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RESEARCH PAPER

Lithofacies, depositional environment, and sequence stratigraphy of the Lower Paleocene Pesteliegh Formation in the eastern Kopet Dagh Basin, Iran

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Abstract
The Pesteliegh Formation (Lower Paleocene) in the Chehelkaman and Tang-e Neyzar area, located in the eastern Kopet Dagh Basin, has been studied to investigate its lithofacies, sedimentary environment, and sequence stratigraphy. In this part of the Kopet Dagh Basin, the Pesteliegh Formation mainly composed of conglomerates, sandstone, mudstone and shales. Petrographic studies and sedimentary structures of the Pesteliegh Formation led to the identification of three lithofacies associations: conglomeratic (Gcm), sandy (Sl, Sr, Sh, St, Sp, Sm), mudstone (Fl, Fm), evaporitic facies, as well as five architectural elements (CH, LA, FF, CR, and CS). Petrological studies, sedimentary facies, architectural elements, and paleocurrent direction indicate deposition of these sediments in a meandering river system with a muddy and sandy bed, as well as floodplain and salina environments. Paleocurrent analysis also indicates a southeast to northwest flow direction which is consistent with sedimentological studies conducted on the studied sections. Sequence stratigraphy analysis of the Pesteliegh Formation indicates their deposition during a relative sea-level fall in the Lower Paleocene, comprising a depositional sequence and part of the subsequent sequence. Since the Pesteliegh Formation in the studied sections is located near the coastline, their sequence stratigraphy model follows the standard model and includes HST, LST, and TST facies associations.

Keywords: Lithofacies, Sequence Stratigraphy, Sedimentary Environment, Pesteliegh Formation, Kopet Dagh.

Introduction

The Kopet Dagh sedimentary basin, with a northwest-southeast trend, is located in the northern parts of Iran (Turan plate) and on the southern margin of the Eurasian supercontinent. This intercontinental sedimentary basin formed after the closure of the Hercynian Ocean during the Early Cimmerian orogeny in the Middle Triassic, concurrent with the opening of the Neotethys Ocean in southwestern Iran (Moussavi-Harami and Brenner, 1992; Afshar-Harb, 1994; Wilmsen et al., 2009; Bretis et al., 2012; Robert et al., 2014). The sedimentary sequences of this structural zone in northeastern Iran, with a thickness of several kilometers, extend from the Jurassic to the Miocene (Afshar-Harb, 1994). As a result of the Laramide orogeny at the beginning of the Tertiary period, the sea regressed from the south to the north of this basin so the first sequences of the Tertiary are continental deposit types (Pesteliegh Formation) which

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are obtained from the erosion of the folds created in the south of Kopet Dagh basin (Aghanabati, 2003). The continental deposits of the Pesteliegh Formation, which are deposited in a fluvial environment (Moussavi-Harami, 1993), are placed on the Kalat Limestone Formation (Maastrichtian) with an erosional boundary and are followed gradually by the Chehelkaman Formation (Thanetian). The present study focuses on understanding the Lithofacies, sedimentary environment, and sequence stratigraphy of the Pesteliegh Formation in the eastern Kopet Dagh Basin to provide a better understanding of the paleogeography and Paleogene depositional history in this part of the Kopet Dagh Basin.

Geological setting

Two stratigraphic sections in the Tang-e- Neyzar and Chehelkaman areas, located in the eastern parts of the Kopet Dagh Basin, were selected, measured and studied.

Tang-e- Neyzar stratigraphic Section: This section is located 122 kilometers from Mashhad in the Mashhad-Sarakhs road, near Tang-e- Neyzar, about 6 kilometers from the Shourloq village, intersecting the main road (Figure 1) with the coordinates 36°17'29"N and 60°33'10"E. The thickness of the Pesteliegh Formation in this section is 347 meters and mainly consists of sandstone, mudstone, and minor amounts of conglomerate.

Chehelkaman stratigraphic Section: This section with the coordinates 36°28'34"N and 60°28'51"E is located 3 kilometers from the Chehelkaman village and 90 kilometers from Sarakhs (Figure 1). Additionally, the distance of this section from the Karizak and Neyshaburak villages is 6 kilometers. The measured thickness of this section is 221.5 meters and consists of sandstone, mudstone, and abundant evaporitic deposits.

Method and materials

In order to investigate the Lithofacies, sedimentary environment, and sequence stratigraphy of the siliciclastic Pesteliegh Formation (Lower Palaeocene) in the eastern parts of the Kopet Dagh basin after collecting the data and selecting suitable stratigraphic sections, field sampling was conducted from these sections. Based on this, 90 samples from different lithological units were taken perpendicular to the bedding. In field studies, lithological characteristics, layer thicknesses, bedding conditions, boundaries between lithological units, and other properties were examined. Thin sections were prepared from the collected samples.

For the analysis of paleocurrent direction, the azimuth of 94 directional structures, including various types of cross-beddings, was plotted using Stereonet software. Mial classification (2014) was used for the analyses of lithofacies in the field based on the structure type and texture.

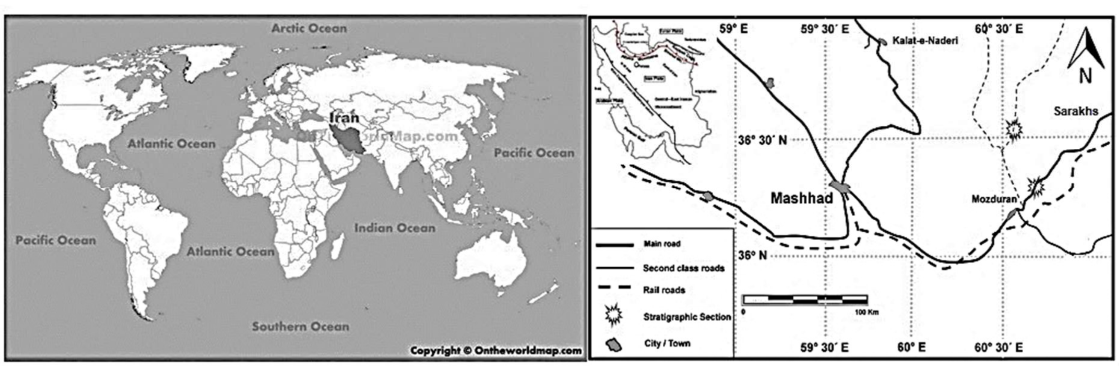

Figure 1. Location map of the study area and the access roads to the studied sections

The classification of Pettijohn (1975) was used for nomenclature of coarse-grained siliciclastic rocks and the classification of Folk (1980) for medium-grained siliciclastic rocks. Additionally, textural characteristics (size, shape, and roundness of grains, sorting, and textural maturity in sandstones) and diagenetic characteristics were studied. Catuneanu's (2006) studies were used for sequence recognition in field studies.

Lithofacies and architectural elements

Lithofacies are controlled by synsedimentary processes, and therefore, synsedimentary processes can be interpreted using lithofacies (Catuneanu, 2003). Recognizing facies association can be used for reconstructing the paleo-depositional environment (Kwon et al., 2006) and interpreting sequence stratigraphy. Petrographic studies and sedimentary structures of the Pesteliegh Formation led to identification of three lithofacies associations: conglomeratic (Gcm), sandy (Sl, Sr, Sh, St, Sp, Sm), mudstone (Fl, Fm), and evaporitic facies (Table 1), which have been named based on their textural and structural characteristics in the field, according to the facies codes provided by Miall (1985, 2014).

Conglomerate Facies

The conglomerate facies in the studied sections include Gcm sedimentary facies.
- Gcm Sedimentary Facies (Clast Supported- massive Gravel):
The massive gravel facies with a poorly matrix and without bedding or imbrication (Kim et al., 2009). The pebble sizes vary, and their cement is mostly carbonate. Pebbles are mostly rounded and sub rounded, primarily composed of limestone, but silica pebbles are also present. This facies is often deposited by high-velocity currents with high sediment load (Mial, 2014; Petit et al., 2005; Ito et al., 2006).

Table 1. Identified lithofacies in the siliciclastic deposits of the Pesteliegh Formation according to the facies codes provided by Miall (2014)

Lithofacies Codes	Lithofacies	Sedimentary Structure	Interpretation
Gcm	Clast-Supported Gravel	Massive To Horizontal-Bedded	Debris Flow Deposits
Sm	Medium To Coarse Sand	Massive Or Fine Lamination	Sediment-Gravity Flow Deposits
Sp	Fine To Coarse Sand	Planar Cross-Bed Or Lamination	Transverse & Linguoid Bedforms (Ripple Or 2-D Dunes)
St	Medium Sand	Trough Cross-Beds	Sinuous-Crested & 3-D Dunes
Sh	Very Fine To Medium Sand	Horizental Lamination Or Beds	Plane Bed Lower & Upper Flow Regims
Sl	Fine To Medium Sand	Low Angle (X<10) Cross Beds	Humpback Or Washed-Out Dunes
Sr	Very Fine Sand ,Silt & Mud	Ripple Cross-Lamination	Ripples (Lower & Upper Flow Regims)
Fl	Very Fine Sand, Silt & Mud	Fine Lamination,Very Small Ripple & Mud Cracks	Over Bank,Abandoned Channel Or Waning Flood Deposits
Fm	Mud & Silt	Massive, Mud Cracka	Over Bank,Abandoned Channel Or Drap Deposits

Gcm sedimentary facies in the studied sections have erosional contacts and laterally transition into sandy facies (Figure A2).

