Arab J Geosci (2017) 10:55
DOI 10.1007/s12517-016-2800-4

ORIGINAL PAPER

The Wajid Sandstone around Abha/Khamis Mushayt and in its type area: lithostratigraphic architecture and correlations

Martin Keller[1,2] · Bassam Abu Amarah[3] · Hussain F. Al Ajmi[2]

Received: 9 October 2015 / Accepted: 20 December 2016

Abstract The Wajid Sandstone of southeastern Saudi Arabia is a prolific aquifer and a recent target for hydrocarbon exploration, but a sedimentologic model and the stratigraphic architecture of the sediments have only recently been presented for the type area of the Wajid Group around Wadi Dawasir. Farther to the west, the Wajid Sandstone was also recognized, but stratigraphic architecture and sedimentology are poorly known. This paper presents the preliminary results of investigations targeted at the outcrops west and south of the type area, covering the area between Wadi Dawasir, Najran in the south, and Abha in the west. Two successions are recognized, a lower red one and an upper beige one. Although the lower one sedimentologically shares several features with the lowermost unit in the type area, the marine Dibsiyah Formation, a correlation remains doubtful. The red succession lacks the *Skolithos* fauna of the Dibsiyah Formation, and its facies associations point to a fluvial depositional environment. From its stratigraphic position and from its lithology, the red succession is similar to the Siq Formation of the northern Kingdom and it will be discussed whether the red succession might be a yet unrecognized equivalent of the Siq Formation. The lower red unit is bounded by a major unconformity, separating it from the underlying basement. This pan-African unconformity developed during a latest Neoproterozoic–Cambrian episode of intensive weathering and peneplanation. It is characterized by a thick weathering zone and an overlying coarse but thin quartz pebble breccia to conglomerate, which together represent a regolith. The beige succession is definitely correlated to the Khusayyayn Formation. Both successions are characterized by macro-scale to giant 2D and 3D submarine dunes and share many other phenomena. The basal unconformity also shows regolith development with a quartz pebble conglomerate, whose clasts seem to have been reworked from the pan-African regolith.

Keywords Wajid Group · Saudi Arabia · Stratigraphy · Abha · Cambrian · Devonian · Pan-African unconformity

Introduction

The Wajid Sandstone of southern Saudi Arabia is a Cambrian through Permian siliciclastic succession that is widely exposed between the eastern edges of the Rub' Al Khali desert in the east and the watershed of the Asir Mountains in the west. The eastern outcrop belt (Fig. 1), south of Wadi Ad Dawasir in the north and Najran in the south, includes the type area described by Powers et al. (1966) and Kellogg et al. (1986). In the subsurface toward and beneath the Rub' Al Khali desert, the Wajid Sandstone is a prolific aquifer and recently also has been an exploration target for hydrocarbons by several companies (e.g., Moscariello et al. 2009). Consequently, most of the previous studies dealing with the stratigraphy and sedimentology of the Wajid Sandstone concentrate on this type area. Farther toward the west, the Wajid Sandstone is present as isolated outliers on

✉ Martin Keller
martin.keller@fau.de

Bassam Abu Amarah
babuamarah@ksu.edu.sa

Hussain F. Al Ajmi
hussain.alajmi@yahoo.com

1 GeoZentrum Nordbayern, Universität Erlangen, Schlossgarten 5, 91054 Erlangen, Germany

2 Ministry of Water and Electricity, Water Resources Development Department, Riyadh, Saudi Arabia

3 Department of Geological Sciences, King Saud University, Riyadh, Saudi Arabia

Published online: 24 January 2017

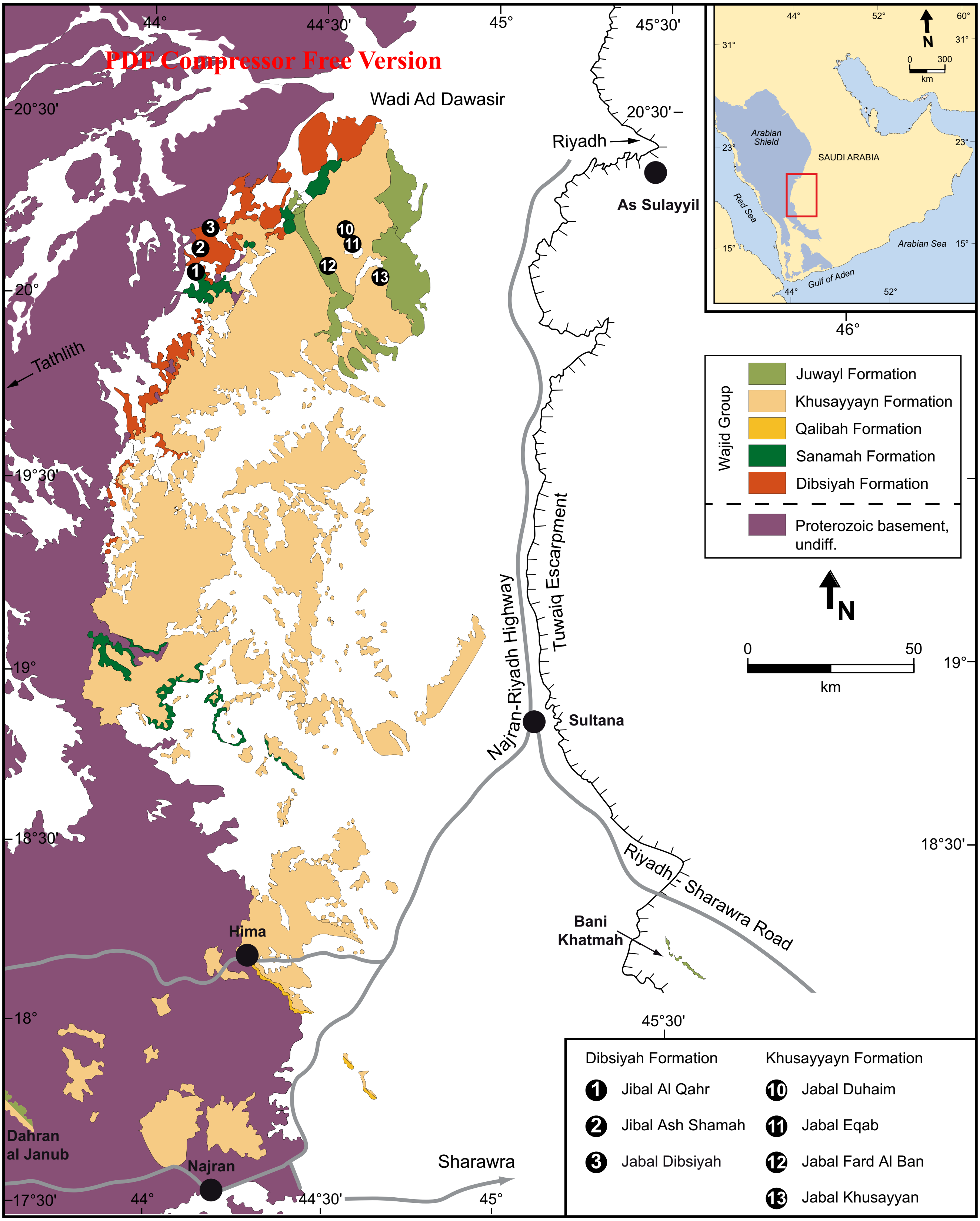

Fig. 1 Simplified geologic map with the distribution of the Wajid Group and the bounding Precambrian basement of the Arabian Shield. *Section numbers* of Dibsiyah and Khusayyayn formations are those of Al Ajmi et al. (2015)

