrust belt of Iran (after Alavi, 2003).

2.1.2.1.3. Jurassic to Upper Cretaceous Continental-Shelf Deposits

Neyriz (Lower Jurassic): thin-bedded dolomite and greenish gray shale grading upward to quartzose sandstone.
Surmeh (Lower to Upper Jurassic): massive gray Lithiotis-bearing dolomite and limestone (Alavi, 2004).
Sargelu (MiddleJurassic; Bajocian to Bathonian): thin interval of dark gray, organic-rich papery shale.
Najmeh (Middle to Upper Jurassic; Callovian to Oxfordian): cyclic alternations limestones (Alavi, 2004).
Alan/ Adaiyah (Upper Jurassic): evaporites (gypsum, anhydrite), interlayered with thin intervals of limestone and shale.
Hith/ Gotnia (Upper Jurassic): evaporites (anhydrite, halite).
Fahliyan (uppermost Jurassic-Cretaceous; Tithonian to Hauterivian): massive gray to brown oolitic and pelletal limestone.
Dariyan (Lower Cretaceous; upper Aptian): thick-bedded gray to brown, Orbitulina limestone.
Kazhdumi (Lower Cretaceous; Albian): dark, ammonoid-bearing limestone, interbedded with dark argillaceous limestone and shale (Alavi, 2004).
Garau (Lower to Upper Cretaceous; Neocomian to upper Toronian): dark gray to black radiolarian and ammonoids-bearing shale, limestone and marl.
Sarvak (Lower to Upper Cretaceous; upper Albian to upper Turounian): gray limestone.

2.1.2.1.4. Upper Cretaceous to Recent Proforeland Basin Deposits

Surgah (Upper Cretaceous; uppermost Turonian to Santonian): dark gray to brown, calcareous shale and limestone.
Ilam (Upper Cretaceous; Santonian to Campanian): light gray shallow-marine limestones with intercalations of black shale (Alavi, 2004).
Gurpi (Upper Cretaceous; Santonian to Maastrichtian): dark bluish gray Globigerina-bearing marl and marly limestone.
Amiran (Upper Cretaceous; Maastrichtian and probably older): dark gray to reddish brown conglomerate, sandstone, siltstone, shale (Alavi, 2004).
Tarbur (Upper Cretaceous; Maastrichtian): light gray, thick-bedded to massive, rudist limestone with a basal conglomerate.
Sachun (uppermost Maastrichtian to Palaeocene): green argillite, red shale, evaporites.
Kashkan (Palaeocene to Middle Eocene): dark reddish brown polymict conglomerate sandstone, siltstone, and red shale. (Alavi, 2004).
Shahbazan (Eocene): Brown Nummulites-bearing dolomitic limestone. (Alavi, 2004).
Pabdeh (upper Paleocene to lowermost Oligocene): thin-bedded gray and greenish blue calcareous shale and marl.
Jahrum (Paleocene to upper Eocene): gray dolomite interbedded with *Alveolina*-bearing and *Nummolites*-bearing dolomitic limestone (Alavi, 2004).
Ahwaz (medial to Upper Oligocene): well bedded, light gray, calcarenite interlayered with sandy limestone, sandstone and sandy to silty shale.
Kalhur (Oligocene, locally lower Miocene): evaporites interbedded with gray shale.
Asmari (Oligocene to lower Miocene): medium-bedded to thick-bedded, locally shelly or oolitic, Nummulites-bearing limestones (grainstone, packstone, wackestone) shoaling upward above a thin basal conglomerate from fine-grained (low-energy) deep-marine marly limestone to high-energy shallow-marine skeletal grainstone; composed of a number of

