ORIGINAL ARTICLE

Facies analysis and depositional setting of the upper pliocene Akchagyl Formation in southeastern Caspian Basin, NE Iran

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Abstract

Pliocene deposits of the Cheleken and Akchagyl Formations constitute the most important hydrocarbon reservoirs in the Caspian Basin of Iran and other adjacent countries. In this study, facies characteristics and depositional setting of these sequences were examined using detailed field observations, petrographical studies, wireline-log and 2D seismic interpretations. Three outcrop sections were measured as the oldest and thickest Paleogene–Neogene units in the southeastern part of the Caspian Sea. Based on macroscopic and microscopic investigations, eleven sedimentary facies were identified in the studied sequence. These facies indicate deposition in alluvial fan, mud-flat, foreshore, shoreface and offshore of a wave-dominated lacustrine environment. The Akchagyl Formation is mainly composed of foreshore and shoreface facies with low gamma-ray values, which grades into offshore facies towards southwestern parts of the basin. The presence of marine biota such as *Globigerinoides fistulosus, Ammonia becccarii, Pullenia praecursor, Cardium dombra* and nanoplanktons (*Discoaster brouweri* and *Discoaster pentaradiatus*) demonstrate that this lacustrine setting was periodically connected to the global oceans, particularly in the Late Pliocene–Pleistocene. The stratigraphic correlation of the studied sections shows significant changes in lithology, facies and thickness of the Pliocene deposits. These changes were controlled by tectonic subsidence and clastic sediment supply during the Early-to-Middle Pliocene along with sea-level fluctuation as a consequence of the Akchagylian transgression episode in the Late Pliocene. Lateral changes in the geological parameters of the Akchagyl deposits indicate a more stable condition within the most part of the study area, especially towards the South Caspian Basin.

Keywords Facies analysis · Depositional setting · Akchagyl Formation · Southeastern Caspian Basin · NE Iran

Introduction

The Caspian Sea, known as the largest inland-isolated basin in the world, includes three depositional basins comprising the South Caspian Basin (SCB), Central Caspian Basin (CCB) and North Caspian Basin (NCS). The SCB is a large inland basin within the Alpine–Himalayan orogenic belt (Jackson et al. 2002; Reilinger et al. 2006; Kadirov et al. 2008). Since the Middle Pliocene, the basin is surrounded by compressional orogens including the Great Caucasus on the west, Talysh and Alborz on the south, and Kopet Dagh to the east.

As a prolific hydrocarbon basin, the SCB has unusual and complex geologic properties among the deepest sedimentary basins in the world (Smith-Rouch 2006). The most unique characteristics of the basin are its very high rate of deposition (about 4.5 km/my), loose nature of sediments, relatively low geothermal gradient (15 °C/1 km) and high pressures within some parts of the basin (Smith-Rouch 2006; Abdullayev et al. 2015). These significant characteristics have resulted in the occurrence of suitable petroleum system. Depth and age of the oldest sediments within the SCB are still unknown because of the large thickness (more than 20 km) of the overlying Mesozoic to upper Cainozoic deposits. The large amount of this sedimentary fill (about 10 km) was only deposited during the Pliocene–Quaternary period (Smith-Rouch 2006). The thick (~ 5–7 km) Pliocene deposits of non-marine lacustrine setting with deeper marine

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facies are the main reservoir units in adjacent countries (e.g., Azarbajan, Turkmenistan; Ali-zade et al. 1995).

Recently, the Iranian part of Caspian Basin has been considered a potential hydrocarbon province and, consequently, some appraisal wells have been drilled to define its various geological and reservoir aspects. Despite the significant importance of the Caspian petroleum system elements (i.e., Cheleken, Akchagyl, Apsheron), there is no available information on their stratigraphy, lithological characteristics, sedimentary environments, diagenetic history and reservoir quality, particularly in southeastern areas of the SCB. Due to the presence of vegetation in the studied area, limited outcrops of the Pliocene units are available for geological studies. Furthermore, loose nature of these sediments has resulted in low core recovery and drilling problems.

Despite some biostratigraphic reports and studies (e.g., Faridi 1964; Vatan and Yassini 1969), there is no detailed investigation on sedimentological characteristics and depositional environment of the Pliocene units in the studied area. This research is based on three outcrops along with two wells at the Kopet Dagh–Caspian zone in Golestan Province (Fig. 1). The main objectives of this study are facies analysis, depositional environment, lateral facies variations and tectono-sedimentary evolution of the Pliocene strata in the Iranian sector of SCB that can help get a better understanding of the Pliocene tectonic and sedimentation in this region.

Regional geology

Tectonic setting

Based on the sedimentary-structural division of Iran, the study area is considered as a part of the Caspain and western Kopet Dagh zones (Aghanabati 2004). The present tectonic framework of the SCB is the result of two main compressional phases through the final closure of the Neo-Tethys Ocean associated with the Arabian–Eurasian continental collision during the Oligocene to present time (Brunet et al. 2003). The first is early Arabian compression stage (Oligo-Miocene) and the second is late Arabian compression stage (Plio-Pleistocene). Early Arabian compressional phase was led to the occurrence of the mainly NW–SE trending folds and reverse faults as well as northward thrusting of Alborz orogens and subduction of the SCB (Khalilov et al. 1987; Allen et al. 2002; Knapp et al. 2004).

According to many researchers (e.g., Zonenshain and Le Pichon 1986; Allen et al. 2002; Brunet et al. 2003), a back arc spreading and extensional phases within Caucasus Trough resulted in the formation of the early SCB during the Middle Jurassic (Callovian) to the Eocene time. The oceanic crust of the SCB appears to being subducted underneath the Alborz Arc and Great Caucasus toward southeast–northwest due to the separation of oblique slip into strike-slip

and thrust faults (Priestley et al. 1994; Jackson et al. 2002) (Fig. 2). Based on recent studies (e.g., Allen et al. 2003; Brunet et al. 2003), the major uplift phase in the Kopet Dagh and Alborz orogens occurred due to the Late Eocene/Early Oligocene transpressional stages (Fig. 2a) simultaneously with the rapid subsidence phase of the SCB (Fig. 2b).

Stratigraphy

During the Late Miocene, both deep Black Sea and Caspian Sea were isolated by tectonic reactivation. As a result, the SCB became as inland freshwater lake having no connection with the ocean (Popov et al. 2006; Abdullayev et al. 2010), and consequently with the main regional sea-level falling over the basin (Jones and Simmons 1996). The Caspian Basin turned into an under-filled lake type during this isolation period (Bohacs et al. 2000; Abdullayev et al. 2010). Then, fluvial–deltaic sandstones and shallow water lacustrine shales (i.e., Productive Series) were deposited during Kimmerian- Balakhanian Stage within the SCB (Abdullayev et al. 2010, 2015). This stratigraphic unit (also known as Brown Beds or Chelekanian) is attributed to continental setting in the SCB. It is lithologically composed of a relatively high thickness of yellowish and brownish claystone, marl, siltstone, calcareous sandstone and yellowish brown to red conglomerate with calcareous pebbles as well as some fresh water Ostracods. These components are mainly originated from the Miocene and Cretaceous deposits (Hinds et al. 2004; Reynolds et al. 1998). The Cheleken deposits along with upper units (i.e., Akchagyl and Apsheron) contain about 8 km of sediment, which have been deposited in the central part of SCB since 5.5 Ma. These large amounts of sediments coincide with a marked increase in tectonic subsidence rate within the basin (Allen et al. 2002). It appears that the subsidence rate through the Caspian Basin was a function of the type of crust (continental or oceanic) and the amount of eroded sediments from the Kopet Dagh and Alborz mountains. The flexural mechanism is also suggested by Brunet et al. (2003), which explained the great rate of subsidence with increasing sediment supply from the surrounding orogens due to the different thickness and nature of the Caspian Basin lithosphere.