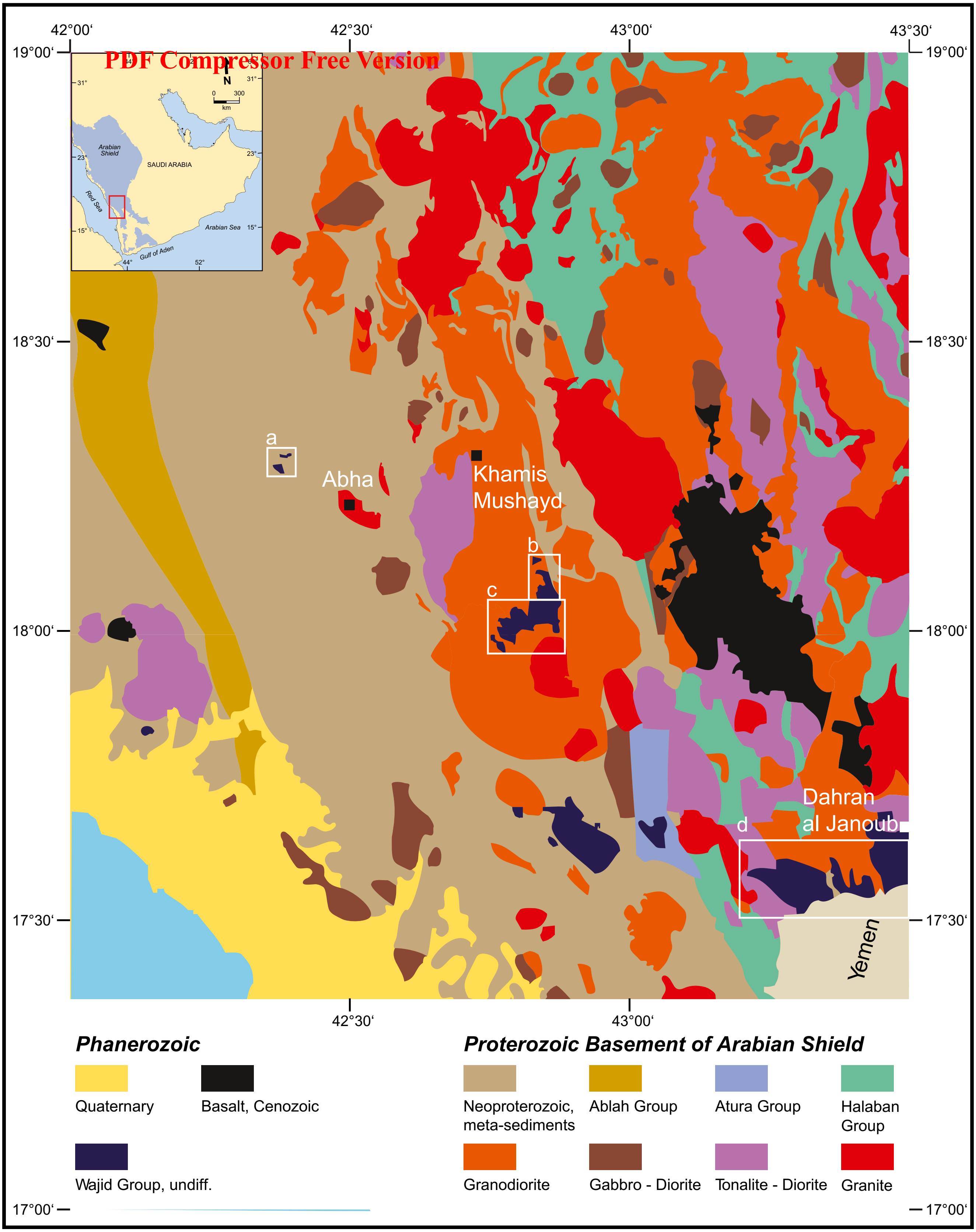

Fig. 2 Simplified geologic map of the Abha and Wadi Baysh quadrangle sheets (SGS map sheets 18f and 17f, Greenwood 1985; Fairer 1985) and areas in which sections have been studied. Localities mentioned in the text and figures are designated through coordinates *a* Soudah area, *b* Ahad Rufaidah area 1, *c* Al Habalah area, and *d* Yemeni Border area

the Precambrian Arabian Shield (Fig. 2) and nowhere are subsurface occurrences of this unit are known. Consequently, as there is no economic interest in the Wajid Sandstone in these areas, the knowledge about the Wajid Sandstone is rather limited and was mainly provided by Babalola (1999) and Babalola et al. (2003).

The purpose of this paper is to project the latest insights gathered during our preliminary fieldwork in the outcrops around Abha and Khamis Mushayt (Fig. 1) onto the Wajid Sandstone in its type area (Fig. 2) as recently documented by Al Ajmi et al. (2015). We will test the hypothesis of Babalola (1999) that the lower red succession might be equivalent to the Dibsiyah Formation and the beige succession to the Khusayyayn Formation of the type area in order to enhance the knowledge about the Wajid sedimentary basin.

The Wajid Sandstone in the type area

Five formations are recognized within the Wajid Group (Stump and van der Eem 1995; Al Ajmi et al. 2015; Fig. 3). These are the Dibsiyah Fm., the Sanamah Fm., the Qalibah Fm., the Khusayyayn Fm., and the Juwayl Fm.

Sedimentology, stratigraphic architecture, and age of the Wajid Sandstone in its type area have recently been described and interpreted in detail by Al Ajmi et al. (2015). The lithofacies with their original numerical assignment are listed in Table 1 and do not need to be repeated here again. The depositional environments of the Dibsiyah and Khusayyan formations, the two formations of the Wajid Group that seem to be represented in the Abha/Khamis Mushayt area, have been interpreted to be vast shallow-marine siliciclastic shelves dominated by migrating 2D and 3D dunes. Both depositional systems have been interpreted as evolving under starved conditions in times of regionally rising sea level flooding peneplained hinterlands. Sediment input onto the shelves was not sufficient to catch up with sea-level rise so that the sediment was reworked repeatedly.

