PALAEOENVIRONMENT AND BASIN ARCHITECTURE OF THE LOWER JURASSIC AB-HAJI FORMATION, EAST-CENTRAL IRAN

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Abstract.- The Lower Jurassic Ab-Haji Formation of the Kalmard, Tabas and Lut blocks, east-central Iran, has been studied using an integrated stratigraphic-sedimentologic approach. The Ab-Haji Formation is mostly composed of greenish sandstones and siltstones and locally contains thin coal seams. Four well exposed sections were measured and studied in order to identify lithofacies and facies associations and to interpret the palaeoenvironment. This formation reaches a thickness up to 350 m in northern Tabas Block but may locally be reduced to few tens of meters or even missing. Field studies have led to the recognition of sixteen lithofacies grouped into five facies associations: fluvial plain, coastal plain, delta front, prodelta and shallow siliciclastic shelf. Reconstruction of the palaeogeography of east-central Iran marks a west–east continental-to-marine gradient. Thickness variations, lateral facies changes and basal unconformity of the siliciclastic rocks of the Ab-Haji Formation on the Kalmard, Tabas and Lut blocks show palaeo-relief on the fault-bounded Yazd Block in the west and the Shotori Swell at the eastern edge of the Tabas Block. The pattern of thickness variations and rapid EW facies changes is best explained by a tectonic model showing large tilted fault blocks in an extensional basin. The obtained results are important for palaeogeographic and palaeoenvironmental reconstructions of the east-central Iran since its sediments record the geodynamic history of this region, as well as an even larger area, during and in the aftermath of the main Cimmerian event, from the beginning of the Early Jurassic.

Keywords: Early Jurassic; Lithofacies; Facies association; Palaeoenvironment; East-central Iran.

Resumen.- ***Paleoambientes y architectura de cuenca de la Formación Ab-Haji (Lower Jurassic), centro-este de Irán***.- Los depósitos de la Formación Ab-Haji (Jurásico Inferior) en los bloques Kalmard, Tabas y Lut se han estudiado integrando métodos estratigráficos y sedimentológicos. Esta formación se compone primariamente de areniscas y limolitas verdosas las cuales localmente contienen delgados niveles carbonosos. El estudio comprende cuatro secciones bien expuestas, seleccionadas para la identificación de litofacies y asociaciones de facies con el objetivo de interpretar el paleoambiente. En el sector norte del Bloque Tabas la Formación Ab-Haji alcanza un espesor de hasta 350 m aunque localmente puede observársela reducida a pocas decenas de metros o inclusive estar ausente. Las observaciones de campo nos permitieron reconocer dieciseis litofacies que hemos agrupado en cinco asociaciones faciales: planicie fluvial, planicie costera, frente de delta, prodelta y plataforma somera siliciclástica. La reconstrucción paleogeográfica del centro-este de Irán obtenida para el Jurásico Temprano indica un pasaje gradual en sentido oeste-este, de ambientes continentales a marinos. Las variaciones de espesor, los cambios laterales de facies y la discordancia de las rocas siliciclásticas de la Formación Ab-Haji en la región estudiada indican un paleorelieve sobre el Bloque Yazd en el oeste y el altofondo Shotori en el borde oriental del Bloque Tabas. La conjunción del patrón de variaciones de espesor y los rápidos cambios faciales en sentido este-oeste se explica satisfactoriamente a partir de un modelo tectónico que incluye grandes bloques basculantes en una cuenca extensional. Los resultados obtenidos son importantes para las reconstrucciones paleogeográficas y paleoambientales de la región centro-oriental de Irán donde sus sedimentos registran la historia geodinámica de esta región. Esto es extensible a un área mayor durante el Evento Cimmérico principal, a partir del inicio del Jurásico Temprano.

Palabras clave: Jurásico Temprano; Litofacies; Asociación de facies; Paleoambiente; Centro-este de Irán.

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INTRODUCTION

The Cimmerian Orogeny largely governed the Late Triassic and Jurassic sedimentation patterns of the composite Iran Plate, including the Central-East Iranian Microcontinent (CEIM; see Wilmsen et al. 2009a, b). The CEIM (name introduced by Takin 1972) consists of three large fault-bounded structural units of north–south-orientation, named the Lut, Tabas and Yazd blocks (Fig. 1A). The tectonic instability of the area is reflected by several sedimentologic and stratigraphic signatures (see Fürsich et al. 2003, Wilmsen et al. 2003, Seyed-Emami et al. 2004a, Fürsich et al. 2009b, Wilmsen et al. 2009a, 2009b, Wilmsen et al. 2010, Zamani-Pedram 2011).

Geodynamic models place Jurassic deposits of east-central Iran in an extensional continental back-arc basin (Brunet et al. 2003, Wilmsen et al. 2009b; Fig. 2 this report). Previous lithostratigraphic and palaeoenvironmental studies of the underlying Upper Triassic deposits and the overall stratigraphy and facies of Jurassic strata in east-central Iran in fact suggested that the three blocks Lut, Tabas, and Yazd represent large tilted fault blocks in an extensional basin (Fürsich et al. 2005, Wilmsen et al. 2009a, Wilmsen et al. 2010).

On this framework, the Lower Jurassic Ab-Haji Formation has been proposed to be largely non-marine and to show a west-east continental-marine gradient (Wilmsen et al. 2009a). However, because the formation had not yet been studied in detail, its large thickness variations and facies distribution patterns remained unexplored.

In order to test the hypothesis that the Ab-Haji Fm records Early Jurassic tilting, uplift and erosion of the above mentioned central-east Iranian blocks, we performed a detailed lithostratigraphic study, as well as a facies analysis of these deposits. The obtained results also document the facies development and evolution of the Ab-Haji Basin. This case study provides an important piece for understanding the complex geodynamic puzzle of the Mesozoic evolution of the Tethysides super-orogenic complex (Sengör 1984, Sengör et al. 1988).

TECTONIC AND PALAEOGEOGRAPHIC FRAMEWORK

The Iran Plate, an element of the Cimmerian microplate assemblage, became detached from Gondwana during the Permian and collided with the Turan Plate of Eurasia during the Late Triassic, thereby closing the Palaeotethys (Eo-Cimmerian event; e.g., Stöcklin 1974, Stampfli & Borel 2002, Fürsich et al. 2009a, Wilmsen et al. 2009b, Zanchi et al. 2009; see Fig. 2A this report). This Eo-Cimmerian Orogeny transformed the northern margin of the Iran Plate into an underfilled Carnian-Rhaetian flexural foreland basin (Wilmsen et al. 2009b). At the same time, Neotethys subduction started at the southern margin of the Iran Plate. This process reduced the compression of the Iran Plate so that subsequently extensional basins formed which were filled with up to 3000 m of marine Norian-Rhaetian sediments (Nayband Formation of central Iran; see e.g. Fursich et al. 2005).

Palaeogeographic reconstructions for the Early Jurassic (Thierry 2000, Barrier & Vrielynck 2008) place the Iran Plate at the northern margin of the Neo-Tethys (Fig. 2A). Sedimentological and stratigraphical analyses (i.e., distribution of marine and non-marine strata) indicate that the Lut and part of Tabas blocks were mostly covered by the sea during the Early Jurassic whereas most of the Yazd Block remained emergent (Lower Jurassic stratigraphic gap).

The main Cimmerian uplift and foreland deformation event during the Cimmerian Orogeny occurred at the Triassic-Jurassic boundary, followed by a rapid denudation of the Cimmerian Mountains in northern Iran (Wilmsen et al. 2009b,

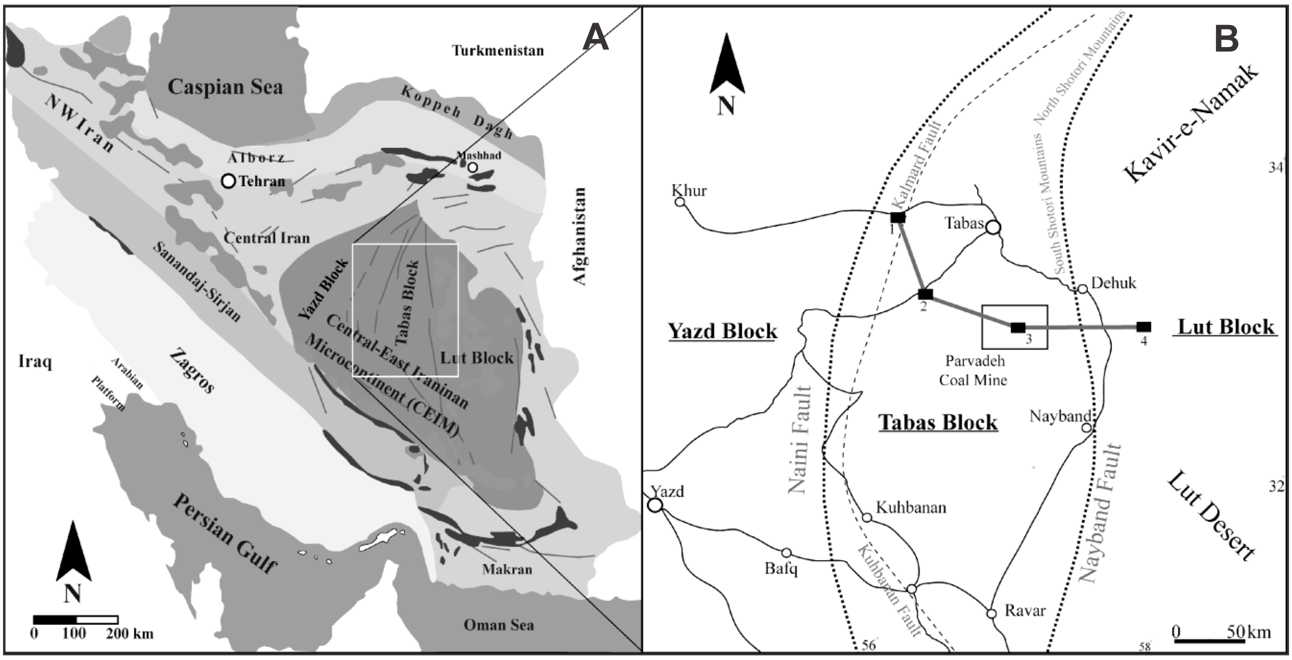

Figure 1. **A:** Structural, geological and geographic framework of Iran showing the main structural units and geographic areas. **B:** Locality map of east-central Iran with major structural units (blocks and block-bounding faults modified from Wilmsen et al. 2009a). The studied sections are indicated by black rectangles: Kuh-e-Rahdar (1), Simin-Sepahan (2), Parvadeh (3), Kuh-e-Shisui (4). The broken line through sections 1-4 indicates the lithostratigraphic W-E cross section shown in Fig. 8.