The present Mediterranean Sea was established in Early Pliocene time through a transgressive stage, which flooded the dry basin with the Atlantic marine waters. The Eastern Para-Tethys including Caspian Sea was inundated again through the straits of Aegean and Dardanelles at the maximum flooding of the Middle Pliocene transgression (Rögl and Steininger 1983; Rögl 1999). This condition resulted in deposition of the Akchagyl Formation during the Late Pliocene (2.6 Ma), which overlain the Productive Series (Cheleken unit). According to Degens and Paluska (1979), the "Akchagyl transgression" reestablished a short-term
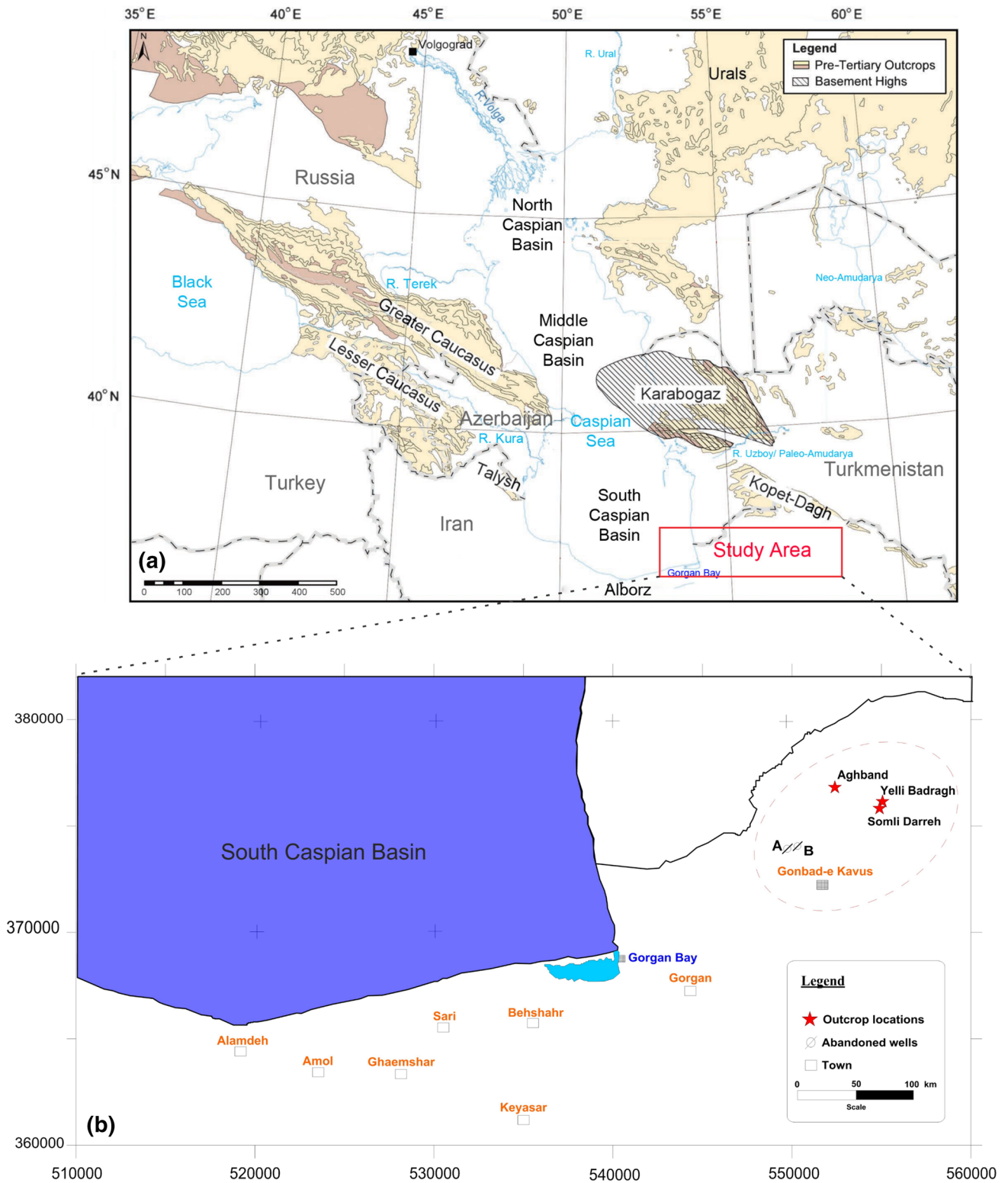
Fig. 1 a Location map of the different parts, major surrounding oro-gens and river systems (e.g., Kura and Paleo-Amudarya) in the Cas-pian Basin region (Abdullayev et al. 2010). The study area (outlined in red text box) is located in northeastern Iran of the southeastern Caspian Basin (SCB), b The measured stratigraphic sections are marked by red stars as well as wells A and B in their southwestern part
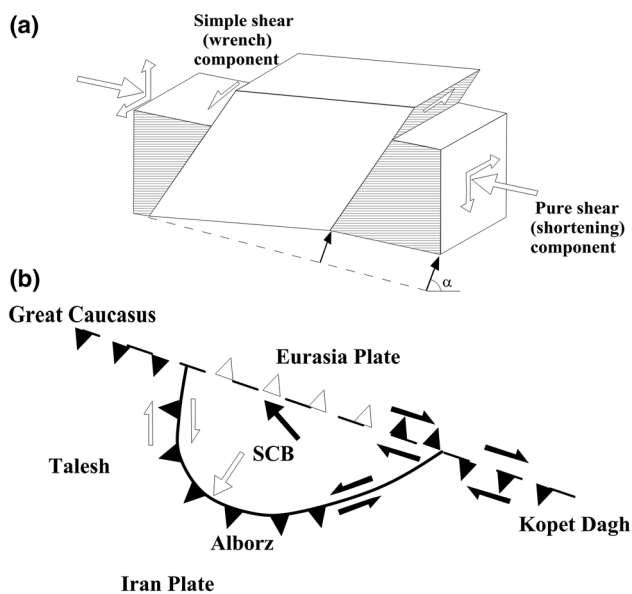
Fig. 2 a Schematic model for transpressional stages as a combination of pure shear component and simple shear component (modified from Tavarnelli et al. 2004), **b** Right-lateral component in the western Kopet Dagh and left-lateral component in the eastern Alborz representing possible motions of the SE Caspian Basin relative to Eurasia and Iran Plates Modified from Jackson et al. (2002)

marine condition in the Late Pliocene. This is supported by the presence of Mediterranean benthos (in Maeotian and Akchagylian) as well as phytoplanktons (Popov et al. 2006). After this marine flooding, the continued compressional phase associated with the Arabia–Eurasia collision led to the formation of a deep lacustrine setting (Allen et al. 2002). At the type section in Turkmenistan, the Akchagyl sequence consists of marls, clays and grey–white sands containing ostracods, gastropods and lamellibranche bivalves. It overlies the Lower Pliocene deposits (Cheleken Series), along a disconformity, and overlain by the Quaternary sequences (Ovsyuchenko et al. 2017). In Azerbaijan, the Akchagyl Formation mainly includes grey-color mudstones, siltstones, fine-grained calcareous sandstone, micritic limestone and rarely grey volcanic tuffs. It has a thickness of 75–107 m in many drilled wells in Azarbyjan. Based on the dating of tuffs and volcanic ashes, the age of the Akchagyl Formation is determined by 3.4–6 Ma (van Back et al. 2013).

The Pliocene strata in northern Iran (including Gorgan, Mazandaran, Gilan and Moghan plains) are composed of two main rock units; the first, Cheleken unit (also known as Continental/Red/Productive series) with continental and mainly coarse-grained facies, consisting of red beds with the age of Lower-Middle Pliocene, and the second, Achchagyl unit with white carbonate/clastic facies. There is no deposition of Cheleken unit in most parts of the measured outcrops (Fig. 3). In these areas, the Upper Pliocene Akchagyl

deposits directly overlaid the Cretaceous–Tertiary unconformity (Fig. 3).
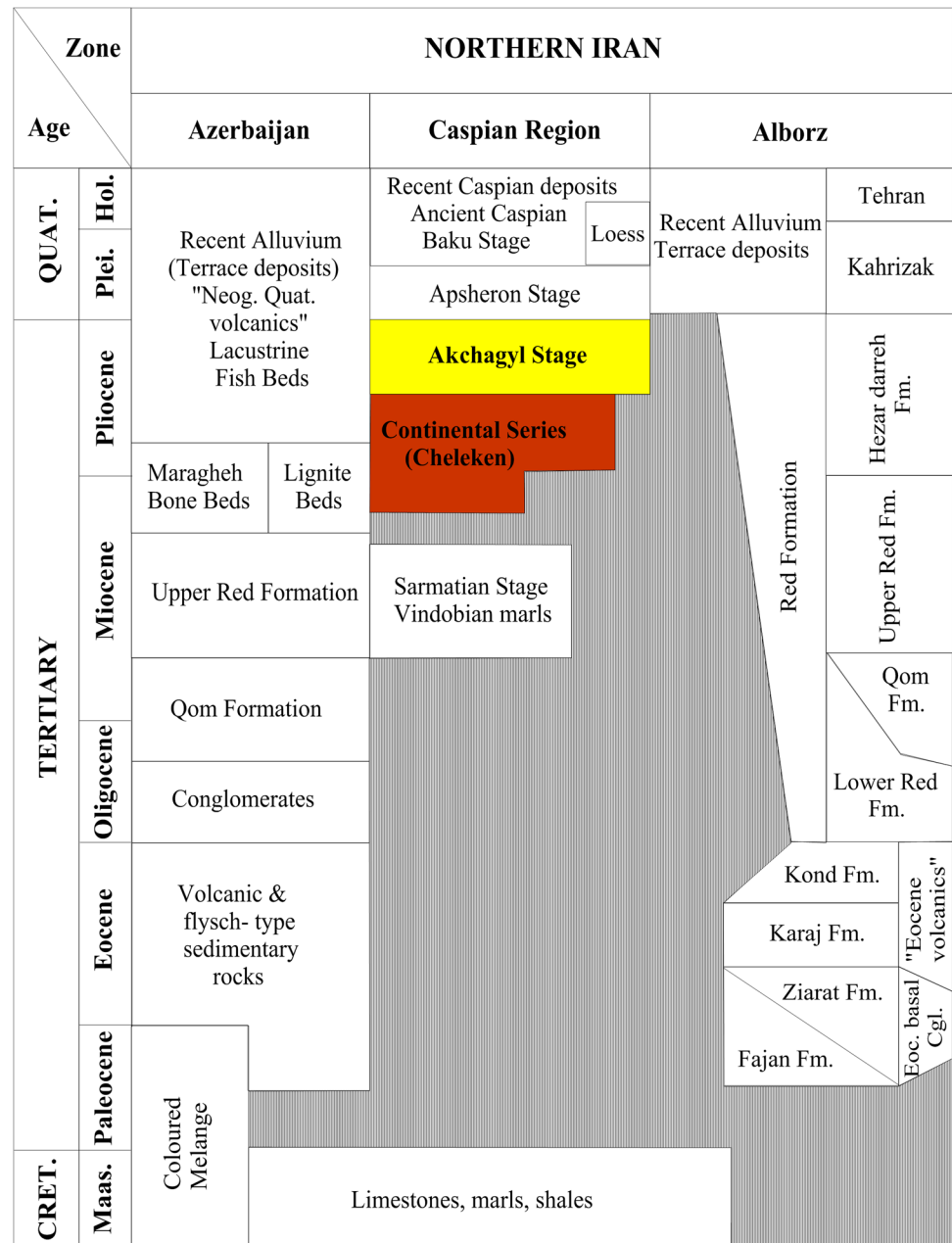
In the measured outcrops of northeastern Gonbad-e Kavous, the Akchagyl unit mainly consists of conglomerate, mudstone, marl, and bioclastic limestone representing shoaling-upward sequences. The outcrops were mapped as the thickest in the area. The maximum thickness (20 m) of the Akchagyl unit was reported from the Abadan Tappeh (NE Gonbad-e Kavous) by Ehsani (2006). In drilled wells in Gorgan plain, this thickness varies between 100 and 200 m (Yassini 1981). Planktonic foraminifera (e.g., *Globigerinoides fistulosus*, *Pullenia praecursor* and *Cardium dombra*) propose the late Pliocene age for this stratigraphic unit in Gonbad-e Kavous plain (Yassini 1981; Ehsani 2006). Some genus of Ostracoda (*Leptocythere*) and brackish water gastropods (*Potamia caspius*) indicate the late Pliocene age in the wells of Gorgan–Mazandaran Provinces, too (Faridi 1964; Vatan and Yassini 1969).