Sandy Facies

This lithofacies represents sedimentation in one-directional and bi-directional environments (Tucker, 2001; Longhitano et al., 2012; Davis, 2012; Zamaniyan et al., 2021). The sandy facies of the Pesteliegh Formation in the studied sections include Sm, St, Se, Sh, Sp, and Sr.

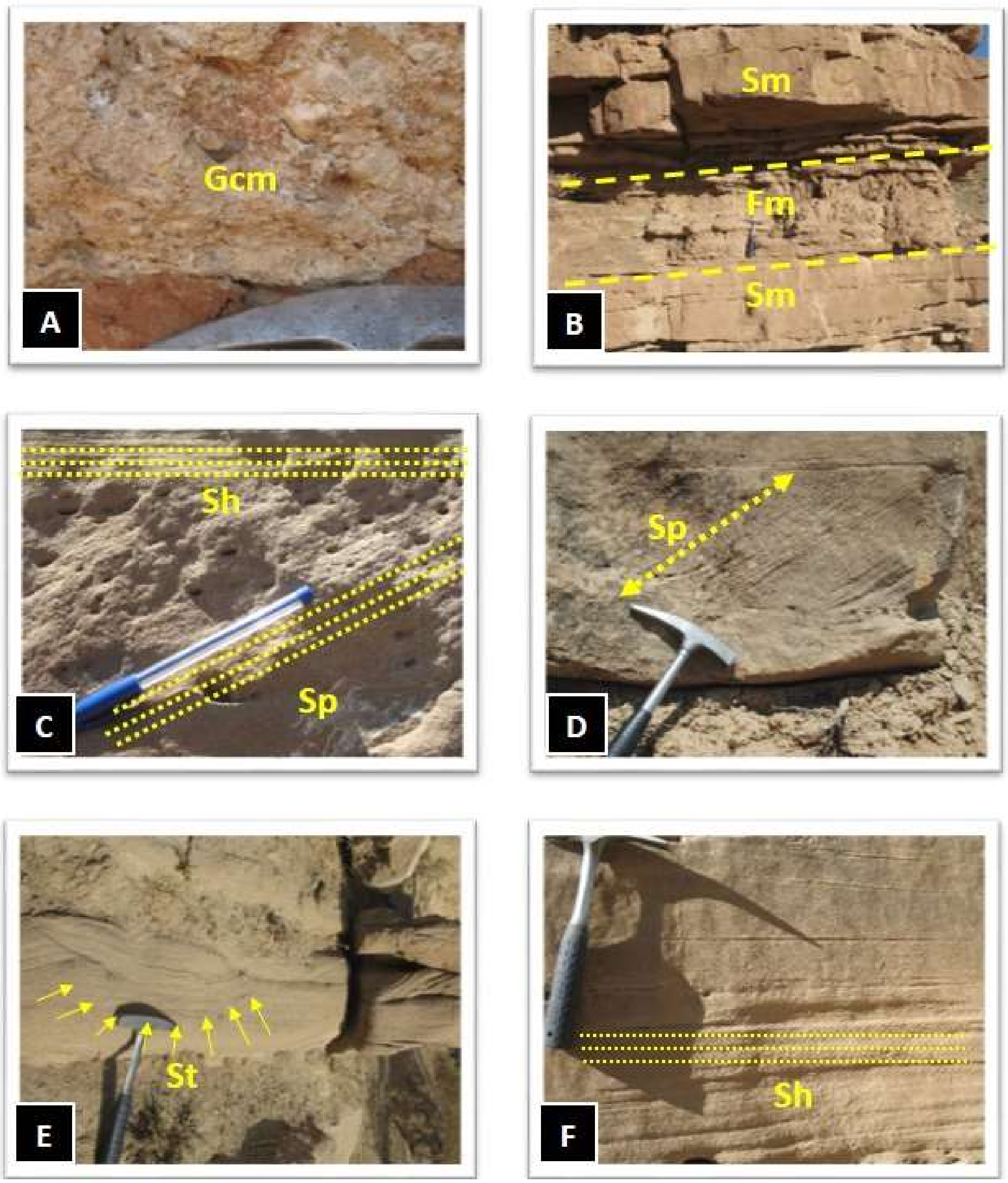

Figure 2. Identified lithofacies of the Pesteliegh Formation in the studied sections. A: Grain- supported gravel facies. B: Sandy facies with massive structure. C: Sandy facies with planar cross beddings together with sandy facies with parallel lamination. D: Sandy facies with planar cross beddings. E: Sandy facies with trough-cross bedding. F: Sandy facies with parallel lamination

Massive Sand (Sm) Sedimentary Facies

This facies consists of massive sandstones. The formation of this massive state can be related to bioturbation by organisms or diagenetic factors (Khalifa & Catuneanu, 2008). However, wall collapse of channels or rapid deposition can also be contributing factors. This sedimentary facies is observed in various parts of both studied sections, although it is more abundant in the Tang-e- Neyzar section (Figure 2 B). Additionally, this facies is observed in layers known as Lag Deposits. The thickness of this sedimentary facies varies between 0.5 to 5 meters. This sandstone facies may have been deposited under high sedimentation rates and gravitational flows (Harms et al., 1982; Miall, 2014). The formation of this type of sandstone facies can include a mixture of sediment gravity flows and sandy flows or high-concentration flows formed by rapid deposition (Martin and Turner, 1998; Khalifa & Catuneanu, 2008).

Planar-Cross Bedded Sand (Sp) Sedimentary Facies

This facies consists of flat-planar cross-bedded layers (Kjemperud et al., 2008) and is frequently observed in both studied sections (Figures D and C2). It varies in grain size and sorting. Usually, this sandstone facies is formed in low-flow velocity water currents (Khalifa & Catuneanu, 2008) and is formed by migration of bi-dimensional megaripples with straight crests (Therrien, 2006; Ghosh et al., 2006; Lee & Chough, 2006). This facies laterally transitions into Sh and Sr facies.

Trough-Cross Bedded Sand (St) Sedimentary Facies

This facies consists of sandstones with trough-cross bedding (Mial, 2014; Khalifa & Catuneanu, 2008) and is formed by the migration of three-dimensional mega-ripples with sinusoidal crest lines (Therrien, 2006; Ghosh et al., 2006). In many cases, pebbles may accumulate at its base in the form of Lag Deposits. It is poorly sorted, with variable rounding and grain size. This facies is only observed in the middle sandstone units of the Tang-e- Neyzar section, where it laterally transitions into Sr and Sh facies. However, it is more abundant in the Chehelkaman section (Figure E2).

Horizontally Bedded Sand (Sh) Sedimentary Facies

This facies consists of sandstones with planar bedded layers (Mial, 2014). Parallel lamination, referred to as flat, smooth, or horizontal lamination, is created in several ways and is commonly observed in the studied sections. This sandstone facies is formed under different conditions; for example, if the sand deposits are very fine to coarse, it indicates upper flat-bedded conditions, and if the grain deposits are coarse, it indicates lower flat-bedded conditions (Mial, 2014; Khalifa & Catuneanu, 2008). This sandstone facies is one of the most abundant facies in both sections and mostly consists of fine to medium sandstones with moderate sorting. Therefore, this facies association in the Pesteliegh Formation in the studied sections was formed under high water flow regimes (Figure F2). Sh sedimentary facies inside channels usually indicate the final stage of backfilling after seasonal flooding (Mcloughlin & Drinnan, 1997; Khalifa & Catuneanu, 2008). Allen (1982) and Harms et al. (1982) suggest that such thin-layered sandstones may be associated with one-directional flows.

Low Angle Cross Bedded Sand (Sl) Sedimentary Facies

The Sl facies is formed when inclined layers with a slope of less than 15 degrees (on average less than 10 degrees) are deposited, which is very similar to the Sh sandstone facies and is usually found together. Linear separation may also be observed on the surface of its layers. In terms of formation mechanism, it may be formed in both low and high flow regimes, but it is mostly formed in high water flow rates and low sediment loads (Harms et al., 1982; Miall, 2014). This sandstone facies is mostly observed in the middle part of the Tang-e- Neyzar section along with the Sh facies (Figure 3A). Low-angle cross-bedding may be deposited under high-energy conditions in specific locations within channels, such as in longitudinal bars or at channel intersections (Mcloughlin & Drinnan, 1997; Khalifa & Catuneanu, 2008).

