

Sedimentary environment and palaeogeography of the ?Palaeocene–Middle Eocene Kashkan Formation, Zagros fold-thrust belt, SW Iran

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Abstract

The Kashkan Formation (?Palaeocene to Middle Eocene) in the Zagros fold-thrust belt, SW Iran, which is intercalated between to marine limestone formations, consists of conglomerates, sandstones and siltstones. The sedimentology and the palaeogeography of the Kashkan Formation had not received any attention thus far, but have now been studied in seven sections, situated in the province of Lorestan. The sediments form twelve lithofacies, three ichnosubfacies and seven architectural elements, which are described, depicted and analysed. The analysis leads to the conclusion that most sediments accumulated in a low-sinuosity, low-gradient braided-river system (characterised by mainly unidirectional palaeocurrent directions, and by sheetfloods), that occasionally showed meandering characteristics (represented by overbank deposits and large bars). The deposits of this system closely resemble those of the South Saskatchewan River in Canada, which is considered as the classical example of a sand-bed braided river. The river flowed roughly from North to South, as deduced by palaeocurrent indicators such as imbrication and large- to medium-scale trough cross-stratification (direction measured in the trough axes). This current direction is supported by the southward to south-westward thinning of the formation and by the diminishing average grain size in the same direction. The trace fossils in the Kashban Formation fit all in the *Skoyenia* ichnofacies, which has here three ichnosubfacies which allow a more detailed palaeoenvironmental reconstruction, indicating that the braided stream passed into the low-energy shoreface zone of a tidally-influenced sea.

Keywords: Kashkan Formation, Zagros fold-thrust belt, trace fossils, facies architecture, braided river, shoreface, Palaeocene, Eocene, Iran

1. Introduction

The Zagros fold-thrust belt (ZFTB), which extends for about 2000 km from south-eastern Turkey through northern Syria and Iraq to western and southern Iran (Fig. 1), is well known for its numerous giant hydrocarbon fields. It is

also the most resources-rich fold-thrust belt of the world (Alavi, 2004). More than a hundred stratigraphic sections have been surveyed in various parts of the Zagros belt (see, among others, Leturmy & Robin, 2010). One of the lithological units that were distinguished is the Kashkan Formation. Its name was proposed by

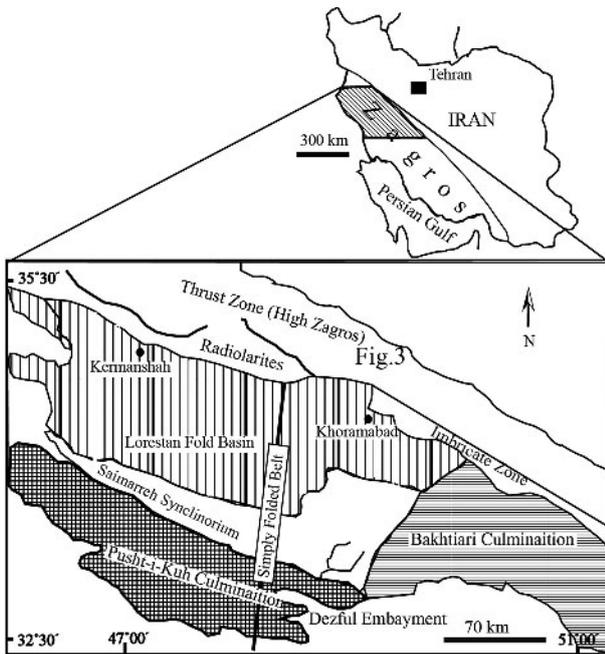


Fig. 1. Location and geological setting of the study area, showing structural parts of the Zagros fold-thrust belt in Iran (modified from Falcon, 1967).

James & Wynd (1965), who assigned a ?Palaeocene to Middle Eocene age to this formation on the basis of its stratigraphic position; there are no index fossils (Motiei, 1993). The proposed name has been accepted and the formation has been adopted as a formal stratigraphic unit by the Stratigraphic Committee of Iran.

The Kashkan Formation rests upon the Palaeocene-Middle Eocene Talezang Formation and is overlain by the shallow-marine Middle-Late Eocene Shahbazan Formation (Fig. 2).

The entirely siliciclastic Kashkan Formation, of which the type section is located at kuh-Amiran (the Amiran anticline) in the ZFTB, has received surprisingly little attention thus far. Neither a sedimentological analysis nor a palaeogeographical reconstruction has hitherto been performed. The present contribution describes and depicts the lithofacies, the architectural elements and the trace fossils of this formation, and reconstructs on this basis the sedimentary environment and the palaeogeography.

Most data for this study were obtained by measuring seven sections in the study area, which is located in the ZFTB in the province of Lorestan (SW Iran): they are named here the Darabi, Dom-sorkh, Mamoolan, Golgekhalag, Malavi, Moorani and Sepiddasht sections (Fig. 3).

2. Geological setting

2.1. Pre-Tertiary history

Following the late Precambrian Katangan orogeny, the craton on which Iran, Pakistan,

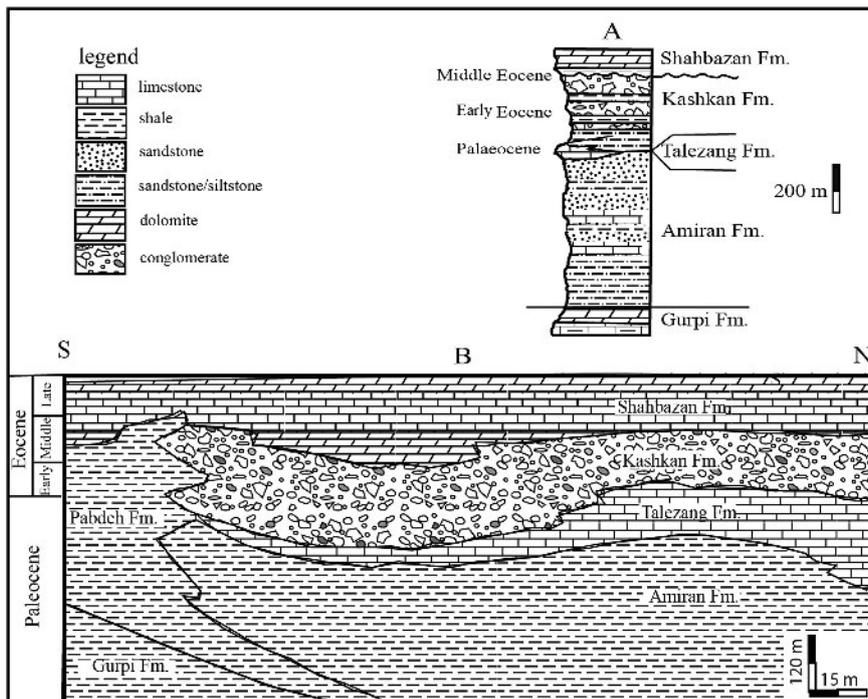


Fig. 2. The Kashkan Formation. **A:** Schematic sedimentary log of the type section. **B:** Schematic cross-section, showing the relationships with adjoining formations (modified after James & Wynd, 1965).

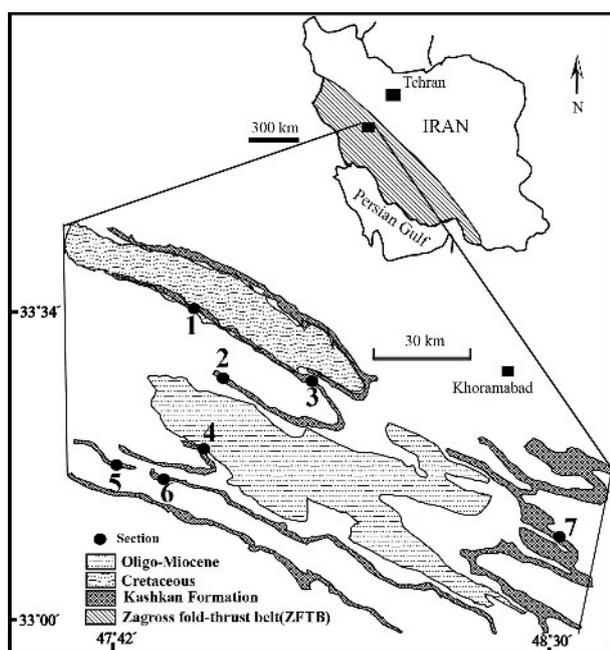


Fig. 3. Schematic geological map of the study area, with the locations of the sections under study. 1 = Darabi, 2 = Domsorkh, 3 = Mamoolan, 4 = Golgekhalag, 5 = Moorani, 6 = Malavi, 7 = Sepiddasht section.

central Afghanistan, south-eastern Turkey and Arabia are situated, became a relatively stable continental platform where sediments accumulated on an epicontinental shelf. No major magmatism or folding then took place (Stocklin et al., 1964). Most of the Zagros Basin emerged during Late Ordovician to Early Silurian tectonics. The area underwent erosional activity until the end of the Late Palaeozoic, resulting in a sedimentary gap. During the Permian, a regional transgression followed, and the partly eroded Ordovician and Silurian became covered, via a low-angle unconformity, by Permian sediments of the Zagros Basin (Szabo, 1977).

During the Early Permian, an elongated zone of the Zagros Basin became uplifted and folded; this was defined by Szabo and Kheradpir (1978) as the Zagros fold-thrust belt. Unlike the Permian of Arabia, no glacial clastics have been found in the Zagros Basin. During Middle Triassic orogenic movements, all of Iran was folded and uplifted, except for the Zagros Basin where the movements were less intense (Berberian and King, 1981). Marine carbonates accumulated here throughout the Per-

mian and Early Triassic (Szabo & Kheradpir, 1978). Regressive conditions in the Middle Triassic resulted in the deposition of the evaporites, indicating hot and arid conditions (Stocklin, 1968). No Upper Triassic has been found in the Zagros so far (Szabo, 1977), probably as a result of a sea-level lowering.