Materials and methods

Detailed field studies and microscopic analyses were carried out on three measured stratigraphic sections including Aghband, Yelli Badragh, and Somli Darreh with a thickness of 58, 62, and 30 m, respectively. Lithology and petrophysical log data, belonging to two appraisal wells A and B, were also used for correlation with the surface sections (Fig. 1). In addition, a surface gamma-ray log was surveyed at the Aghband section using a MiniSpec Exploranium GR 130 gamma-ray spectrometer. A total of 149 samples were collected from the Upper Pliocene Akchagyl Formation. The outcrops were logged using a Jacob Staff and their samples collected systematically every 1–2 m, depending on lithological changes.

All thin sections prepared from the outcrop samples were stained by Alizarin Red-S to determine their mineralogical composition according to the Dickson (1965) approach as well as impregnated with the blue-dyed epoxy resin to identify reservoir facies. Microfacies nomenclatures were conducted using Dunham (1962), Readings (1996), Miall (2000, 2013), and Flügel (2010) classifications. Facies with the same sedimentological properties are grouped as facies association (Miall 2000). Petrographic characteristics and sedimentological features in comparing to the modern environments were used to interpret facies types and their depositional settings (e.g., Purser 1973; Wilson 1975; Tucker and Wright 1990; Flügel 2010). A conceptual depositional model is presented for the Akchagyl unit in the studied area. Finally, lateral development of depositional facies and the nature of stratal surfaces are discussed through a seismic profile.

Fig. 3 Lithostratigraphic column for the Tertiary deposits in northern areas of Iran, from Moghan to Gonbad-e Kavous plains (adopted from Stratigraphic Chart of Iran). Pliocene units (Cheleken and Akchagyl) are marked in brown and yellow colors, respectively; grey area shows unconformity, *CRET* Cretaceous, *Mas* Maastrichtian, *QUAT.* Quaternary, *Neog.* Neogene, *Plei.* Pleistocene, *Hol.* Holocene, *Fm.* Formation, *Cgl.* Conglomerate)

Zone / Age			NORTHERN IRAN			
			Azerbaijan	Caspian Region	Alborz	
QUAT.	Hol.		Recent Alluvium (Terrace deposits) "Neog. Quat. volcanics" Lacustrine Fish Beds	Recent Caspian deposits / Ancient Caspian Baku Stage / Loess	Recent Alluvium Terrace deposits	Tehran
	Plei.					Kahrizak
				Apsheron Stage		
TERTIARY		Pliocene		**Akchagyl Stage**	Red Formation	Hezar darreh Fm.
				Continental Series (Cheleken)		Upper Red Fm.
			Maragheh Bone Beds / Lignite Beds			
		Miocene	Upper Red Formation	Sarmatian Stage Vindobian marls		Qom Fm.
		Oligocene	Qom Formation			Lower Red Fm.
			Conglomerates			
		Eocene	Volcanic & flysch- type sedimentary rocks		Kond Fm.	"Eocene volcanics"
					Karaj Fm.	
					Ziarat Fm.	Eoc. basal Cgl.
	Paleocene		Coloured Melange		Fajan Fm.	
CRET.	Maas.			Limestones, marls, shales		

Results and discussion

The Akchagyl stratigraphic unit overlaid the Cretaceous equivalent sediments and overlain by Apsheron sedimentary unit in the study area (Fig. 4). The lower boundary is often associated with unconformity, and therefore, the Lower-to-Middle Pliocene Cheleken stratigraphic unit has not been deposited in the area. Lithology and stratigraphic characteristics of the outcrops are as follows:

• *Aghband outcrop section* This outcrop can be suggested as a type section of the Akchagyl unit in the study area. Thickness of the Akchagyl unit is 58 m in this section. It

is located on the Cretaceous glauconite bearing of Aitamir Formation (showing the highest recorded gamma ray) with the defined angular unconformity (Fig. 4). This unconformity boundary is characterized by a red to brown colored conglomerate layer with high thickness variation of several centimeters to several meters (Fig. 4a). The Akchagyl stratigraphic unit, from bottom to top, consists of mudstones interbedded with very thin layers of evaporites, thin-to-medium and hard layers of porous limestone with cream-to-milky color, an alternation of mudstones and hard layers of limestone and the medium to thick bedded bioclastic limestone (Fig. 4). Bivalves, gastropods and foraminifera constitute the
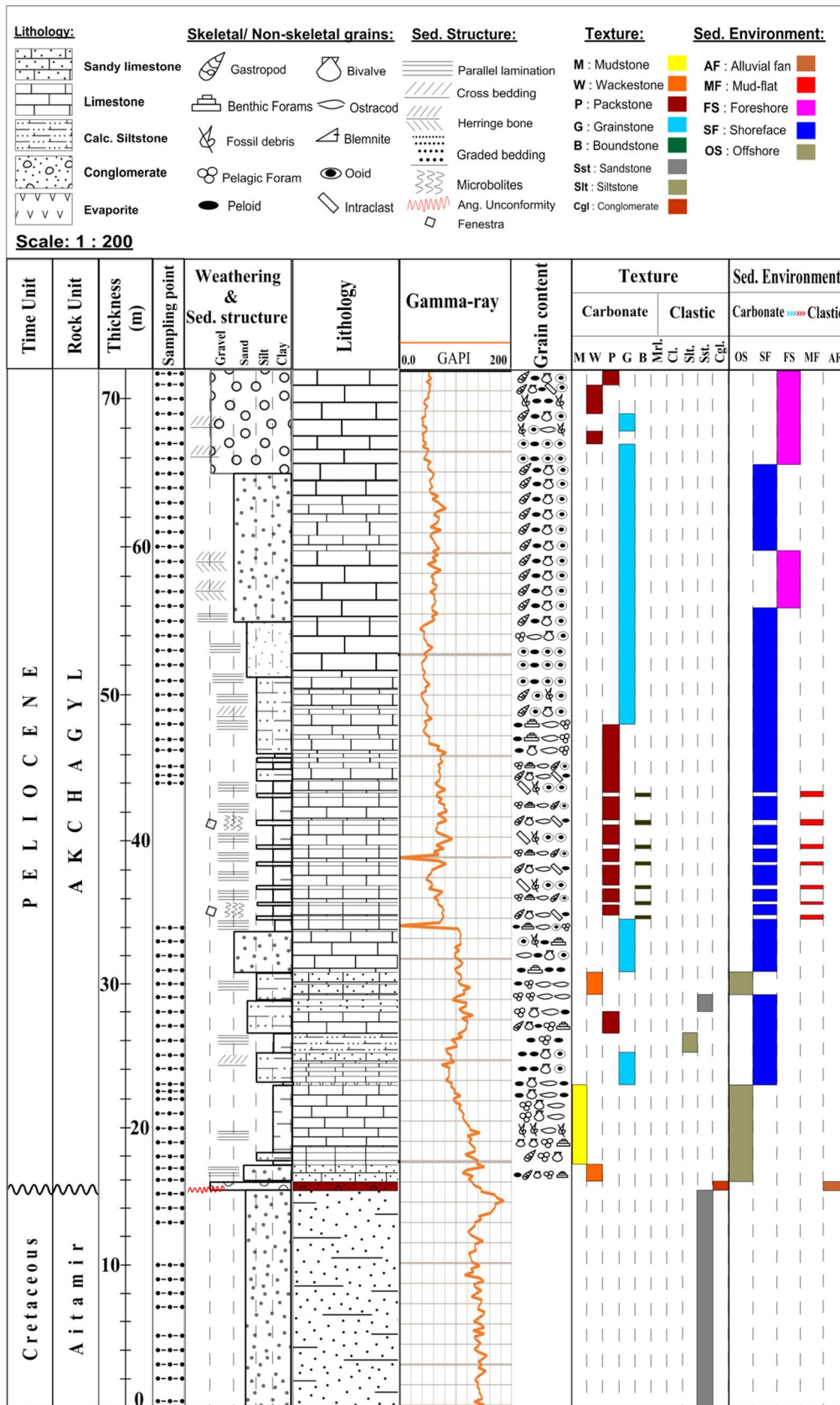
Fig. 4 Representative sedimentological characteristics of the Akchagyl Stage in Aghband section, Gonbad-e–Kavous area; the main components, grain texture and facies belts of the facies are determined

major fossil components in this interval. The size of bivalves and gastropods increases towards the upper-most sequence. The most common sedimentary structures include lamination, cross bedding and herring bone (bidirectional cross bedding). It is generally characterized by a shallowing and high-energy upward trend as well as a gradual decreasing in the amounts of gamma-ray log due to cleaning upward carbonates with very low micrite content (Fig. 4). It is generally characterized by a shallowing and high-energy upward trend as well as a gradual decreasing in the amounts of gamma-ray log due to cleaning upward carbonates with very low micrite content (Fig. 4).

- *Yelli Badragh outcrop section* The total thickness of Akchagyl unit in this section is 62 m. The lower boundary of the section is an unconformity characterized by an erosional contact at the Cretaceous greenish-grey marl. Akchagyl stratigraphic unit at the base starts with sandy conglomerate layers with finning-upward trend (Fig. 8). This succession follows upward with greenish-yellow-to-greenish-grey colored and small gastropod/bivalve bearing marls interlayered with 3–6 cm-thick gypsum and white-to-milky porous bioclastic limestone intervals. Finally, this stratigraphic unit ended by a porous interval composed of larger gastropod and bivalve shell beds at the uppermost part (Fig. 8).