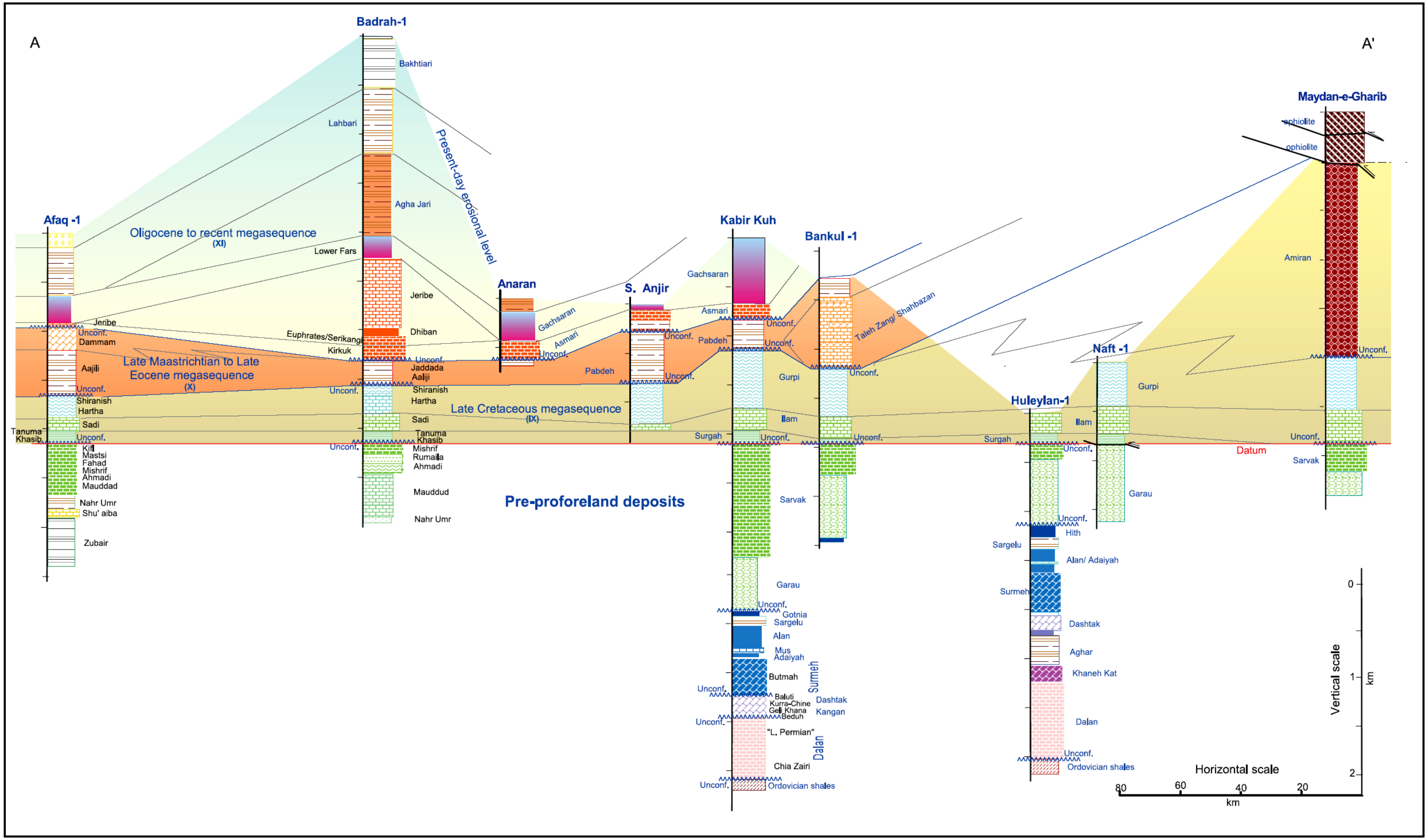
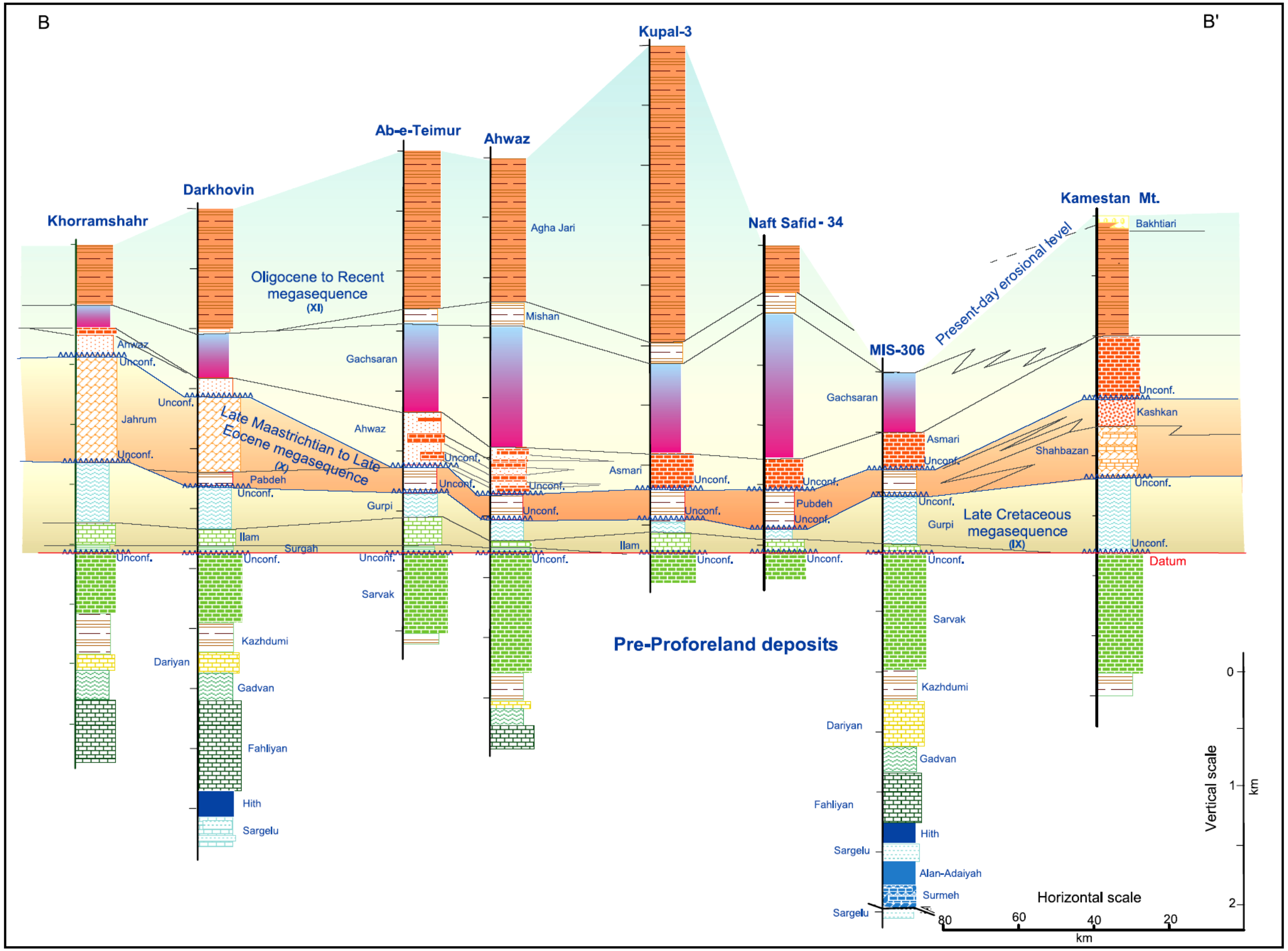


Figure 2.3., A, B, C, D. Four stratigraphic correlation profiles across the Zagros fold-thrust belt of Iran. See Figure 2.1 for locations of the stratigraphic profiles. Three megasequences (IX, X, and XI of Figure2.2) of the proforeland basin are distinguished. The stratigraphic columns restored to their pre-Zagros-deformation positions. The latest Turonian regional unconformity is chosen as the datum. Non-Iranian stratigraphic nomenclatures are shown in black (after Alavi, 2004).