The Wajid Sandstone in the Abha/Khamis Mushayt area

Babalola (1999) subdivided the Wajid Sandstone in the Abha/Khamis Mushayt area into two informal units: a lower red succession and an upper beige succession. He tentatively correlated the red succession to the Dibsiyah Formation and the beige succession to the Khusayyayn Formation (Fig. 3). He gave a brief lithologic description of the rocks and a detailed mineralogy and petrography of the sediments. From his investigations, he concluded that the depositional environment was mainly a fluvial one and that locally nearshore marine, tidally influenced environments existed.

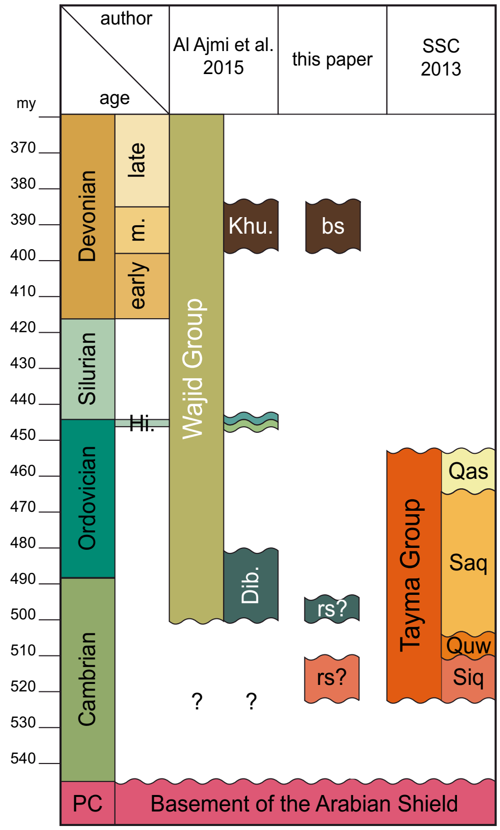

Fig. 3 Stratigraphic chart for the formations discussed in the text. Not shown is the Juwayl Formation of the Wajid Group in the type area as it is of Permian age. The second column shows the attribution of the beige succession to the Khusayyayn Formation. For the red succession, the two possibilities discussed in the text are shown. In stratigraphic order: *Dib.* Dibsiyah Formation, *rs.* red succession, *Khu.* Khusayyayn Formation, *bs.* beige succession, *Quw.* Quweira Formation, *Qas.* Qasim Formation, *Hi* Hirnantian

Lithofacies of the Wajid Sandstone in the Abha/Khamis Mushayt area

In the following, the lithofacies present in the Abha/Khamis Mushayt area are described and interpreted. As unequivocal evidence for either a marine or a fluvial depositional environment is absent in most lithofacies described, sediments are interpreted first following Miall (2006), who developed a classification scheme for fluvial deposits, and second, they are discussed in the context of a probable nearshore marine environment. A definite assignment to a depositional environment is then attempted in the framework of the lithofacies associations described subsequently.

Subsequently, and where possible, these lithofacies were correlated to the lithofacies types of Al Ajmi et al. (2015) and the corresponding numbering. These correlations are shown in Table 1. However, not all facies described from the Abha/Khamis Mushayt area are present in the type Wajid area and vice versa.

Table 1 Comparison of lithofacies between the type-Wajid area as described by Al Ajmi et al. (2015) and the Abha/Khamis Mushayt area is discussed in this paper

Lithofacies description and subfacies	Lithofacies code Wajid Group	Wajid Group occurrence	Dep. env. Wajid Group	Lithofacies code Abha/Khamis Mushayt	Abha/Khamis Mushayt occurrence	Dep. env. red beige	
						Red	Beige
Shale and silty shale	–	–	–	AKM-LF1	Red succession, beige succession	Terrestrial	Marine
Siltstone	LF3	Dibsiyah, Khusayyayn	Marine	AKM-LF2	Red succession, beige succession	Fluvial	Marine
Siltstone, laminated	LF3.2	Dibsiyah, Khusayyayn	Marine	AKM-LF-2	Red succession	Fluvial	
Siltstone, laminated, bioturbated	LF3.3	Dibsiyah	Marine	–	–		
Sandstone, horizontal to low angle cross-bedding	LF7	Dibsiyah	Marine	AKM-LF3	Red succession	Fluvial	
Coarse horizontally bedded sandstone	LF7.2	Dibsiyah	Marine	AKM-LF3	Red succession	Fluvial	
Sandstone, horizontally bedded and strongly bioturbated	LF7.3	Dibsiyah	Marine	–	Red succession	Fluvial	
Strongly variable group of sandstones, locally conglomeratic, deposited in thin to medium tabular cross-beds	LF8	Khusayyayn	Marine	AKM-LF5	Red succession, beige succession	Fluvial	Marine
Medium to coarse sandstone, tabular cross-beds	LF8.2	Dibsiyah, Khusayyayn	Marine	AKM-LF5	Red succession, beige succession	Fluvial	Marine
Fine- to medium-scale cross-beds, locally feldspar clasts	LF8.2.1	Dibsiyah	Marine	AKM-LF5	Red succession	Fluvial	
Medium- to large-scale cross-beds	LF8.2.2	Dibsiyah, Khusayyayn	Marine	AKM-LF5	Beige succession		Marine
As 8.2.1 and 8.2.2 but with slumping	LF8.2.3	Khusayyayn	Marine	AKM-LF5	Beige succession		Marine
Fine- to medium-scale cross-beds, some bioturbation	LF8.2.4	Dibsiyah	Marine	–	–		
Medium to coarse sandstone, fining-up from coarse at the base of the bed to fine at the top	LF8.4	Khusayyayn	Marine	AKM-LF5	Red succession, beige succession	Fluvial	Marine
Medium to coarse sandstone, graded foresets; trace fossils (*Cruziana, Skolithos*)	LF8.5	Upper Dibsiyah	Marine	–	–		
Medium to coarse sandstone, entire bed is graded	LF8.6	Dibsiyah	Marine	AKM-LF5	Beige succession		Marine
Medium to coarse sandstone, macro-scale 2D-trough cross-bedding	LF9	Dibsiyah, Khusayyayn	Marine	AKM-LF6	–		
Medium to coarse sandstone	LF9.1	Dibsiyah	Marine	AKM-LF6	Red succession, beige succession	Fluvial	Marine
Uniformly medium-grained or coarse-grained sandstone	LF9.2	Dibsiyah	Marine	AKM-LF6	Red succession, beige succession	Fluvial	Marine
Moderately to intensively bioturbated, mainly by *Skolithos*	LF9.3	Dibsiyah	Marine	–	–		
Dominantly coarse sandstone to pebbly sandstone, macro-scale 2D-trough cross-bedding	LF10	Dibsiyah, Khusayyayn	Marine	AKM-LF6	Beige succession		Marine
Medium to coarse sandstone, varying amount of pebbles, deposited in 2D-trough cross-beds	LF10.1	Dibsiyah, Khusayyayn	Marine	AKM-LF6	Beige succession		Marine
Coarse sandstone with graded foresets	LF10.2	Dibsiyah, Khusayyayn	Marine	AKM-LF6	Red succession, beige succession	Fluvial	Marine
Entire bed graded	LF10.2.1	Dibsiyah, Khusayyayn	Marine	–			
Individual foresets with pebbles at the base and coarse sand at the top	LF10.2.2	Dibsiyah, Khusayyayn	Marine	AKM-LF6	Red succession, beige succession	Fluvial	Marine
Inversely graded, pebbly sandstone, different amounts of silty clasts	LF10.3	Dibsiyah	Marine	–	–		
Pebbly sandstone with *Cruziana* ichnofacies	LF10.4	Dibsiyah	Marine	–	–		
Pebbly sandstone with *Skolithos* ichnofacies	LF10.5	Dibsiyah	Marine	–	–		
Massive sandstone	LF12	Khusayyayn	Marine	AKM-LF7	Red succession, beige succession	Fluvial	Marine
Medium to conglomeratic sandstone completely homogenized by burrowing of *Skolithos* ("Tigillites")	LF12.5	Dibsiyah	Marine	–	–		
Conglomerate	LF13	Sanamah	Marine	AKM-LF8	Red succession	Fluvial	
Monomictic	LF13.2.1	Dibsiyah	Marine	–	–		
Breccia	–	–		AKM-LF9	Red succession	Terrestrial	