- *Somli Darreh outcrop section* Akchagyl stratigraphic unit has a thickness of about 30 m at this outcrop section. The lower boundary of the section with the Cretaceous sediments is not clearly defined. The Akchagyl unit in this section consists of greenish-grey calcareous clay-stone, yellowish grey-to-greenish-grey-colored bioclastic sandy limestone, thin layers of creamy hard limestone, an alternation of loose and porous shell beds overlain by

an interbeds of shallowing-upward bioclastic (gastropods and bivalves) limestones and cream-to-milky colored, hared, cross bedded bioclastic limestones from bottom to top. General lithologic correlation between the three outcrop sections and the wells are given in Fig. 8.

Facies analysis

Field observations and detailed petrographic investigation of 149 thin sections belonging to the outcrops led to the recognition of 11 carbonate and siliciclastic facies. Silici-clastic deposits of the Pliocene units comprise conglomerate, sandstone and silty mudstones. They have the most thickness in southwestern part of the study area (well locations), which grade into carbonate-dominated facies towards the surface sections in northeastern part. These sedimentary facies were determined based on different parameters including lithology, geometry, constituent allochems/orthochems, texture and sedimentary structures through microscopy and field studies. The main characteristics of the identified facies associations (FAs) are discussed below (summary in Table 1 and Figs. 5, 6, 7).

FA-I (alluvial facies: F1)

This siliciclastic facies is composed of conglomerate with boulder, cobble and pebble sized clasts, which are dispersed in sandy and clayey matrix and overlaid the Cretaceous deposits (Fig. 5a, b). Some coal remnants and bivalve, belemnite fragments as well as other components such as glauconite, phosphate, pyrite and organic matter are observed in this facies. This sedimentary facies could be known as polymictic conglomerate, which is brown to reddish brown in color and considered as the base conglomerate

Table 1 Facies/facies association, sedimentary structures, major constituents and depositional settings of the upper Pliocene Akchagyl Formation in the studied outcrops

| Facies/facies association	FA-I	FA-II	FA-III	FA-IV	FA-V
	F1: Conglomerate	F2: Anhydrite F3: Silty mudstone F4: Microbial lam-inite	F5: Bioclastic sandy packstone F6: Bioclastic pack-stone	F7: Bioclastic peliod grainstone F8: Peloid–ooid grain-stone	F9: Ostracod bearing mudstone to wack-stone F10: Planktonic mud-stone F11: Marl
Sedimentay stractures/ fabrics	Graded bedding	Fenestrae, lamination	Cross bedding	Cross bedding (her-ring bone)	Lamination
Major constituents	Bivalve and foram fragments, heavy mineral, glauconite/minor phosphate in matrix	Silt, evaporite, heavy mineral, peloid, bivalve, gastropod, pisoids	Peloid, gastropod, bivalve, minor benthic forams	Bivalve, gastropod, intraclast, milliolid, peloid, ooid, glau-conite	Micrite, very fine sand and silt, glauconite, phosphate, pyrite, bivalve, ostracod, benthic and pelagic forams
Depositional setting	Alluvial fan	Coastal Sabkha/Mud-flat	Foreshore	Shoreface	Offshore
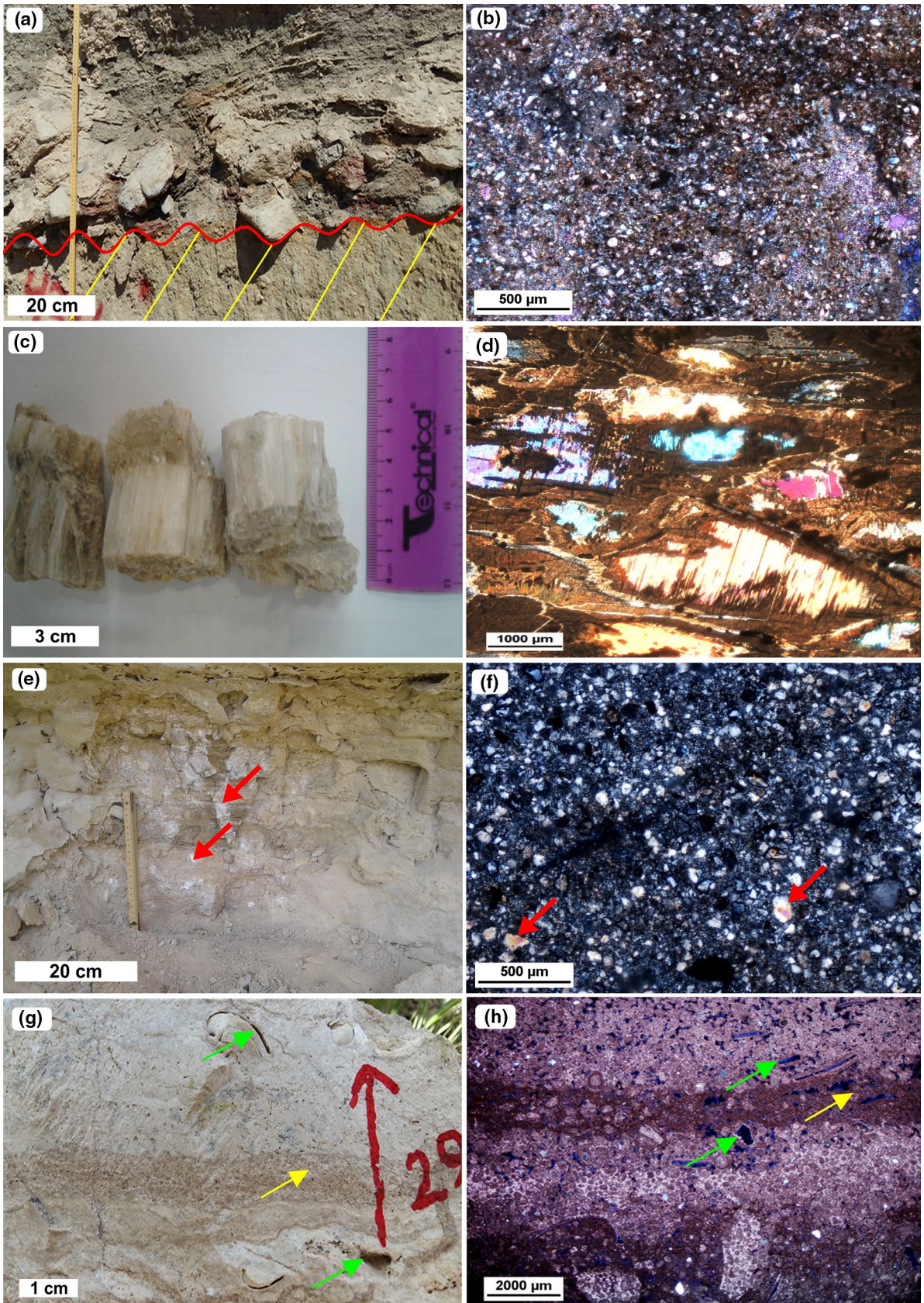
◀**Fig. 5** Representative macroscopic/microscopic photographs of the Alluvial and mud-flat facies. **a** Basal conglomerate lithofacies at the Aghband section, angular unconformity (marked in red color wavy curve) between the Cretaceous sedimentary layers (yellow oblique-parallel lines) and conglomerate (F1), **b** Sandy to silty context of the conglomerate, **c, d** Gypsum/anhydrite (F2), **e, f** Silty mudstone (F3) with evaporate and heavy mineral (red arrows), and **g, h** Microbial laminates (F4) with fenestral fabric (yellow arrows) and vadose dissolution (green arrows)

of Akchagyl unit (Akchagylian transgressive conglomerate) (Fig. 5a). It is observed in both Aghband and Yelli Badragh outcrop sections with different thickness of about 20 cm and 15 m, respectively. The conglomerate facies is also recorded in lower parts of the wells A and B of the study area as 2–6 thick layers (Fig. 8). This facies is similar to standard facies code of Gcm (Miall 2013).

The presence of poor sorting and roundness and massive nature of the conglomerate suggest a high density turbulent/debris flow of the alluvium/fan delta system originated from the high lands in vicinity of depositional environment (Miall 2013; Marchetti et al. 2015).

FA-II (mud-flat facies: F2, F3, F4)

Mud-flat facies are composed of thin bedded gypsum/anhydrite, silty mudstone and microbial laminate (Table 1 and Fig. 5c–h). Anhydrite was observed in thin bedded and cream colored intervals. This facies can be represented in Yelli Badragh section in two horizons that are located below the mud to wackestone facies and on the top of Marl facies with the thickness of 5–6 cm. The silty mudstone facies is grey-to-greenish grey in color lacking any fossil content and comprises thinly laminates of silty quartz grains and heavy minerals (Fig. 5e, f). In the Aghband and Somli Darreh outcrops, the thickness of this facies varies 80 cm–1 m. The lower boundary of this facies is not clear at the Somli Darreh outcrop section, but at the Aghband section, it overlaid the conglomerate unit and overlain by mudstone facies. The microbial laminate occurs as a pisolithic cover (microbial/algal bands) surrounding the grain-dominated facies (bioclastic and peloid–ooid packstone to grainstone) (Fig. 5g, h). The average size of the pisolitic structures is 4–5 mm. The fenestral fabric and burrowing are the other characteristics of the facies.