The evaporites of the Zagros Basin became unconformably overlain by Liassic terrigenous clastics and transitional terrigenous-to-open-marine sediments. During the Late Jurassic, a carbonate platform extended from the Zagros Basin to northern central Arabia; the climate was probably more humid than before (Murriss, 1978). The sea deepened during the Cretaceous, when a marine transgression occurred over most of Iran. The Cretaceous sediments follow the Jurassic succession disconformably. In the north-western part of the Zagros Basin (where now Lorestan is situated), Cretaceous grey-black radiolarians-bearing shales and deep-water argillaceous limestones were deposited disconformably over the Jurassic evaporites, and deeper-water sedimentation continued from the Albian to the Turonian. Late Turonian movements reactivated NW-SE trends in Lorestan, where these trends had existed already since the Permian (James & Wynd, 1965). In most parts of the Zagros Basin, the Upper Cretaceous starts with neritic carbonates, followed by deeper-water marls and shales. During the Campanian to Maastrichtian, the present-day Zagros trend became fully developed. At the end of the Maastrichtian an important regression took place, so that the overlying Palaeogene is separated from the Mesozoic by a major unconformity throughout the Zagros Basin (Setudehnia, 1978).

2.2. Tertiary development

The Zagros Basin was part of the southern margin of the Neo-Tethys Ocean (Murriss, 1980) and became filled by terrigenous and carbonate sediments. The deepest part of this basin was located in the province of Lorestan, which covers the NW part of the basin. Geological interest in the Zagros Mountains in SW Iran was raised in the beginning of the 20th century,

when giant oil occurrences were discovered. Since the 1908 discovery, the main production has been from limestones of the Asmari Formation, an Oligo-Miocene limestone. This formation is overlain by the Talezang Formation, a reefal limestone. This unit is disconformably overlain by the Kashkan Formation, which is entirely siliciclastic in the study area, but which passes towards the SE into the limestones of the Shahbazan Formation.

The relatively coarse, siliciclastic character of the Kashkan Fm. makes this unit fairly exceptional in the total succession, and its lithofacies characteristics suggest that it is unlikely that hydrocarbons are present. That is most probably why thus far little attention has been paid to this formation. The present contribution is the first to provide a detailed sedimentological analysis and a reconstruction of the depositional environment.

2.3. The Kashkan Formation

The type section of the Kashkan Formation was established by James & Wynd (1965) at kuh-e Amiran, where the Kashkan river cuts through the north-eastern flank of the anticline. The formation is composed here of deep-red coloured siltstones, sandstones and conglomerates, showing an overall coarsening-upward tendency from roughly 0.8–1.5 cm in the basal

part to 2–3 cm in the top part. The bed thickness is 30–50 cm, the size of the average clasts is 2–2.5 cm and the size of the largest clasts is 7–10 cm.

The contact with the underlying Talezang Formation is abrupt (possibly a hiatus is present), whereas the upper boundary consists of a limonitic, weathered zone with dolomite layers of the Shabazan Formation. The siliciclastic Kashkan Formation is thus both underlain and overlain by limestones. All three formations have at least partly a Middle Eocene age in the type locality of the Talezang and Shahbazan Formations at the Tang-e Do. The Palaeocene-Middle Eocene age of the Talezang Fm. there has been proven by the occurrence of *Miscellanea* sp., *Nummulites globules*, *Glomalveolina* sp., *Opertorbitolites curvoispira* and *Halkyardia* sp. The basal conglomerate of the Kashkan Formation directly overlies Palaeocene Talezang limestone in the Amiran anticline (the type section of the Kashkan Fm.) and has also been assigned there a ?Palaeocene age itself by James & Wynd (1965); this implies that the lower boundary of the Kashkan Formation is strongly diachronous.

The accumulation of the Kashkan Formation resulted from the supply of clastic particles that had been eroded due to orogenesis in the area to the North-East (James & Wynd, 1965). The formation becomes thinner and finer-grained in the southern part of the study

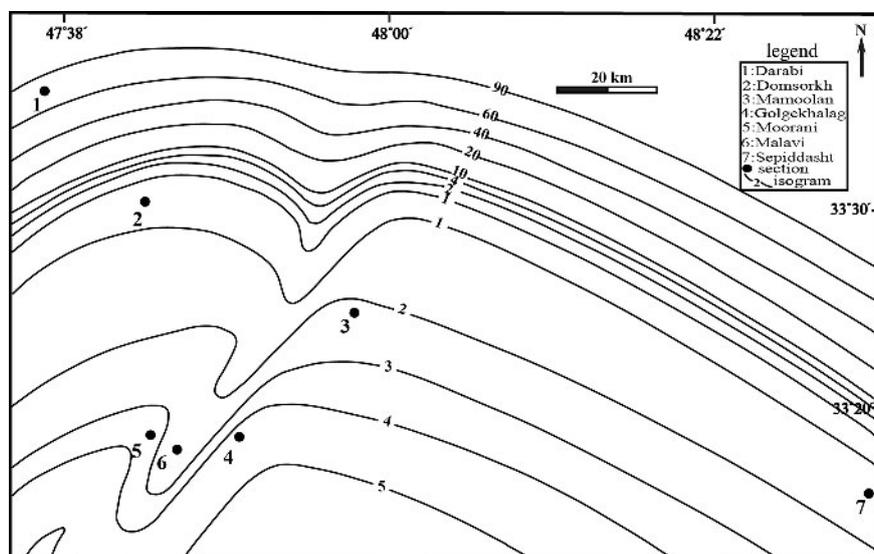


Fig. 4. Isoratio map (conglomerate + sandstone / shale) showing the diminishing dominance of coarse units towards the South.

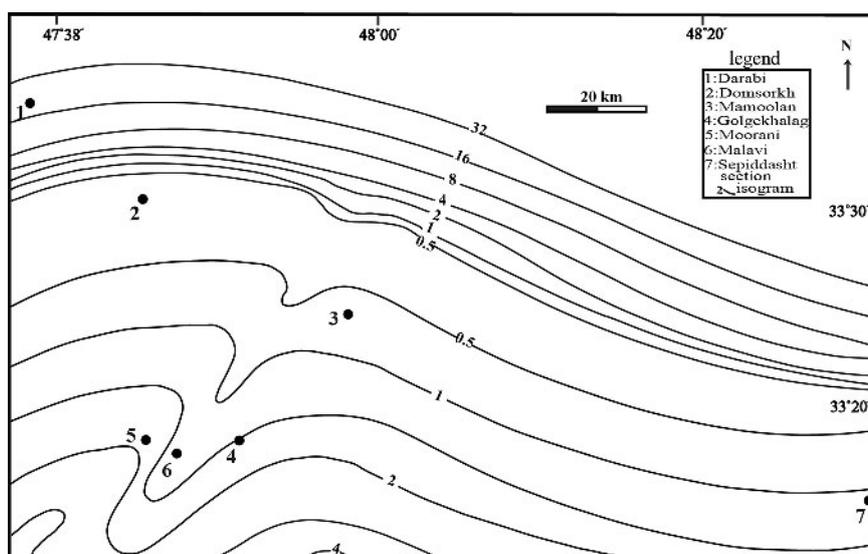


Fig. 5. Isoratio map (sandstone / shale) showing the increasing amount of fine-grained sediments towards the South.

area (Figs 4–5). South-west from the type-section area, the Kashkan Formation interfingers, like the under- and overlying formations, with the Pabdeh Formation (Fig. 2).

3. Methods

The present study included analysis of the sedimentary facies and the architectural elements, and an inventory and facies interpretation of the trace fossils. As part of the collection of field data aimed at the reconstruction of the palaeogeography, palaeocurrent directions were determined from large- to medium-scale trough cross-stratification (direction measured in the trough axes) and from the imbrication of clasts. Clast analyses and palaeocurrent measurements were carried out exclusively in outcrops of at least 1 m² in exposures perpendicular to the bedding, and only after cleaning the surface from lichens.

The analysis of the trace fossils did not restrict itself to identification and reconstruction of the habitat in which the animals lived, but included also the state of preservation and changes in the type and frequency of the trace fossils. Particularly the internal structure, size, wall nature, and branching of burrows were analysed.

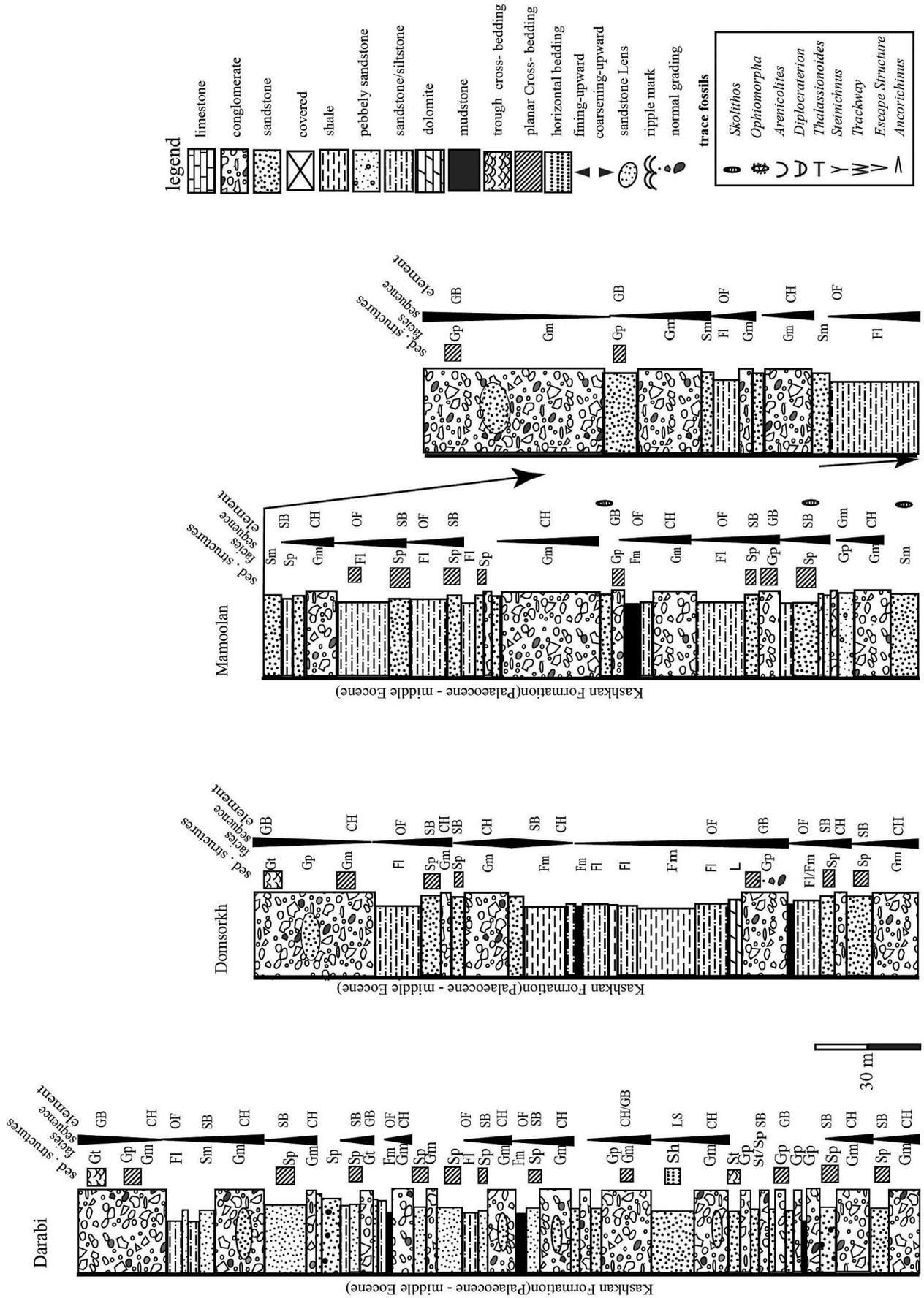
4. Lithofacies

Twelve lithofacies have been distinguished. They are indicated in the following according to the lithofacies codes of Miall (1985, 1996). The seven sections that were studied in detail (Fig. 3) show various lithofacies that are presented here as sedimentary logs (Fig. 6).