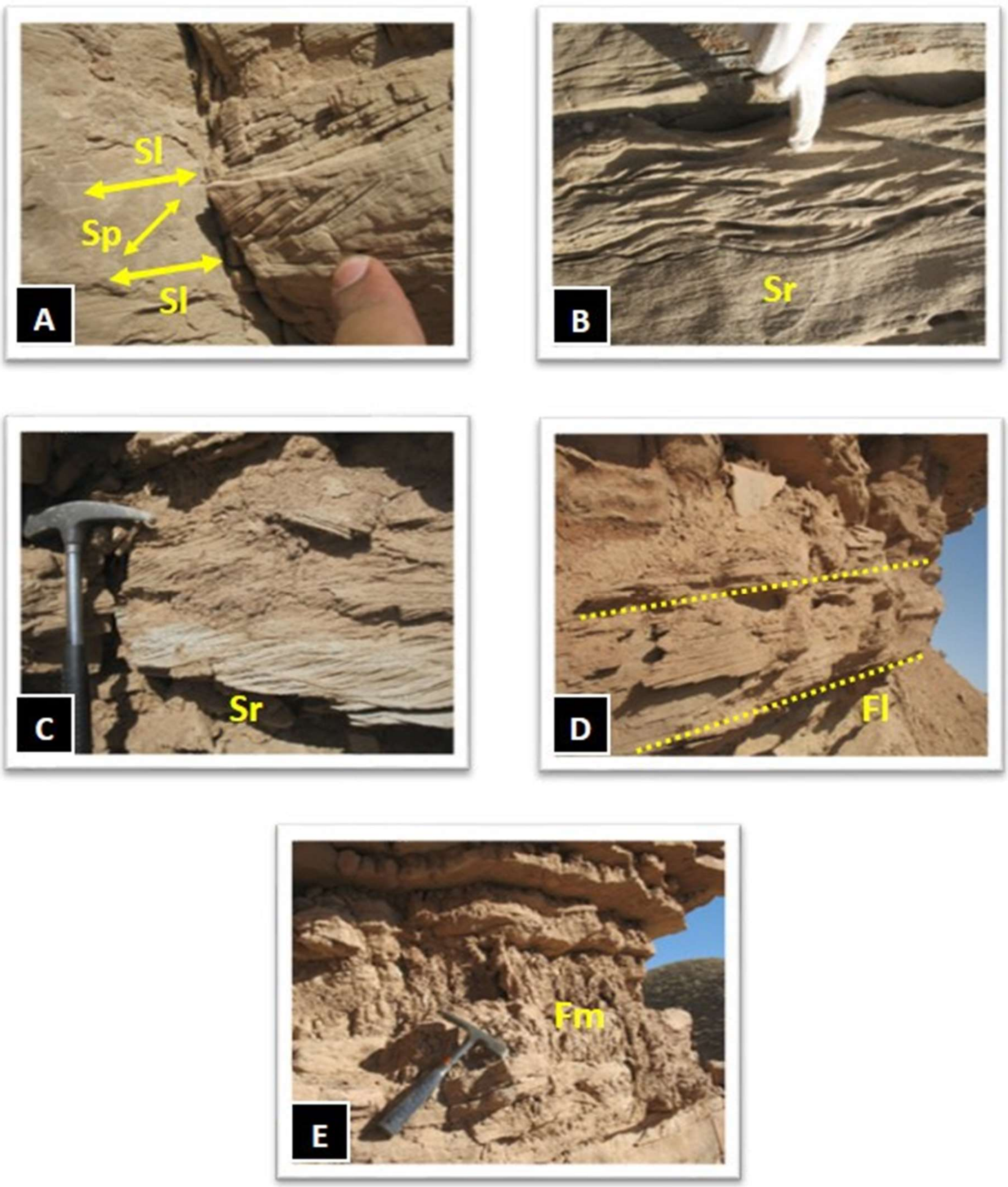

Figure 3. Some other identified facies of the siliciclastic deposits of the Pesteliegh Formation. A: Sandy facies with low-angle cross-bedding and planar cross-bedding in the middle parts. B: Sandy facies with ripple cross bedded. C: Other sandy facies with ripple cross bedded. D: Mudstone facies with cross lamination. E: Massive mudstone facies without any sedimentary structure

Ripple Cross Bedded Laminated (Sr) Sedimentary Facies

This facies is characterized by various types of ripples. These facies are usually observed in the upper parts of channel sandstones that are vertically stacked (Kjemperud et al., 2008). The grain size is usually fine to coarse sand, but the average grain size is the most common (Figures C and B3). The most important sedimentary structures in this facies in the studied sections are asymmetric ripple marks, which are usually formed in low-flow regimes (Harms et al., 1982). This facies often laterally transitions into Sp and Sh facies.

Mudstone Facies

These facies are composed of particles ranging in size from silt to clay, which are mostly deposited as suspended loads. Usually, fine-grained particles in fluvial systems move as suspended loads and settle when fluid energy decreases and in relatively calm depositional environments (Miall, 2014; Powell et al., 2016). In the studied sections of the Pesteliegh Formation, two mudstone facies, Fl and Fm, have been identified.

Laminated Sand, Silt & Mud (Fl) Sedimentary Facies

This facies usually settles as a suspended load during river floods in floodplain environments, resulting in the formation of laminated sediments. Therefore, the possibility of mud cracking, bioturbation by plant roots, and soil formation on the sediment surface occurs. The diversity in the abundance and distribution of this facies reflects classification related to changes in the depositional environment (Kjemperud et al., 2008; Longhitano et al., 2012; Zamaniyan et al., 2018). This facies is also deposited outside the channel and is laterally replaced by Crevass or Levee deposits (Kjemperud et al., 2008). This facies is particularly abundant in both studied sections, especially in the Tang-e- Neyzar section, and laterally transitions into sandstone facies (Figure 3D).

Massive Mud & Silt (Fm) Sedimentary Facies

This facies is commonly observed in the Pesteliegh Formation, particularly in the Tang-e-Neyzar section (Figure 3E). In areas where its thickness is low, it appears to be related to the deposition of suspended loads in floodplain environments or mud coverings on river levees (Ito et al., 2006; Khalifa & Catuneanu, 2008). However, in areas with significant thickness, especially in the upper parts of the Tang-e- Neyzar section, it may result from deposition in relatively low-energy meandering river environments (Peakall et al., 2007). This sandstone facies is usually devoid of bedding and has a completely massive texture in the studied sections. The absence of clear fabric in this facies may result from bioturbation processes in which the initial fabric is destroyed by organism activity (Kjemperud et al., 2008). The Fm facies is also formed in areas far from the source of the floodplain under the influence of seasonal desiccation and oxidizing conditions (Catuneanu et al., 2001; Khalifa & Catuneanu, 2008). This facies is also formed in interchannel areas during periodic flooding events (Tye & Coleman, 1989; Catuneanu, 2006; Khalifa & Catuneanu, 2008).

Evaporitic Facies (P)

In the lower part of the Chehelkaman section, with a thickness of 38 meters, and the upper part with a thickness of 52 meters, Evaporative deposits were observed along with mudstone. Two samples from the lower and upper parts of the Chehelkaman section were analyzed using XRD to identify the constituent minerals of these sediments, indicating that the constituent mineral of these sediments is gypsum (Figure 4). Also, four microscopic sections were studied to identify evaporitic minerals, which confirms this. Gypsum precipitates when about 19% of its initial volume of seawater evaporates (El-Tabakh et al., 2004a, b). Gypsum crystals settle in various environments with different crystal shapes, most of which are in the form of fibrous and crystalline in the studied samples.

Architectural Elements

Architectural elements are part of the sedimentary system that are equivalent to or smaller than channel-filling sediments but larger than individual sedimentary units (Lowey, 2007). Architectural elements are classified based on underlying and overlying contacts, geometrical shape, and lateral relationship between facies, grain size, sedimentary structures, and paleocurrent direction (Miall, 1996; Allen & Fielding, 2007). Based on the identified facies, geometrical shape, and grain size in the studied sections, architectural elements CH, LA, CR, CS, and FF have been identified (Table 2).

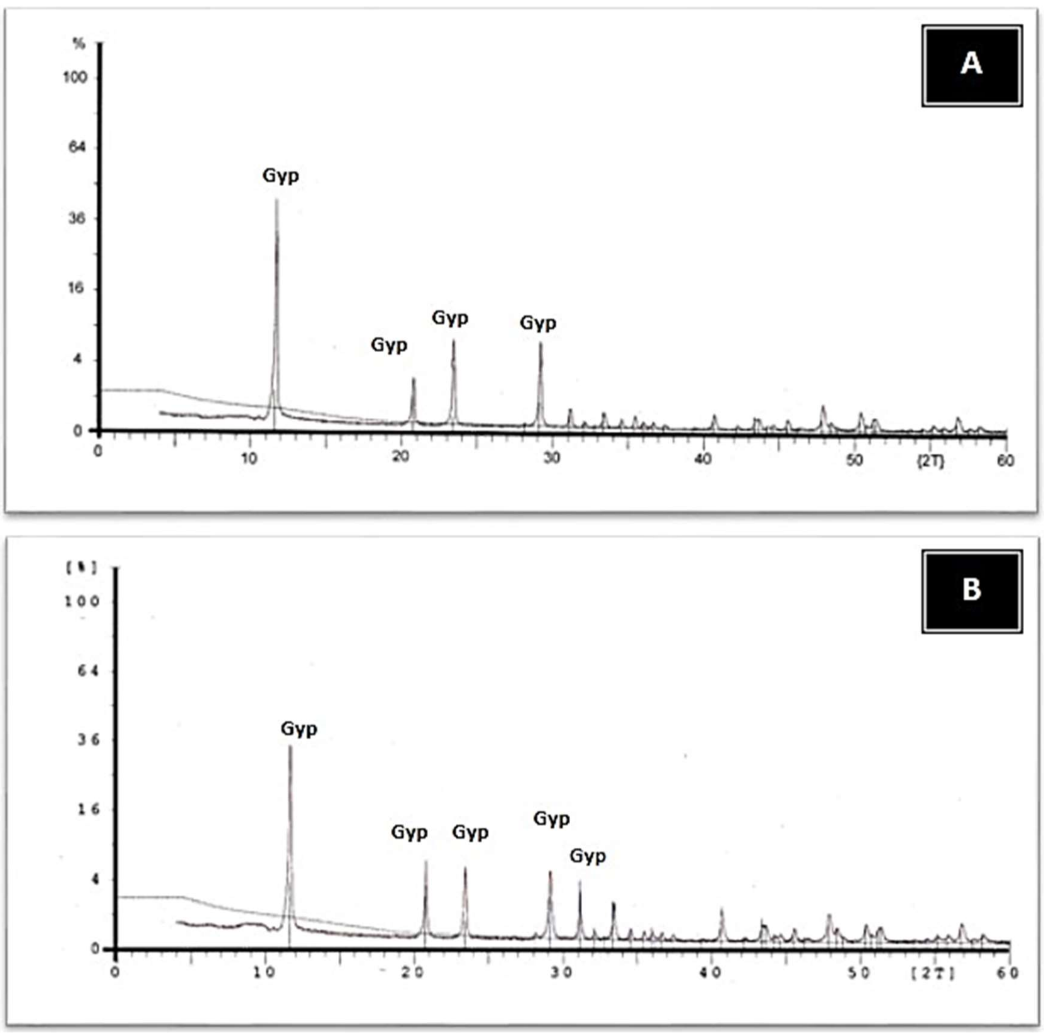

Figure 4. XRD analysis of the evaporate samples of the Pesteliegh Formation in the Chehelkaman section. A: XRD analysis of the evaporate samples from the lower parts of the Chehelkaman section. B: XRD analysis of the evaporate samples from the upper parts of the Chehelkaman section