The thin layer evaporites with local distribution in the study area can be attributed to the marginal and lake deposits during evaporation of the isolated water body (Marchetti et al. 2015). Also, deposition of the evaporites can be interpreted as evidence for the temporary isolation of this part of the area from Para-Tethys basin, possibly resulted from an abrupt eustatic sea-level fall creating conditions for the precipitation of the evaporite (gypsum/anhydrite) layers (van Buchem et al. 2010). The fine-grained nature of the silty

mudstone and lack of fauna suggest that deposition occurred in a tidal flat setting. The presence of fenestral fabrics can be represented as irregular and laminoid fenestral fabric probably formed by gas trapping during desiccation/lithification in more frequently exposed sediments resulting in hard horizons in tidal flats. The fossil constituents (gastropods and bivalves) suggest a brackish to hypersaline condition in the limited sub-environment. This facies can be assigned to the vadose area (above the water table), which is affected by meteoric diagenesis (Fig. 5g, h) (Flügel 2010).

FA-III (foreshore facies: F5, F6)

Foreshore deposits are mainly composed of and poorly sorted to rounded bioclastic sandy packstone and bioclastic packstone (Table 1 and Fig. 6a–d). The most common constituents of the facies comprise gastropod, bivalve, minor benthic foraminifera and quartz grains (Fig. 6b–d). Bioclastic sandy packstone is composed of grey-to-greenish-grey thin-to-medium beds with the thickness of 20–30 cm, which are only observed in the Aghband outcrop section. The most constituent grains of the facies include fragments of pelagic foraminifers, ostracods, bivalve as well as some glauconites and phosphates. Cross bedding and cross lamination are the most common sedimentary structures in these facies (Fig. 6a). The foreshore facies lie between mud-flat and shoreface coarsening-upward succession of bioclastic peloid and ooid–peloid grainstones. These facies associations are only present in the upper part of the Aghband outcrop characterized by very low amounts of gamma ray (Fig. 4) due to lack of micrite or negligible matrix.

The large skeletal grains (e.g., gastropods and bivalves) and grain-dominated texture along with cross bedding structures display a high-energy wave-dominated depositional system above the fair-weather wave base (FWB) (Flügel 2010).

FA-IV (shoreface facies: F7, F8)

Shoreface belt contains bioclastic ooid grainstone and peloid–ooid grainstone (Table 1 and Fig. 6e–h), which separate foreshore and offshore facies. Bioclastic sandy packstone is composed of grey-to-greenish-grey thin-to-medium beds with the thickness of 20–30 cm, which only observed in the Aghband outcrop section. The most constituent grains of the facies include fragments of pelagic foraminifers, ostracods, bivalve as well as some glauconites and phosphates. The peloid–ooid grainstone facies mainly includes peloid, ooid, intraclast, ostracod and minor miliolid with medium to good sorting/roundness and high mouldic porosity (Fig. 6h). These facies dominate the main uppermost part of Akchagyl succession in the Aghband outcrop section, while their thickness decreases towards the Somli Darreh and particularly
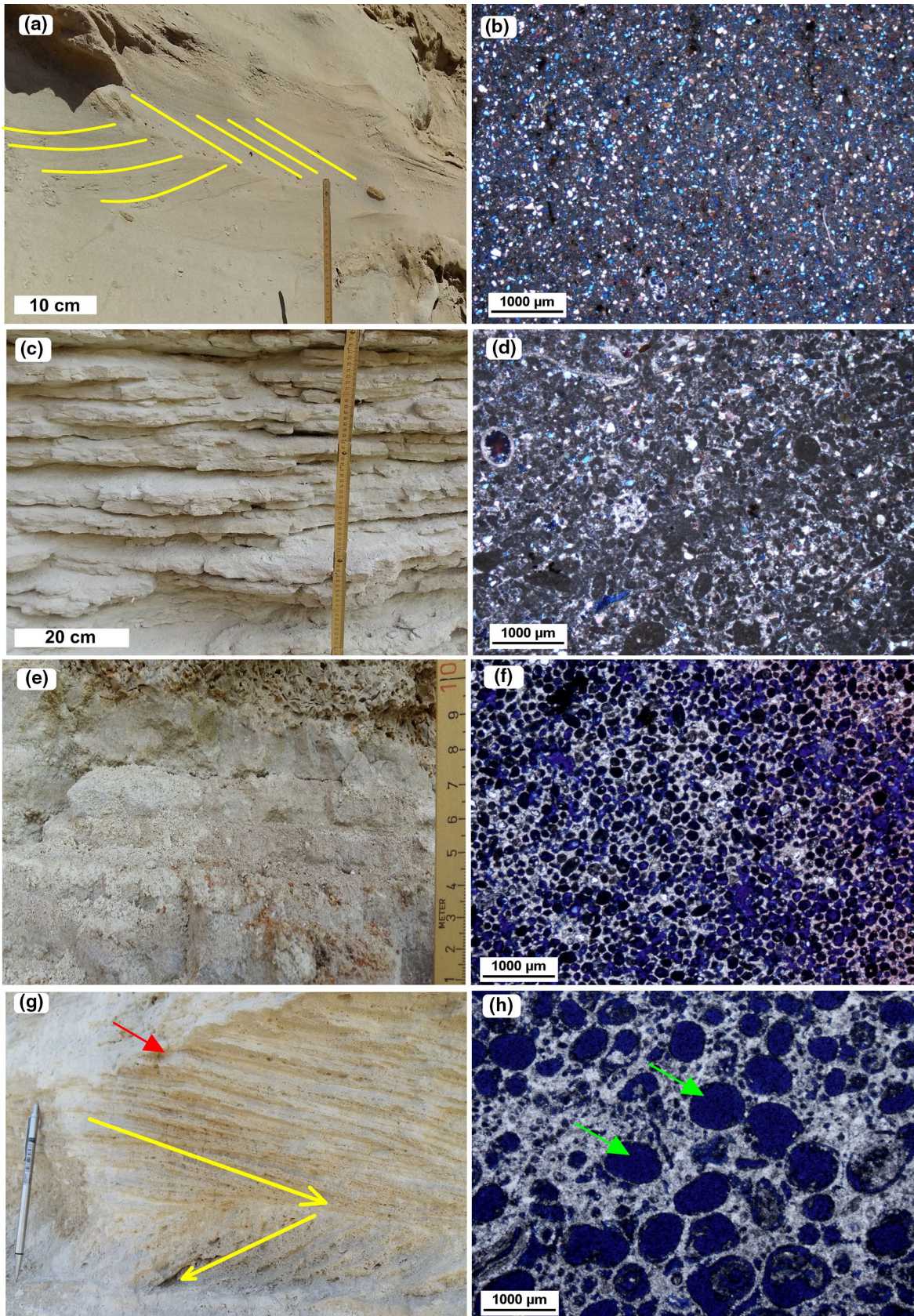
◀**Fig. 6** Representative macroscopic/microscopic photographs of the foreshore and shoreface facies associations. **a**, **b** Cross bedding (yellow lines and curves) in bioclastic sandy packstone (F5), **c**, **d** bioclastic packstone (F6), **e**, **f** hard layers of bioclastic (well-sorted) peloid grainstone (F7), **g** bidirectional cross bedding (yellow arrows) and reactivation surface (red arrow), and **h** mouldic dissolution (green arrows) in well-sorted/rounded peloid–ooid grainstone (F8) at the upper parts of the Akchagyl Formation. See detailed in the text

Yelli Badragh in which these facies are only present in upper part of the sequence (Fig. 6g). Some laminated mudstones associated with the shoreface facies represent flow regime fluctuation of the basin. These facies associations are considered the highest energy depositional setting affected by wave and tide agents.

The presence of well-sorted, well-rounded non-skeletal components (peliod, ooid) as well as the bidirectional (herring bone) sedimentary structures and reactivation surface reflects relative tidal current influence of transport and sedimentation within depositional setting (Tucker 2001). The dissolved moulds are indicative of the vadose/meteoric zone diagenesis (Flügel 2010).

FA-V (offshore facies: F9, F10, F11)

The offshore belt consists of silty bioclastic mudstones, bioclastic wackestones and silty marls (Table 1 and Fig. 7). The most important bioclasts include planktonic foraminifera (blue arrows), small bivalves and ostracods and some benthic foraminifer fragments (blue arrow in Fig. 7f). Non-skeletal grains such as glauconite (green arrows), phosphate, pyrite (yellow arrows) and some peloids are present (Fig. 7d–f). Thin laminations are the main features observed in mudstones (Fig. 7c). This facies belt was mainly observed in the Aghband and Yelli Badragh outcrop sections; its thickness increased from Aghband towards Yelli Badragh.

The presence of planktonic foraminifera, pyrite and lack of mechanical sedimentary structures indicate that this facies was deposited in low-energy deep basin settings with normal salinity (Wilson 1975; Flügel 2010).

Depositional model

Based on the microfacies characteristics, five depositional sub-environments including alluvial, mud-flat, foreshore, shoreface and offshore belts were determined for studied intervals of Akchagyl unit (Upper Pliocene). In the study area, most parts of this unit are dominated by carbonate shoreface–foreshore sub-environments containing bioclastic packstone to grainstone and peloid/ooid grainstone. The beach facies belt is strongly wave-dominated and constantly changing with sediments input by the influx from rivers, erosion of adjacent orogens (mainly Kopet Dagh), accumulation of shell beds and the deposition of non-consolidated deposits

by low tides. The substrate condition is different from loose bioclastic sandy packstone in foreshore setting to hard layers of bioclastic peloid–ooid grainstone in shoreface belt (Nichols 2009). Such a feature is similar to the low-latitude warm-water beaches (Scoffin and Stoddard 1983), which is gently dipping towards the offshore. The low angles (2°–3°) cross bedding of well-sorted, well-rounded peloid–ooid grainstones are associated with the wave-dominated beach environment (Clifton 2007). The beach setting is connected to the land via mud-flat facies (low tidal microbial laminitis and evaporite layers). Accordingly, results of this study propose a shoreline depositional model for the Akchagyl Formation in the studied area (Fig. 8b), which is dominated by high wave energy facies, but low tidal range facies (c.f. Reinson 1992; Tucker 2001; Flügel 2010). The depositional environment of Akchagyl succession also could be mainly associated with the lacustrine carbonates deposited within a lake or at the shorelines of a lake (c.f. Flügel 2010) with the coarsening-upward pattern. However, the existence of some fossils such as *G. fistulosus, Ammonia becccarii, P. praecursor* and *C. dombra* as well as some nanoplanktons such as discoasters namely *Discoaster brouweri* and *Discoaster pentaradiatus* within the Akchagyl sediments (at the Yelli Badragh section) indicate that this lacustrine setting was periodically connected to the global oceans (probably Mediterranean sea), particularly in the Late Pliocene–Pleistocene (Akchagyl marine transgression event) (Abdullayev et al. 2015; Zubakov and Borzenkova 1990). The mentioned biota of the Upper Pliocene Akchagyl are likely to have originated from the Mediterranean basin. Marine components such as bivalves, ostracods, foraminifers and polyhaline nanoplankton associations reported from Azerbaijan represent possible passage from the eastern Mediterranean to eastern Transcaucasia or South Caspian depression (Fig. 8a) (Popov et al. 2004, 2006).