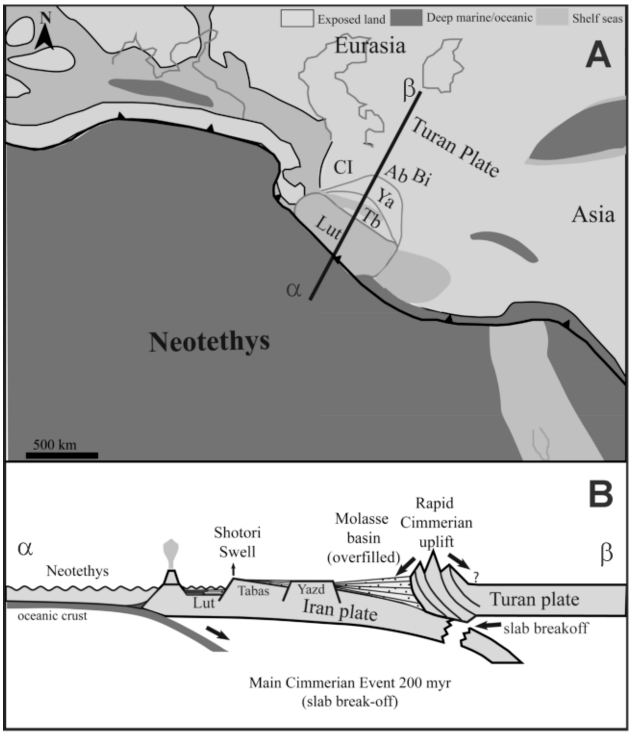

Figure 2. A: Early Jurassic palaeogeography of the central Tethys (modified after Barrier & Vrielynck 2008). The Lut, Tabas and Yazd blocks are shown in assumed Early Jurassic orientation. Ab: Alborz, CI: Central Iran, Tb: Tabas, Ya: Yazd, Bi: Binalud. **B:** Geodynamic model of Iran during the Hettangian-Pliensbachian (main-Cimmerian event) through the transect α-β indicated in **A**. Modified from Wilmsen et al. 2009b.

2009c). This event also resulted in the termination of the marine sedimentation, followed by non-deposition or erosion, source-area rejuvenation, and deposition of the Lower Jurassic Ab-Haji Fm in east-central Iran (Wilmsen et al. 2009a).

Evidence of the Mid-Cimmerian tectonic event (Bajocian in age) is observed all across the Iran Plate (northern and east-central Iran) where it is documented by conspicuous inter-regional unconformities. Their origin can be related to plate-tectonic processes in the South Caspian area (Brunet et al. 2003, Fürsich et al. 2009b) and at the southern margin of the Iran Plate (Wilmsen et al. 2009a). On the Tabas Block, the Mid-Cimmerian unconformity is well developed and associated with considerable erosion and, locally, mild folding (Wilmsen et al. 2003, Wilmsen et al. 2009a). The Late Cimmerian event (Late Jurassic-earliest Cretaceous) resulted in intensive block-faulting in east-central Iran (Wilmsen et al. 2010).

Published geodynamic models (e.g., Davoudzadeh et al. 1981, Soffel & Förster 1984, Soffel et al. 1996, Alavi et al. 1997, Besse et al. 1998) have suggested that the CEIM experienced post-Triassic counterclockwise rotation (about 135°) around a vertical axis to its present-day position, and that this rotation was associated with considerable lateral movements along the block-bounding faults (Figs. 1A, 2A). Rotation took mainly place in post-Jurassic times (Esmaeily et al. 2007, Bagheri & Stampfli 2008, Wilmsen et al. 2009b) although the timing has been questioned by some recent studies (e.g., Muttoni et al. 2009). Nevertheless, Cifelli et al. (2013) recently suggested that the block-bounding fault between the Tabas and Lut blocks changed from an extensional regime during the Jurassic to a right-lateral transpressional regime between the Early Cretaceous and Palaeocene. Furthermore, Mattei et al. (2012) have documented significant Neogene counterclockwise rotation (20–35°) of the Tabas and Yazd blocks.

UPPER TRIASSIC-MIDDLE JURASSIC STRATIGRAPHY

There is a conspicuous change from Middle Triassic platform carbonates (Shotori Fm) to Norian-Bajocian siliciclastic rocks of the Shemshak Group of east-central Iran (Seyed-Emami 2003, Fürsich et al. 2005, Fürsich et al. 2009a). This unconformity-bounded group is bordered by the Eo-Cimmerian unconformity at its base and the Mid-Cimmerian unconformity at its top (Fig. 3).

In all the studied areas (Kalmard Block, northern Tabas Block, Lut Block), the Upper Triassic Nayband Fm of the lower Shemshak Group is well developed (Fig. 3). This widespread unit consists mainly of fine-grained marine siliciclastics and carbonates containing abundant fossils (Hautmann 2001, Fürsich et al. 2005, Senowbari-Daryan et al. 2010, Hautmann et al. 2011). Upwards the Nayband Fm is overlain by the siliciclastic strata of the Lower Jurassic Ab-Haji Fm. The type area of the formation is located in the Kalmard area, near Kuh-e-Rahdar, northwestern Tabas Block (Aghanabati 1975) where, however, it is only 82 m thick (see below and Fig. 1B).

The Ab-Haji Fm crops out from the eastern margin of the Yazd Block throughout much of the Tabas Block, except at its eastern margin (Shotori Mountains), and onto the western Lut Block (Fig. 3). It reaches a thickness of up to 350 m, but locally may be reduced to a few tens of meters. It mainly consists of thin- to thick-bedded greenish sandstones and siltstones and locally contains rare thin coal seams (Fig. 4A). Over much of the Tabas Block, the basal contact is marked by coarse-grained quartzarenite (Fig. 4B, C). Depositional environments range from fluvial plain, coastal plain, delta and shallow marine (see below).

During the Aalenian in the southern Tabas Block and already in the Toarcian on the Lut Block, a pronounced transgression initiated the deposition of the comparatively condensed, ammonite-rich and dark, often oolitic limestones, marls and siliciclastic rocks of the Badamu Fm (Seyed-Emami 1971, Seyed-Emami et al. 2000, Seyed-Emami et al. 2004b; Figs. 3, 4D this report).

The overlying Early Bajocian Hojedk Fm is usually easily identified as the siliciclastic package between the carbonates of the underlying Badamu Fm and the overlying Parvadeh Fm (see Fig. 3). Its top is below the Mid-Cimmerian unconformity. In the eastern part of the Tabas Block and on the Lut Block, the Hojedk Fm is generally marine and can be dated by its ammonites (e.g. Seyed-Emami et al. 2004b). Towards the west, its character changes to marginal marine and fluvial, and includes coal seams. The Hojedk Fm, like the Ab-Haji Fm, is characterized by rapid lateral facies and thickness changes.

The pronounced transgression following the Middle Bajocian Mid-Cimmerian unconformity initiated deposition of the Late Bajocian to Early–Middle Bathonian condensed, oncolitic-microbial limestones and siliciclastic rocks of the Parvadeh Fm (30 to 150 m; Wilmsen et al. 2009a; Fig. 3 this report). Strata of the Parvadeh Fm were deposited across the Tabas Block and also onlap the Shotori Swell. In the western part of the Lut Block, the Parvadeh Fm is replaced by the marine sandstones of the informal Qal'eh Dokhtar Sandstone formation (Fig. 3).