Similar lithofacies are present in both areas. Based on the occurrence of trace fossils, both formations in the Wajid area are interpreted to be marine in origin. While a marine origin is also likely for the beige unit, the red succession is, despite almost identical lithofacies, interpreted to be of terrestrial-fluvial origin

AKM-LF1: shale and silty shale

Shales are rather rare in the successions of the Wajid Sandstone in the Abha/Khamis Mushayt area. Red to purple silty shale is found at the base of the red succession, where the beds rarely surpass 15 cm in thickness (Fig. 5a). They are also present locally in the beige succession, where they form the uppermost succession of sandstone–siltstone–shale fining-upward cycles (Fig. 5a, b). Brown shales, sometimes strongly encrusted by iron oxides, are present locally on top of the red succession, just beneath the beige succession (Fig. 5c, d). White dense shales form thin structureless layers in both stratigraphic units. Repeatedly, they are reworked into the overlying beds as large intraclasts up to 10 cm × 5 cm across (Fig. 5e).

Following Miall (2006), shale and silty shale (facies codes Fsm and Fm) in a fluvial environment are the products of abandoned channels or overbank deposits. They are found both in braided river and meandering river systems. In near-shore marine environments, these sediments are found in interdune areas, where they settle out protected from the main transport agents.

AKM-LF2: siltstone

Siltstones are mainly present in the lower red succession (Fig. 4). They are red to white either from iron impregnation or from a kaolinitic matrix. Locally, some internal low-angle cross-bedding or parallel lamination has been observed. Their general appearance in the field, however, is massive.

These siltstones are often associated with fine sandstones; they form rapid alternations on a millimeter to centimeter scale. The bedding and the laminae are accentuated by a rapid change in color from white to red; the color, however, is independent from grain size. Horizontal bedding dominates, but channel-fill geometries have locally been observed.

These sediments correspond to facies Fl of Miall (2006). They form in abandoned channels, as overbank deposits or during the waning flood stage. Scouring, however, indicates that these sediments locally were deposited in small channels.

AKM-LF3: sandstone with horizontal to low-angle cross-bedding

These are fine- to coarse-grained sandstones. Locally, at the base of graded deposits, fine quartz pebbles form the basal layers of the individual foresets (Fig. 5f). Micro-scale and meso-scale cross-beds (nomenclature of Al Ajmi et al. 2015; see also Fig. 4) dominate. Two subfacies have been observed: Fine- to medium-grained sandstones, which are moderately sorted, and medium- to coarse-grained sandstones, which at their base may be pebbly. Sorting is poor in these latter deposits. In the fine-grained deposits, mainly present in the red succession, kaolinite frequently is present as matrix.

In coarse-grained sediments, horizontal lamination is mainly produced under high-energy, upper flow regime conditions (Cheel 1984; Paola et al. 1989). For one, they are the product of high frequency scouring and subsequent filling; secondly, they result from low-frequency migration of bedforms. The corresponding bedforms have a height of several grains and amplitudes of up to 100 cm; they are superimposed to form the laminae.

In fluvial environments, these deposits correspond to facies Sh and Sl of Miall (2006). Horizontal lamination (facies Sh) is caused by plane bed flow, while variations in current velocity initiate scouring and the formation of antidunes or washout dunes (facies Sl). In a marine environment such as the Wajid Sandstone of the type area, such beds develop from unidirectional flow under upper flow regime conditions (Harms et al. 1982), where sand is transported in discrete thin sheets along the bed and net sand input into the system. Similar structures of Early Paleozoic age in Laurentia (Jordan Sandstone; Runkel 1994; Byers and Dott 1995) have been interpreted as beach swash lamination. These deposits correspond to LF7 of Al Ajmi et al. (2015) (Table 1; Fig. 4).

AKM-LF4: sandstones with ripple-drift cross-bedding

Locally, medium- to coarse-grained sandstones are present that show ripple-drift cross-bedding (facies Sr of Miall 2006). Individual beds are several centimeters thick; bed sets attain thicknesses of up to 1 m. Most prominent are beds with climbing ripple lamination (Fig. 5e).

AKM-LF5: fine- to coarse-grained sandstone with tabular cross-beds

These sandstones were deposited in micro-scale to macro-scale beds (according to Al Ajmi et al. 2015) with planar and dominantly horizontal bed boundaries (Fig. 5g, f). Internally, the geometry of the foresets is variable with angular forests, concave foresets, or sigmoidal foresets. Individual foresets may be a few millimeters to several centimeters thick.

Within the successions, intervals can be distinguished, in which the bed sets are dominated by micro-scale to meso-scale beds; other intervals are almost entirely composed of meso- to macro-scale beds. While there are foreset bundles with a rather uniform grain-size distribution, there are others, in which the foresets are graded from coarse sand, locally even pebbly, near the base to medium sand close to the top (Fig. 5g).

These sandstones are present in both the red and the beige succession (Fig. 4). In the red succession, the sandstones frequently have a kaolinitic matrix (Fig. 6a).