The comparison of wells and outcrops indicate that the Akchagyl Formation has different thickness, lithological characteristics and sedimentary settings (Fig. 9). In the studied wells A and B, deposition of the Cheleken Formation has been begun from the Middle Pliocene and its age is limited to the Middle Pliocene, which is mainly composed of the claystone, silty claystone, sandstone, sandy conglomerate with intercalations of limestone without any index fossil, which deposited in fluvio-deltaic to shallow lacustrine basin. The varying facies in the studied well-A were also clarified by aggrading pattern of the GR and Neutron signatures (interbedded shales and sands) (Siddiqui et al. 2013; Cant 1992) from the Cheleken rocks. The Cheleken stratigraphic unit ranges in thickness between 70 and 90 m, which disconformably overlaid the Cretaceous deposits. The overlying Akchagyl unit (Upper Pliocene in age) has thickness of 110 m, consisting of claystone and interlayers of sandstone with relatively constant and irregular trends of gamma ray
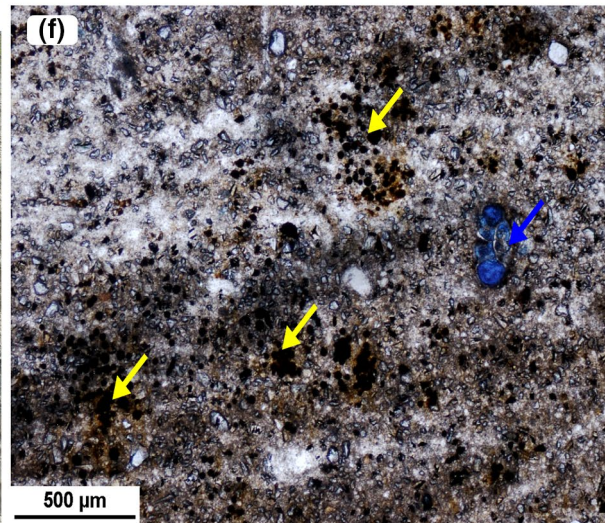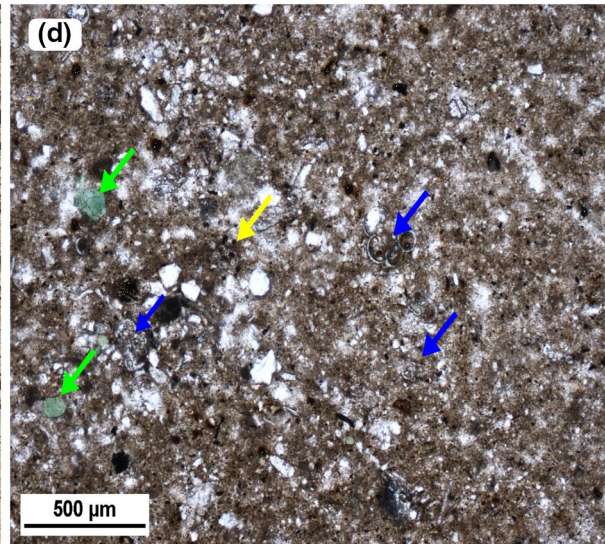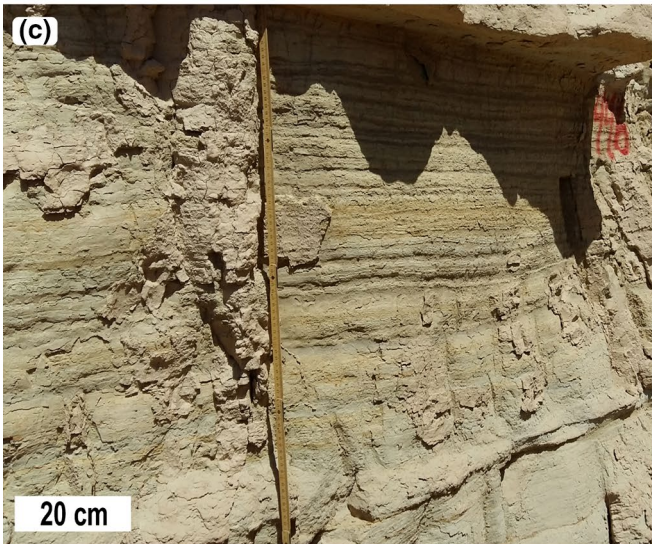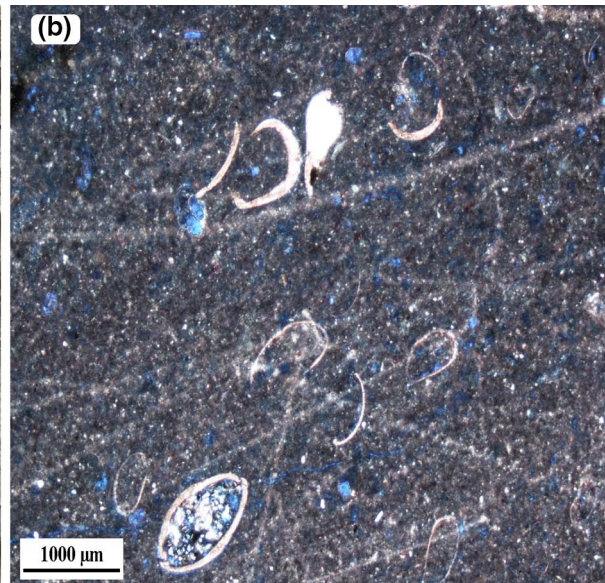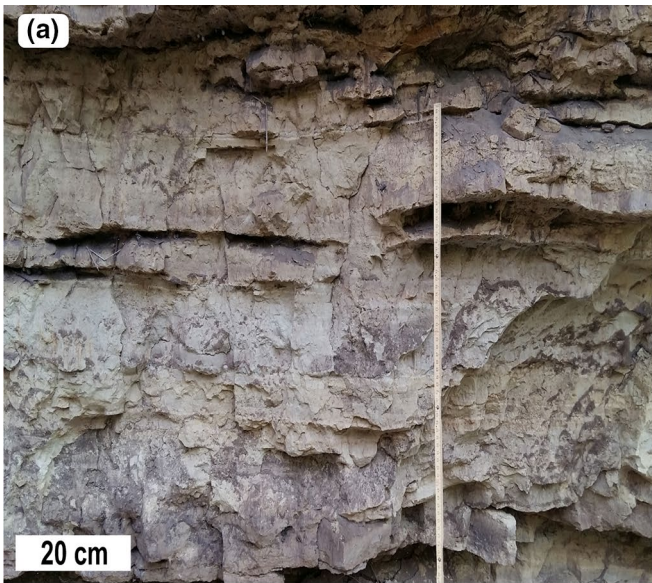
◀**Fig. 7** Representative macroscopic/microscopic photographs of the offshore facies. **a**, **b** Ostracod bearing mudstone to wackestone (F9), **c**, **d** alternation of laminated siltstone and mudstone (F10) with glauconite (green arrows) and planktonic foraminifera (blue arrows), **e**, **f** high framboidal pyrite (yellow arrows) and foraminifer (blue arrow) in sandy silty marl facies (F11)

and neutron readings, respectively. So that GR and Neutron logs in well-A show aggradational pattern indicating relative consistent lithology (Cant 1992).

The thickness of the Upper Pliocene Akchagyl in other drilled appraisal wells in the study area varies from 80 to 120 m with the same lithological properties. This uniform characteristic can suggest stable condition of the basin during the Akchagyl stratigraphic unit deposition. The most identified fossils from cuttings and cores in these wells include *C. dombra*, *Mactea sp.*, *Avimactra subcaspia*, *A. karabugasica* as well as types of brackish water gastropods such as *P. caspius* (Vatan and Yassini 1969). Theses deposits are considered as basinal or offshore part of lacustrine environment. The Akchagyl unit in the study outcrops indicates different lithological characteristics (grain-dominated limestones) and depositional system (shoreline environments) with respect to the wells in other parts of the Para-Tethys Basin (Figs. 8, 9). Unlike the southern and western parts of the South Caspian Basin in which assumed the Akchagyl Formation is a cap rock (e.g., Ettehad and Taati 2017), it is considered a porous stratigraphic unit in the study area based on microscopic and field characteristics, or at least a combination of reservoir/cap possibly representing tectonic activities, lateral changes of the facies and deposition of carbonates in the high-energy setting.

Tectonics and sedimentation rate

The Pliocene orogenic phases formed the present evolution and geomorphology of the different sub-basins in the Para-Tethys domain (e.g., Mediterranean, Romanian, Dacian and Pontic-Caspian) during the late Pliocene (i.e., 3.4–1.8 Ma; Popov et al. 2004, 2006). In the South Caspian Basin, huge amounts of depositional infill were deposited during Oligocene to Pliocene, which are possibly associated with syncompressional phases of the rigid basement basin at the beginning of the Alpine orogeny (Robert et al. 2014).