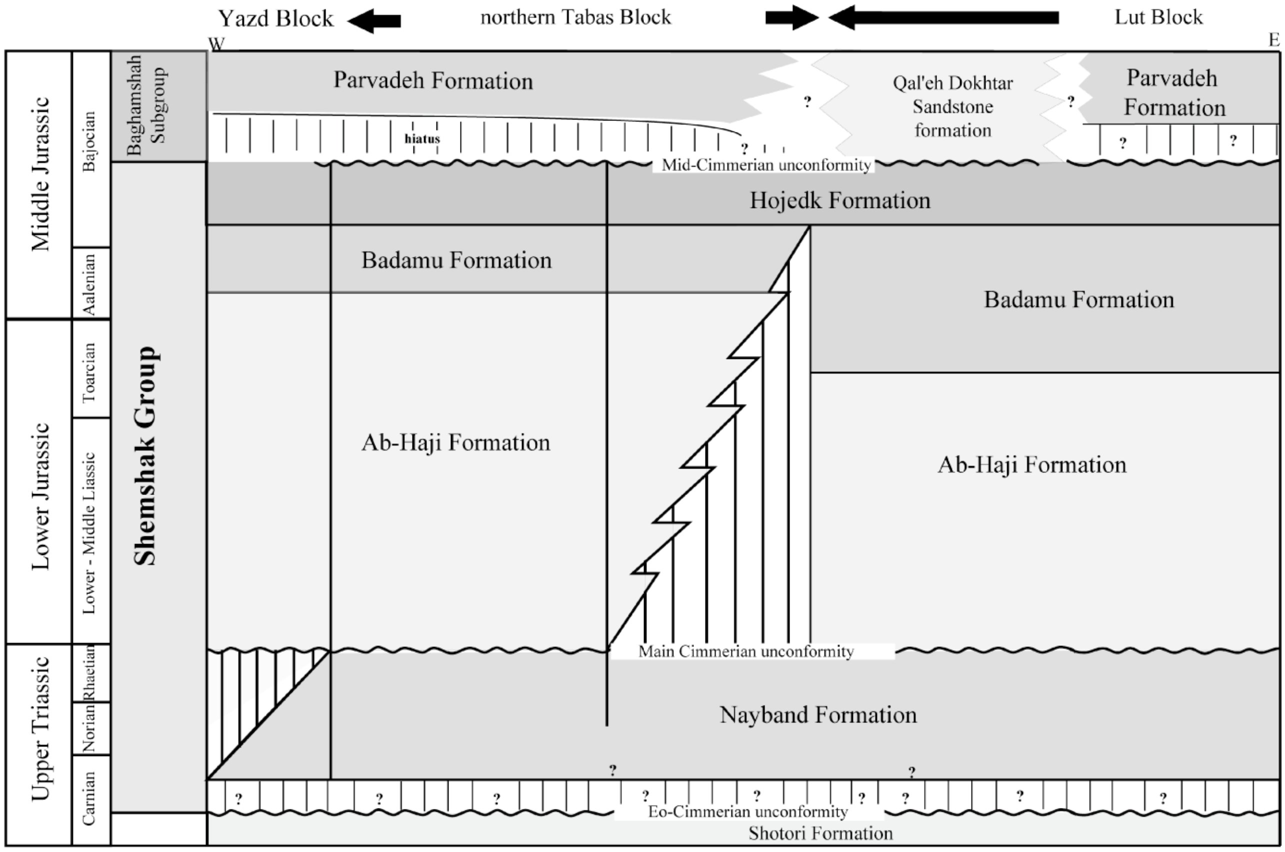

Figure 3. Lithostratigraphic framework of the Upper Triassic to Lower Middle Jurassic series of the northern Tabas Block, as well as the western Lut Block, east-central Iran (modified from Wilmsen et al. 2009a).

MATERIAL AND METHODS

This study integrates lithostratigraphic and sedimentologic data collected during three field seasons in the Lut, Tabas and Kalmard blocks. Four stratigraphic sections were measured bed-by-bed in considerable detail using a Jacob Staff (Sdzuy & Monninger 1985). Analysis of sedimentary structures, grain-size and components (using hand-lens), study of stratal architecture and field tracing of individual strata to document lateral and vertical stacking patterns and facies distribution supplemented the data.

Lithofacies were defined based on sedimentary structures and lithology. We used a modified lithofacies classifications of Miall (1985, 2006) for facies analysis. Sixteen lithofacies types (Table 1) and five facies associations were established. Facies associations were defined by stratal characteristics or by groups of genetically related strata sets, grain size, constituent lithofacies, and vertical and lateral relationships which allowed the interpretation of depositional settings and the palaeogeography of east-central Iran during the Early Jurassic. In addition, paleocurrent indicators were measured at eight locations to constrain dispersal patterns.

THE STUDIED SECTIONS

The four studied sections are part of a cross-section trending east-west through the Kalmard, Tabas, and Lut blocks (Fig. 1B). In the following, the Ab-Haji Fm is briefly described from base to top in the four stratigraphic sections.

Kuh-e-Rahdar section (Fig. 5A): The Ab-Haji Fm reaches 82 m in thickness in its type area, Kuh-e-Rahdar in northwestern Tabas Block. The thickness of 480 m reported by Aghanabati (1975) also included the overlying Badamu Fm, which is very thick at this locality, consisting of more than 200 m of intercalated packages of oolitic limestone, sandstone and shale (Wilmsen et al. 2009a). The contact with the bioclastic limestone of the underlying Permian Khan Fm is sharp, being marked by a 1-m-thick, red conglomerate (Figs. 4A, 5A). Up-section, the Ab-Haji Fm continues with 30 meters of inter-bedded shale and green sandstones with small climbing ripple lamination and hummocky cross-stratification (at 16 m; Fig. 5A). This unit gradually grades into about 10 m of laminated green shale. The uppermost part of the succession constitutes a 40 m thick coarsening-upward sequence with thick-bedded, grey to green, fine- to medium-grained sandstone rich in plant debris. The boundary to the overlying oolitic limestone of the Badamu Fm is sharp.

Simin-Sepahan section (Fig. 5B): The Ab-Haji Fm in western Tabas Block was measured at Simin-Sepahan, approximately 60 km west of Tabas, north of the road from Tabas to Yazd. The contact to the underlying Nayband Fm is gradual and was placed on the top of thick-bedded, grey marginal-marine sandstones (Fig. 5B). The overlying fine-grained siliciclastic strata have been logged as the Ab-Haji Fm. In the lower 160 m of the section, green siltstones and shales which are rich in plant

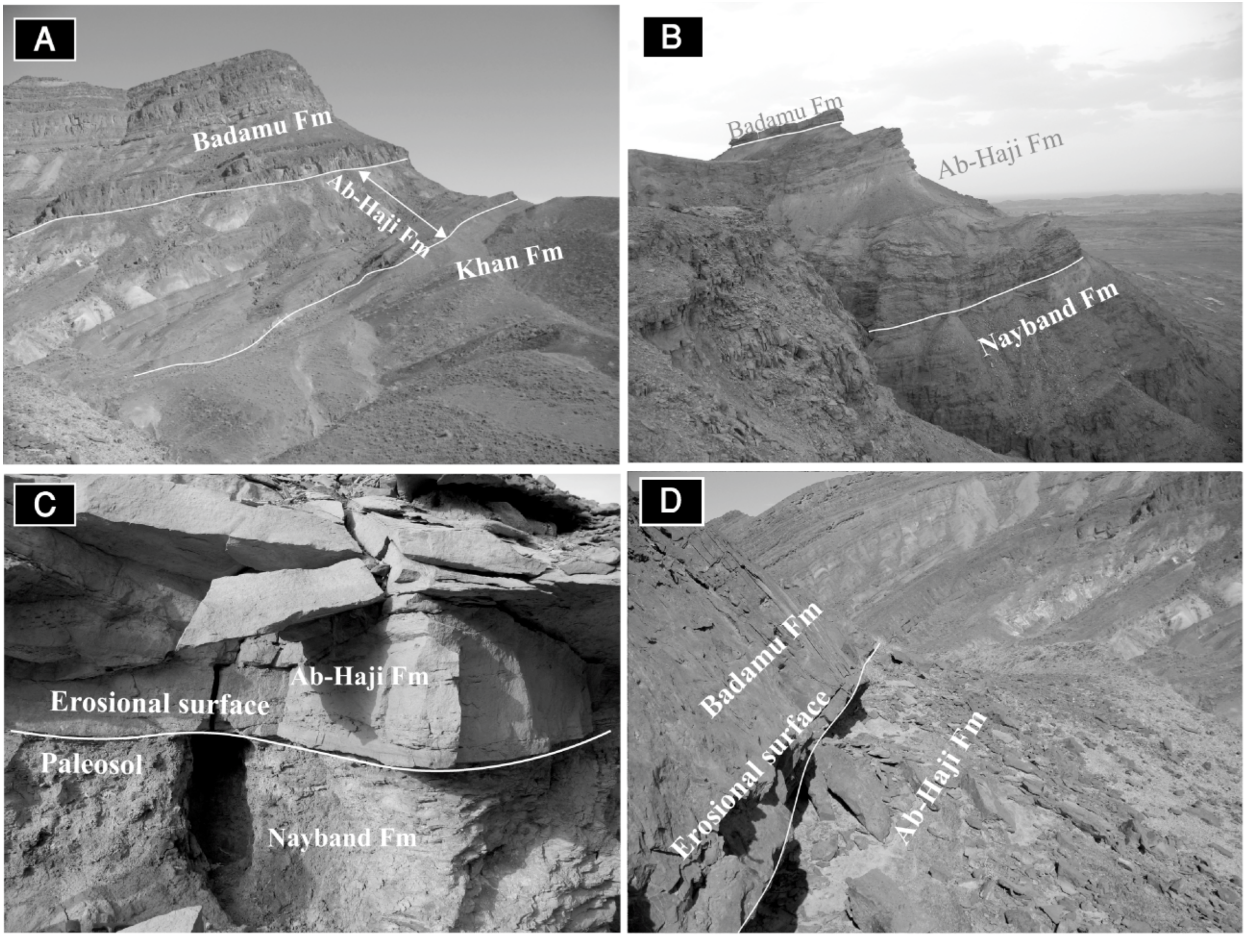

Figure 4. Overviews field photographs of the Ab-Haji Fm at different sections. **A**. Overview of the Kuh-e-Rahdar section, view to the north from the top of the Permian Khan to the Lower Jurassic Ab-Haji and Badamu formations. **B**. Overview of the Parvadeh section, view to the south from the top of the Upper Triassic Nayband to the Lower Jurassic Ab-Haji and Badamu formations. **C**. Sharp contact (erosional surface) of the fine-grained siltstones of the Nayband Fm and coarse-grained sandstones of the Ab-Haji Fm (Parvadeh section). **D**. Interbedded sandstones and siltstones of the upper part of the Ab-Haji Fm are overlain by the Badamu Fm with erosional boundary (Kuh-e-Rahdar section). View to the northwest.

debris with thin lenses of sandstone predominate. They are followed by several fining-upward sandstone packages that are usually cross-bedded, rich in plant debris, and with sharp but shallow erosional bases, alternating with shales. The upper 70 m of the section consists of fine-grained green to grey shales. Limestones of the Badamu Fm overlie the siliciclastic Ab-Haji Fm.