4.1. Massive conglomerates (lithofacies Gm)

Facies Gm extends over tens of metres across various outcrops in the middle and upper parts of the Kashkan Formation. It generally consists of massive, clast-supported conglomerates with a matrix of coarse sandstone or gravel (2–4 mm) filling the space between the larger clasts. The clasts are mostly rounded to sub-rounded, fine to coarse pebbles, but cobble-sized clasts also occur in the lower parts (Fig. 7-B,C). The lower boundary of this facies is erosional and irregular but the upper boundary is gradational, passing into much less coarse conglomerates. The conglomerates become thinner and finer in the southern part of the study area (Fig. 5).

The conglomerates form cycles in each of which the clast size decreases upwards (Fig.



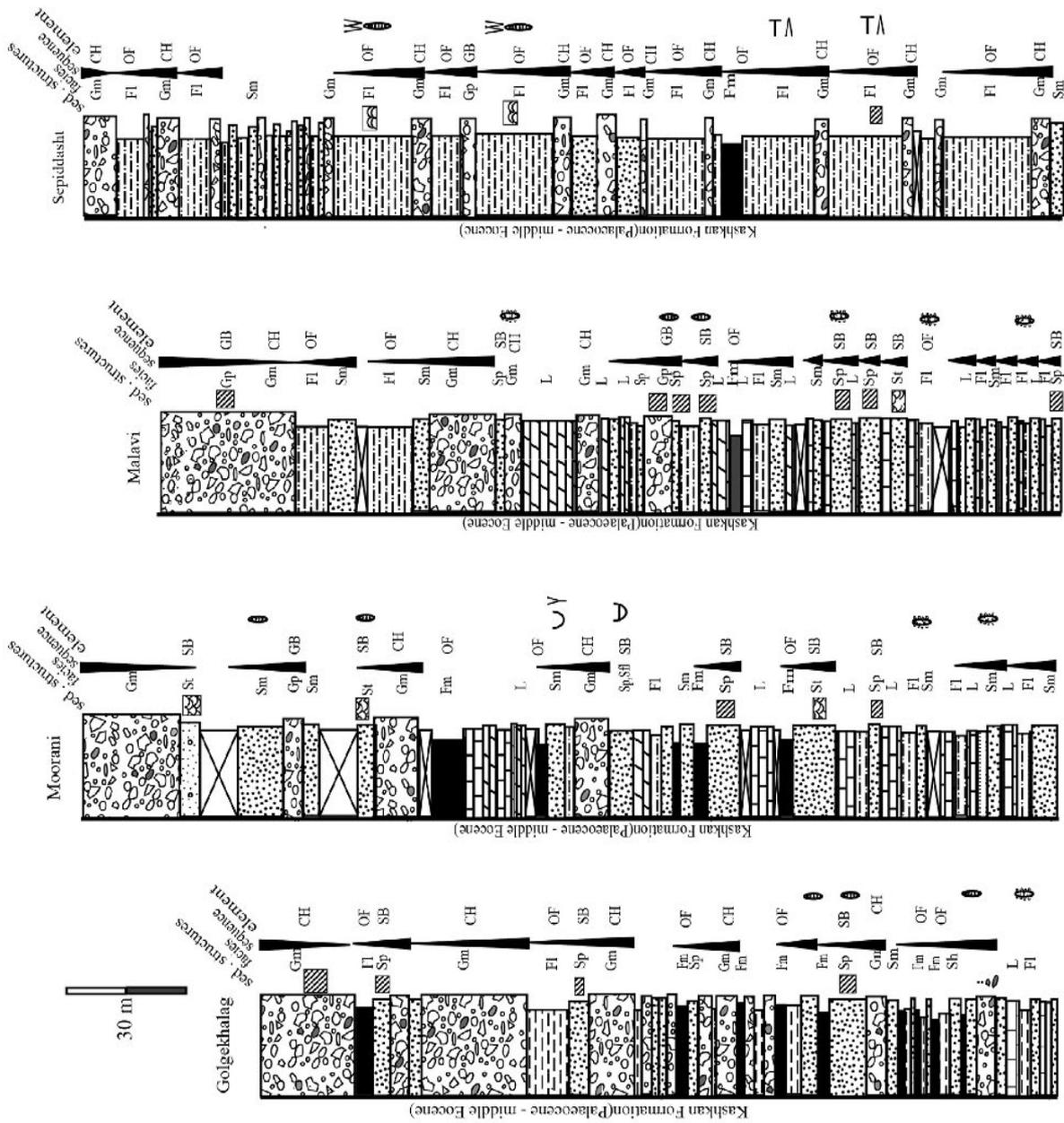


Fig. 6. Sedimentary logs, from N to S, with lithofacies, sedimentary structures, architectural elements and trace fossils of the Kashkan Formation.

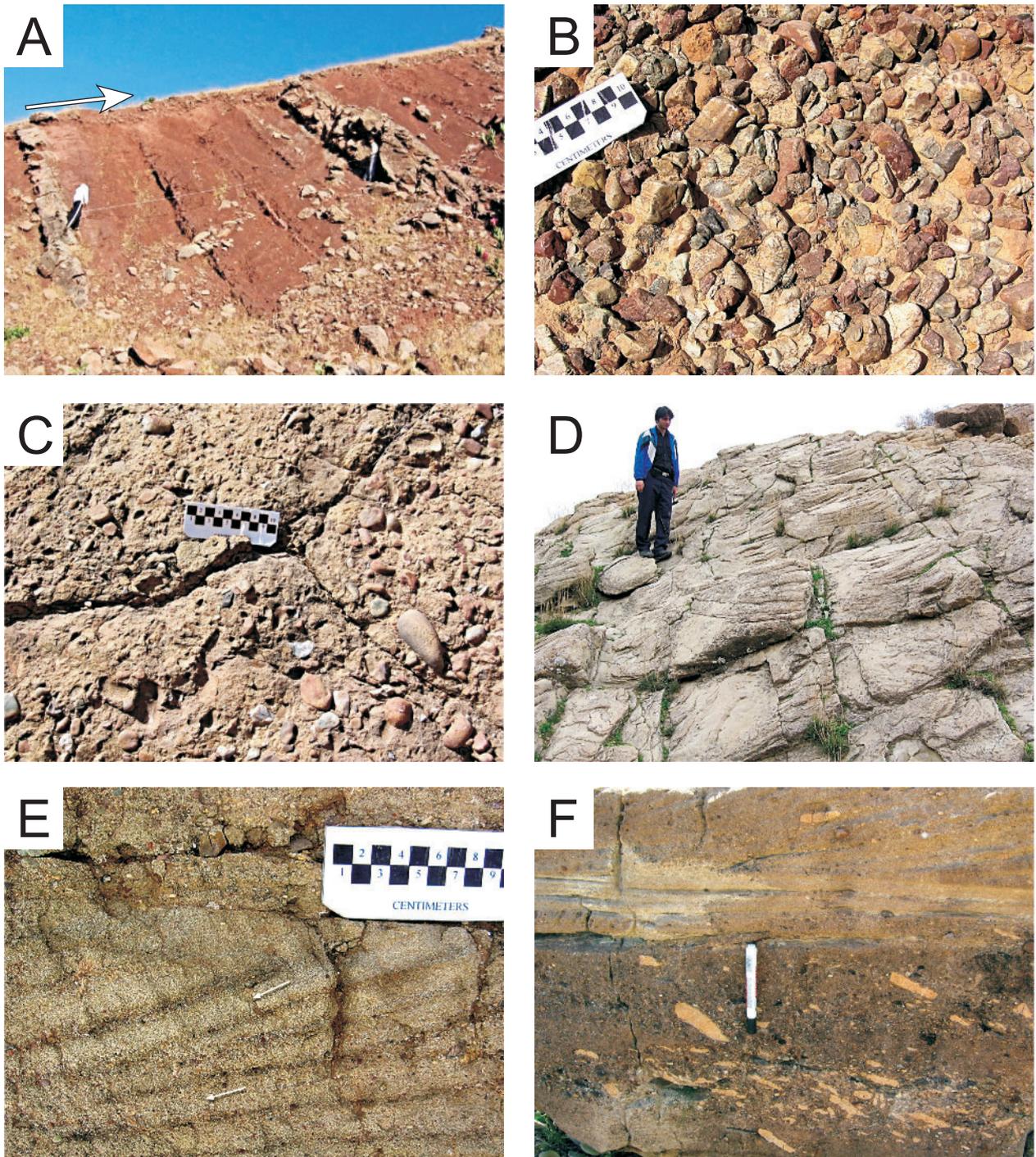


Fig. 7. Conglomerate facies Gm (A-C), Gt (D) and Gp (E, F). Scales are in cm. **A:** Fining-upward sequence from conglomerate to sandstone and siltstone. **B:** Massive lithofacies Gm. **C:** Lithofacies Gm with fine-grained matrix. **D:** Stacked trough cross-bedded conglomerates. **E-F:** Planar cross-bedded conglomerates.

7-A). Individual cycles are 0.5–6 m thick, and some cycles show amalgamation (Fig. 7-D).

Some lenses of cross-bedded, coarse-grained pebbly sandstone are present in this overall massive facies.

4.2. Planar cross-stratified conglomerates (lithofacies Gp)

Facies Gp consists mainly of clast-supported conglomerates with tabular cross-bedding,

but some lenses of planar cross-bedded sandstones are also present. The facies is 0.5–1.5 m thick, with individual sets being mostly 25–50 cm thick. The lower boundary of this facies is only locally erosional.