In northern Iran, Para-Tethys deposits including the Pliocene stratigraphic units of Cheleken and Akchagyl are regionally extended from Dasht-e Moghan (Western part of SCB) to the Gonbad-e Kavous (Eastern part of SCB) areas, with various thickness and lithological characteristics (Fig. 10). Correlation between the outcrops and wells indicate that thickness of the Cheleken unit decreased from west to east of the studied area and reached to the minimum in the Gonbad-e Kavous region, while the Akchagyl

unit has a relatively constant thickness throughout the area (Figs. 10, 11). This is also supported by seismic data interpretation. In this regard, below the unconformity, the thickness of clastic Cheleken deposits greatly increases from the Gonbad-e Kavous towards the South Caspian Sea as a result of several transgressive phases. Above the unconformity, the 2D seismic section displays a flat and horizontal geometry pattern of the strata during deposition of the upper Pliocene (Fig. 10). This could be in relation with development a stable condition of the sedimentary basin at that time.

During the Late Miocence and Late Pliocene (7–0.6 Ma) the Rhodanian and Passadenian motions are considered the major controlling factors on sedimentation in Northern parts of Iran (Maghfuri Moghadam, 2013). As a result, there is a great hiatus between the Sarmation and Akchagyl intervals in the most regions. The Para-Tethyan rock units of Dasht-e Moghan are older (at least Oligocene) than those of Mazandaran, Gorgan and Gonbad-e Kavous areas. In this area, the thickness of Akchagyl deposits (about 200 m) is more than those of the Mazandaran (100–120 m), Gorgan and Gonbad-e Kavous (20–60 m). Also, based on the presence of fossils like *Dreissena rostiformis Desh* (Maghfuri Moghadam 2013), Para-Tethys basin was deeper in the Moghan area, in comparison with its eastern parts (i.e., Mazandaran, Gorgan and Gonbad-e Kavous).

In terms of facies, the Akchagyl unit is mainly composed of high-energy carbonate facies in Gonbad-e Kavous area changing into the deeper shale and siltstone facies towards the westernmost part of the Caspian region (Fig. 11). It could be stated that the effect of Cheleken deposition has increased the rate of depression within basin due to the large amount of sediment loading rather than the tectonic motions (c.f. Green et al. 2009). The impact of this sediment loading is well known in western part of the study area in the Amol to Gorgan plains in which thicker deposits of Cheleken unit may coincide with uplift and erosion of the Kopet Dagh Mountains (e.g., Brunet et al. 2003).

Conclusions

In this study, three outcrop sections were measured from the Akchagyl Formation in the Gonbad-e Kavous of northeastern Iran. Detailed field and microscopy investigation led to the identification of 11 carbonate and siliciclastic facies, which classified into five facies belts as alluvial fan, mudflat, foreshore, shoreface and offshore. They are attributed to a wave-dominated lacustrine environment.

At the lower part, the Akchagyl stratigraphic unit is composed of mud-dominated facies (mudstones and bioclastic wackestones) indicating low-energy conditions of the basin. Towards the top, it has mainly grain-dominated
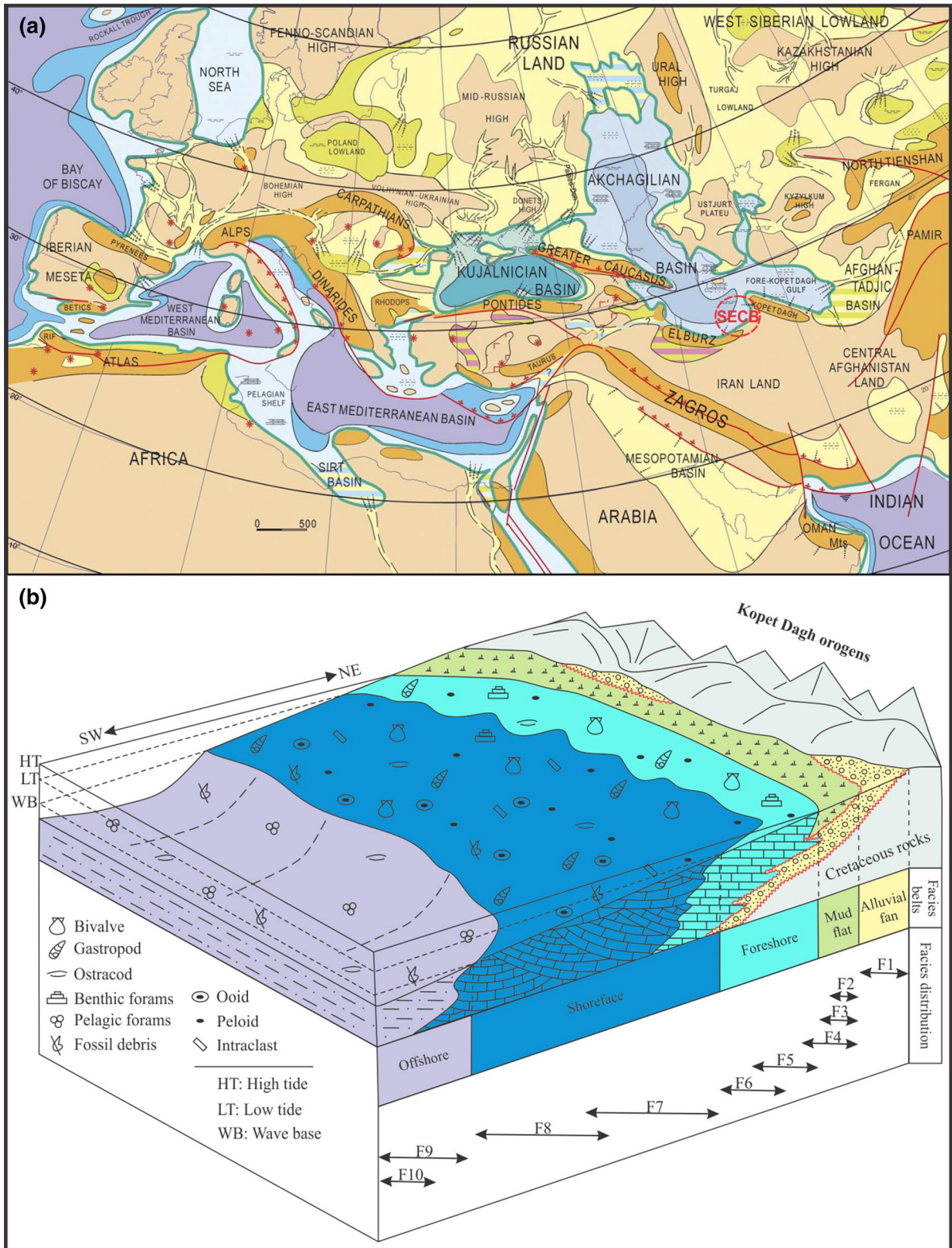
Fig. 8 a Palaeogeography map for the Middle- Late Pliocene representing the marine reconnection during 3.4–1.8 Ma (Popov et al. 2004, 2006), the location of the Southeastern Caspian Basin (SECB) is marked in dashed red circle, **b** Hypothetical schematic depositional model for the Upper Pliocene Akchagyl unit in the study area showing the main facies belts of a shallow lacustrine setting
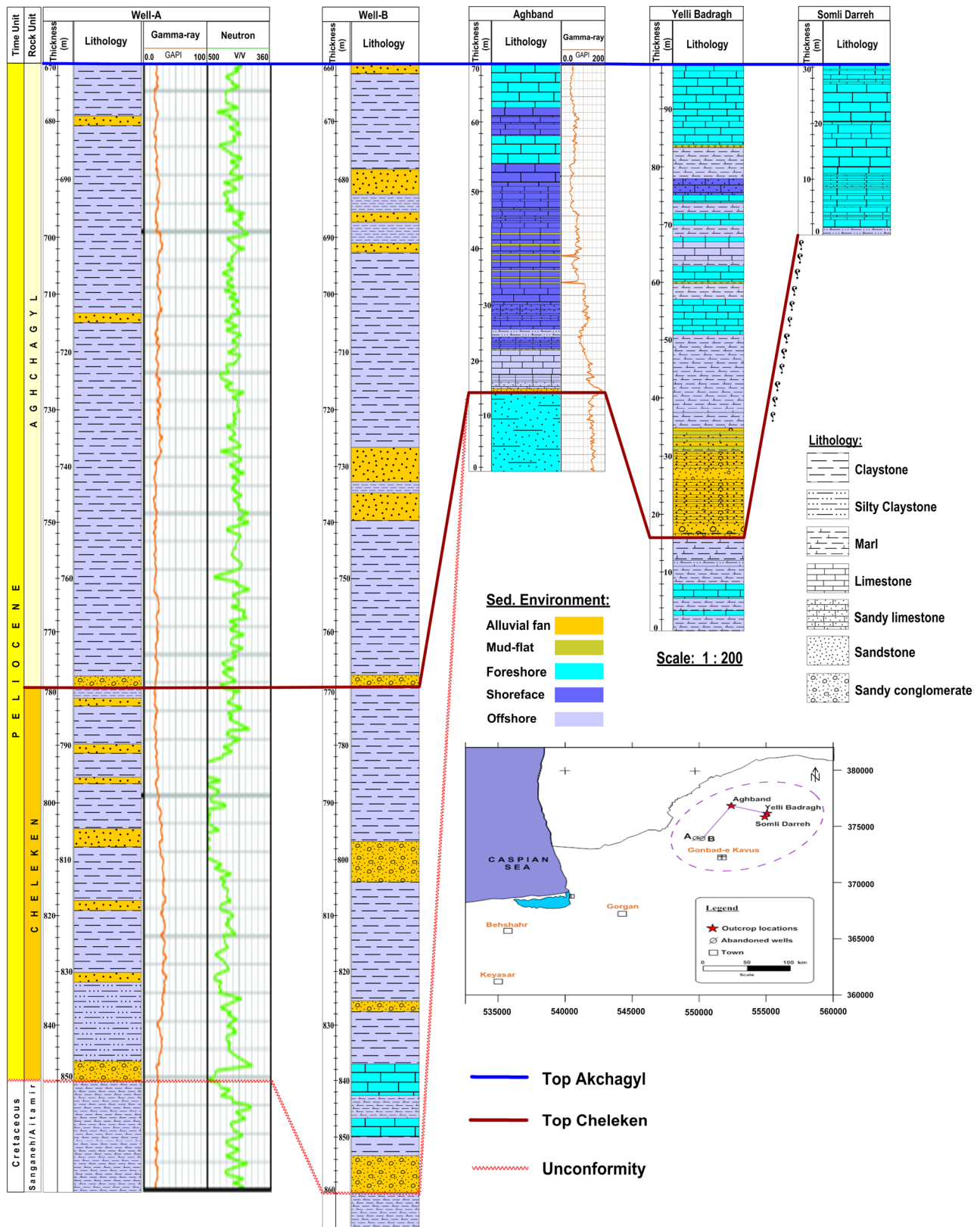
Fig. 9 Correlation of the Pliocene deposits in two wells (A and B) and their comparison (in terms of thickness and facies lateral changes) with the measured outcrops throughout the study area
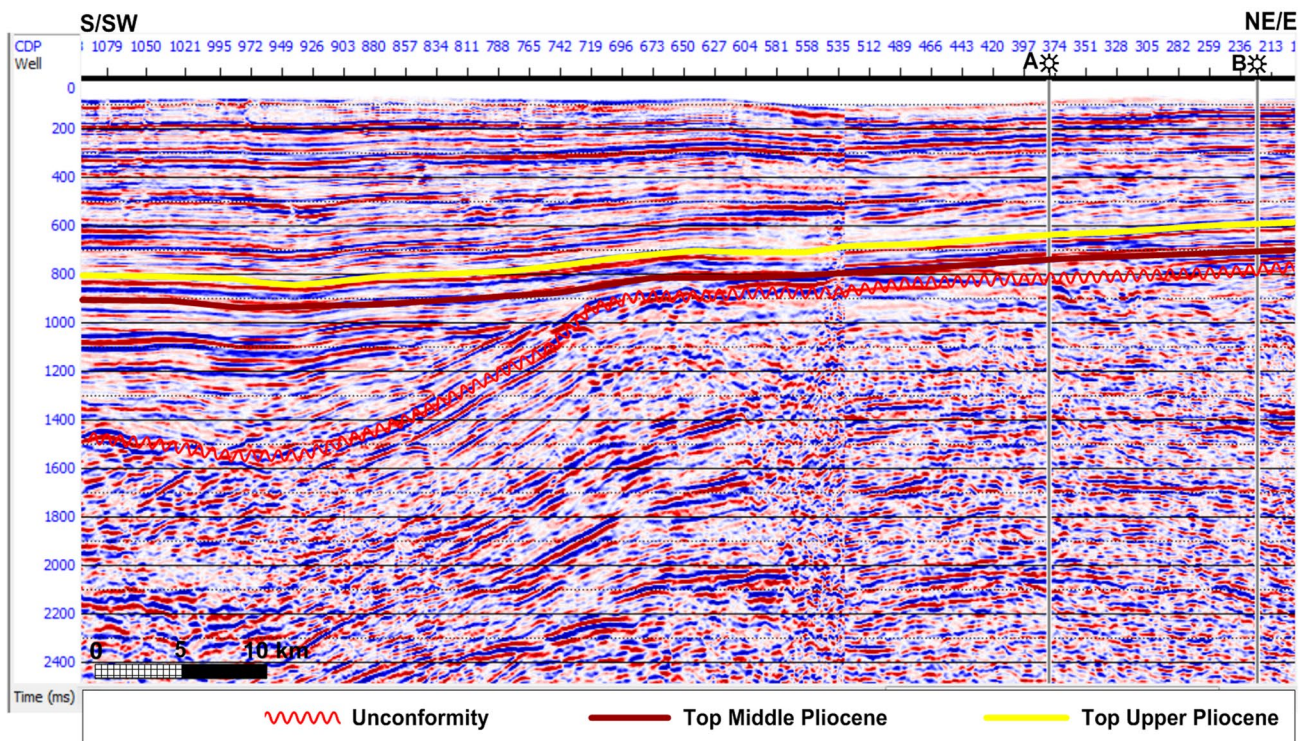
Fig. 10 2-D seismic profile below the Gorgan–Gonbad plains to the well locations (A and B) and Western part of the measured outcrop sections; the wavy red horizon represents the unconformity, the reddish brown line corresponds to the near top Mid-Pliocene, the yel- low horizon denotes the near top Pliocene. The section clearly shows the progressive onlap (Lower-to-Middle Pliocene strata) above the unconformity overlain by the Akchagyl Formation