Parvadeh section (Fig. 5C): The Parvadeh section was measured at the Parvadeh Coal Mine area where the Ab-Haji Fm reaches a thickness of about 75 m (Fig. 4B). In this section large-scale trough and planar cross-bedded sandstones overlie with erosional contact the fine-grained siliciclastics of the Nayband Fm. Locally, a palaeosol is developed. Characteristic features are two fining-upward, fine- to medium-grained channelized sandstone packages (60 m), interbedded between siltstones and shales rich in plant debris. Below the upper sandstone, a thin coal seam occurs (at 39 m, Fig. 5C). The remaining section consists of 15 m of laminated, green shales with marine fauna including bivalves and brachiopods. This unit is capped by a thick oolitic limestone of the Badamu Fm.

Kuh-e-Shisui section (Fig. 5D): The section at Kuh-e-Shisui lies on the Lut Block about 30 km south of the road from Boshrouyeh to Ferdows. Here the sedimentary succession differs totally from those of other localities. The basal contact overlies the uppermost limestone bed of the underlying Nayband Fm which contains a coral patch reef at this location (at 391.5 m, Fig. 5D). The succession begins with about 130 m of green siltstones and shales with interbedded white, thin-bedded and quartzose sandstones. Occasionally, thin beds of calcareous sandstone with marine bivalves occur, and disarticulated bivalve shells occur as pavements in the topmost bed of this unit (at 518 m, Fig. 5D). Plant debris is rare. The upper part of the succession consists of several thick-bedded, fine- to medium-grained coarsening-upward sandstones. The Ab-Haji Fm is overlain by thick-bedded oolitic limestones of the Badamu Fm.

FACIES ANALYSIS AND DEPOSITIONAL ENVIRONMENTS

Identification and description of sedimentary facies are frequently considered as the most important factors for interpreting the palaeoenvironmental conditions (Walker 2006). In the present study sixteen lithofacies have been identified in the field. Our analysis indicates the following

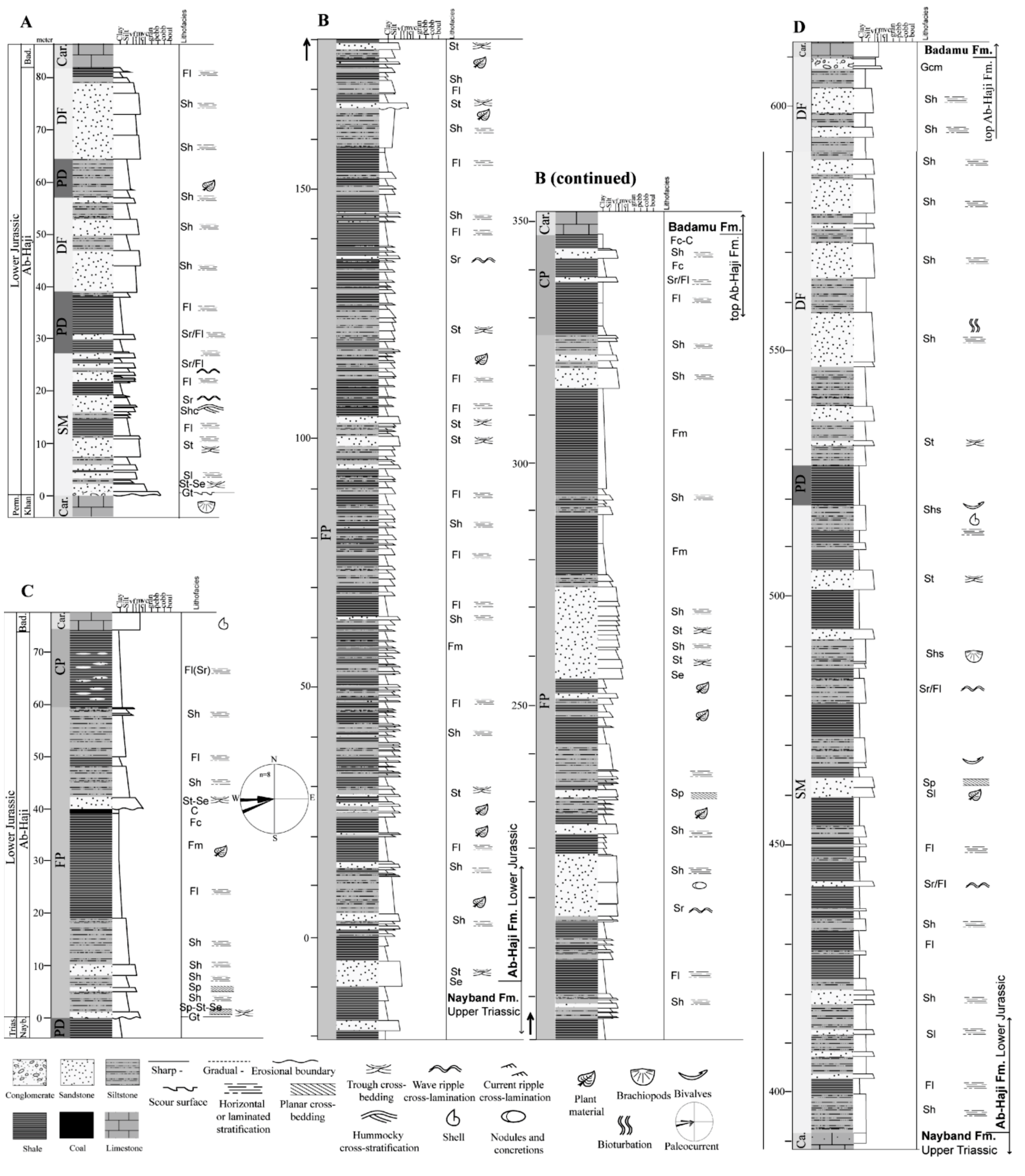

Figure 5. Stratigraphic logs of the Ab-Haji Fm at different sections. **A**. Kuh-e-Rahdar section (33°38'40"N, 56°21'10"E). **B**. Simin-Sepahan section (33°15'44"N, 56°28'48"E). **C**. Parvadeh section (33°00'10"N, 56°50'14"E). **D**. Kuh-e-Shisui section (33°37'11"N, 58°00'8"E). Grain-size code: vf: very fine-; f: fine-; m: medium-; c: coarse-; vc: very coarse sand. FP: flood plains, DF: delta front, CP: costal plain, PD: pro delta, SM: shallow siliciclastic sea.

lithofacies: two siliciclastic coarse-grained (Gcm, Gt), eight medium-grained (St, Se, Sp, Sr, Sh, Shc, Sl, Shs), three fine-grained (Fl, Fm, Fc), two interbedded sandstone-claystone (Fl(Sr), Sr/Fl) and one of coal (C). Details of the lithofacies are presented in Table 1 and their distribution along the study area is shown in representative logs in Fig. 5.

Based on lithofacies, textures, and spatial associations, we identified five major facies associations, representing fluvial to shallow marine depositional environments within the Ab-Haji Fm. Each facies association consists of a number of lithofacies characteristic of specific sub-environments (Table 1).

Facies Association I

This facies association includes three sub-associations: channels, floodplains and swamps.

Table 1. Description and interpretation of sedimentary facies (codes modified after Miall 1985, 2006).