The mean dip of the foresets is 25° (Fig. 7-E,F), commonly toward the south-west. Some of the foresets show erosional (re-activation) surfaces. The cross-bedded layers show normal grading.

4.3. Trough cross-stratified conglomerates (lithofacies Gt)

Facies Gt is characterised by clast-supported, trough-shaped cross-bedded conglomerates, with a basis that shows both symmetrical and asymmetrical undulations (Fig. 8-A).

The clasts are generally similar to those of lithofacies Gm, but they are somewhat smaller than in Gm. The cross-bedded sets are usually

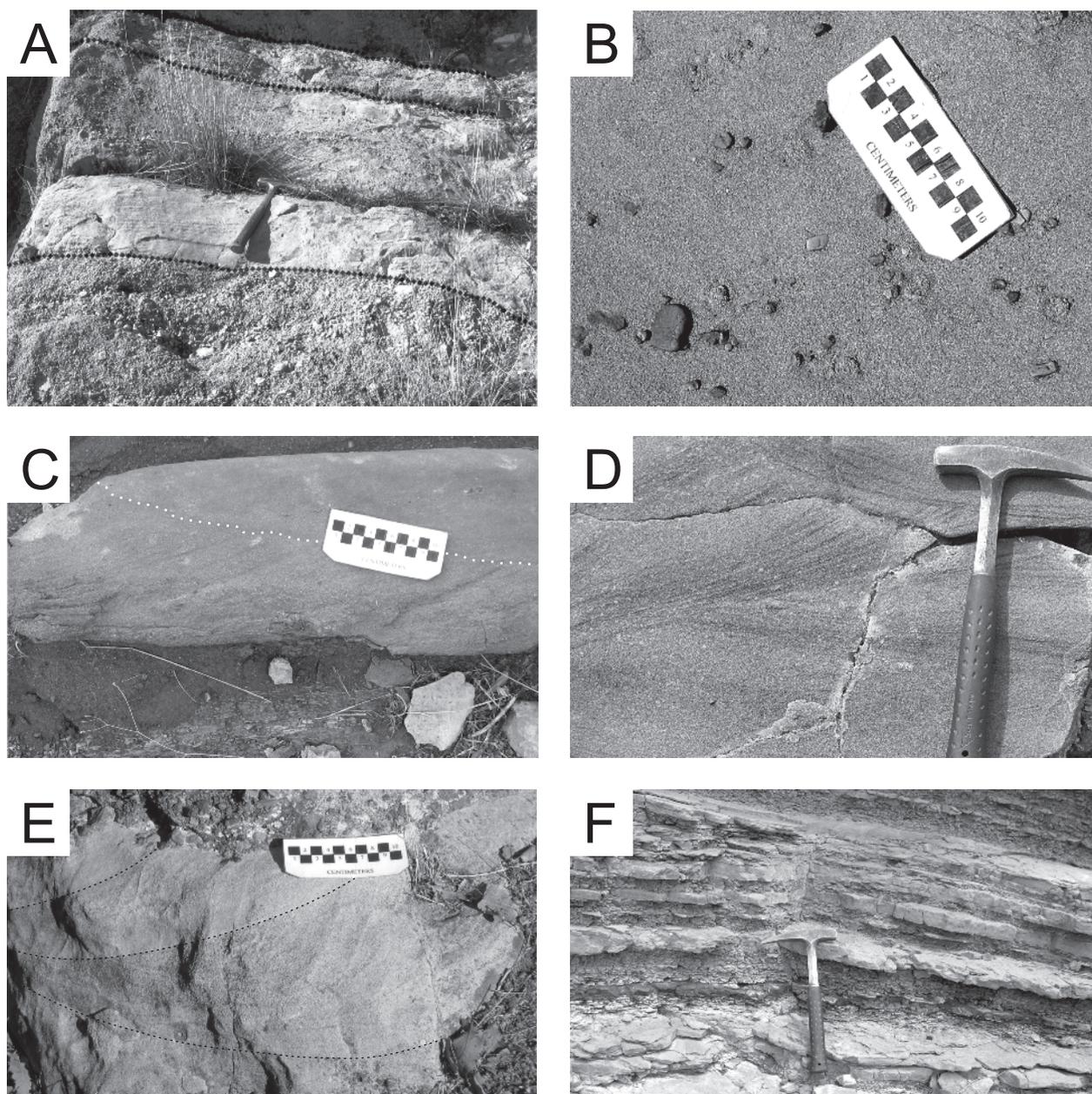


Fig. 8. Sandstone lithofacies Sm (B-C), Sp (C), St (D-E) and Sh (F). Scales in cm. **A:** Trough cross-stratified conglomerates (Gt). **B:** Massive sandstone (Sm). **C:** Erosional contact between Sp and Sm. **D-E:** Close-up of trough cross-stratified sandstone St. **F:** Horizontally stratified sandstone (Sh).

graded. The palaeocurrent direction, as measured from the trough axes, is most commonly towards the south-west.

Lenses of planar to trough cross-bedded sandstones (Sp and St) are also present. The individual sandy units are 0.5–1 m thick and usually 1–3 m wide.

4.4. Massive pebbly sandstones (lithofacies Sm)

Facies Sm comprises massive beds of medium- to coarse-grained sandstones. The lower boundary is locally erosional, though not always distinctly, but the upper boundary is commonly sharp, often undulating or irregular. The thickness of individual beds varies between 0.2 and 1.5 m. The grains are poorly to well sorted, and well-rounded to subrounded. Rare floating pebbles or gravels are present (Fig. 8-B).

4.5. Planar cross-bedded sandstones (lithofacies Sp)

Facies Sp consists of medium- to very coarse-grained sandstones. Scattered quartz and chert pebbles of various colours are present in some beds, thus forming pebbly sandstones (Fig. 8-C). Some lenses with more frequent pebbles occur, thus forming lenses of conglomeratic sandstone. Facies Sp is lenticular or irregularly wedge-shaped. The lower boundary of this facies is sharp, whereas the upper boundary is erosional.

Planar cross-stratification is present in solitary sets or as cosets. Cross-sets are 15 cm to a few decimetres thick. Most foresets are fining upward and dip toward the south-west. The thickness of these planar cross-bedded sets typically decreases with decreasing grain size.

4.6. Trough cross-bedded sandstones (lithofacies St)

Facies St consists of medium- to very coarse-grained, moderately to poorly sorted

sandstones. Some of the sandstones contain scattered cherty pebbles. This facies forms lenticular or wedge-shaped bodies.

The sandstones are well stratified, with sets and cosets, with sharp boundaries between them, commonly marked by thin siltstone layers. Sandstone layers with trough cross-bedding dominate. They are 10–80 cm thick (Fig. 8-D,E); the thickness is, as a rule, proportional to the grain size. The cross-bedding is of a low-angle type, and the troughs show a long wavelength (of some tens of centimetres on average). The trough axes dip commonly toward the south-west.

4.7. Horizontally stratified sandstones (lithofacies Sh)

Facies Sh consists of moderately to well sorted, horizontally stratified fine to coarse sandstone layers, which alternate. This facies is present within all other sandstone facies. Parting lineation is visible at the surface of very fine to fine sandstones (Fig. 8-F).

Each unit is about a few decimetres to a few metres thick. The upper and lower boundaries with other facies are sharp. The bounding surfaces may be traced for tens of metres.

4.8. Ripple cross-laminated sandstones (lithofacies Slr)

Facies Slr consists of moderately to well sorted, fine to coarse sandstones with thin intercalations of laminated siltstones. This facies is yellow to chocolate-coloured (Fig. 9-A). The grain size decreases upwards, simultaneously with thickening of the intercalated siltstones. The layers show an irregularly undulating lamination, with thin mud laminae on top of the sandy beds; some either asymmetrical or symmetrical ripples are present.

4.9. Flaser laminated sandstones (lithofacies Sfl)

Facies Sfl consists mainly of moderately sorted, wavy layers of fine sandstones and siltstones. The finest sediments occur as thin laminae, which are confined to ripple troughs (Fig. 9-B). This type of bedding is known as wavy flasers; the sediments represent ripple troughs and crests without a continuous bed form.

4.10. Massive mudstones (lithofacies Fm)

This facies mainly consists of siltstones and homogeneous mudstones, with a minor portion of fine- to coarse-grained sandstones that are scattered within this facies in the form of thin layers of nodular patches. The facies has a sheet-like geometry and its colour varies from brownish red to dark red to purple.

The lower boundary is commonly flat and irregular. Although facies Fm is generally massive, it contains rain-drop imprints and desiccation cracks indicating subaerial exposure during sedimentation (Mazumder & Sarker, 2004; Bridge, 2006).

4.11. Laminated mudstones (lithofacies Fl)

This sheet-like facies is composed mainly of parallel laminated siltstones (or mudstones) and shales. The lamination is caused by alternations of mudstone and siltstone. The lower

boundaries of the laminae are often erosional. The lower and upper boundaries of the individual beds are generally sharp and planar. Each unit is 10–80 cm thick.

4.12. Carbonate mudstones/wackestones (lithofacies L)

This facies is characterised by milky white to gray massive mudstone/wackestones with bioclastic fragments such as foraminifers (Figs 10-A, B, C). The upper and lower boundaries are sharp and planar, and are a few decimetres to a few metres thick. In some cases, fossils were selectively dolomitised.