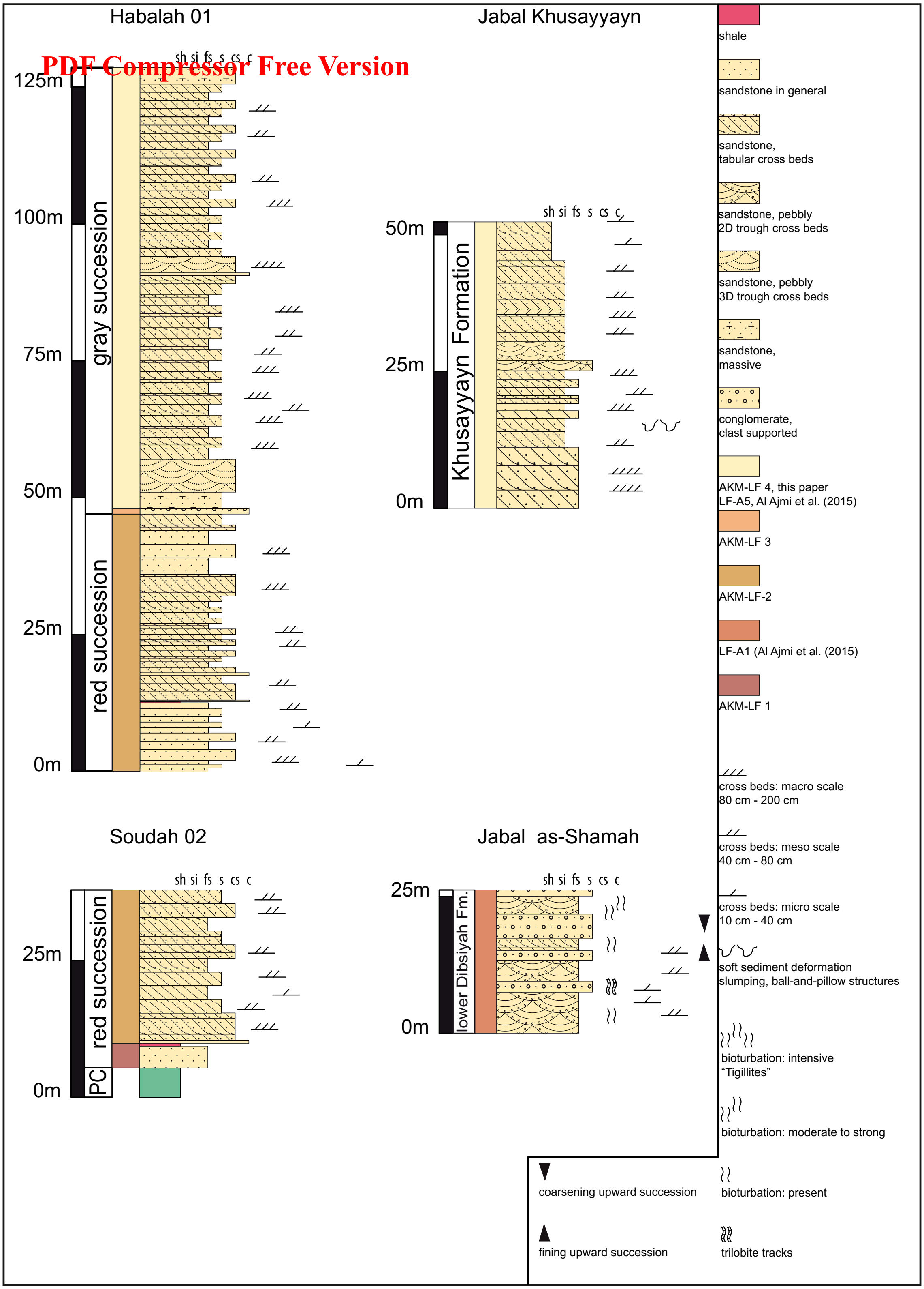

Fig. 4 Contrasting juxtaposition of sections in the Abha/Khamis Mushayt area and the type Wajid area. Typical examples of each outcrop area with the corresponding lithofacies associations are shown as examples. Wajid sections are those of Al Ajmi et al. (2015). Note good correlation of lithologic/sedimentologic features between the beige succession and the Khusayyan Formation, but less commonalities between the red succession and the basal Dibsiyah Formation. Localities as in Figs. 1 and 2

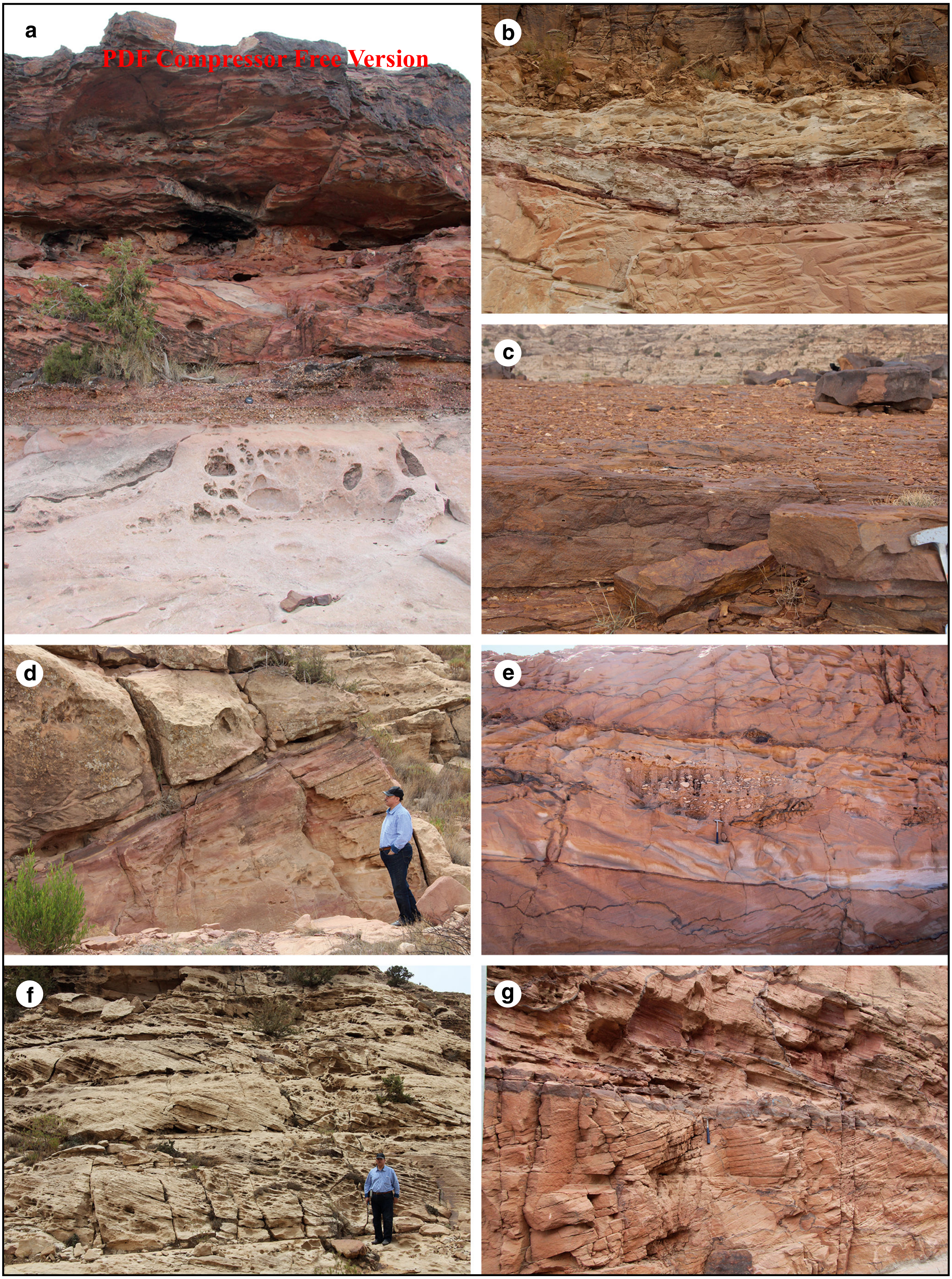
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Fig. 5 **a** The basal succession of the Wajid Group at Soudah (18° 17.700′ N, 42° 22.283′ E). Kaolinitic white sandstones unconformably overlie strongly weathered basement rocks. They are in turn overlain by the basal conglomerate of the Wajid Group. Up section, coarse red sandstones form the base of the red succession. Outcrop approximately 8 m high. **b** Detail of the overlying fine-grained succession with white kaolinitic siltstones and red shale and siltstone. Above these are kaolinitic white sandstones with micro-scale cross-beds, in turn overlain by macro-scale cross-beds of the upper part of the Khusayyayn Formation in Dhahran Al Janoub area (17° 30.819′ N, 43° 31.961′ E). **c** Detail of the contact zone with thin-bedded red silty and shaly sediments. The upper part of the red succession is composed of fine-grained, iron stained, and thin-bedded deposits. Habala area (18° 2.542′ N, 42° 49.399′ E). **d** The erosional contact between the red succession and the massive basal Khusayyayn Bed in the Habala area (18° 0.317′ N, 42° 52.433′ E). Note the red iron-stained uppermost deposits beneath the massive white sandstone. **e** Medium- to macro-scale tabular cross-beds. Chute channel in the middle is filled with kaolinitic shale–siltstone clasts. Locality as in **a**. **f** The contact between the red succession and the Khusayyan Formation in the Halaba area (18° 2.542′ N, 42° 49.399′ E). **g** Succession of cross-beds, all of which are graded from coarse to medium sand. The basal unit shows pebbles at the base of most of the foresets. Dhahran Al Janoub area (17° 39.322′ N, 43° 28.454′ E)