Table 2. Architectural elements together with facies associations of the Pesteliegh Formation

Element	Symbol	Facies Assemblage	Geometry and Relationships
Channels	CH	Gcm Sh, Sp, Sm, St, Sr, Sl	Wedge, Lens
Lateral-accretion macroform	LAA	Sh, Sp, St	Wedge, Sheet, Lens
Overbank fine	FF	Fl, Fm, Sr	Blanket or Sheet, commonly Interbedded with SB
Crevasse splay	CS	Fl, Sh, Sp, Sr	Ribbon and Blanket

Architectural Element CH

This element is mainly composed of gravels and sands that deposits inside channels in river systems (Kim et al., 2009). The gradual decrease in grain size upward in channel-filling sediments indicates vertical fining sequences (Miall, 2014; Allen & Fielding, 2007). The lower contact surface of these architectural elements is usually erosional and has a wide, lens-shaped geometry. Its sedimentary facies are usually Gcm, but St may also be present. The CH element has a basal surface with scoured and convex surfaces (Matchen & Kammer, 2006). In the Pesteliegh Formation, the CH architectural element, with a lenticular shape and a lateral extent of 5-15 meters and a thickness of 2-3 meters, has been observed in the studied sections. It includes sedimentary facies such as Sm, Sr, Sl, Sp, St, and Gcm and is alternately observed with the LA structural element (Figure A5).

Architectural Elements CR, CS

When a river floods, natural levees are breached, and secondary channels from the main river channel enter the floodplain and deposit sand sediment on the fine-grained sediments outside the channel (Gani & Alam, 2004; Slingraland & Smith, 2004; Haschenburger & Cowie, 2009). The CR architectural element, in terms of facies assignment, is similar to channel-filling sediment, meaning it has an erosional base and structures such as trough and various ripple laminations (Miall, 2014; Kim et al., 2009). The sandstone deposits of CR, with a smaller thickness and smaller grain size compared to the main river channel, are distinct (Amorosi et al., 2008). Deposits with a distinct lower boundary and upward-fining cycles are interpreted as CR deposits, while coarsening-upward deposits that ultimately end under the conglomerate are indicative of the CS architectural element (Amorosi et al., 2008). This architectural element is frequently found in the Pesteliegh Formation in the studied sections, especially in sections with fine-grained sediments and sedimentary facies such as Sh, Sp, and Sr (Figure B5).

Architectural Element LA

This architectural element is formed when a river moves laterally and downstream. When the river channel moves from one side to the other, a meandering form is created, in which case erosion occurs on one side and deposition (point bar) occurs on the other side. The geometry and lithological structures of this element are variable and depend on the channel shape and sediment load (Miall, 2014; Allen & Fielding, 2007). This architectural element is present in the Tang-e- Neyzar section with a sand and clay bedload, and in the Chehelkaman section, it is mostly shale and includes sedimentary facies such as Sp and Sh, and Sr and Sl facies are also recognizable (Figure D5).

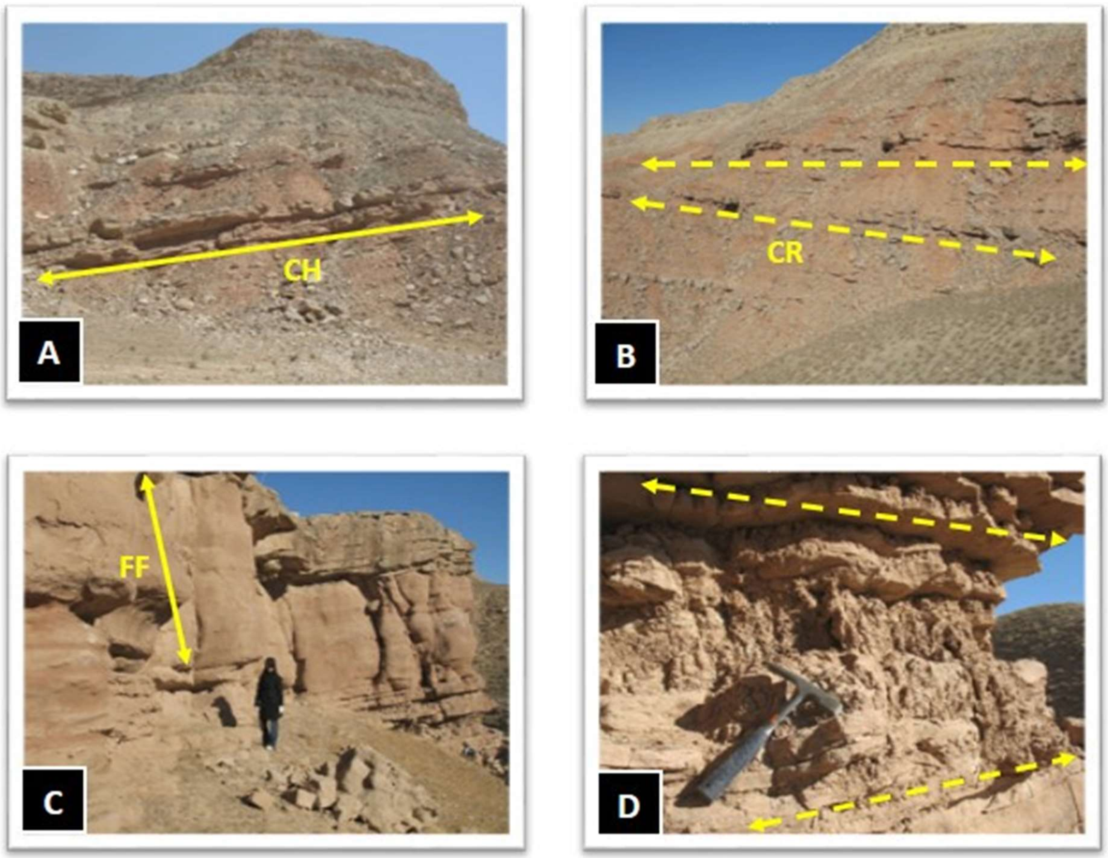

Figure 5. Identifies architectural elements in the siliciclastic deposits of the Pesteliegh Formation. A: Architectural elements related to the channel. B: Crevasse splay architectural elements between the floodplain deposits. C: Architectural element FF. D: Architectural element LA

Architectural Element FF

This architectural element is usually associated with off-channel environments and mostly encompasses mud facies (Miall, 2014; Le Heron et al., 2008). This architectural element usually has a massive texture or slightly horizontal laminations and rarely shows inclined bedding. They are usually found in the upper parts of upward-fining sequences, indicating formation in temporary shallow streams (Tunbridge, 1981; Miall, 2014). The main sedimentary facies associated with the FF environments element in the Pesteliegh Formation are Sr and Sh, and it also includes Fm and Fl facies (e.g., Mathews et al., 2007) (Figure C5). This element is often observed as massive shapes and sometimes slightly diagonally with parallel layers, where soil formation processes and vegetation cover are visible on its surface.

Depositional Environment

The presence of an erosional base accompanied by lag deposits, upward-fining cycles, red colors of the deposits, low lateral extensions of the sedimentary facies, geometric shape of the layers, absence of fossils, and the presence of one-directional sedimentary structures indicate the formation of siliciclastic sediment of the Pesteliegh Formation in a fluvial system (e.g., Roberts, 2007; Crouvi et al., 2006; Amorosi et al., 2008). Generally, the contact of fluvial deposits with their underlying deposits is destructive due to lateral channel movement and changes in water intensity, which result in the erosion of a considerable amount of sediments

and bedrock (Mousavi Harami, 2004). In fluvial environments, various factors such as weathering, erosion, transport of sediment, and their deposition influence river morphology.
The geomorphological interpretation of rivers is based on their texture, form, and arrangement within sedimentary masses. According to this interpretation, fluvial environments are categorized into channel forms (ripples, bars, dunes, etc.), channel edge forms (levee, Splay), and forms outside the channel for flooded rivers (floodplain) (Gurnell et al., 2008). In the Pesteliegh Formation in the study area, due to the abundance of upward-fining cycles and the thickness of fine-grained sequences, it can be concluded that these deposits have settled in a meandering river system. Upward-fining cycles indicate periods of channel filling and energy reduction (Nichols & Fisher, 2007). The presence of gravel and coarse sand deposits can be attributed to the channel areas (CH) and point bars (Ghosh et al., 2006; Matthews et al., 2007).