5. Architectural analysis

As will be discussed below, the combination of the various lithofacies is a first indication of an overall fluvial setting. It was therefore decided to analyse also the architectural elements of the Kashkan Formation, as the application of concepts on fluvial architecture and sandstone body-forms (Allen, 1983; Friend, 1983; Hirst, 1991; Miall, 1985, 1994, 1996; Jones et al., 2001) gives more insight into fluvial sequences (López-Gómez et al., 2009). The architecture is particularly important because a river can produce a wide variety of facies sequences, and because similar sequences can be formed in rivers of different styles (Bridge, 1985; Miall, 1996; Salamon & Zielinski, 2010). Architectural analysis pays particular attention to large-

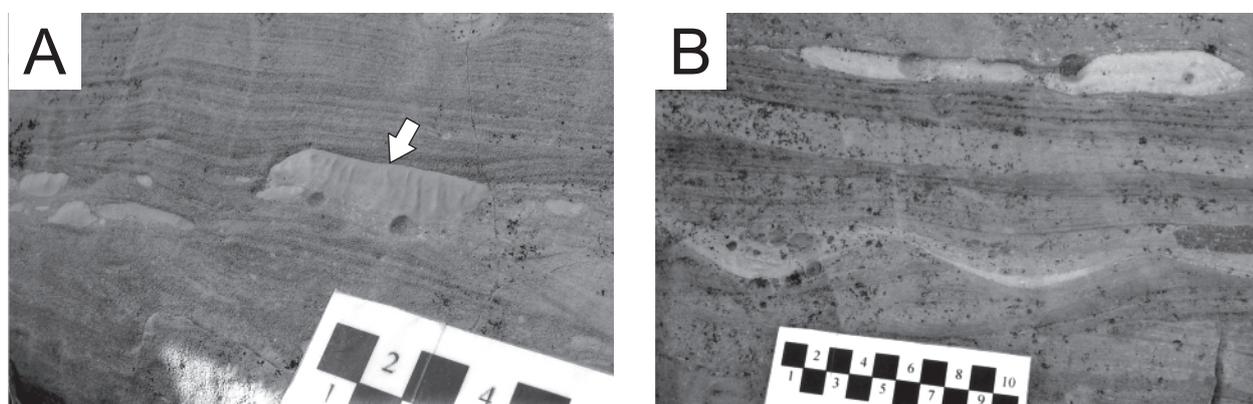


Fig. 9. Structures in sandy lithofacies. Scales in cm. **A:** Ripple cross-laminated sandstone (lithofacies Slr). Arrow shows a mudstone clast. **B:** Flaser-laminated sandstone (lithofacies Sfl).

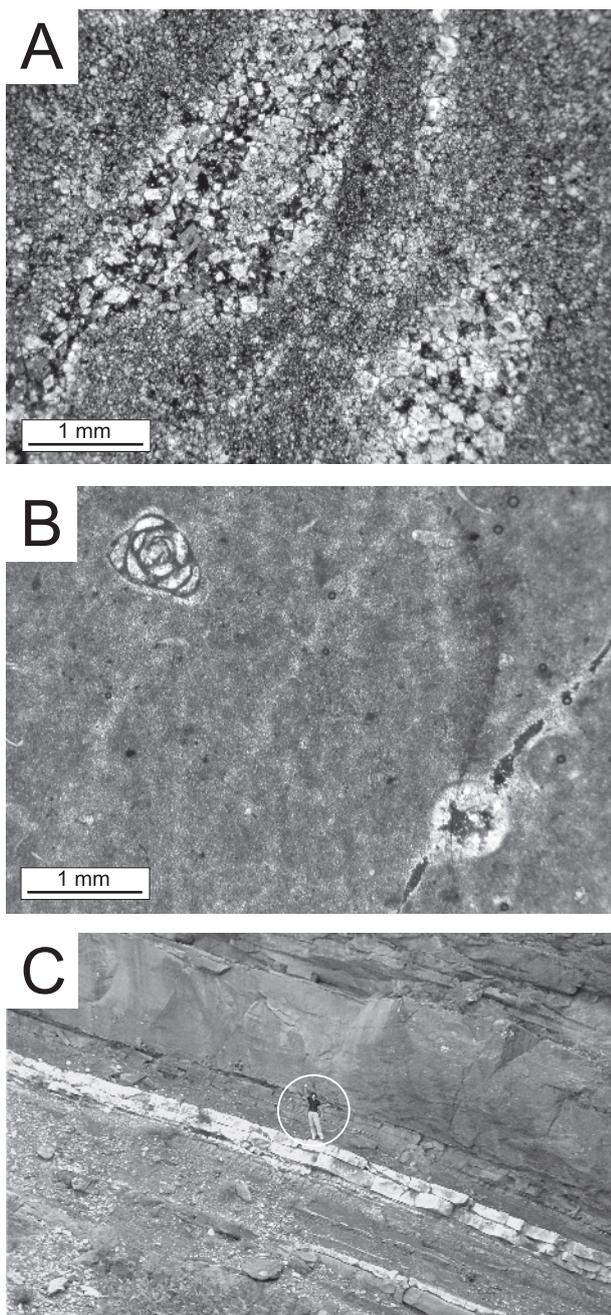


Fig. 10. Shoreface lithofacies L. **A:** Dolomitized fossil fragments. **B:** Micrite with miliolid foraminifer. **C:** Milky white limestone, man for scale.

scale sedimentary structures that are believed to reflect the type and behaviour of bars and channels (Allen, 1983, 1985, 1988, 1994; Willis, 1993). The reorganisation of large morphological expressions of rivers such as bars and channels by architectural analysis is crucial for the interpretation of ancient fluvial systems (Allen, 1983; Miall, 1988). Architectural elements can be defined on the basis of large-scale stratal

patterns and constituent facies (Miall, 1988). The spatial arrangement of the various elements reflects the spatial relationships between the morphological units and the changing positions of channels within a channel belt (Miall, 1994; Brierley, 1996).

The architectural elements in the Kashkan Formation have been identified on the basis of Miall's (1985) classification. The individual architectural elements have a hierarchical arrangement, with some smaller elements occurring within larger elements.

5.1. Channel-fill element (CH)

The channel-fill element is characterised in the Kashkan Formation by stacked, multi-storey channel bodies that incise the underlying sediments. The boundaries are, as a rule, undulatory, showing low-angle accretion surfaces. A channel fill often comprises the facies Gm, Gt and Gp, with subordinate facies St/Sp that are covered by facies Fm and Fl. The individual channel-fill elements have all a lenticular geometry, and can be traced laterally up to 300 m (Fig. 11-A).

This element abounds in the middle and upper parts of the Kashkan Formation.

5.2. Gravel-bar element (GB)

The gravel-bar element consists of vertically stacked layers of facies Gp and Gt and forms wedges or shows a lenticular form. Most of these elements show a fining-upward trend. They occur as isolated forms but are also found within element CH (Fig. 11-B).

5.3. Sandy-bedform element (SB)

The sandy-bedform element is composed of trough-shaped or planar sandstone bodies. It forms wedges or has a lenticular shape, and it is overlain by thin, sheet-like medium- to fine-grained sandstone beds or even finer-grained sediments. Facies Sp and St are the constituents; they become thinner towards the top of the SB

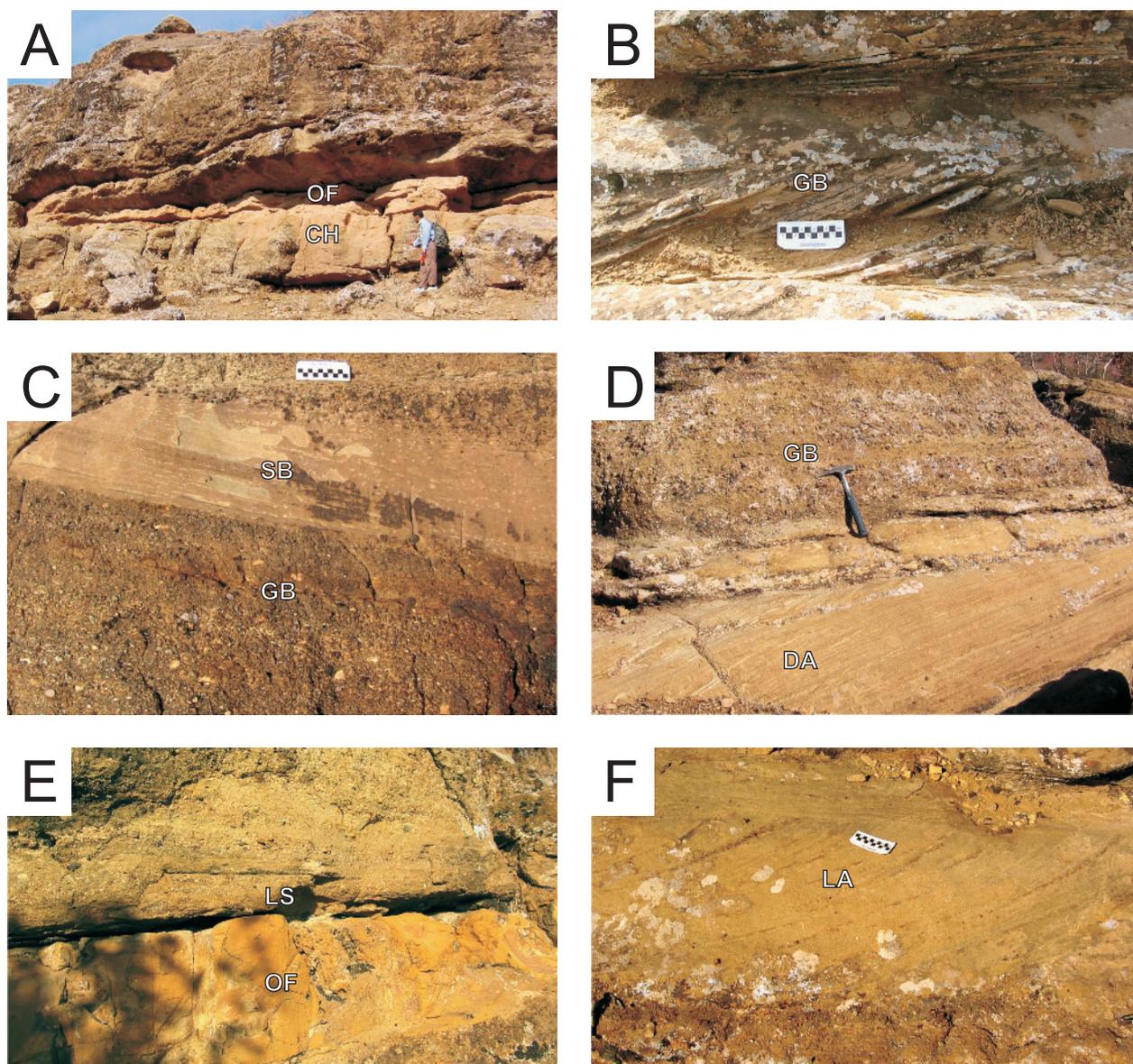


Fig. 11. Architectural elements. **A:** Channel fill element (CH) and floodplain element (OF). **B:** Gravel-bar element (GB). **C:** Gravel-bar element (GB) and sandy-bedform element (SB). **D:** Downstream-accretion element (DA). **E:** Laminated-sand-sheet element (LS). **F:** Lateral-accretion element (LA).

element (Fig. 11-C). The trace fossils *Diplocraterion* and *Skolithos* occur in this element.