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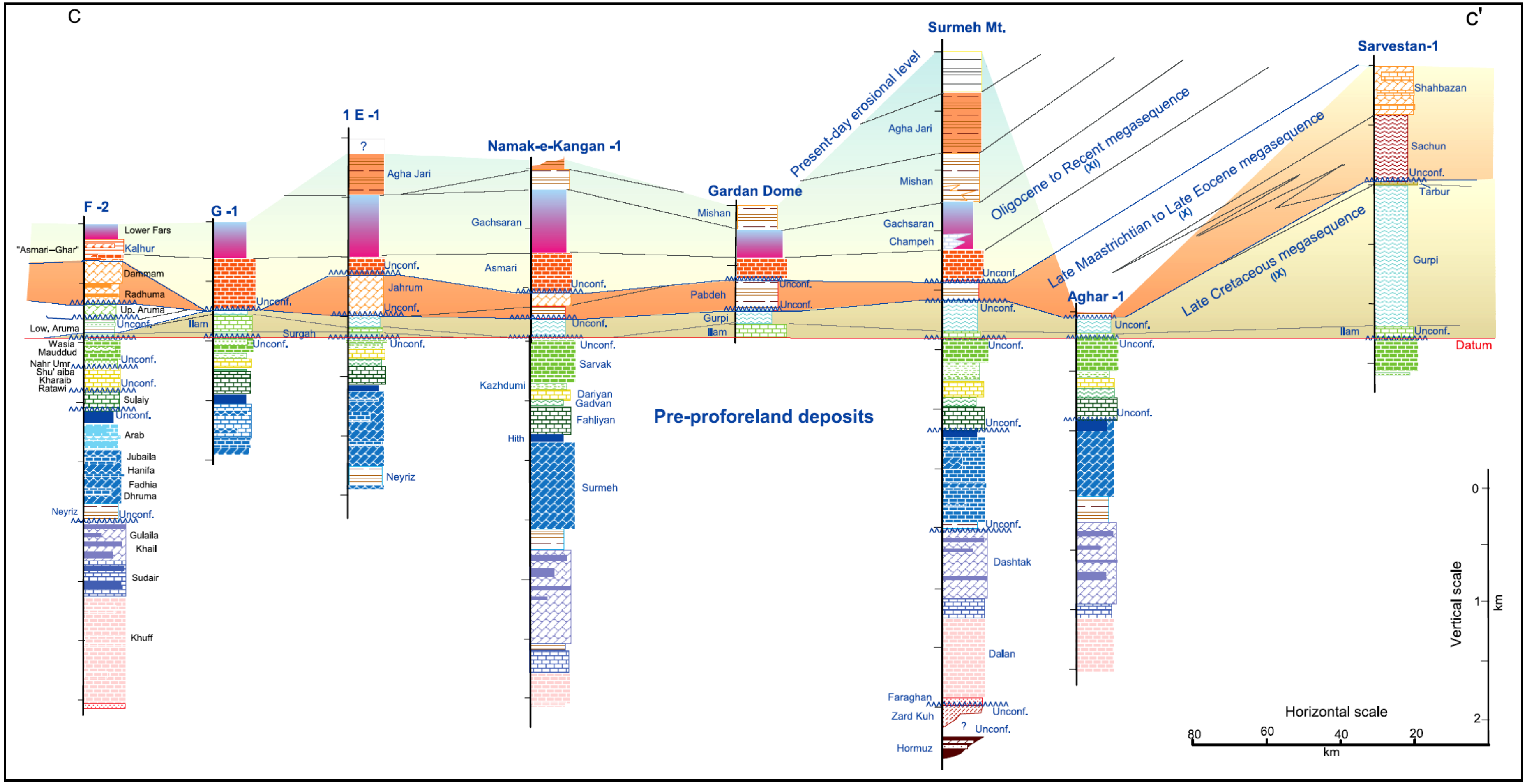