In Tang-e- Neyzar and Chehelkaman sections, both in the lower and upper parts of the river, due to the abundance of fine-grained deposits, the river is considered meandering with mud load, and in the middle part, due to the abundance of sandy deposits and small amounts of gravel, the river is considered meandering with a sandy bed. The grain size in the studied sections of the Pesteliegh Formation is mostly sand and silt, which mud deposits are more related to floodplain. The grain size of the deposits in the floodplain is mostly fine sand, silt, and clay, formed from suspended particles in the water. Deposition rate in floodplain is very slow because the particles are suspended and slowly settle down. In addition to grain size, structures such as horizontal layering and cross-bedding indicate floodplain (Mousavi Harami, 2004). Presence intercalations of sandstone with mudstone layers on sandstone facies indicates that these deposits were formed during the repetition of the cracking stage of the main channel and entry into the floodplain (Allen & Fielding, 2007). Also, sandstone and mudstone intercalations indicate floodplain positions close to the source, which were deposited under high initial energy currents, so that during periods of high energy, sandstone sequences were formed and then with the decrease in energy, suspended sediments were deposited (Allen & Fielding, 2007; Gurnell et al., 2008). Since meandering rivers have twists and lateral movements (LA), suspended fine-grained deposits of outside the channel and floodplain deposit under low energy and shallow on channel sediments and these lateral movements can be observed by forming cross beddings in the channel floor (Roberts, 2007; Matthews et al., 2007).

Usually, in rivers, the grain size decreases exponentially downstream (Rengers & Wahl, 2007), which can be observed in the Pesteliegh Formation with a decrease in the size of sedimentary structures in the Chehelkaman section compared to the Tang-e- Neyzar section (Nichols & Fisher, 2007; Matthews et al., 2007; Zamaniyan et al., 2018).

Another characteristic of the Pesteliegh Formation in the studied sections is the presence of broad crevasse deposits with Sp and Sh lithofacies and architectural elements CR and CS, with a thickness of 3-5 meters and a spread of 10-25 meters among mud facies. Broad crevasses usually occur in flood situations where water breaks parts of the natural levee and deposits them in a conical form within the floodplain. The constituent particles of these deposits are mostly sand-sized, and their size decreases as they move away from the river. The cross-bedding formed in these deposits is small-scale and ripple laminations (Mousavi Harami, 2004). Analysis of paleocurrent direction using data obtained from cross-bedding indicates a southeast to northwest flow direction, which is consistent with sedimentological studies conducted on the studied sections, so that the grain size in the Tang-e- Neyzar section is coarser than in the Chehelkaman section (closer to the origin).

In the lower and upper parts of the Chehelkaman section, thick layers of evaporative deposits are observed. High thickness of the evaporative deposits indicates deposition in a salina environment. A salina environment is a depression near the coast influenced by seawater and non-marine waters. The formation of these thick evaporite sequences requires a closed basin, and depending on the subsidence of the basin floor, it should have the capacity to retain salts for a long time or be permanently fed by saline currents (Warren, 2006). The formation of such evaporites and the continuity of deposition in them depend on various factors such as climatic conditions, basin size and eustatic changes and static, hydrographic, and tectonic changes (Warren, 2006; Aldega et al., 2020). Evidence such as the presence of mud cracks and red coloration of deposits due to the presence of hematite and thick evaporite layers indicate the deposition of the Pesteliegh Formation in oxidized conditions, warm, and semi-arid climates (Tucker, 2001).

In general, the proposed model for the deposition of the Pesteliegh Formation in the study area is a meandering river (Figure 6), with muddy bed in the Chehelkaman section and sandy bedload in the Tang-e- Neyzar section. Also, the outside channel deposits (floodplain) and salina environment in the Chehelkaman section have a significant extent. The abundance of fine-grained sediments in both sections also indicates high river meandering (Roberts, 2007). These rivers have a low width-to-depth ratio, and the deposits are highly prone to lateral and vertical growth (Brooks, 2003).

Sequence Stratigraphy

The investigation of lithofacies and structural elements of the Pesteliegh Formation deposits indicates a fluvial depositional environment with a sandy and muddy bed. Sequence stratigraphy in fluvial environments is very different from other environments (Blum & Aslan, 2006). River systems are formed in response to several allogeneic controlling factors on sedimentation, including eustasy, climate, tectonics of the origin area and basin subsidence (Shanely & McCabe, 1988; Schmid et al., 2006; Mather et al., 2008).

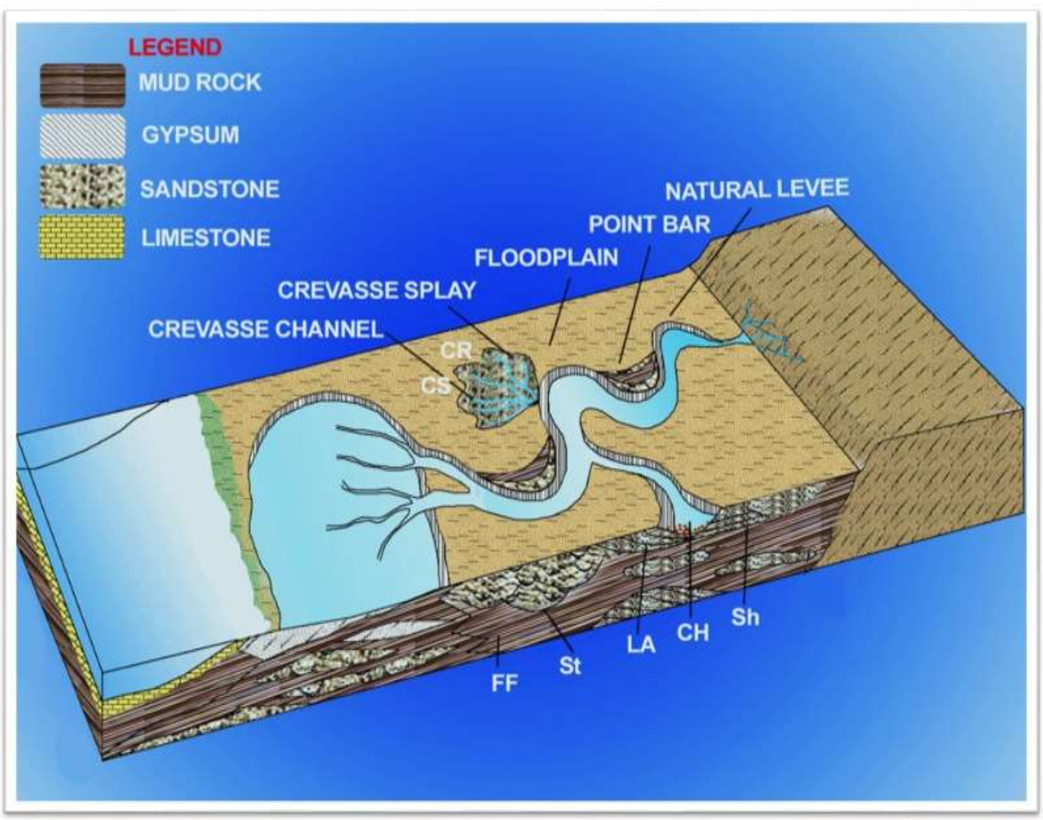

Figure 6. Facies model of the siliciclastic deposits of the Pesteliegh Formation in the study area and the beginning of the Chehelkaman Sea progradation

In most cases, to complete the information related to sequence stratigraphy in fluvial deposits, it is better to use relative sea level changes in equivalent marine deposits. Sequence stratigraphy models for fluvial deposits in the upstream and downstream areas are different because of the influence of relative sea level changes on sequence stratigraphy. So that in the upstream areas of the river, which are close to the origin area, they are under the influence of upstream controlling factors, which are actually the tectonics and basin subsidence, and in such river systems, terms like high and low accommodation sedimentation are used which depends on the subsidence pattern in the same basin (Catuneanu, 2006; Mather et al., 2008). However, in such systems, the effects of climate should also be considered because, along with basin subsidence, it increases and decreases sedimentation accommodation (Catuneanu, 2003).

In both studied sections of the Pesteliegh Formation, the lower sequence boundary with the Kalat Formation (Late Maastrichtian) is of type SB1 due to the presence of an erosional base (Figures A7 and A8). This sequence boundary is considered equivalent to a discontinuity (Catuneanu, 2006). Since the Pesteliegh Formation in the studied sections is close to the coast, its sequence stratigraphy model follows the standard model and has LST, TST, and HST facies associations (Figure 9).