The tabular sandstone beds represent migrating large 2D dunes (Ashley 1990; Miall 2006), which occur both in fluvial (facies Sp) and marine environments. They originate under unidirectional flow conditions with bedload transport. Sigmoidal structures represent fully preserved ripples (Reineck and Singh 1970). Strictly angular foresets are formed in the absence of fine-grained material. If fine-grained material is present in the environment, it will settle out of suspension under waning flow conditions and the shape of the foresets becomes curved near the base. This is the characteristic feature of LF8.1 of Al Ajmi et al. (2015).

Beds with graded foresets (Fig. 5g) and often a tangential basal contact (LF8.3, LF8.4; Al Ajmi et al. 2015; Table 1), together with a sometimes diffuse internal lamination, are caused by the presence of fine-grained material. These phenomena indicate fallout of suspended material during unsteady flow conditions. These conditions are typical of tidal environments (Dalrymple and Rhodes 1995), although they are not restricted to this environment.

AKM-LF6: sandstone, pebbly sandstone, and fine conglomerate with 2D trough cross-bedding

These rocks are present in medium-scale to macro-scale bedforms. Their typical geometry is that of trough cross-beds in 2D cross sections with the third direction showing planar bounding surfaces (Fig. 6b). Individual beds extend over hundreds of meters or even kilometers in transport direction. The quartz grains are subangular to rarely rounded, and the sediments are moderately to poorly sorted. Locally, the individual foresets are graded. These sediments correspond to LF9 of Al Ajmi et al. (2015).

Ashley (1990) pointed out that 2D trough cross-bedded sandstones result from the migration of 3D dunes (Fig. 4) and that transport energy must have been higher to produce 3D geometries than during the migration of the 2D dunes. 3D dunes are present both in fluvial environments, where they correspond to facies St (Miall 2006), and in marine environments.

AKM-LF7: sandstone, massive

LF7.1: Massive white kaolinitic sandstones are present beneath the main unconformity at the base of the red succession (Fig. 5a). They wedge out over distances of several tens of meters. A maximum thickness of about 5 m has been observed. Internally, some cross-bedding is preserved in these otherwise massive rocks (Fig. 6c). Similar but thin-bedded deposits are intercalated in the basal succession of the red succession (Fig. 6d).