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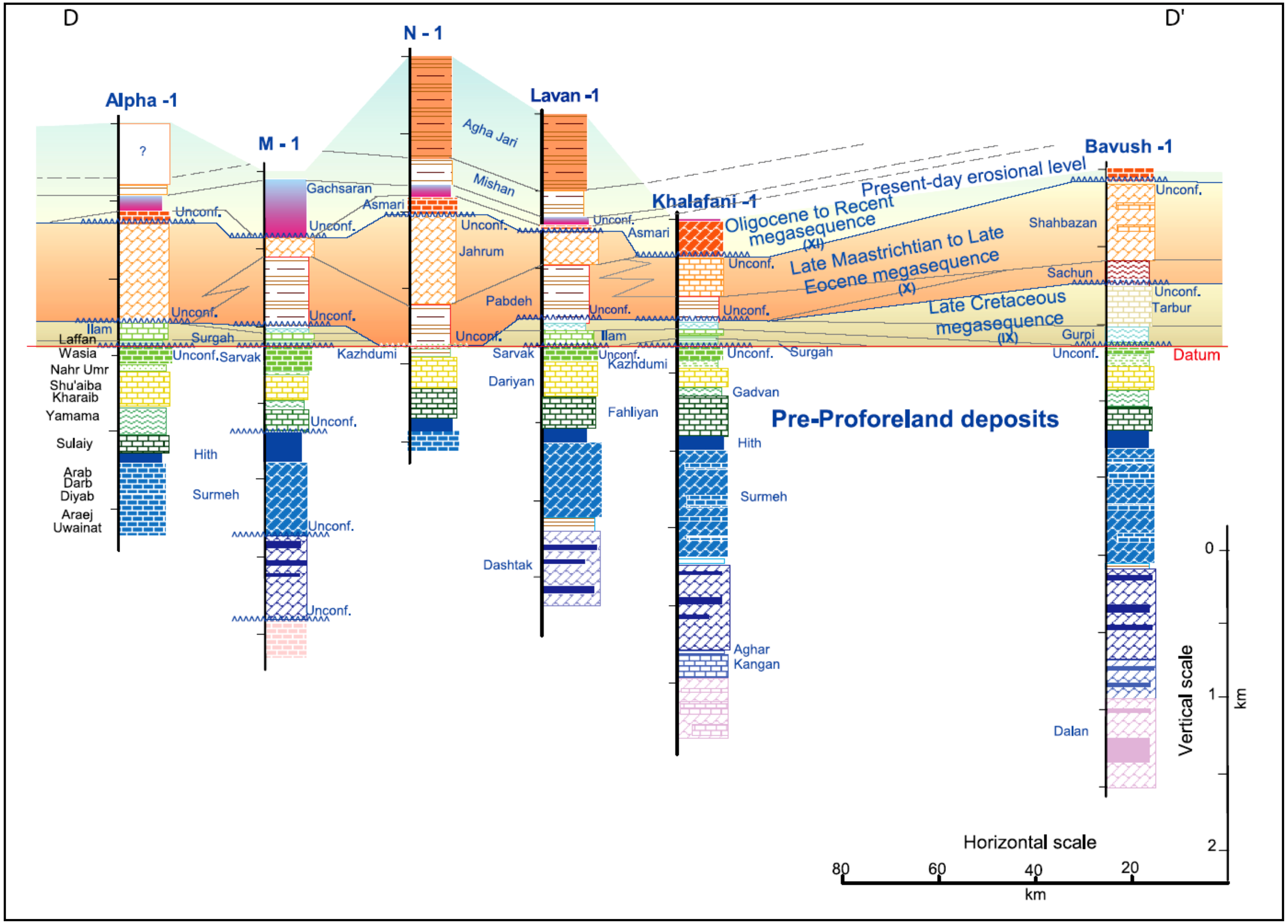

Figure 2.3. continued

sequences; an unconformity-bounded, highly prolific reservoir; interpreted as transgressive-regressive foredeep facies of the proforeland basin.
Razak (Oligocene to lower Miocene): variegated (gray, red, green), including polymict conglomerate, argillaceous limestone; interfingers with Asmari limestones toward the southwest, and also interfingers with and Asmari limestones toward the southwest, and interfingers with lower Gachsaran evaporitic beds to the northeast; deposited in the distal wedge-top depozone of the proforeland basin.
Gachsaran (lower Miocene): variable thickness and lithology including alternations of gray evaporites (gypsum, anhydrite, subordinate halite), dark red shale, gray to red marl, sandstone and locally conglomeratic.
Mishan (lower to middle Miocene): gray marl, calcareous shale and sandstone (Alavi, 2004).
Agha Jari (upper Miocene to Pliocene): composed of carbonate-clast and polymict conglomerate, calcarenite, gray sandstone, siltstone and marl.
Lahbari (upper Miocene to Pliocene): calcareous argillite, siltstone and sandstone.
Bakhtiari (Pliocene to Pleistocene): massive to thick-bedded polymict conglomerate, sandstone, siltstone, and shale. (Alavi, 2004).

2.2. Stratigraphic Units of the Asmari Formation

2.2.1. Lithostratigraphic Units

The name Asmari Formation is derived from Mount Asmari in southwest of Masjed Soleyman, northwest Haftgel in the Zagros Fold belt (Thomas, 1948). The Oligo-Miocene Asmari Formation of the Zagros Mountains of southwest Iran is one of the world's most important reservoirs. Despite this, its sedimentology has received relatively little attention, particularly in terms of outcrop studies. This is surprising, as it can be examined in exposures within ravines cutting through the huge and striking whaleback anticlines that make up the Zagros fold belt. Many of these exposures occur close to existing fields, allowing the opportunity to see the reservoir at surface.

The Asmari Formation lithologically comprises medium-bedded to thick-bedded, locally shelly or oolitic, Nummulites-bearing limestones (grainstone, packstone, wackestone) shoaling upward above a thin basal conglomerate from fine-grained (low-energy) deep-marine marly limestone to high-energy shallow-marine skeletal grainstone; composed of a number of sequences; an unconformity-bounded, highly prolific reservoir; interpreted as transgressive-regressive foredeep facies of the proforeland basin.

Lithostratigraphic units of Asmari Formation were introduced by Adams and Bourgeois (1965). These units coincide with biostratigraphic units of Asmari Formation. The Asmari limestone is typically around 500 m in thickness, and is generally divided into three parts:

- The Lower Asmari is marly in character near the base and overlain by foraminiferal and coralline algal limestones
- The Middle Asmari comprises dolomitised, lagoonal limestones
- The Upper Asmari is more evaporitic.