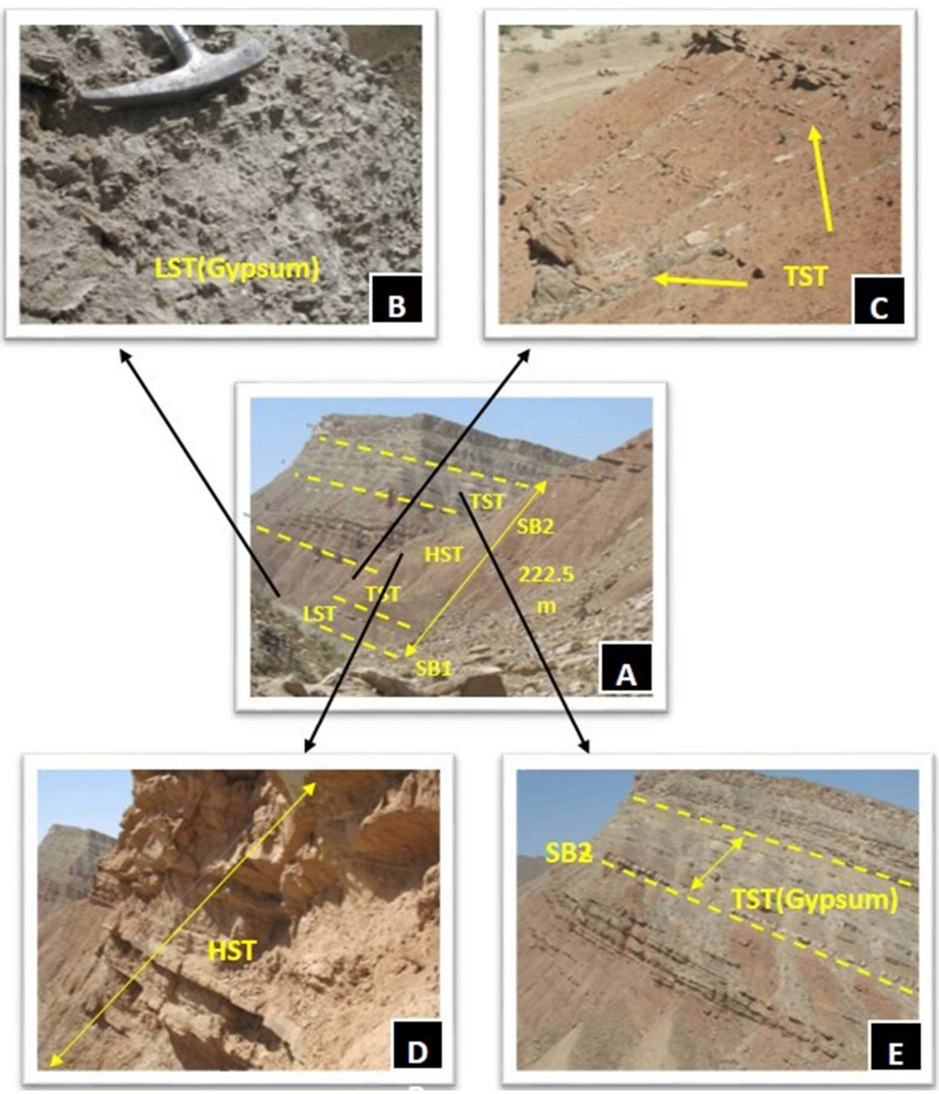

Figure 7. Position of sequence boundary and facies associations LST, HST, TST of the Pesteliegh Formation in the Chehelkaman section

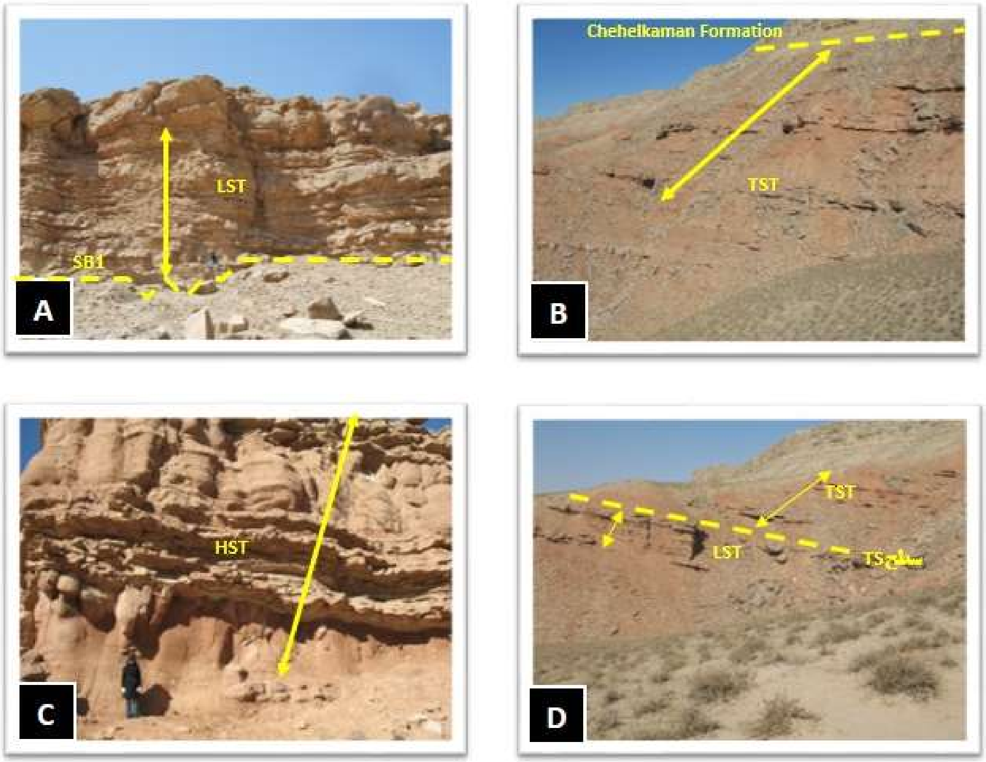

Figure 8. Field aspects of sequence boundary and identified facies associations of the Pesteliegh Formation in the Tang-e-Neyzar section

After this sequence boundary, the sea-level regression begins, and the LST facies association is deposited on the Kalat Formation (Figures B7 and A8). This facies association in the Chehelkaman section is formed of 38 meters of evaporative deposits, which mostly consist of gypsum with thick lenses of evaporative deposits at the bottom and have alternations of gypsum and evaporite in the upper part, which have probably settled in a salina environment. In the Tang-e- Neyzar section, the LST facies association, with a thickness of 95 meters, is formed of sandstone cycles deposited in a meandering river with a sandy bed, and at the base of some of these cycles, conglomerate layers with an erosional base are observable (Figure A8). In fluvial environments, LST phase in deposits near the coast are usually covered by TST and HST facies associations (associated with expansion of the floodplains) (Bourquin et al. 1998)

After the LST facies association, sea level begins to rise (TS surface), and the TST facies association is formed (Figures C7 and B8). In both sections, the TST facies association is placed after the TS surface, which is mostly composed of mudstone sequences with sandstone lenses and indicates deposition in a floodplain environment (Haschenbuger & Cowie, 2009). The reduction in tectonic activity and the rise in sea level have led to the expansion of the floodplain and deposition of fine-grained sediments (Catuneanu, 2006; Khalifa et al., 2008). Along with this sea-level rise, extra channel facies expand, which increases the accommodation space (e.g.: Catuneanu, 2006). With the rise in the river base level due to various allogenic and autogenic processes, a low-energy environment is created, resulting in the formation of mudstone facies with sandstone lenses related to crevasse environment, forming the TST facies association (Khalifa et al., 2008). This facies association in the Chehelkaman section consists of 37 meters of muddstone with lenses of sandstone, indicating the deposition of these facies in the floodplain. In the Tang-e- Neyzar section, the TST facies association has a thickness of 120 meters (Figure B8). The significant expansion of the TST facies association in this section may result from the rapid rise in the sea level base (Catuneanu, 2006).

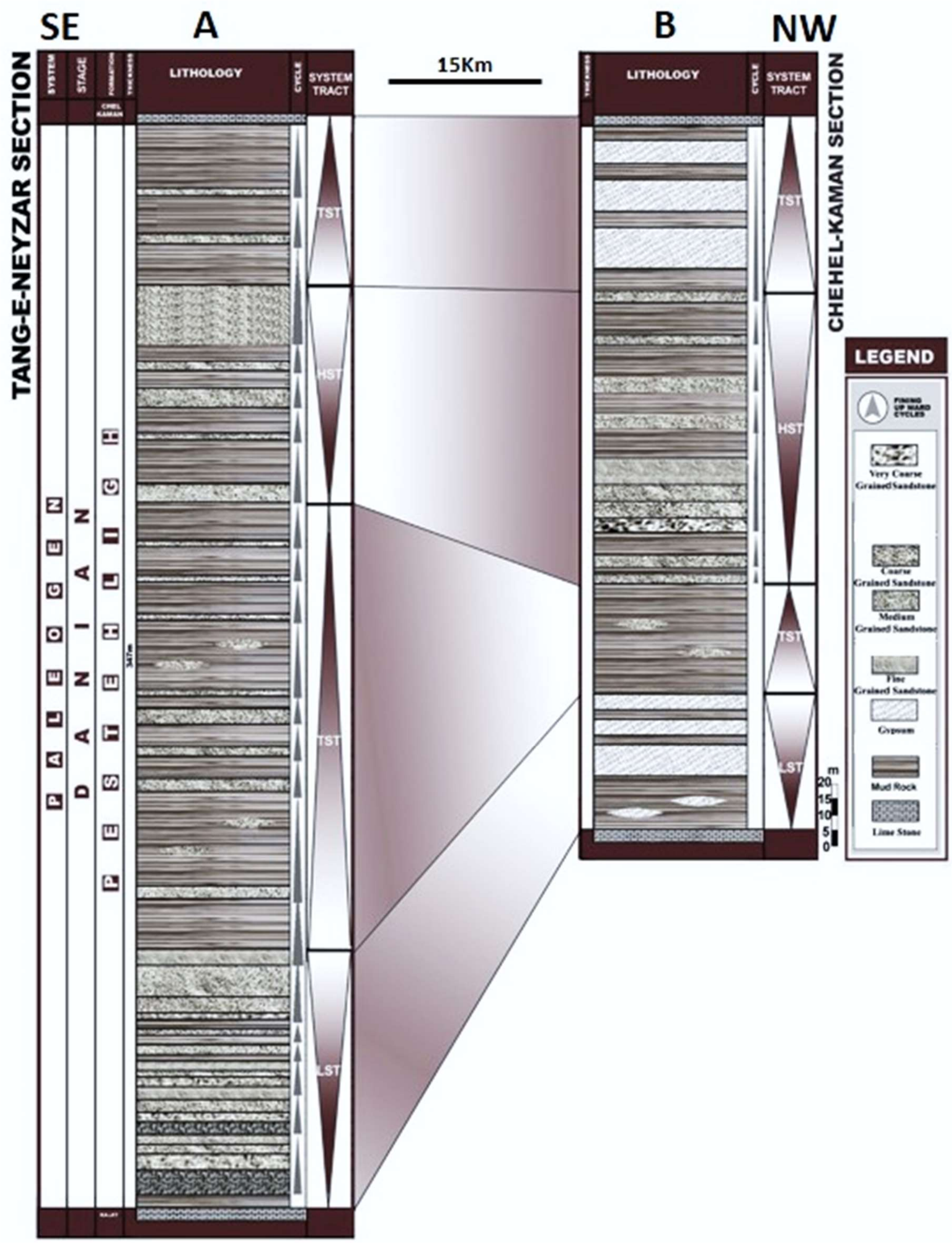

Figure 9. Sequence stratigraphy correlation of the studied sections. A: Tang-e-Neyzar section. B: Chehelkaman section