5.4. Downstream-accretion element (DA)

The downstream-accretion element consists of low-angle accretion units with internal grading; it is composed of medium- to coarse-grained sandstones of facies Sp. This element, which is lenticular in shape (Fig. 11-D), forms a fining-upward granulometry in its lower part. It tends to show a convex-up shape for

the entire element, but commonly also for individual units within a single element (cf. Miall, 1985). The trace fossil *Skolithos* occurs in this element.

5.5. Laminated-sand-sheet element (LS)

The laminated-sand-sheet element occurs in the upper part of fining-upward cycles, where it is usually associated with element Fl (Fig. 11-E). This element is up to 0.5 m thick, and mostly has a sheet-like shape. LS consists

of fine-grained sandstones that are laterally continuous for about 15 m. *Laminites kaitiensis*, *Diplocraterion*, *Ophiomorpha*, *Thalassinoides* and escape structures are trace fossils in this element.

5.6. Floodplain element (OF)

The sheet-like floodplain element occurs in the upper parts of all cycles in the Kashkan Formation. It is characterised by red shales with intercalations of fine-grained sandstone beds. The element has a lateral extension of about 100 m and its thickness from 20 cm to 105 cm (Fig. 11-E). Trace fossils are present in the form of trackways.

5.7. Lateral-accretion element (LA)

The lateral-accretion element is characterised by units of 1–2 m thick and 20 m wide (Fig. 11-F). It is dominated by fining-upward packages composed of fine- to medium-grained sandstones forming low-angle, planar composite cosets. *Skolithos* is the only trace fossil found in this element.

6. Trace fossils

Structures formed by the action of plants and animals are classified as bioturbations (Van Loon, 2009); the group consisting of trac-

es left by any movement (or resting) of animals is known as trace fossils or ichnofossils. Some animals graze or crawl on the sedimentary surface, other species rest or live just below it, whereas still other animals construct much deeper burrows for dwelling or feeding. It is rarely known which trace fossils in the geological record have been produced by a specific species, but it has been found that different trace fossils were produced by animals living at different depths and in different environments.

Consequently, trace fossils can be useful for palaeoenvironmental studies, especially as tools for distinguishing between marine and non-marine deposits in the rock record. In general, trace fossils tend to be more abundant, diverse and morphologically distinctive in a marine than in a non-marine setting (D'Alessandro et al., 1987). In addition, in the numerous environmental settings where body fossils are poorly preserved, trace fossils may provide the only evidence of past life; they are an integral part of the substrate and cannot readily be transported (Crimes & Droser, 1992).

Ichnological analysis thus can yield information on the depositional environment and water depth, rates and styles of deposition, sequence-stratigraphic markers of environmental change, any limiting stress factors such as oxygen abundance and salinity levels (Stow, 2005). The trace fossils from the Kashkan Formation, represented mainly by endichnial traces, have therefore been inventoried, and they

Table 1. Occurrence of ichnofossils in the various lithofacies.

Ichnofossil type	Lithofacies type												
	Gm	Gp	Gt	Sm	Sp	St	Sh	Slr	Sfl	Fm	Fl	L	
<i>Arenicolites</i>				A			C						
<i>Diplocraterion</i>					R		C						
<i>Laminites kaitiensis</i>				C			R						
<i>Ophiomorpha</i>				C			R						
<i>Skolithos</i>				A	C			R					
<i>Steinichnus</i>				R									
<i>Thalassinoides</i>							C						
escape structure						R							
trackway				R					C	C			

A=abundant; C=common; R=rare.

are described below shortly. Table 1 shows the distribution of the trace fossils found in the reconstructed palaeoenvironmental setting of the Kashkan Formation. It is worth mentioning here that only the massive pebbly and horizontally-bedded sandstones and the laminated or massive mudstones contain trace fossils. The other lithofacies are barren.

6.1. Description of the trace fossils

The trace fossils in the Kashkan Formation consist of typical burrows (in alphabetical order *Arenicolites* isp., *Diplocraterion* isp., *Laminites kaitensis*, *Ophiomorpha* isp., *Skolithos* isp. and *Steinichnus* isp.), escape structures and trackways.

Arenicolites isp. (Fig. 12-B) consists of simple, vertical U-shaped tubes without spreiten. It is commonly preserved in full relief. In plane view, it may be recognised by paired openings. *Arenicolites* is abundantly present in the Sm and Sh lithofacies.

Diplocraterion isp. occurs in the Kashkan Formation as vertical U-shaped 'Spreiten' burrows (Fig. 12-D). The limbs of the U are often divergent. The space between the 'Spreiten' is filled by yellow mud. The size of these traces ranges from 5 to 15 cm. This trace fossil is abundant in the Sp and Sh lithofacies.

Laminites kaitensis occurs mainly as simple to horizontal burrows filled with chevron-shaped menisci backfill (Frey and Pemberton, 1984) (Fig. 12-A). It is abundant in the Sm and Sh lithofacies.

Ophiomorpha isp. ranges from simple individual burrows to complex networks consisting of cylindrical tunnels and shafts that typically bifurcate at acute angles (cf. Frey et al., 1978). The burrows are lined with agglutinated pelletoidal sediment (Pemberton et al., 2001). *Ophiomorpha* is sensitive to stability of the substratum, grain size, energy levels and rate and nature of sedimentation (Anderson & Droser, 1998). The *Ophiomorpha* traces from the Kashkan Formation are found in some well-sorted sandstones. The interior of the burrows is commonly smooth, but rarely can be irregular due to pelleting. The burrows are support-

ed by a yellow mud lining wall (Fig. 12-E,F). This trace fossil is abundant in the Sm and Sh lithofacies.

Skolithos isp. is a vertical to subvertical, straight to curved, unbranched burrow. The burrows are relatively short, up to about 20 cm. They are unlined, with commonly smooth walls; occasionally, changes in diameter occur. The burrow fills are composed of fine-grained sediments that are less cemented than the host sediment and that have a different colour. This trace fossil is common in fine- to medium-grained, poorly sorted sandstones of the Sm, Sp and Slr lithofacies (Fig. 13-A,B).

Steinichnus isp. is a cylindrical burrow that may or may not show T- and Y-branching (Fig. 13-C). This trace fossil is abundant in lithofacies Sm.

Thalassinoides isp. is present in the Kashkan Formation as large branched burrows with a smooth surface. These burrows are Y- to T-shaped and become wider at the points of bifurcation (Fig. 13-D). The sizes of the burrows are fairly identical and their cross-sections vary from half-moon-shaped to cylindrical. This trace fossil is abundant in the Sh lithofacies.

Escape structures are formed by organisms when they try to escape from a sudden burial under sediment after a short pulse of sedimentation. The escape burrows show chevron-like laminations, indicating the upward movement of the organism (Fig. 13-E). Escape structures are abundant in lithofacies Sh.

Trackways can be left by several types of walking vertebrates. Birds and mammals are the most common producers. Tracks represent walking, running, sliding and resting. This trace fossil is abundant in lithofacies Fm and Fl.

6.2. Ichnofacies

As trace fossils do not occur randomly but rather occur in specific combinations that are related to the sedimentary environment, they can be grouped in ichnofacies. Initially, ichnofacies were supposed to depend on a basin's depth (Seilacher, 1957), but it is now recognised that they rather are a manifestation of be-

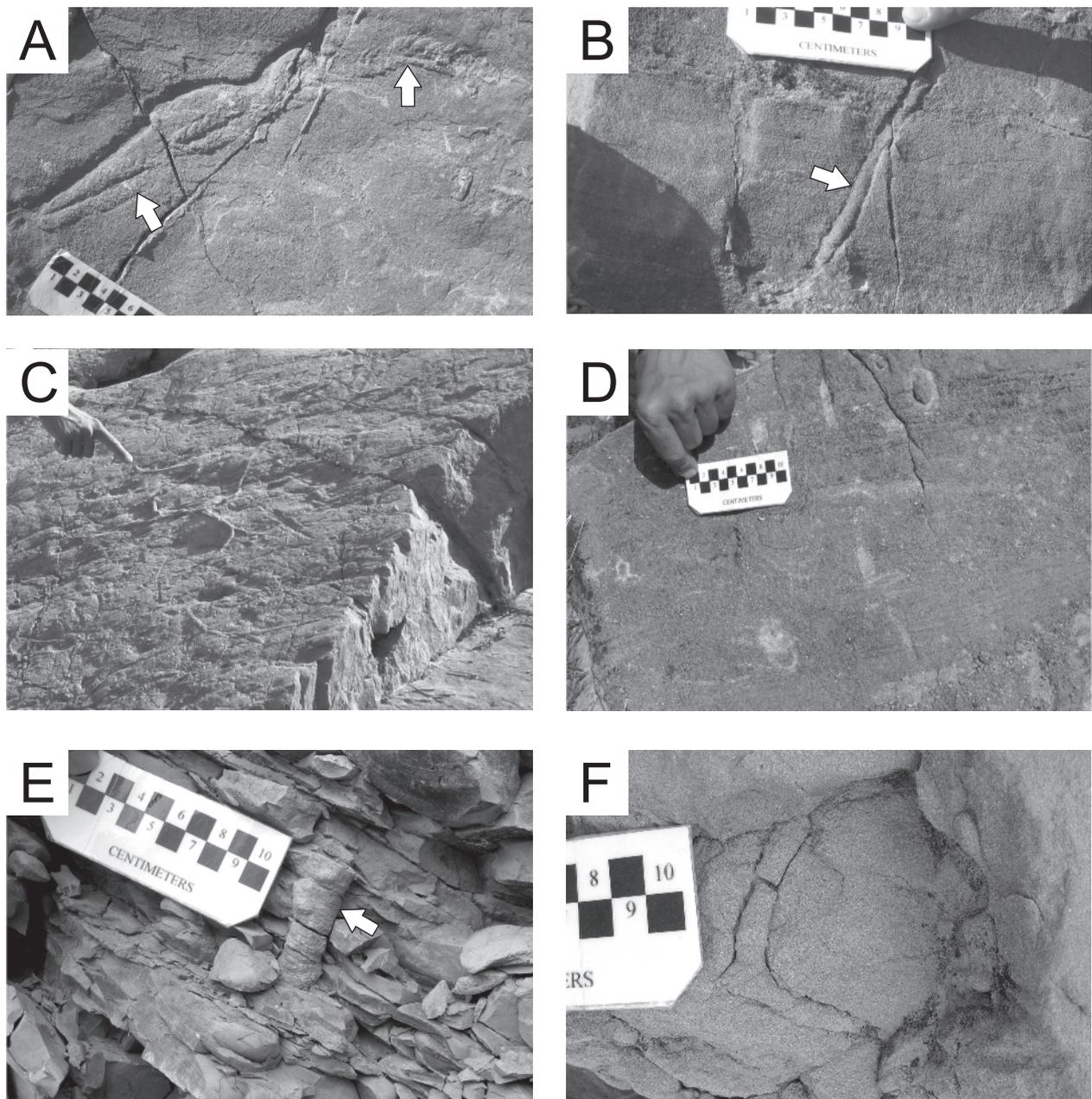


Fig. 12. Trace fossils. Scales in cm. **A:** *Laminites kaitiensis* in massive sandstone. **B:** *Arenicolites* forming a simple, vertical U-shaped tube. **C:** ?Mammal trackway in sandstone. **D:** *Diplocraterion*. **E:** *Ophiomorpha* in siltstone (arrow). **F:** *Ophiomorpha* in well-sorted sandstone.

haviour (which, indeed, partly depends on the environment). The distribution and behaviour of benthic organisms is limited by a number of palaeoecological factors such as the sedimentation rate, the nature of substrate, flow regimes, oxygen level and food resources (Pemberton et al., 2001). Thus, ichnofacies reflect similar environmental conditions during the production of trace fossils and have no meaning regarding evolution or time (Pemberton et al., 1992).