The detailed sedimentological data collected during the fieldwork has been used to develop a sequence stratigraphic framework, subdividing the Asmari limestone into four cycles, and then into 33 subordinate cycles. This framework has then been applied regionally to explain the distribution of lithofacies within the Asmari Formation across the Zagros. The deposition of the contemporaneous Ghar and Ahwaz sandstone members is examined, suggesting that the northeastward progradation of these sand bodies may have been controlled by relative changes in sea level. This may in turn allow the potential stratigraphic position of low-stand wedges to be predicted. The Ahwaz Asmari formation (Figure 2.4 and 2. 5) has 16 wells that have recovered cores. The mixed siliciclastic/ carbonate reservoir has undergone post depositional diagenesis, which have had an impact on reservoir characteristics. Calcite cementation and dissolution, dolomitization and particularly precipitation of anhydrite cements have destroyed porosity in both the carbonates and siliciclastic sands in the Ahwaz field. In this oil field, the Lower Asmari sands were deposited in a restricted area during sea-level Low-stands, while the Middle and Upper Asmari were deposited over a widespread carbonate ramp and contain Transgressive and High stand sands. The development of the thick Kalhur evaporites to the northwest has been addressed in Figures 2.4 and 2.6.

A relatively 15º angular unconformity of late Eocene-early Oligocene age occurs between the Pabdeh and Asmari formations about 75 km west of Shiraz along the northeastern part of the Zagros Simply Folded Zone (Tectonic movement locally folded and uplifted the Pabdeh Formation exposing it to erosion along the crests of anticlines before this unconformity was buried beneath the Asmari Limestone). However, to the NE of this unconformity, the shelf deposits of the Jahrom Formation (time-equivalent of the Pabdeh Formation) do not show this relationship (Motiei, 1993).

Instead, they have been exposed to subaerial weathering (James & Wynd 1965; Mina et al., 1967; Motiei 1993) ever since the onset of this tectonic movement. The unconformity between the Pabdeh and Asmari Formation and its weathering that this phase of orogeny began with a few individual folds and uplifted the area to the northeast at the end of the Eocene.

In many places within the Simply Folded Zone of the Zagros (e.g. 120 km west and 5 km east of Shiraz), the Razak Formation onlaps the Asmari Formation. One of the most obvious exposures of this onlap crops out some 100 km south of Shiraz. In this locality, the top 20 m of the Asmari Limestone exhibits palaeo-weathering along joints suggesting subaerial exposure of the Asmari near the crest of an anticline. A monomict conglomerate with clasts composed only of the Asmari Limestone occurs at the top of the Asmari Limestone 5 km east of Shiraz (Fars Province). Similar conglomerates are reported at the same stratigraphic level in the northwest Zagros of Iraq (Motiei, 1993). Such onlaps and conglomerates are due to gentle movements at the end of Asmari times (Burdigalian). They indicate that particular anticlines capped by the Asmari Formation reached wave-base or even subaerial conditions in these areas. Hence, present outcrops of the Asmari Formation in these areas of the Simply Folded Zone record local erosion of highs uplifted by folding so that younger sediments were deposited only along syncline axes (Hessami et al., 2001).

In this part, the stratigraphic relationships between various units of Asmari Formation and also single stratigraphic columns (Figures 2.5 to 2. 8) for each member at different localities in Zagros region have been introduced (see Figure 2.4. for location).

Recently, some research has been done on the stratigraphy of the Asmari Formation in the Zagros region. For example Nadjafi et al. (2006) studied depositional history and sequence stratigraphy of outcropping tertiary carbonates in the Jahrum and Asmari Formations in Shiraz area (Fars Province). They show that the Asmari Formation rests on the thin bedded limestones/dolomites of the Jahrum Formation (Palaeocene-Eocene) and reported on the lithofacies characteristics of these two formations using data from three measured outcrop sections in study area.