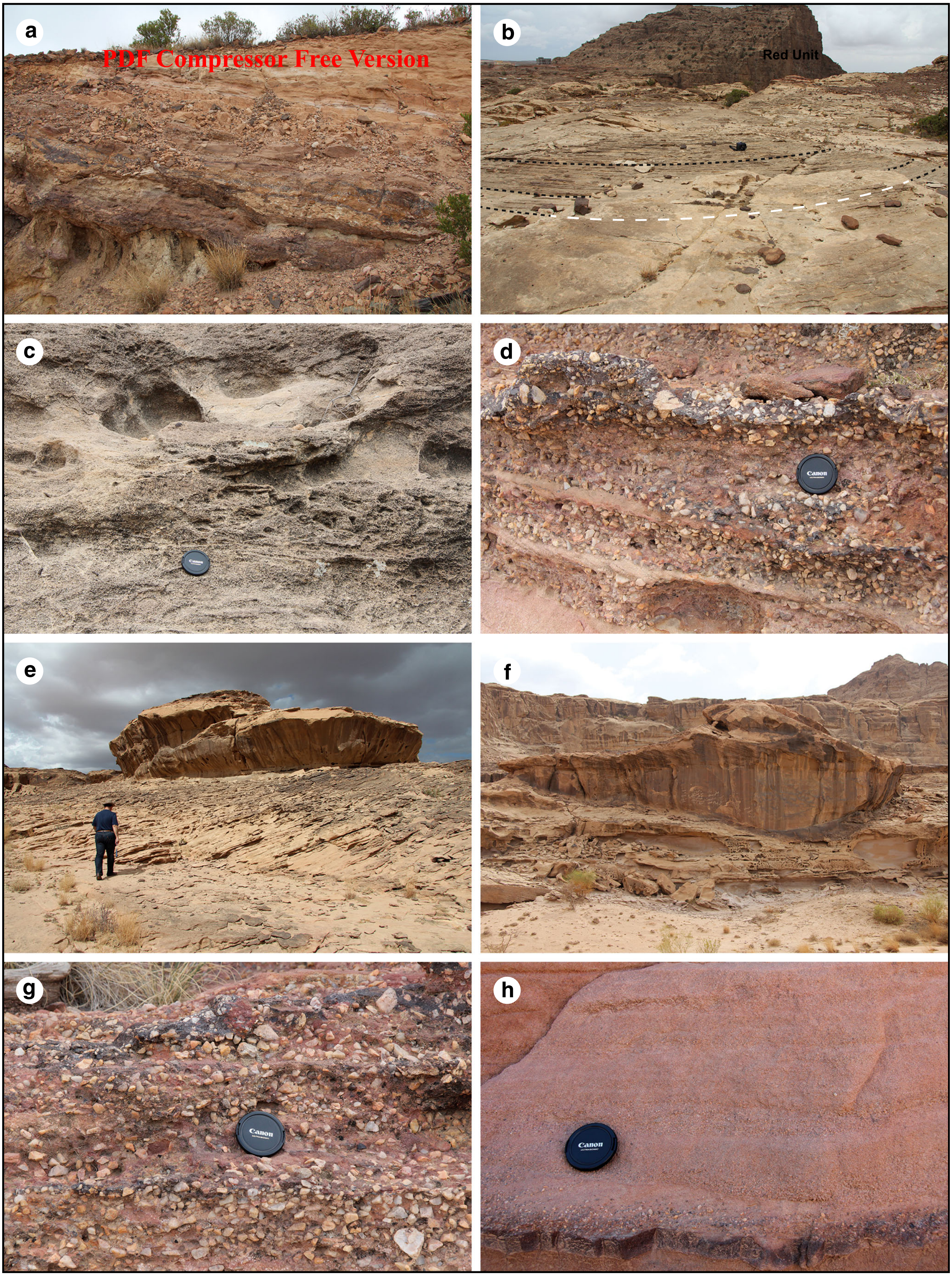
LF7.2: Close to the base of the beige succession 8 (Fig. 4), there is 3 to 4 m thick massive sandstone in many sections (Fig. 6e, f). Locally, some faint cross-bedding is observed. This sandstone cuts erosionally into the underlying strata of the beige succession and locally even into the upper beds of the red succession.

The genesis of such massive sandstones is not well understood. Assuming that this is indeed a single horizon, this horizon would cover an area several 100 km^2. As it occurs just above an unconformity, a turbiditic origin off a Gilbert-type delta, as described, e.g., by Nemec (1990), can be excluded as the deposits occur just above an unconformity with peneplanation and as all other structural elements of deltas are missing.

Martin (1995) discussed and summarized different processes and models for massive sandstone deposition mainly reported from low-sinuosity braided river systems. Depositional models include bank or bar collapse, formation of hyper-concentrated flow, and deposition from upper flow regime conditions, e.g., Conaghan and Jones (1975), Conaghan (1980), Jones and Rust (1983), Rust and Jones (1987), and Turner and Monro (1987). All these deposits correspond to Miall's (2006) Sm facies. Eschner and Kocurek (1986) envisaged a tide dominated shelf for massive sandstone beds, where large submarine dunes were reworked during major storms through slumping and formation of liquefied flows.

AKM-LF8: breccia

A breccia to locally conglomerate is present at the base of the entire succession in the Wajid Sandstone of Abha/Khamis Mushayt (Fig. 6d, g). In this basal succession, the quartz pebbles are up to 6 cm across and mostly angular to subangular. Only locally, a better degree of rounding has been observed. Clasts of the directly underlying basement rocks are rare. The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Red Unit
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◀**Fig. 6** **a** The Basement—Wajid contact at Soudah (18° 19.323′ N, 42° 23.185′ E) shows a deeply weathered volcanic succession overlain by a zone of iron-incrusted erosional debris, which in turn is followed by the main conglomerate. Outcrop is about 4 m high. **b** Cross section of a 3D dune at the base of the massive upper unit of the Khusayyan Formation in the Habala area (18° 0.317′ N, 42° 52.433′ E). **c** Detail of the white sandstones at the base of the red unit. Note the bi-polar cross-bedding and the granular surface, which is caused by kaolinitic aggregates. Soudah (18° 17.700′ N, 42° 22.283′ E). **d** The basal conglomerate of the Wajid Group. It is composed of angular fragments of vein quartz and some clasts derived from the kaolinitic sandstones. Thin ripple-drift cross-bedded sandstones of the same composition as the underlying unit are present. Locality as in **a**. **e** Giant cross-beds of the Khusayyayn Formation erosionally overlain by massive sandstone. Dhahran Al Janoub area (17° 28.499′ N, 43° 41.987′ E). **f** Erosional contact of the massive sandstone with underlying beds. Dhahran Al Janoub area (17° 28.499′ N, 43° 41.987′ E). **g** The basal conglomerate consists of several individual layers of badly sorted conglomerate with sandstones, which together show a crude fining-upward pattern. Locality as in **a**. **h** Succession of cross beds, all of which are graded from coarse to medium sand. The basal unit shows pebbles at the base of most of the foresets. Dahran Al Janoub area (N17° 39.322′ E43° 28.454′)

matrix consists of hematite and gives these rocks a dull red appearance. This horizon is up to 15 cm thick.

AKM-LF9: conglomerate

A quartz pebble conglomerate has been observed along the surface that separates the lower red succession from the upper beige succession (Figs. 4, 5d, and 7a). Pebbles have a maximum diameter of approximately 4 cm and are subrounded to rounded. They, too, are frequently found in an iron-cemented bed. Most of the pebbles are of vein quartz origin; locally, however, iron-stained intraclasts of the underlying shale have been observed.

Lithofacies associations and depositional environments

The individual lithofacies described above may have their origin in a variety of depositional environment. However, the repeated co-occurrence of some of them may be more indicative of the depositional setting. Hence, the sediments described above have been combined into four lithofacies associations (Abha-Khamis Mushayt 1 through 4; *AKM*-1 through *AKM*-4).

AKM-1: regolith association

This association is present at the base of the Wajid Group (Figs. 5a and 6d). It is composed of breccia, red shale, and a variable amount of white, kaolinitic sandstone (Figs. 5a and 6c). This basal package testifies to a prolonged episode of intensive weathering around the Precambrian/Cambrian boundary affecting invariably all different underlying basement rocks of the Arabian Shield. Formation of kaolinite, the absence of any appreciable amount of feldspar and the provision of large amounts of dissolved iron are consistent with a lateritic environment. As the red shales rest mainly directly on top of the weathered basement rocks, they probably represent a primitive kind of soil. The clasts of the conglomerate show very few indications of transport. The majority of the clasts have most probably accumulated more or less in situ during the weathering process. Current activity only provided the sand that constitutes the matrix and rolled over the clasts so that their edges were chipped off. Together, these two lithologies represent a regolith.