After the TST facies association, upward-fining cycles begin, where in the lower and upper parts, these cycles are composed of sandstone in the base and end in shale, while in the middle part, they consist of upward-fining sandstone cycles. This part represents the HST facies association, and its lower boundary with the TST facies association is identified by the maximum flooding surface (MFS) (Figures D7 and C8). Since these cycles usually have a uniform appearance, the sedimentation pattern for them is progressive-regressive. In fact, the

HST facies association begins to deposit when the sea level base rises to its last limit (MFS) (Catuneanu, 2006). In addition to changes in the sea level base in the formation of upward-fining cycles, tectonic factors (subsidence) in the basin can also cause a decrease or increase in accommodation space. In other words, HST facies associations can be formed as a result of autogenic river processes or lateral movements of the meandering river, which are influenced by sea level base and tectonics (Khalifa et al., 2008). The maximum flooding surface (MFS) in continental systems corresponds to the boundary between the sea level rise and fall (Einsele, 2000; Parize et al., 2008). Based on this, this boundary can be selected between fine grained floodplain facies and upward-fining cycles. This part in the Chehelkaman and Tang-e- Neyzar sections has thicknesses of 95 and 120 meters, respectively, and its deposition pattern is uniform and progressive-regressive type, belonging to the HST facies association.

After the HST facies association, the SB2 boundary is located. After the SB2 boundary in Chehelkaman section, thick evaporative sequences (52 meters) with mudstone intercalations have been deposited in a salina environment, which is located between the continental and coastal environments, and are interpreted as the TST facies association (Figure 10 E). In the Tang-e- Neyzar section, after the SB2 boundary and due to the rise in the river base level following various processes, a low-energy and calm floodplain environment has formed. In these conditions, crevasse mudstone facies are deposited (Haschenbuger & Cowie, 2009), which form the TST facies association (Khalifa et al., 2008). The thickness of this facies association is measured to be 50 meters. After this facies association, the Chehelkaman Formation has been deposited.

In both sections, after the HST facies association, the SB2 boundary is located, and then the TST facies association is formed. In the Chehelkaman section, this facies association is formed of mudstone and evaporative sequences deposited in a salina environment, while in the Tang-e- Neyzar section, it consists of mudstone intercalations with minor sandstone. The TST facies association in both sections marks the beginning of Chehelkaman sea transgression.

Conclusion

The Pesteliegh Formation in the eastern part of the Kopeh Dagh Basin is primarily composed of conglomerates, sandstones, shales, and minor evaporite deposits. Based on petrographic and mineralogical studies, two petrofacies, including conglomeratic (oligomictic) and sandy (quartzarenite, sublitharenite, and litharenite), have been identified in the Pesteliegh Formation. The analysis of lithofacies and structural elements of the siliciclastic deposits of the Pesteliegh Formation led to identification of four lithofacies associations: Conglomeratic (Gcm), Sandy (Sm, Sp, St, Sr, Sl, Sh), Mudstone (Fl, Fm), and Evaporitic (P) lithofacies, as well as structural elements (CS, CR, FF, LA, CH). Some evidence, such as facies changes, one-directional structures, the presence of upward-fining cycles with an erosional base, and the absence of fossils, indicate that the siliciclastic deposits of the Pesteliegh Formation were formed in a meandering river system with clay and sandy beds. Furthermore, the off-channel deposits and the salina environment also show considerable expansion in the Chehelkaman section. Based on the paleocurrent analysis, the ancient flow direction of this river was probably from southeast to northwest. Sequence stratigraphic analysis of the Pesteliegh Formation indicates that the studied sections represent a sedimentary sequence formed during a sea-level fall in the early Paleocene and the beginning of the subsequent sequence. Since the Pesteliegh Formation in the studied sections is located near the coastline, their sequence stratigraphy model follows the standard model and includes HST, LST, and TST facies associations.

References

Afshar-Harb, A., 1994. Geology of Kopet Dagh. Treatise on the Geology of Iran, 11: 1–275.

Aghanabati A, 2003. Geology of Iran. Publication of the Geological Survey of Iran, 586 p. (In Persian)

Aldega L, Brandano M, Cornacchia I., 2020. Trophism, climate and paleoweathering conditions across the Eocene-Oligocene transition in the Massignano section (northern Apennines, Italy). Sediment Geol, 405:105701

Allen, J. R. L., 1982**.** Sedimentary Structures, Their Character and Physical Basis. Elsevier, Amsterdam, 593 p.

Allen, P.J., R. Fielding, C., 2007. Sedimentology and stratigraphic architecture of the late Permian Betts Greek Beds, Queensland, Australia, Sedimentary Geology, 202, pp. 5-34.

Amorosi, A., Pavesi, M., Ricci Lucchi, M., Sarti, G., Piccin, A., 2008. Climatic signature of cyclic fluvial architecture from the Quaternary of the central Po Plain, Italy, Sedimentary Geology, 209:.58-68.

Blum, M.D., Aslan, A., 2006. Signatures of climate v.s. sea-level change within incised valley-fill successions: Quaternary examples from the Texas Gulf Coast. Sedimentary Geology, 190: 177-211.

Bretis, B., Grasemann, B., & Conradi, F., 2012. An Active Fault Zone in the Western Kopeh Dagh (Iran). Austrian Journal of Earth Sciences, 105: 3.

Bourquin S., Rigollet C., Bourges P., 1998. High-resolution sequence stratigraphy of an alluvial fan - fan delta environment: stratigraphic and geodynamic implications - Example of the Chaunoy Sandstones, Keuper of the Paris Basin. Sedimentary Geology, 121: 207-237.

Brooks, G.R., 2003. Alluvial deposits of a mud-dominated stream: the Red River, Manitoba, Canada. Sedimentology, 50: 441–458.

Catuneanu, O. & Elango, H. N., 2001. Tectonic control on fluvial styles: the Balfour Formation of the Karoo Basin, South Africa, Sedimentary Geology, 140: 291-313.

Catuneanu, O., 2003. Sequence Stratigraphy of Clastic Systems. Geological Association of Canada, Short Course Notes, 16, 248p.

Catuneanu, O., 2006. Principles of Sequence Stratigraphy. First Edition, Elsevier, Amsterdam, 375p.

Crouvi, O., Ben-Dor., E., Beyth, M., Avigad, D. and Amit, R., 2006. Quantitative mapping of arid alluvial fan surfaces using field spectrometer and hyperspectral remote sensing, Remote Sensing of Environment, 104: 103-117.

Davis, R.A., 2012, Tidal signatures and their preservation potential in stratigraphic sequences, in avis, R.A. and Dalrymple, R.W. (Eds.), Principles of Tidal Sedimentology, Springer, 35-55

Einsele. G., 2000. Sedimentary Basins, Evolution, Facies, and Sedi Springer, 792p.

El Tabakh, M., Mory, A., Schreiber, B.C., Utha-Aroon, C., Coshell, L., Warren, J.K., 2004a. Digenetic origin of basal anhydrite in the Cretaceous Maha Sarkham salt; Khorat Plateau, NE Thailand, Sedimentology, 45: 579-594.

El Tabakh, M., Mory, A., Schreiber, B.C., Yasin, R., 2004b. Anhydrite cement after dolomitization of shallow marine carbonate of the Gascoyne Platform, Southern Cannarvon Basin, Western Australia, Sedimentary geology, 164: 75-87.

Folk, R.L., 1980. Petrology of Sedimentary Rocks. Hemphill Publishing Co., Austin, Texas, 182 pp.

Gani, R.M., Alam, M.M., 2004. Fluvial facies architecture in small scale river system in the Upper Dupi Tila formation, North east Bengal Basin, Bangladesh, Journal of Asian Earth. Sciences, 24: 225-236.

Ghosh, P., Sarkar, S., Maulik, P., 2006. Sedimentology of a muddy alluvial deposit: Triassic Denwa Formation, India. Sedimentary Geology, 191: 3–36.

Gurnell, A., Blackall, T.D., Petts, G.E., 2008. Characteristics of freshly deposited sand and finer sediments along an island-braided, gravel-bed river: The roles of water, wind and trees, Geomorphology, 99(1-4): 254-269.