The trace fossils of the Kashkan Formation can for the major part be identified as typically belonging to the *Scoyenia* ichnofacies. This ichnofacies dominates the unconsolidated sedimentary cover on the continents and is characteristic of low-energy settings which are periodically subjected to subaerial conditions (MacEachern et al., 2007). Most *Scoyenia* settings are areas that become overflow occasionally with fresh water. Common depo-

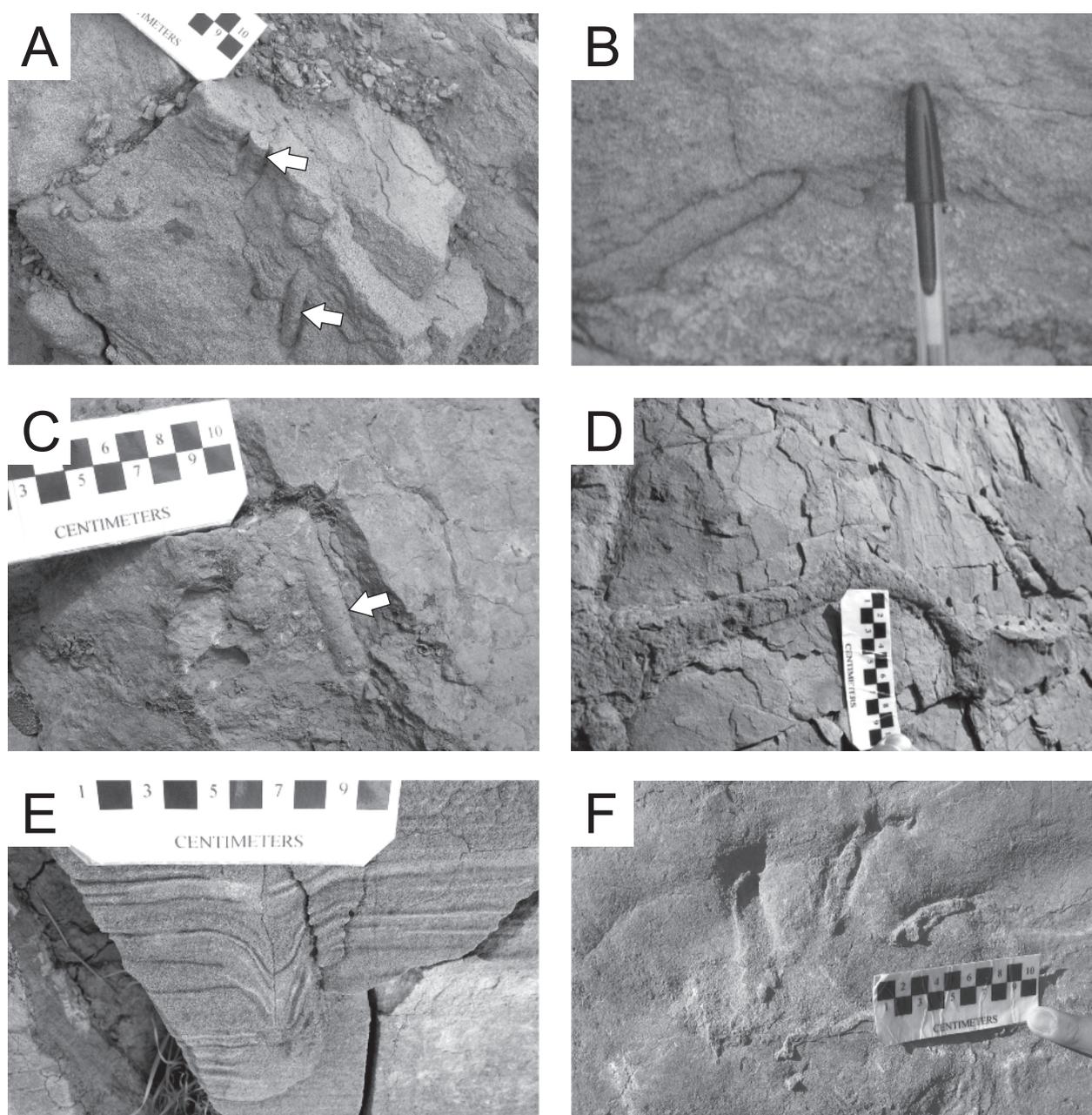


Fig. 13. Trace fossils. Scales in cm. **A:** *Skolithos*, as a vertical burrow in well-sorted sandstone. **B:** *Skolithos*, as a subvertical burrow. **C:** *Steinichnus* in massive sandstone. **D:** *Thalassinoides* in fine-grained sandstone. **E:** Escape structure with chevron pattern. **F:** Trackway in fine-grained sandstone.

sitional environments are lake margins, areas covered by braided streams, the channel margins and overbank areas (floodplains) of meandering rivers, and wet interdune areas (Frey & Pemberton, 1984; Buatois & Mángano, 2004).

Three ichnosubfacies of the *Scoyenia* ichnofacies can be distinguished on the basis of the trace fossils of the Kashkan Formation. They differ in lithofacies, frequency, energy-level changes and structures left by the organisms.

The three ichnosubfacies as distinguished in the Kashkan Formation are described shortly below. Figure 14 shows the interpreted trace-fossil distributions in the Kashkan Formation, based on the concept of the *Scoyenia* ichnofacies.

6.2.1. *Skolithos-Arenicolites* ichnosubfacies

This ichnosubfacies includes abundant *Arenicolites* isp. and *Skolithos* isp. *Ophiomorpha*

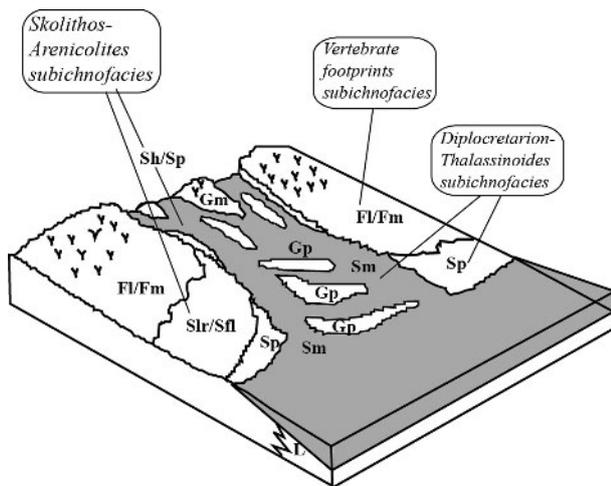


Fig. 14. Depositional model and palaeogeographical reconstruction (not to scale) of the Kashkan Formation and its *Scoyenia* ichnosubfacies.

isp. and *Laminites karitiensis* are common, while *Steinichnus* isp. and vertebrate tracks are relatively rare. This ichnosubfacies dominates particularly the Sm lithofacies as a lateral accretion and sandy bedform substratum.

6.2.2. *Diplocretarion-Thalassinoides* ichnosubfacies

In this ichnosubfacies, *Diplocretarion* isp. and *Thalassinoides* isp. are abundant, while *Arenicolites* isp., *Skolithos* isp., *Ophiomorpha* isp. and *Laminites karitiensis* are also present. This ichnosubfacies occurs in the Sh and Slr lithofacies.

6.2.3. Ichnosubfacies of vertebrate footprints

Vertebrate foot imprints are common in the *Scoyenia* ichnofacies. These trace fossils indicate at least temporary subaerial exposure. This ichnosubfacies is found in the laminated and massive mudstone lithofacies (Fm and Fl).

7. Genetic interpretation

The Kashkan Formation is positioned in between two limestone formations with a distinctly marine fauna. The lower boundary is sharp, possibly representing a hiatus, whereas the upper boundary is formed by a limonitic interval. These boundaries suggest a change in the environmental conditions. In combination with the sudden change in lithology (the

Kashkan Fm. is siliciclastic) this suggests that the Kashkan Formation is not marine, but rather continental. This is supported by the absence of marine fossils, apart from some trace fossils that, as will be detailed below, may be marginal-marine.

The precise depositional environment(s) can be reconstructed on the basis of the combined information of the lithofacies, the architectural elements and the trace fossils (and their ichnofacies and ichnosubfacies). Obviously not each lithofacies, architectural element or trace fossil is diagnostic, but jointly they provide a good picture. We will therefore shortly mention here interpretations of the various parameters as commonly given in the literature.

7.1. Lithofacies

Lithofacies Gm: the internal characteristics and their lateral extent suggest that they were formed as longitudinal bars in gravelly rivers (cf. Hein & Walker, 1977). This suggests that the entire facies developed due to processes that built longitudinal bars, as described by Williams & Rust (1969). The erosional lower boundary fits well in this picture; it indicates that fluctuations in the current energy or turbulence led to erosion of the underlying sediments.

Lithofacies Gp is commonly interpreted as a product of the down-stream movement of transverse bars in low-sinuosity channels (cf. Miall, 1988; Pisarska-Jamroz et al., 2010).

Lithofacies Gt developed as a result of the infilling of minor channels or depressions that were formed by scouring, and by the migration of 3-D gravel dunes (cf. Miall, 1977; Rust, 1978).