facies (bioclastic packstone and peloid–ooid grainstone) belonging to high-energy beach setting.

Foreshore deposits are overlain by shoreface deposits that indicate a transgression condition or land-ward movement of the shoreline. Furthermore, the existence of marine biota shows reconnection of the basin to global oceans (probably Mediterranean Sea), particularly during deposition of the Late Pliocene Akchagyl unit.

Comparison of the upper Pliocene deposits in the study area revealed that the Akchagyl sequence in outcrops made up of foreshore and shoreface facies changing into the mud-dominated offshore facies towards the wells in southwestern parts of the study area. Unlike to the southern and western parts of the SCB that the Akchagyl unit was introduced as a cap rock, it could be considered as a porous reserve in the study area or at least a combination of reservoir/cap.

Lithostratigraphic interpretations have revealed that the Cheleken unit has not been deposited in the easternmost part of the study area (NE Gonbad-e Kavous). This could be associated with the effect of uplift and erosion of the Alborz and Kopet Dagh Mountains during this time interval. The impact of this sediment loading during Lower-to-Middle Pliocene is well known in the western part of the study area of the Amol to Gorgan plains. It appears that the thick deposits of Cheleken unit have increased the rate of subsidence within basin due to the large amount of sediment loading.

Discrepancies in both thickness and lithological variations of the Pliocene deposits indicate the influence of tectonic movements and clastic sediments supply during deposition of the Cheleken rock unit (the Lower-to-Middle Pliocene) as well as sea-level rising towards the Late Pliocene. They caused lateral changes of the facies and establishment of a high-energy carbonate setting in the study area. It appears that the more stable condition was dominated during deposition of the Akchagyl stratigraphic unit (Late Pliocene) within the most part of the study area, especially towards the SCB.
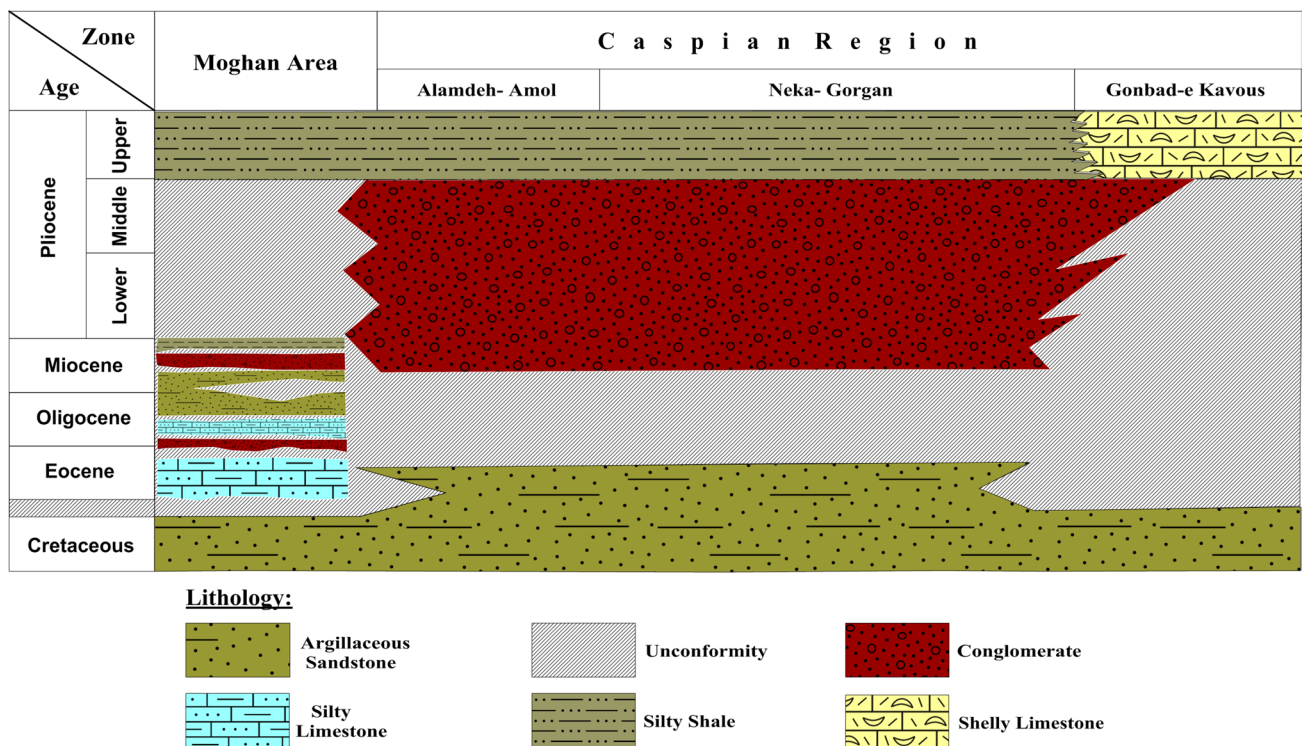
Fig. 11 Schematic model representing comparison of thickness and lithological changes of Tertiary rock units in the northern parts of Iran (from Moghan towards Gonbad-e Kavous plains); note the sig-nificant thickness of the Cheleken Formation (Lower-Middle Plio-cene) and facies lateral variation of the Akchagyl Formation (Upper Pliocene) in the Caspian region

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