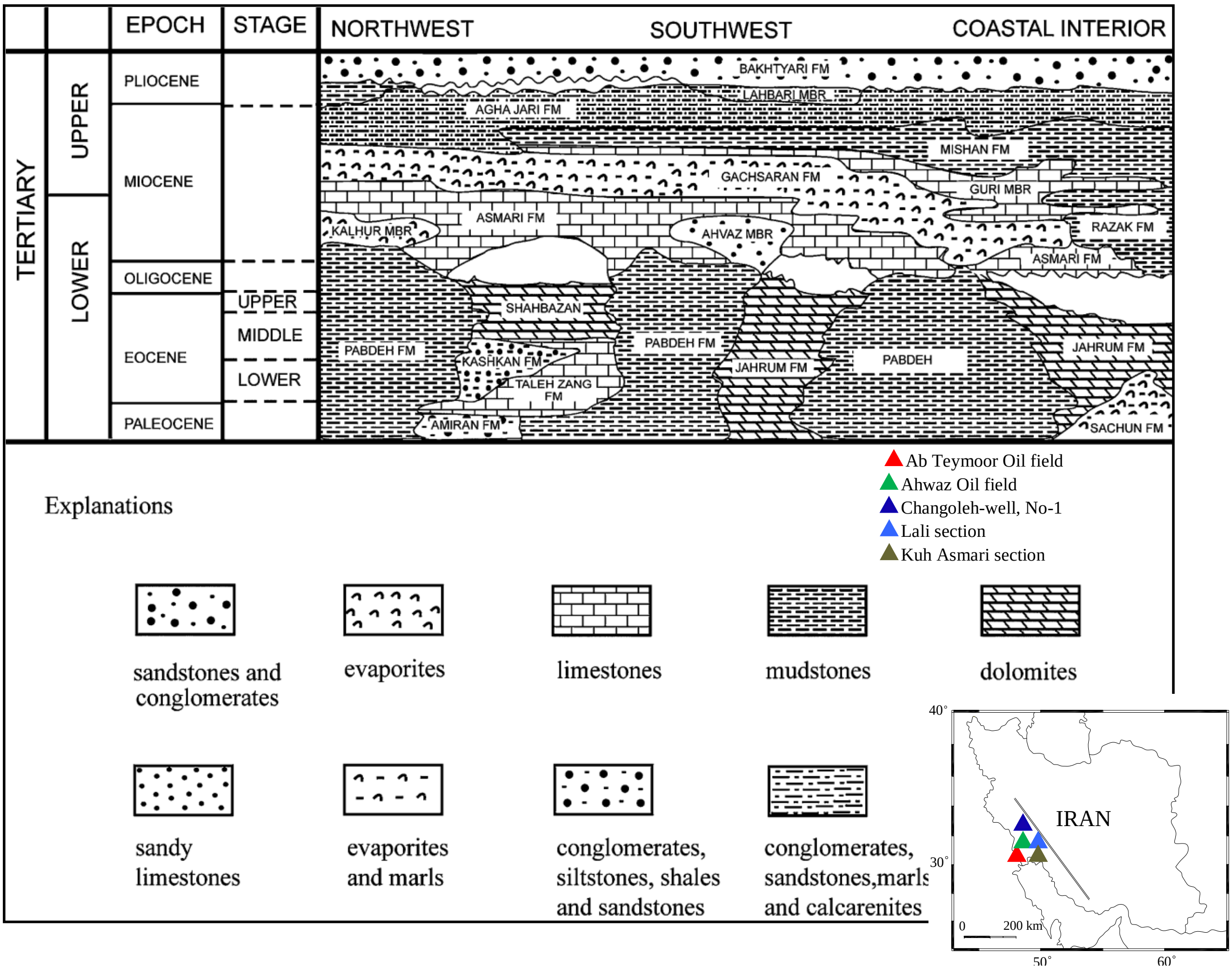

Figure 2.4. Correlation chart of the tertiary of southwest Iran (after Vaziri et al., 2006, adopted from Ala, 1982). The line indicates the correlation direction and the triangles show locality of some geological columns that are described in Figures 2.5 to 2.8.

From field and petrographic data, they have identified four major lithofacies and twelve subfacies which are interpreted to have been deposited in open-marine, shoal, lagoon and tidal flat settings. Also, they showed that the Asmari and Jahrum Formations constitute two separate depositional sequences which are separated by a thin palaeosol, representing a type-one sequence boundary which can be correlated with global curves of relative sea-level. Each depositional sequence is composed of several metre-scale shallowing-upward parasequences. This is the first time that the Asmari and Jahrum Formations have been differentiated in the study area. This study will lead to a better understanding of the Asmari Formation in the subsurface in other parts of the Zagros Basin.

Vazirimoghadam et al. (2005) studied microfacies, palaeoenvironments and sedimentary sequences of Asmari Formation in Lali, Kuh-Asmari and Khaviz area at Khuzestan Province (Figures 2.7 and 2. 8). Detailed petrographic analysis of the deposits led to the recognition of ten microfacies types. In addition, five major depositional environments were identified in the Asmari Formation.

These include tidal flat, shelf lagoon, shoal, slope and basin environmental settings and are interpreted as a carbonate platform developed in an open shelf situation but without effective barriers separating the platform from the open ocean. The Asmari carbonate succession consists of four, thick shallowing- upward sequences (third-order cycles). No major hiatuses were recognized between these cycles. Therefore, the contacts are interpreted as SB2 sequence boundary types. The Pabdeh Formation, the deeper marine facies equivalent of the Asmari Limestone is interpreted to be deposited in an outer slope- basin environment. The microfacies of the Pabdeh Formation show similarities to the Asmari Formation.