Lithofacies Sm was probably formed by rapid sedimentation after relaxation of a heavy sediment-laden flow (cf. Soegaard & Eriksson, 1985; Maizels, 1993; Jo & Chough, 2001; Simpson et al., 2002), but post-depositional deformation may also have played a role in forming the final texture (cf. Doe & Dott, 1980; Allen, 1986; Tucker, 2003). Due to the lack of cross-bedding or horizontal stratification, it is impossible, however, to recognise soft-sediment deforma-

tion structures (see Van Loon, 2009), so that we consider post-depositional deformation – if present – as of minor importance.

Lithofacies Sp was formed by the migration of straight-crested (2-D) dunes or bars deposited under conditions of the lower flow regime (cf. Miall, 1996; Capuzzo & Wetzel, 2004).

In lithofacies St, the uniform orientation of the trough cross-bedding suggests a bedform typical of a fluvial environment (cf. Miall, 1996; Eriksson et al., 1998). These sandstones are interpreted as the product of 3-D dunes migrating in channels under conditions of the upper part of the lower flow regime, and of the infilling of depressions formed by scouring (cf. Miall, 1977; Harms et al., 1982; Collinson & Thompson, 1989).

Lithofacies Sh has been commonly interpreted as due to migration of either low-amplitude bedforms or deposition under the plane-bed conditions of the upper flow regime (Allen, 1984; Bridge, 1993). Alternatively, the sandstones may derive from high-energy sheetfloods that spilled over from channels into a lower-energy environment during discharges that were too voluminous to be confined in the main fluvial channel system (Ghazi & Mountney, 2009).

Lithofacies Slr represents alternating periods of ripple migration and settling from suspension during tidal cycles (Reineck & Singh, 1980). The beds with current-generated ripples are common in sandy tidal flats (Meyer et al., 1998).

In lithofacies Sfl, the silt/sand and mud alternations were formed in response to a fluctuating flow regime. The flasers of the type present here are common in a tidal-flat environment (Bhattacharaya & Chakraborty, 2000).

Lithofacies Fl accumulated by settling of fine particles from suspension in an overbank setting. The red to purple colour is evidence of a well-drained, oxidising floodplain environment (cf. Mack & James, 1992; Retallack, 1997).

Lithofacies L must, considering its fine-grained character in combination with the occurrence of foraminifer fragments, have formed in ponds on a shoreface.

It thus turns out that a majority of the lithofacies (Gm, Gp, Gt, St, Sh, Fl) show characteris-

tics that point to a fluvial origin; these characteristics are almost identical to those described from the South Saskatchewan River, which is a sandy braided river with deposits that can be easily – but erroneously – confused with those of a meandering river (Scholle & Spawning, 1982). The large, complex braided system of the South Saskatchewan River has, however, like the sediments of the Kashkan Formation, more planar cross-bedded sets, more irregular grain-size trends and less floodplain sediments (Tucker, 1991).

A shoreface environment is indicated by lithofacies L, and shallow-marine conditions are indicated by lithofacies Slr and Sfl. Two lithofacies (Sm, Sp) are insufficiently characteristic to ascribe them to a particular environment.

7.2. Architectural elements

The channel-fill elements (CH), which are built by the three gravel and two fine-grained lithofacies and one sandstone lithofacies that were all interpreted as fluvial (with, in addition, one sandstone facies of unknown nature), are in all respects characteristic of a river environment.

The gravel-bar elements (GB) are commonly interpreted as consisting of fluvial transverse bars with a curved crest line (cf. Capuzzo & Wetzel, 2004).

The sandy-bedform elements (SB) are commonly considered to represent the deposits of migratory dune-shaped bedforms in either mid-channel bars or on the flanks of point bars (Cant & Walker, 1978; Miall, 1985).

Downstream-accretion elements (DA) are commonly formed by migrating linguoid or transverse bars (Collinson, 1996), commonly in a fluvial setting.

Laminated-sand-sheet elements (LS) suggest, according to Miall (1985), based on their sheet-like geometry and fine-grained lithology, deposition as a sand sheet on top or on the flank of a bar.

Floodplain elements (OF), with their sheet-like geometry and fine grain size, indicate deposition in a wide area with predominantly low-energy conditions. The red colour suggests

intense oxidation, probably resulting from sub-aerial exposure. This is more common in floodplains than in a marginal marine setting.

Lateral-accretion elements are commonly interpreted as representing components of point bars (Olsen, 1988).

Taken all characteristics of the various architectural elements together, the conclusion must be that most units of the Kashkan Formation were deposited in an extensive braided setting. It should be noticed, however, that the analysis of these elements was largely based on the work by Miall (1985, 1994, 1997), who focused on fluvial architecture. It is therefore well possible that elements suggestive of another depositional environment have not been established equally well.

7.3. Trace fossils and their ichno(sub)facies

Not all trace fossils are diagnostic for a specific depositional environment, but some ichnospecies give some indications, which we mention below.

Arenicolites is generally associated with arenaceous substrates in a low-energy shoreface setting or in sandy tidal flats (Pemberton et al., 2001). It commonly indicates moist conditions and a high water table, typically above groundwater level (Hasiotis, 2006).

Diplocraterion is, based on analysis its morphological features, interpreted as the dwelling burrow of a suspension-feeder (Fürsich, 1974). This trace is a common element in the distal zone of the *Skolithos* ichnofacies in middle shoreface settings; it is also common on sandy tidal flats (Pemberton et al., 2001).

Laminites kaitiensis is reported from the littoral zone (Narbonne, 1981) and from marginal-marine environments (Webby, 1969) but has also been found in flysch deposits (Ghent and Henderson, 1966).

Ophiomorpha represents the dwelling burrow of a suspension-feeding shrimp and is commonly associated with the *Skolithos* ichno-

facies, and abounds in marine shoreface environments (Pemberton et al., 2001).

Skolithos can be constructed by numerous organisms, and is found in almost all environments, from marine to continental (Pemberton et al., 2001).

Steinichnus is produced by either mud-loving beetles or mole crickets, and commonly is found in wet habitats associated with alluvial and marginal lacustrine environments (Hasiotis, 2006).

Thalassinoides is generally regarded as a dwelling or feeding burrow and is associated with the *Cruziana* ichnofacies in lower shoreface to offshore environments (Pemberton et al., 2001).

Escape structures do not indicate a specific environment, but reflect rather a setting where pulses of sediment result occasionally in a sudden, fast vertical accumulation.

Tracks are typically found in alluvial, aeolian and marginal-marine environments (Figs 12-C and 13-F).

The above environmental interpretations are based on literature data. Such data have been used by ichnologists to establish ichnofacies and ichnosubfacies. As mentioned above, all trace fossils found in the Kashkan Formation fit in the *Skoyenia* ichnofacies, which can here be subdivided in three ichnosubfacies which allow a more detailed palaeoenvironmental reconstruction.

The *Skolithos-Arenicolites* ichnosubfacies is characteristic of a high energy level with a high supply of sandy sediment, mainly in channels.

The *Diplocraterion-Thalassinoides* ichnosubfacies occurs in the Kashkan Formation in sediments that were probably deposited by sheet-floods, indicating periodical changes in energy level.

The ichnosubfacies with footprints of birds and mammals indicates muddy areas, probably either floodplains of a river or shoreface areas that are alternately submerged and subaerially exposed, for instance due to tidal activity.

Taken all together, the trace fossils indicate both a fluvial and a shoreface setting.

8. Depositional environment and palaeogeography

It appears from the above environmental reconstruction of the Kashkan Formation, based on lithofacies, architectural elements and trace fossils, that the various sediments were deposited in a low-gradient river system (cf. Weckwerth, 2011). The deposits of this system closely resemble those of the South Saskatchewan River in Canada, which is now considered as the classical example of a sand-bed braided river after the descriptions by Cant (1978) and Cant and Walker (1978). The river reached the shoreline of the continent. The seven measured sections and the lateral relationships between them confirm this interpretation, but provide also insight into the lateral and vertical facies changes.

The upper part of the Kashkan Formation is built mainly by conglomerates. This thick conglomerate unit thins toward the South and South-West. This suggests that the source area of the conglomerates was situated North to North-East of the study area.

The conglomerates, mainly lithofacies Gm, Gp and Gt, represent longitudinal bars (Gm), channel lag deposits (Gm) and linguoid transverse bars (Gp and Gt). The few interbedded sandstone lenses represent periods of decreased stream competency. Other sandy lithofacies formed during stages of small discharge as a result of the migration of linguoid or straight-crested transverse bars (Sp) and of sinuous dunes or sinuous bars (St) when sand supply dominated in an active channel (cf. Miall, 1985). During stages of high discharge, the river overflowed the alluvial plains, where massive or laminated fine-grained material was left behind (Fm, Fl).

In the south-western part of the study area, the river embouched in a tidally influenced sea, as indicated by sands with flasers and cross-bedding indicating opposite current directions (Sfl and Slr), and by the presence of foraminifer fragments.

This facies-based picture is supported by the distribution of the various architectural elements (Fig. 6). In the sections closest to the

source area, such as the Darabi section, not only are conglomeratic units the most common, but the sedimentary cycles also consist mainly of CH and GB elements. In contrast, the intermediate Mamoolan and Golgekhalag sections, which are somewhat more fine-grained, show sedimentary cycles with more CH, GB, SB and OF elements. These sections also contain the trace fossil *Skolithos*. The fairly southern Moorani and Malavi sections, which are even finer-grained, comprise some intervals with carbonate facies (limestones and dolomites), indicating a marine setting, which is supported by the occurrence of escape structures and the trace fossil *Diplocraterion*, which are indicative of a shoreface environment. The southernmost section (the Sepiddasht section) contains abundant trace fossils such as *Thalassinoides* and *Ancorichnus*, and fine-grained facies are very common.

9. Conclusions

The Kashkan Formation (?Palaeocene to Middle Eocene) in SW Iran mainly consists of coarse, medium and fine siliciclastic lithofacies in which no fossils, apart from trace fossils, occur. This is in strong contrast with the under- and overlying formations that consist of fossiliferous marine limestones. The sharp boundaries with the under- and overlying formations indicate abrupt changes in the depositional conditions. A sudden change is reflected not only by the different lithology, but also by the sedimentological characteristics (lithofacies and architectural elements), which indicate that the sediments were deposited in a fluvial environment that had occasionally meandering (overbank deposits, large bars) and but mainly braided (mainly unidirectional palaeocurrent directions, sheetfloods) characteristics (Fig. 14). Meandering and braided behaviour may have changed from time to time during its depositional history. This is confirmed by the ichnofauna. The river ran roughly from North to South in the study area. In the South and South-West, the river reached a shoreface environment, as indicated by the trace fossils.

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