	Facies code	Characteristics	Sedimentary processes - environmental interpretation	Occurrence
1	Gcm	Clast-supported polymictic conglomerates, pebble to granule with rare boulder grain-size, low roundness (subangular) and sphericity, very poor sorting, immature conglomerate, with reddish brown sandy matrix, common clast includes sedimentary rocks (red sandstone or siltstone and milky chert), massive or crudely stratified, marked by erosional and sharp base and upper contact is usually gradational with Sh and St, thickness ranging from 0.5 to 1 m.	Deposition by rapidly waning flow regime, with sediment transport occurring via traction currents and marked by high sediment supply from the land. Deposition in fluvial channels.	Sections 1, 3
2	Gt	Trough cross-stratified clast-supported conglomerates to microconglomerate, pebble to granule grain-size, sub-rounded to rounded and low sphericity clasts, moderate sorting, sub-mature to mature conglometare, milky quartz, lenticular geometry, set thickness generally 0.1−0.3 m, marked by erosional base and normal grading (fining-up nature), upper contact is usually gradational with Sh and St.	Channel lag under conditions of upper flow regime, with sediment transport occurring via traction currents; Deposition in fluvial channels.	Sections 1, 3
3	St	Trough cross-bedded sandstone, medium- to coarse-grained sand, rounded and high sphericity, good sorting, mature sandstone, set thickness generally 3-5 m, lenticular or wedge-shaped bodies, gradational with facies Gt and is erosional with facies Fm	Deposited as dunes or bars in response to unidirectional currents. Deposition in fluvial channel, delta plain and front, upper shoreface.	Sections 1−4
4	Se	Erosional scours with intraclasts, medium- to coarse-grained sand sometimes pebbly at base, solitary or grouped sets; set thickness generally 5-20 cm, associated with St.	Dunes and scour fills in fluvial plain.	sections 2−3
5	Sp	Planar cross-bedded sandstone, fine- to medium-grained sand, sub-rounded and low sphericity, moderate sorting, sub-mature sandstone, set thickness generally 0.5-1 m, white, grey to yellowish brown, lenticular to tabular geometry, with erosional base and comonly grading to facies (Sh).	Migration of 2D dunes in response to unidirectional currents on fluvial bedforms, mostly close to river banks; also deposition in shoreface of a shallow marine siliciclastic shelf.	Sections 1−4
6	Sr	Current and sometimes wave-rippled, cross-laminated sandstone, very fine - to medium-grained sand, well-rounded with high sphericity, well sorted grains, mature to super-mature sandstone, thin sheets-like geometry, set thickness generally 0.1-0.3 m, associated with Sh and Fl.	Deposition under subaqueous traction conditions by low flow regime; current ripple in fluvial flood plains and wavey ripple in upper shoreface.	Sections 1−4
7	Sh	Horizontally laminated sandstone, fine- to coarse grained sand, sheet or tabular, well-rounded and high sphericity, well sorted grain, mature sandstone, set thickness generally 1-5 m, lower contact is gradational with facies St and its upper contact is with facies Sr, Fl and Fm.	Deposited under the condition of either upper or lower flow regime by unidirectional currents, on shallow marine siliciclastic shelf	Sections 1−4
8	Shc	Hummocky cross-bedded sandstone, fine- to medium-grained sand, well-rounded with high sphericity, well sorted grains, mature to super-mature sandstone, set thickness 0.1–0.3 m, associated with Sl.	Oscillatory and/or combined flow deposits produced by storm on shallow marine siliciclastic shelf.	Sections 1, 4
9	Sl	Low-angle (<10°) cross-bedded sandstone, fine - to medium-grained sand, well-rounded with high sphericity, well sorted grains, mature to super-mature sandstone, large wedge-shaped sets; set thickness 0.2-1 m, associated with Shc and Sr.	Accretionary migration of 2D and 3D dunes in response to unidirectional currents in lower to upper flow regime transition; oscillation of wave on shallow marine siliciclastic shelf.	Sections 1, 4
10	Shs	Shell-dominated calcareous sandstone, parallel orientation, fine- to medium-grained sand, abundant bivalves, set thickness 0.2-0.5 m, associated with Sh and Sr.	Deposition under intermittent tractional currents on shallow marine siliciclastic shelf.	Section 4
11	Fl	Horizontally laminated claystone and siltstone, light green to grey with little organic matter, clay and silt size, plant fossil debris, sheet-like bodies, set thickness generally 10-20 m, gradational contact with facies Sh or Sr in lower part and with facies Fm in upper part.	Deposition from suspension across low relief, abandoned flood plains and/or deposition in distal part of prodelta.	Sections 1−4
12	Fm	Massive claystone to siltstone, clay size, grey to green colours with little organic matter, set thickness generally 5-25 m, lower contact typically gradational, the upper contact usually sharply truncated.	Suspension deposition with little or no current activity in overbank settings or abandoned channel in fluvial and delta plains.	Sections 1−4
13	Fc	Weakly horizontally laminated carbonaceous claystone to siltstone, clay size, black to dark grey colour with high organic content, wood and plant debris, set thickness generally 5-10 m, associated with Fl, C and Sr/Fl.	Deposition from suspension in vegetated coastal swamp or flood plain.	sections 2−3
14	Fl(Sr)	Interbedded rippled sandstone lens in claystone, lenticular bedding and planar laminations, plant debris, set thickness generally 5-8 cm, associated with Fm and C.	Alternating strong and weak flows in coastal plain and inner shelf setting.	Sections 1−4
15	Sr/Fl	Interbedded rippled sandstones and mudstones, with wavy bedding and planar laminations, plant debris, set thickness generally 5-10 cm, associated with Fm and C.	Alternating strong and weak flows in coastal plain and inner shelf setting.	Sections 1, 4
16	C	Carbonaceous claystone grading to coal, clay and silt size, plant debris, set thickness generally 0.3 - 0.9 m.	Deposited most likely in vegetated depressions on coastal swamp or flood plain.	Sections 2−3

Sub-association 1: Channel deposits. Lenticular (mostly with convex base and flat top) to more rarely tabular, fining-upward conglomerates (Gcm, Gt) and sandstones (St, Se, Sr) show a sharp erosional base (Fig. 7A). The sandstone bodies are best developed in the Parvadeh area where they form a belt that consists of multiple isolated lenses (Fig. 7A). The sandstone bodies consist of 5 to 8 m, rarely up to 10 m thick, tens of meters wide, large-scale trough cross-bedded, medium- to coarse-grained, mostly quartzose sandstone that fines upward into interbedded fine-grained sandstone and siltstone, occasionally displaying current ripples. The basal part of the sandstone units is commonly conglomeratic, and bears plant debris and wood fragments. Presence of vertically stacked channels is evidence for limited lateral migration.

The trough cross-bedding in this facies resulted from the migration of large three-dimensional subaquatic dunes that are common in fluvial channels (Miall 2006). The complex, mostly lenticular sandstone belts, occasionally exhibiting lateral migration, likely represent channel deposits of low-sinuosity rivers (e.g. Collinson 1996, Veiga et al. 2002) that drained the adjacent exposed area. Paleocurrent analyses of fluvial channels in the Parvadeh section show unimodal patterns with a very low spread flow direction to the west (Fig. 8A). Fluvial channels also occur in the western Tabas Block, in the Simin-Sepahan section.

Sub-association 2: *Floodplain deposits.* Green to grey silty claystones, argillaceous siltstone or siltstone (Fl, Fm), and parallel-laminated or ripple-bedded 10 to 30-cm-thick of fine-grained sandstone beds (Sh, Sr), bearing plant debris and coalified wood fragments form thick deposits at Parvadeh and Simin-Sepahan. Strata of this facies are comparatively thin at Parvadeh, but are well developed at Simin-Sepahan.

Deposition of greenish grey, unfossiliferous siltstone and argillaceous siltstone took place in inter-channel floodplains. Sand was likely deposited by crevasse splays during periods of flooding (e.g. Farrell 1987). The absence of mudcracks infers that deposition took place under semi-humid to humid climatic conditions (e.g. Smoot 1983, Fralick & Zaniewski 2012).

Sub-association 3: *Swamp deposits.* The facies are dominated by fine-grained siliciclastic rocks such as dark-grey laminated siltstone, carbonaceous claystone (Fc), coal, and coaly shale (C) with intercalations of grey horizontal to low-angle cross-stratified, very fine-grained sandstones (Fig. 6G–H).

Where coal beds and carbonaceous clay- and siltstones occur associated with other fluvial sub-environments, they probably formed in swampy areas of vegetated flood plains (e.g. McCabe 1987). The occasional presence of this facies association in the Ab-Haji Fm (at Parvadeh and Simin-Sepahan) suggests a peat swamp environment undergoing rapid plant accumulation under a humid palaeoclimate.

Facies Association II

In the upper part of the Ab-Haji Fm at Parvadeh and Simin-Sepahan sections, beds of coal (C) and carbonaceous, dark green shale (Fc, Fl, Fm), commonly with abundant plant remains and shells of marine bivalves and brachiopods occur at the top of the uppermost fining-upward fluvial plain deposits (Fig. 7B–C). These strata also include 5-10 cm thick, interbedded rippled, fine-grained sandstone lens in clyastone beds (Fl(Sr)) with ferruginous concretions.

The fine-grained, structureless nature of the bulk of the fine-grained sediment suggests a prevalence of low-energy conditions and probably deposition in a protected coastal setting such as bay or low-energy shoreline. This facies is not associated with any subenvironments of the deltaic system. A marginal marine setting is most probable for the close association of clay and silt with marine shells and coal or highly carbonaceous beds. Because the coal beds are never associated with rootlets, it is likely allochthonous and results from transported plant material derived from densely vegetated coastal plains and swamps into a marginal marine setting. The presence of this facies association in the upper part of the Ab-Haji Fm just below the Badamu Limestones at the Parvadeh and Simin-Sepahan sections represent periods of reduced siliciclastic influx, possibly related to transgression.

Facies associations III and IV

Deltas are generally subdivided in delta plain, delta front, and prodelta environments (e.g. Wright 1985, Elliott 1986, Bhattacharya 2006). In the Ab-Haji Fm, two facies associations characteristic of the delta front and prodelta environments are recognized.

Facies association III - Delta front deposits.- Thick sandstone bodies occur at the Kuh-e-Rahdar in Kalmard Block and at Kuh-e-Shisui in the Lut Block. Their characteristic features are sequences that coarsen upward from fine- to coarse-grained sandstone (Fig. 7D, E). The sandstones are nearly invariably large-scale trough cross-bedded (St), horizontal lamination (Sh) and occasionally slump-folded and contain plant debris and wood fragments with wave and current ripples (Sr). Beds increase in thickness up-section until they form thick packages (Fig. 7D). The base of the sandstones is usually gradational from the underlying siltstones which are interpreted as prodelta deposits (see below; Fig. 7E). The sandstone bodies are usually stacked. Individual packages range from 30 to 50 m. The coarsening-upward sandstone packages show a clear stacking pattern at Kuh-e-Rahdar and Kuh-e-Shisui.

The systematic changes in grain size, bed thickness, and sedimentary structures are characteristic of delta-front deposits (e.g. Wright & Coleman 1974, Wright 1985, Elliott 1986, Bhattacharya 2006). The thickening- and coarsening-upward cycles can be interpreted as shallowing cycles within a deltaic system. This facies association consists of two sub-associations, i.e., upper and lower delta front. Likely, the large cross-bedded (up to 10° dipping), coarse-grained sandstones are related to the upper delta-front deposits (e.g. Li et al. 2010), which gradationally overlie large-scale trough cross-bedded, medium to fine-grained sandstones of the lower delta front (mouth-bar), the latter in close association with pro-delta sediments. Several slump horizons indicate a depositional slope and sediment instability, probably related to high sedimentation rates or over steepening (e.g. García-García et al. 2011). The general stacking pattern in thickening-upward packages reflects periodic progradation of the delta front by strong variations in sediment supply to the delta, possibly due to changes in the tectonic activity.