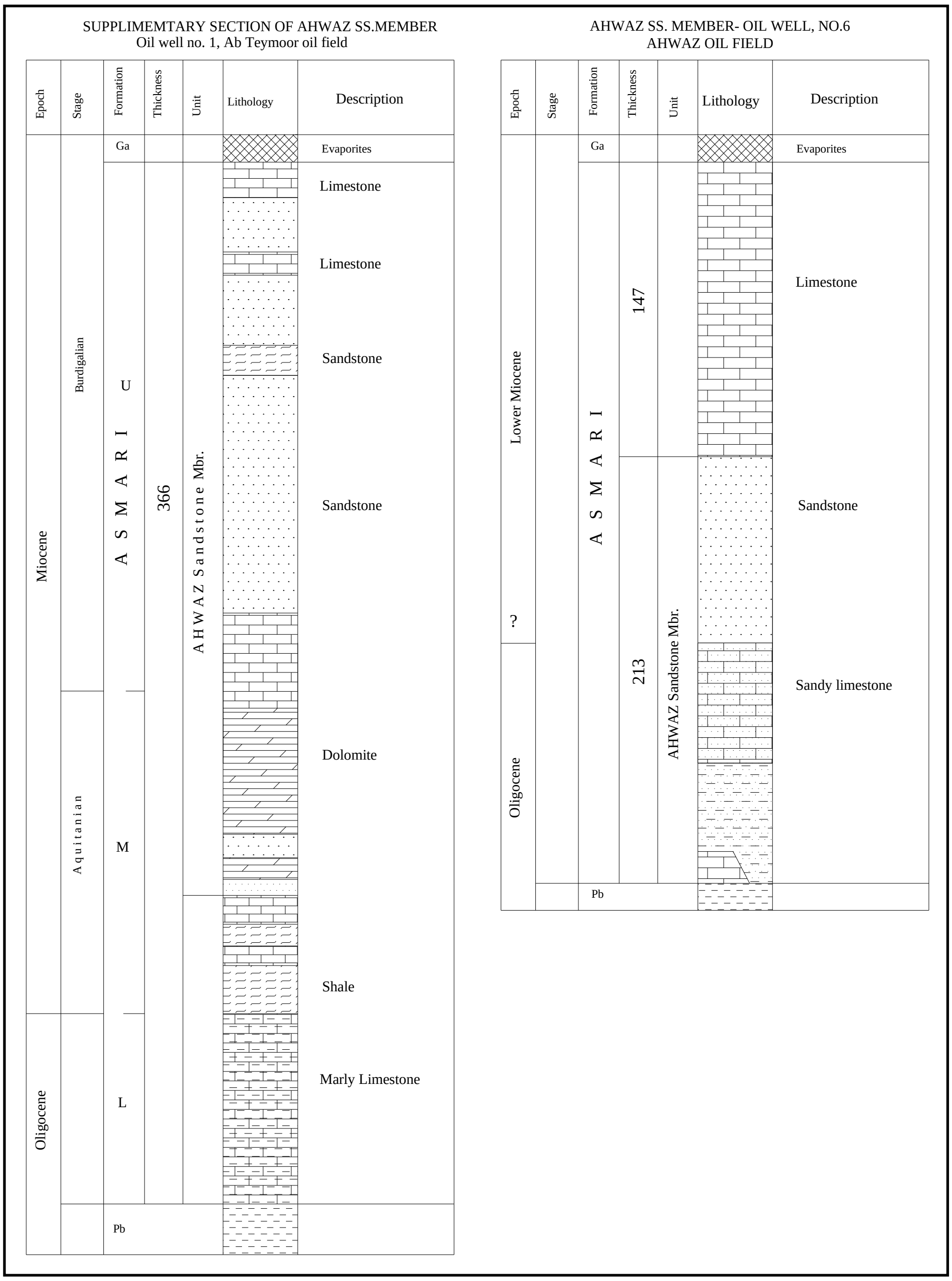

Figure 2.5. Stratigraphic column of Ahwaz Sandstone member in oil well No. 1, Ab Teymoor Oil field (supplementary section (left- 1968) and oil well No.6, In Ahwaz Oil field (right- 1965), (after Motiei, 1993).

Sequence stratigraphy of Asmari Formation was also studied by Hassan Mohseni et. al (2006) on three outcrops and two oil well sections. According to petrography and field observations, the formation is divided into three parts and comprises six microfacies assemblages as: A (open marine); B (bar/shoal); C (lagoon); E (tidal flat) and F (supratidal).

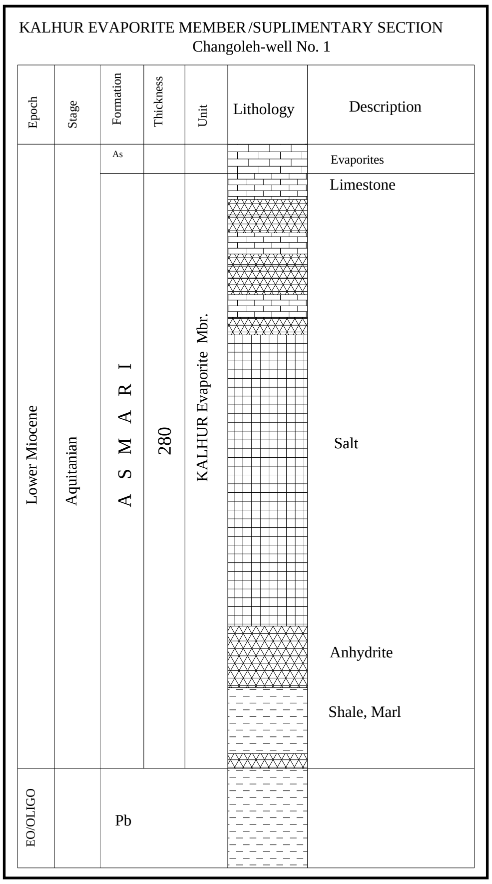

Figure 2.6. Stratigraphic column of Kalhur evaporite member/ Supplementary section, Changoleh, well No.1 (after Motiei, 1993).

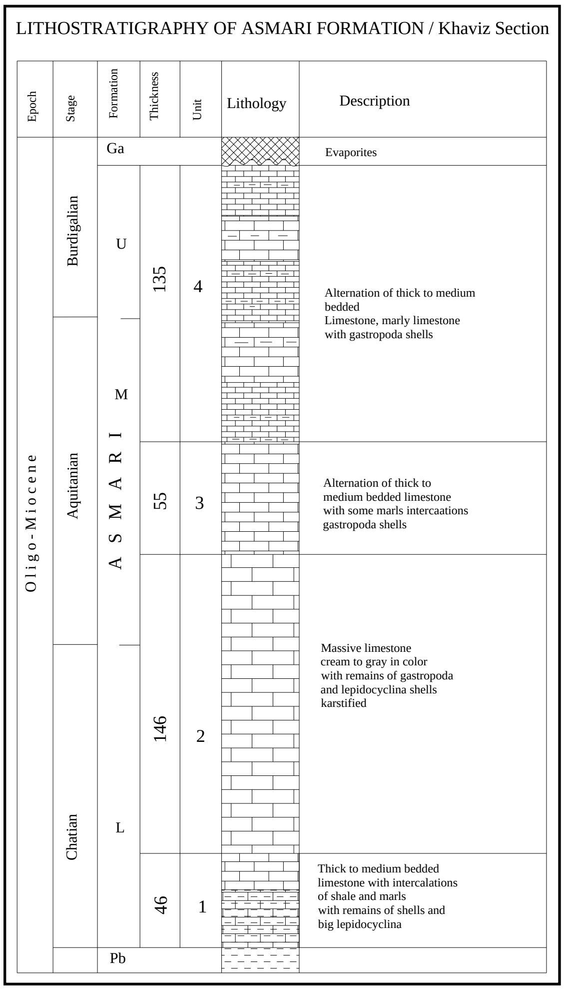

Figure 2.7. Lithostratigraphic columns of the Asmari Formation in the Khaviz section, Khuzestan Province (after Vazirimoghdam et al., 2005).