Harms, J.C., Southard, J.B., Walker, R.G., 1982. Structures and Sequence in Clastic Rock. SEPM (Socity of Economic Paleontologists and Mineralogists), Short Course, Chater 1, 55p.

Haschenburger,K. J., Cowie, M., 2009, Floodplain stages in the braided Ngaruroro River, New Zealand: Geomorphology, 103: 466-475.

Ito, M., Matsukawa, M., Saito, T., Nichols, D.J., 2006. Facies architecture and paleohydrology of a synrift succession in the Early Cretaceous Choyr Basin, Southern Mongolia, Cretaceous Research, 27: 226-240.

Kim, S.B., Kim, Y.G., Jo, H.R., Jeong, K.S., Cjough, S.K., 2009. Depositional facies, architecture and environments of the Sihwa Formation (Lower Cretaceous), mid-west Korea with special reference to dinosaur eggs, Cretaceous Research, 30: 100-126.

Khalifa, M., Catuneanu, Q., 2008. Sedimentary of the fluvial and fluvio-marine facies of the bahariya Formation Early Cenomanian), Bahariya Oasis, Western Desert, Egypt, Journal of African Earth Sciences, 51: 89-103.

Kjemperud,V.A., K. Schomacher, E., A. Cross, T., 2008. Architecture and stratigraphy of alluvial deposits, Morinson Formation (Upper Jurassic), Utah. The American Association of Petroleom Geologists, AAPG Bulletin, 92 (8): 1.55-1.76.

Kwon, Y.K., Chough, S.K., Choi, D.K., Lee, D.J., 2006. Sequence stratigraphy of the Taebaek Group (Cambrian-Ordovician), Mideast Korea, Sedimentary Geology, 192: 19-55.

Lee, H.S., Chough, S.K., 2006. Lithostratigraphy and depositional environments of the Pyeongan Supergroup (Carboniferous-Permian) in the Taebaek area mid-east Korea. Journal of Asian Earth Sciences, 26: 339- 352.

Le Héron , D.P., Khoukhi, Y., Paris, F., Ghienne, J.F., Le Hérissé, A., 2008. Black shale, grey shale, fossils and glaciers: Anatomy of the Upper Ordovician–Silurian succession in the Tazzeka Massif of eastern Morocco, Gondwana Research, 14:3, 483-496.

Longhitano, S.G., Mellere, D., Steel, R.J., Ainsworth, R.B., 2012. Tidal depositional systems in the rock record: A review and new insights: Sedimentary Geology, 279: 2-22.

Lowey, G.W., 2007. Lithofacies analysis of the Dezadeash Formation (Jura–Cretaceous), Yukon, Canada: The depositional architecture of a mud/sand-rich turbidite system. Sedimentary Geology 198, 273–291.

Martin, C.A.L., Turner, B.R., 1998. Origins of massive-type sandstones in braided river systems. Earth-Sci Rev 44(1-2):15–38.

Matchen, D.L., Kammer, T. W., 2006. Incised valley fill interpretation for Mississippian Black Hand Sandstone, Appalachian Basin, USA: Implications for glacial eustasy at Kinderhookian-Osagean (Tn2-Tn3) boundary, Sedimentary Geology, 191: 89-113.

Mather, A., Stokes, M., Pirrie, D., Hartley, R., 2008. Generation, transport and preservation of armoured mudballs in an ephemeral gully system: Geomorphology, 100: 104-119.

Matthews, W.J., Hampson, G.J., trudgill, B.D., Underhill, G.R., 2007. Controls on fluviolacustrine reservoier distribution and architecture in passive salt-diapir provinces: Insights from outcrop analogs. AAPG Bulletin, 91: 1367-1403.

Mcloughlin, S., Drinnan, A. N., 1997. Fluvial sedimentology and revised stratigraphy of the Triassic Flagstone Bench Formation, northern Prince Charles Mountains, East Antarctica. Geological Magazine, 134: 781–806.

Miall, A. D., 1985. Architectural-element analysis: a new method of facies analysis applied to fluvial deposits, Earth Science Review, 22: 261-308.

Miall, A. D., 1996. The Geology of Fluvial Deposits, Sedimentary Facies, Basin Analysis and Petroleum Geology. Springer-Verlag, New York, 582 p.

Miall, A. D, 2014. Fluvial depositional systems, Springer International Publishing, 14: 316

Moussavi-Harami, R., 2004. Sedimentology, 11th edition of Astan Quds Razavi Publications, 474 p.

Moussavi-Harami, R., Brenner, R.L., 1992. Geohistory analysis and petroleum reservoir characteristics of Lower Cretaceous (Neocomian) Sandstone, eastern portion of Kopet-Dagh basin, northeast Iran, American Association of Petroleum Geologist bulletin, 76: 1200-1208.

Moussavi-Harami, R., 1993. Depositional history and palaeogeography of the Lower Paleocene red beds in the eastern Kopet-Dagh basin north eastern Iran (In English). Journal of Science, National Center for Scientific Research Islamic Republic of Iran, 4: 126-143.

Nichols, G.J., Fisher, J.A., 2007. Processes, facies and architecture of fluvial distributary system deposits, Sedimentary Geology, 195: 75–90.

Parize,O., Mulder, T., Cahuzac, B., Fiet, N., Londeix, L., Rubino, J-L., 2008. Sedimentology and sequence stratigraphy of Aquitanian and Burdigalian stratotypes in the Bordeaux area (southwestern France), Comptes Rendus Geoscience, 340(6): 390-399.

Peakall, J., Ashworth, p.J., Best, J.L., 2007, Meander-bend evolution, alluvial architecture, and role of cohesion in sinuous channels, a flume study, Journal of Sedimentary Geology, 77: 197-212.

Petit, F., Gol, F., Houbrechts, G., Assani, A.A., 2005. Critical specific stream power in gravel-bed rivers,

Geomorphology, 69: 92- 101.
Pettijohn, F.J., 1975. Sedimentary Rocks. Harper and Row, New York, 628pp.
Powell, M., Ockelford, A.P. Rice, S., K. Hillier, J., Nguyen, T., Reid, I., J. Tate, N., Ackerley, D. 2016. Structural properties of mobile armors formed at different flow strengths in gravel-bed rivers. Journal of Geophysical Research Earth Surface. 121: 1494-1515.
Rengers, F., Wohl, E., 2007. Trends of grain sizes on gravel bars in the Rio Chagres, Panama., Geomorphology, 83: 282 – 293.
Roberts, E., 2007. Facies architecture and depositional environments of the Upper Cretaceous Kaiparowits Formation, southern Utah, Sedimentary Geology, 197: 207–233.
Robert A.M.M., Letouzey J., Kavoosi M.A, Sherkati Sh., Muller C., Ver´ges, J., Aghababaei, A., 2014. Structural evolution of the Kopet Dagh fold-and thrust belt (NE Iran) and interactions with the South Caspian Sea Basin and Amu Darya Basin. Marine and Petroleum Geology, 57: 68–87.
Schmid, S., Worden, R.H., Fisher, Q.J., 2006. Carbon isotope stratigraphy using carbonate cements in the Triassic Sherwood Sandstone Group: Corrib Field, west of Ireland. Chemical Geology, 225: 137-155.
Shanely, K.W., McCabe, P.J., 1998. Relative role of eustasy, climate and tectonism in continental rocks. SEPM (Society of Sedimentary Geology) spatial publication, 59: 234p.
Slingerland, R., Smith, N.D., 2004. River avulsions and their deposits. Annu. Rev. Earth Planet. Sci. 32: 257–285.
Therrien, F., 2006. Depositional environments and f luvial system changes in the dinosaur-bearing Sânpetru Formation (Late Cretaceous, Romania): Post-orogenic sedimentation in an active extensional basin, Sedimentary Geology, 192: 183–205.
Tucker, M.E., 2001, Sedimentary Petrology. Third Edition, Blackwell, Oxford, 260pp.Tunbridge, I.P., 198. Sandy high-energy flood sedimentation — some criteria for recognition, with an example from the devonian of S.W. England. Sedimentary Geology, 28 (2): 79-95.
Tunbridge, Ian P., 1981. Sandy high-energy flood sedimentation — Some criteria for recognition, with an example from the devonian of S.W. England. *Sedimentary Geology*, 28 (2): 79-95.
Tye, R.S., Coleman, J.M., 1989. Evolution of Atchafalaya lacustrine deltas, south-central Louisiana. Sedimentary Geology, 65 (1) 95-112.
Warren, J.K., 2006. Evaporitees: sediments, resources and hydrocarbons, Springer, Berlin, p.p. 455–566.
Wilmsen, M., Fürsich, F.T., Seyed-Emami, K., Majidifard, M.R., Taheri, J., 2009. The Cimmerian Orogeny in northern Iran: tectonostratigraphic evidence from the foreland. Terra Nova, 21, 211–218.
Zamaniyan. E., Khanehbad, M., MoussaviHarami, R., Mahboubi, A., 2018. Lithofacies and sedimentary environment of Qadir Member of the Nayband Formation on Parvadeh Coal Mines region, east central of Iran: Scientific Quarterly Journal, Geosciences, 28 (109): 295-304.
Zamaniyan, E., Khanehbad, M., Moussavi-Harami, R., Mahboubi A. 2021. Sedimentary environment and provenance of sandstones from the Qadir member in the Nayband Formation, Tabas block, east-central Iran, Boletín de la Sociedad Geológica Mexicana, 73 (1): A140920, 1-35.