Facies association IV - Prodelta deposits.- This facies association is dominated by laminated clystone (Fl) along with subordinate alternations of siltstone and fine-grained sandstones (Sr/Fl), the latter of which contain plant debris, wood fragments and occasionally marine fossils (Fig. 7E-F). Some sandstone beds have hummocky cross-stratification (Shc), and a few show current ripples (Sr). Usually, these sediments represent a coarsening-upward pattern and grade into overlying delta-front sandstones (Fig. 7E). Another common sedimentary feature in this package is the presence of slump folds.

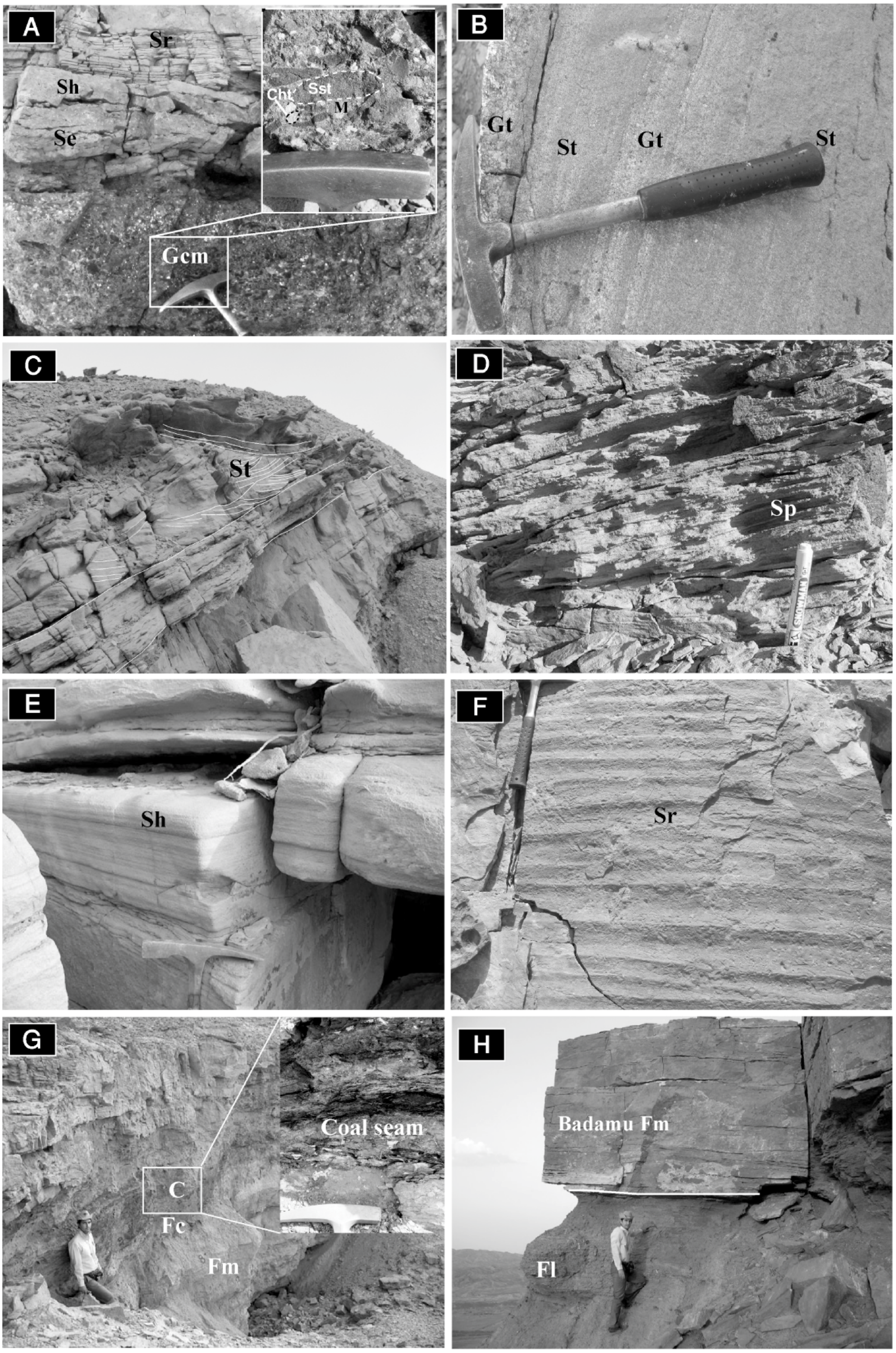

Figure 6. Representative lithofacies of the Ab-Haji Fm at Parvadeh section. **A.** Gcm lithofacies is overlain by Se, Sh and Sr lithofacies sandstone. **B.** Trough cross-bedding in conglomerate (Gt) and sandstone (St) lithofacies. **C.** Trough cross-bedded sandstone lithofacies (St). **D.** Planar cross-bedded sandstone lithofacies Sp. **E.** Beds of horizontal and laminated sandstone (Sh). **F.** Sr lithofacies with wavily-rippled sandstone. **G.** Beds of fine-grained siltstone interbedded with mudstone, showing Fm, Fc lithofacies overlain by coal (C) lithofacies. **H.** Beds of laminated siltstone and mudstone (Fl) lithofacies.

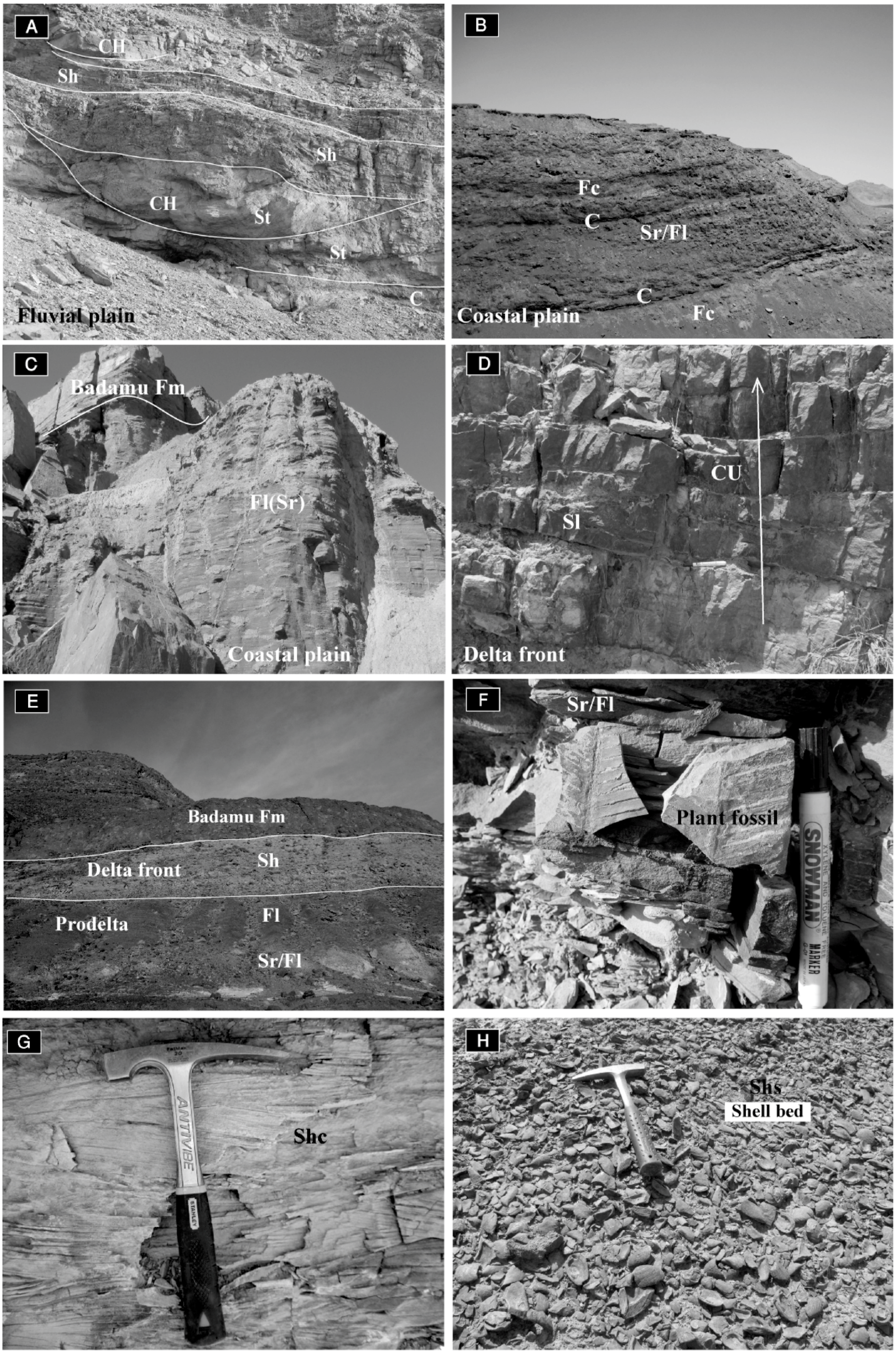

Figure 7. Field aspects of the Ab-Haji Fm. **A**. Channel sandstone of the fluvial facies association (Parvadeh section). **B**. Carbonaceous claystone (Fc), siltstone to fine-grained sandstone (Sr/Fl) and coal (C) of the coastal plain facies association (Simin-Sepahan section). **C**. Interbedded fine-grained rippled sandstones lens in green siltstone and claystone (Fl(Sr)) of coastal plain, capped by oolitic limestones of the Badamu Fm (Parvadeh section). **D**. Coarsening-upward (CU) delta front sandstones of the Ab-Haji Fm (Kuh-e-Shisui section). **E**. Fine-grained, green siltstone of prodelta deposit overlain by a thick coarsening-upward delta front succession (Kuh-e-Rahdar section). **F**. Plant imprint form dark green shales interbedded with siltstone and fine-grained sandstone (Sr/Fl) of prodelta origin (Kuh-e-Rahdar section). **G**. Shallow-marine hummocky cross-stratified sandstone (Shc) (Kuh-e-Rahdar section). **H**. Shell-dominated sandstone (Shs) of shallow-marine shelf (Kuh-e-Shisui section).