On a sequence stratigraphic framework, the lower Asmari was deposited in HST (highstand system tract) stage, whereas TST started during the deposition of underlying Pabdeh Formation and transgression reach to highest level (mfs- maximum flooding surface) just at the boundary of the Asmari and Pabdeh Formations. Succeedingly HST stage is marked by algal boundstones and late HST by lagoon facies (dolomudstone, miliolidae wackestone). Dolomitization increased intercrystaline porosity of the Asmari carbonate reservoir. In the Renu surface section, only the lower Asmari was deposited whereas in the Siahgel surface section, only the middle Asmari was deposited on shale beds of Pabdeh Formation. The middle Asmari is marked as early HST (algal boundstone) and late HST sediments composed of lagoonal facies (miliolidae wackestones and evaporites). This sequence terminated with sandstone facies with hematite cements that imply a Type 1 sequence boundary. In brief the middle Asmari comprises two stages of HST, one LST (lowstand system tract), and one TST.

The Upper Asmari exposed only in the Dezful Embayment, comprises two HST, two TST; the later began with echinoderm wackstone microfacies. Early HST sediments are dolomitized lime mudstones but late HST are miliolidae wackestone, algal wackstone, ostracod wackestone and pellet grainstone that suggest a lagoon setting. Dolomitization occurred in the early HST stage and developed porosity of the formation. Sequence boundary is Type 2 and no evidence of exposure was observed.

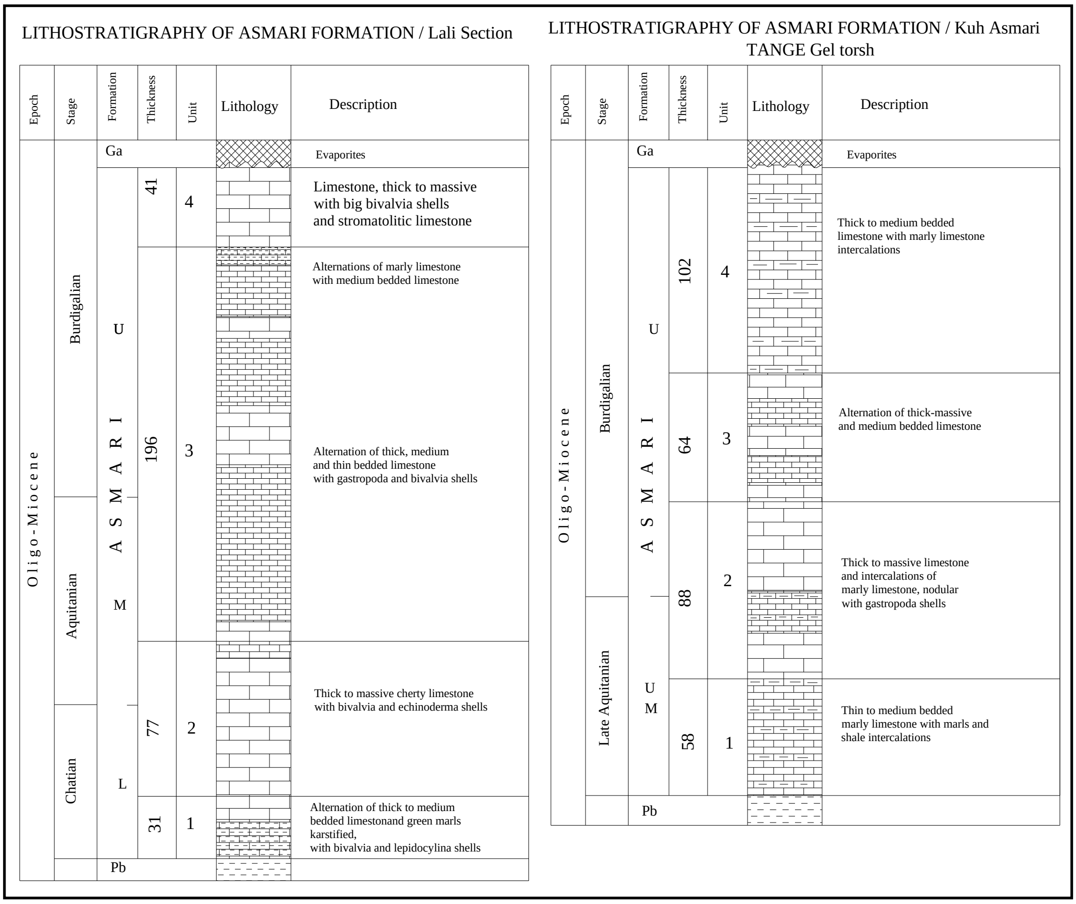

Figure 2.8. Lithostratigraphic columns of the Asmari Formation in Lali and Kuhe Asmari sections – Khuzestan Province (after Vazirimoghadam et al., 2005).

2.2.2. Biostratigraphic Units of the Asmari Formation

The biostratigraphic units of the Asmari Formation was first described by Wynd (1965) and revised by Adam and Bourgeois (1967). They divided the Asmari Formation into three units based on the presence of foraminifera's assemblage zones (Table 2.1).

Table 2.1. Asmari Formation assemblage zones (after Adams and Bourgeois, 1965).

Biozone	**Lithostratigraphic unit**	**Age**
Borelis melo-Meanropsina iranica	Upper Asmari	Burdigalian
Elphidium sp. 14-Miogipsina	Middle-Upper Asmari	Late Aquitanian
Archaias asmaricus- Archaias hensoni	Lower-Middle Asmari	Early Aquitanian
Eulepidina- Nphrolepidina- Nummulites	Lower Asmari	Oligocene