All claystones in this facies association are interpreted to be the result of settling from suspension in very low-energy conditions. The interbedded sandstone layers are interpreted to record flood events that spread sand over the prodelta. Based on their lithological characters and their close association with delta-front sandstones, this facies association is interpreted as representing a prodelta environment with a low to intermediate energy regime (e.g. Wright 1985). Prodelta sediments are developed at the western margin of the northern Tabas Block and at Kuh-e-Shisui in the Lut Block.

Facies association V

Very fine- to fine-grained, horizontally to very low-angle cross-stratified sandstone (Sh, Sl), ranging in thickness from 0.3–0.5 to more than 1 m are occasionally interbedded with siltstones and shales (Fl, Sr/Fl) (Fig. 5A, D). The base of the sandstone beds is either sharp or gradational, but generally not erosional. The sandstones are topped by ripple surfaces and commonly exhibit bioturbation. Hummocky cross-stratification (Shc) and high proportion of ripple cross-lamination was encountered in the Kuh-e-Rahdar sections (Fig. 7G). At the Kuh-e-Shisui section in the Lut Block, abundant marine bivalves in siltstone to very fine-grained sandstone (Shs) form a shell pavement between sandstone (Fig. 7H).

The sandstone units of this facies association represent several sub-environments within a shallow siliciclastic shelf. Large-scale low-angle cross-bedded sandstone, commonly coarsening-upward, is interpreted as shoreface sequence (e.g. Reineck & Singh 1973). Its sharp base is an indicator of high flow velocities, reflecting storm-induced currents (Hunter & Clifton 1982). Shell lags represent high-energy environments above the fair-weather wave-base, in which reworking was frequent (Fürsich & Pandey 2003). Alternating bioturbated and laminated sandstones are characteristic of the lower shoreface, where the effects of storm-induced currents alternate with quiet episodes during which the substrate becomes thoroughly bioturbated. Sandstone packages with large-scale cross-stratification or ripple-lamination record upper shoreface conditions, permanently above the fair-weather wave-base. The hummocky cross-stratification in combination with horizontal lamination and oscillation ripples indicates deposition by combined flows, produced by storm-generated waves (Myrow & Southard 1996).

DISCUSSION

The reconstruction of the palaeogeography of the CEIM during the Early Jurassic requires knowledge of the spatial and temporal distribution of facies within the siliciclastic Ab-Haji Fm. In the following, we discuss the lateral facies and thickness changes, and the tectonic controls on its deposition.

Facies development and thickness changes

The Ab-Haji Fm thickens towards the east from 82 m at Kuh-e-Rahdar to 347 m at Simin-Sepahan (Fig. 8A−B). At Kuh-e-Rahdar, this formation overlies the Permian Khan Fm with a significant stratigraphic gap. Local erosion down to Lower Palaeozoic levels on the Yazd Block confirms the phase of uplift and erosion of the Eo-Cimmerian orogeny (Bagheri & Stampfli 2008).

At Kuh-e-Rahdar, the Ab-Haji Fm is composed of 28 m of shallow-marine sandstone and shale at the base overlain by 54 m of deltaic facies. This shallow-marine and deltaic facies progrades eastward and grades rapidly into a mud-dominated fluvial plain and thin coastal plain deposits at Simin-Sepahan (Fig. 8B).

The fluvial facies –320 m thick at Simin-Sepahan– thins towards the southeast, reaching 60 m at Parvadeh where it is overlain by 15 m of coastal-plain mudstone. At this locality, the fluvial channels of Ab-Haji Fm erosively cut into the sediments of the underlying Nayband Fm. The well-developed channel facies and the poor development of the fine-grained flood plain deposits point to low-sinuosity rivers reaching the exposed area. The coastal plain facies is restricted to 15 m of green laminated shale in the upper part of the Ab-Haji Fm which precedes the transgression of the Badamu Fm.

In the easternmost part of the study area, at Kuh-e-Shisui on the Lut Block, the Ab-Haji Fm consists of 110 m of shallow siliciclastic shelf deposits overlain by 10 m of prodelta sediments which grade into 90 m of stacked delta-front sandstones. There is clear evidence of a eastward-prograding deltaic system (Fig. 8A-B). The poor development of lower delta plain deposits at this locality may indicate a relatively steep gradient.

The observed pattern of facies and thickness changes are evidence of strong differential subsidence with a close association of erosional areas and depocenters which may best be explained by an array of tilted fault blocks (see below).

Geodynamic significance and palaeogeography

The well constrained distribution pattern of the Ab-Haji Fm requires a tectonic explanation. Leeder & Gawthorpe (1987), Alexander et al. (1994), and Gawthorpe & Leeder (2000) suggested general scenarios of extensional-fault-bounded tilted blocks which readily explain thickness variations and rapid east-to-west facies changes of the Ab-Haji Fm. Extensional tectonic pulses were documented in east-central Iran during Late Triassic to Late Jurassic (Fürsich et al. 2003, Fürsich et al. 2005, Wilmsen et al. 2010). The extensional pulse in the Early Jurassic resulted in block faulting with regional differences in subsidence and synsedimentary block movements that produced several basins separated by uplifted areas. These tectonic movements resulted in thickness variations and rapid facies changes of the Ab-Haji Fm in an E-W direction as well as in non-sedimentation and erosion along the N-S-oriented crests of the tilt blocks.

During this time the Tabas Block would have tilted towards the west so that its uplifted part formed the axis of the present-day Shotori Mountains (the so-called Shotori Swell; Fig. 8). The crest area of the tilted block was subaerially exposed (palaeo-relief) and became eroded. Likewise, the uplifted eastern part of the Yazd Block experienced erosion down to Palaeozoic strata (e.g., Kuh-e-Rahdar section). The Ab-Haji Fm through sections 1−4 (Fig. 8B) shows similar E-W oriented changes in thickness as shown by the Upper Jurassic Kamar-e-Mehdi Fm documented by Wilmsen et al. (2010) in the northern Tabas Block. Furthermore, the Shotori Swell remained a topographically elevated area during the Late Cretaceous (Wilmsen et al. 2005). Sediment transport occurred predominantly towards the east and to a lesser extent also in a westerly direction (Fig. 8A). On the western part of the Yazd and Kalmard blocks (at Kuh-e-Rahdar) and on the Lut Block (at Kuh-e-Shisui), subsidence resulted in vertical stacking of thick deltaic sandstones (Fig. 8B). Deltas spread across the subsiding area and occasionally prodelta facies extended towards the east (Fig. 8A). A tendency for terminal deltaic lobes to migrate preferentially towards the axis of maximum tectonic subsidence was also reported by Leeder & Gawthorpe

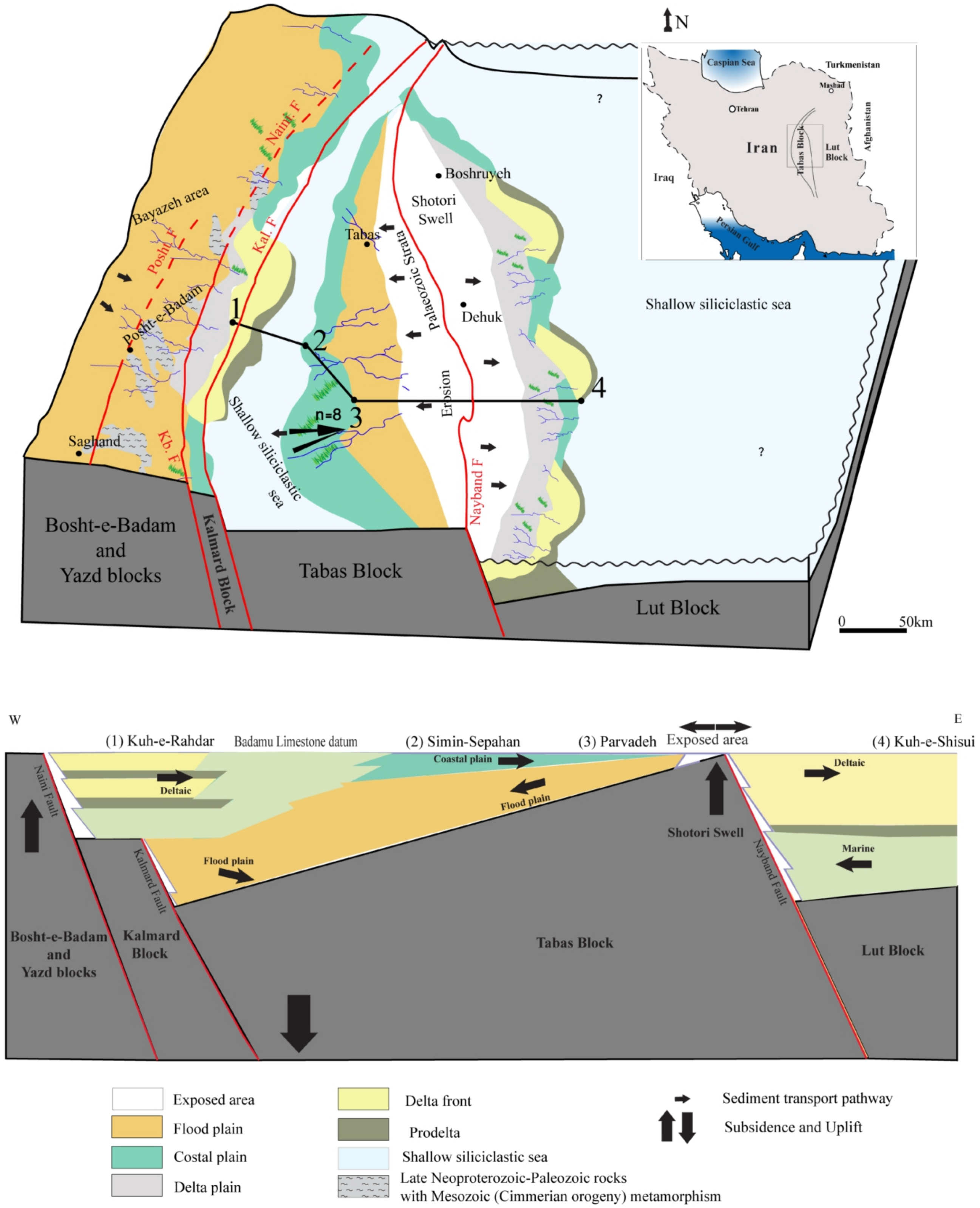

Figure 8. Palaeogeography of east-central Iran, (**A**) showing the distribution of facies associations in the Ab-Haji Fm on the present-day position of three Yazd, Tabas and Lut blocks without considering major post-Jurassic counterclockwise rotation (blocks and faults; modified from Zamani-Pedram (2011). Rose diagrams represent paleocurrents, n indicates the number of paleocurrent measurements. **B**. E–W transect of the assumed environments of the Ab-Haji Fm. In the east, deltaic and shallow marine environments (Kuh-e-Shisui section) change into the exposed part of the Tabas Block (Shotori Swell). Towards the west (Simin-Sepahan and Parvadeh sections), the Ab-Haji Fm reappears again in a coastal and fluvial plain facies and finally grades into deltaic and shallow marine environments (Kuh-e-Rahdar section). Note the thickness variations and facies changes from E to W that follow the pattern of basement uplift and erosion of tilted fault blocks.

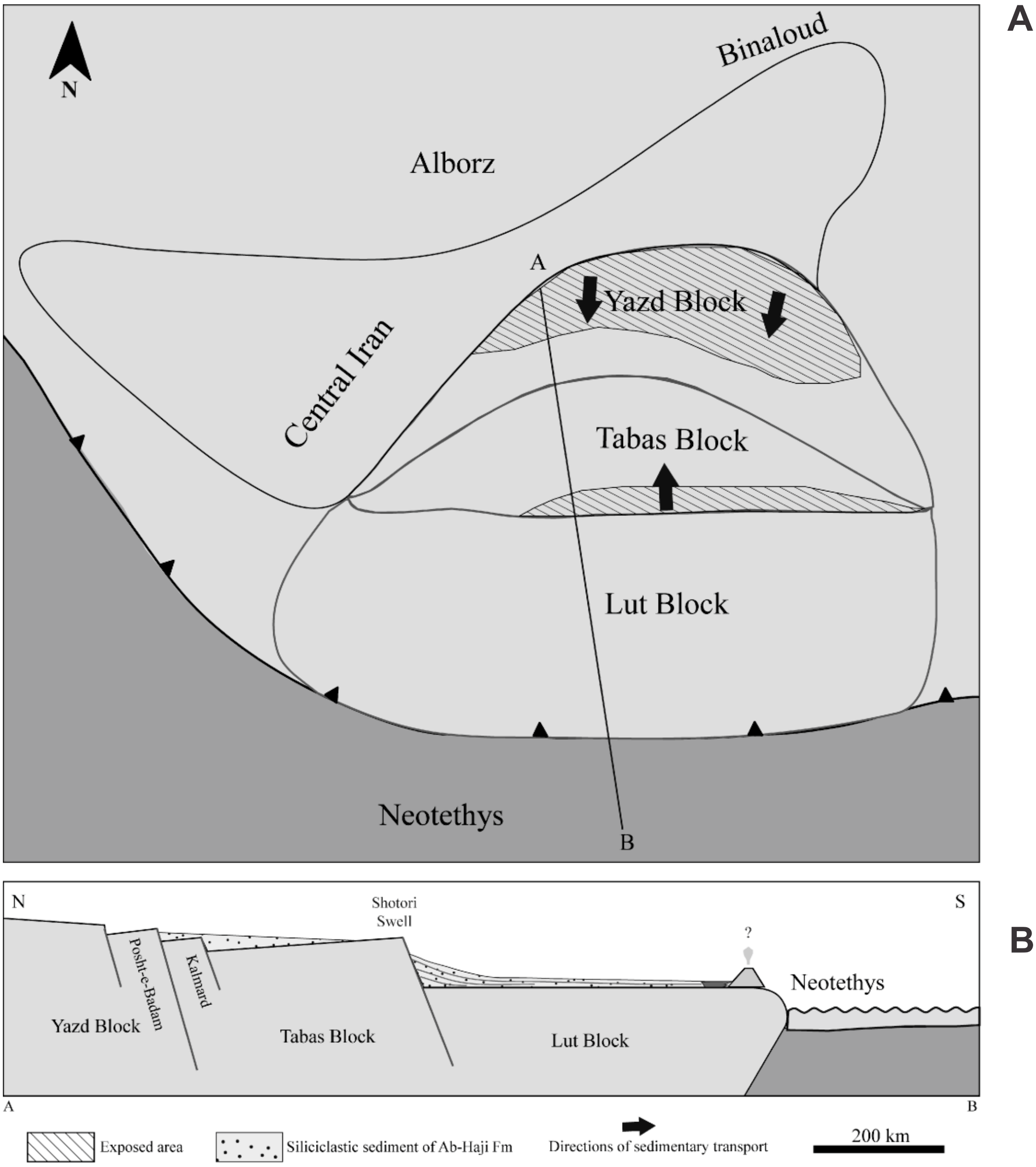

Figure 9. **A**. Early Jurassic siliciclastic systems of Iran (base map modified after Barrier & Vrielynck 2008). The Lut, Tabas and Yazd Blocks are shown in assumed Jurassic orientation. **B**. Cross section (A−B in **A**) through Yazd, Tabas and Lut blocks that shows locations of depocenters and emergents area.

(1987). In contrast, on the eastern margin of the Tabas Block, fluvial plains were fringed by coastal plains (Fig. 8A). Where the Ab-Haji Fm crops out, as at Parvadeh, the east-west trending fluvial channels of the formation cut erosively into the underlying fine-grained siliciclastic sediments of the Nayband Fm. This pattern, along with the westward-directed paleocurrent indicators, indicate the preferred sediment transport direction on the west-dipping tilted Tabas Block (Figs. 7A, 8A).

The source areas of the siliciclastic sediments of the Ab-Haji Fm are reconstructed based on thickness variations, lateral facies changes, changes in the type of the basal contact (from sharp and erosional to gradual), and on their petrography and geochemistry (see Salehi et al. 2014). A likely source for the siliciclastic rocks along the Kalmard and western Tabas blocks must have been the Yazd Block (Fig. 8A). The source area of siliciclastic material of the northeastern Tabas and Lut blocks could have been the subaerially exposed eastern part of Tabas Block, i.e., an area approximately parallel to the present-day strike of the Shotori Mountains (Fig. 8A).

In the Fig. 9A the three blocks of the CEIM are placed in a pre-rotational position, roughly parallel to the Neotethys subduction zone, with the Lut Block in a back-arc setting close to an inferred volcanic arc (cf. Wilmsen et al. 2009a, Salehi et al. 2014). The high siliciclastic input into the depocenter clearly suggests a high relief of the emergent margin of Yazd and Tabas blocks and a semi-humid to humid climate (Salehi et al. 2014; see Fig. 9B herein). This interpretation is supported by the pattern of thickness variations and rapid facies changes in present day orientation of these three blocks.

CONCLUSION

The results of the integrated stratigraphic and facies analysis of the Lower Jurassic Ab-Haji Fm of east-central Iran discussed above, lead us to the following conclusions:

(1) The Lower Jurassic Ab-Haji Fm was deposited across the three tilted fault blocks of the Central-East Iranian Microcontinent (CEIM) and reaches a thickness of up to 350 m in northern Tabas Block but may locally be reduced to a few tens of meters or even be missing.

(2) Lithofacies analysis of four well-exposed sections resulted in the recognition of sixteen lithofacies and five facies associations which are interpreted as representing: fluvial channels with associated flood plain and swamps, coastal plain, delta front, prodelta, and shallow shelf environments.

(3) The observed pattern of rapid E-W directed facies and thickness changes across the three blocks of the CEIM (from W to E: Yazd, Tabas and Lut blocks) is evidence of strong differential subsidence in response to block-tilting with a close association of erosional areas and depocentres.

(4) The Ab-Haji Fm records an Early Jurassic extensional tectonic setting for the three central-east Iranian blocks. Extension resulted in west-dipping fault blocks, differing regionally in their degree of subsidence and synsedimentary movements, and producing several half-graben basins. This configuration explains the variations of thickness and rapid east-west facies changes of the Ab-Haji Fm.

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