The few outcrops of the white kaolinitic sandstones do not permit an interpretation of their depositional environment. However, as they underlie and are intercalated with the breccia and the chemical residue of weathering (Fig. 7b), they are most probably of fluvial origin and likely were deposited in small depressions or stream channels of some rivers.

This facies association has been mapped by Fairer (1985) in the Wadi Baysh quadrangle as “Regolith.” Similar couplets of soil/regolith–breccia/conglomerate are widespread across the Arabian Plate and adjacent areas (Avigard et al. 2005; Kolodner et al. 2006; Gutiérrez-Alonso et al. 2004) at the base of the Phanerozoic succession. In the type Wajid area, however, these sediments are only known from the subsurface (GTZ/DCo 2009).

AKM-2: white sandstone–shale–conglomerate association

At the base of the beige succession, a shale–conglomerate association is present that additionally contains varying amounts of kaolinitic white sandstones (Fig. 5d). The conglomerate mainly covers the red succession but was only locally deposited and preserved where it rests on strongly weathered basement rocks.

The clasts of the conglomerate are smaller and better rounded than those in the Regolith Association. Red, iron-stained shales and siltstones of this association themselves were reworked into the conglomerate. Again, the absence of any feldspar in the sediments is noteworthy and together with the presence of kaolinite and the iron crusts indicates intensive lateritic weathering and, hence, subaerial exposure. Rivers reworked the chemical residue of weathering, removed much of the coarser debris, and transported it into the adjacent sea, where the quartz pebbles became a lag deposit at the base of the next transgressive unit.

AKM-3: shale–siltstone–2D dunes association

This association constitutes the majority of the red succession. The association is dominated by sandstones with horizontal to low-angle cross-beds alternating with 2D dunes. In addition, variably intercalated are shales and kaolinitic siltstones (Fig. 7c, d), as well as sandstones with ripple-drift cross lamination. Bedding is micro-scale to meso-scale; macro-scale

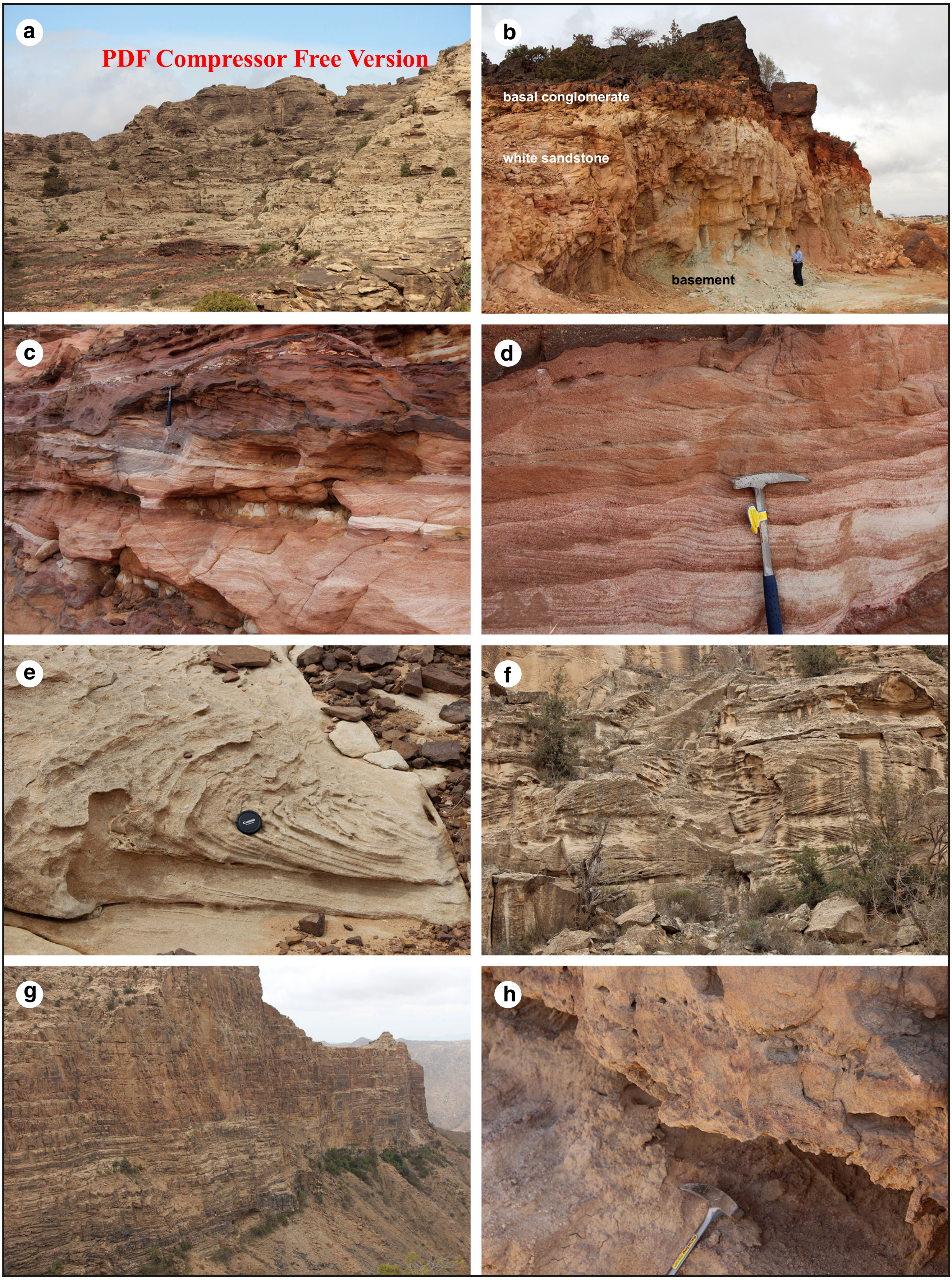
a
PDF Compressor Free Version
b
basal conglomerate
white sandstone
basement
c
d
e
f
g
h

Fig. 7 **a** The contact between the red succession and the Khusayyan Formation in the Habala area (18° 2.542′ N, 42° 49.399′ E). Red sandstones grade into iron encrusted shales and siltstones, which are abruptly overlain by medium- and macro-scale white cross-beds. **b** Weathered basement covered with succession of conglomerates and lenses of white conglomerate with white kaolinitic siltstone clasts. Soudah area (18° 17.700′ 42° 22.283′. c) Small- to medium-scale cross-bedded sandstones of the red succession with abundant intercalations of silty kaolinitic beds. Repeatedly, these layers are reworked to form intraclast layers. Ahad Rufaidah area (18° 7.226′ N, 42° 49.382′ E). **d** Succession of climbing ripples in the red succession. Dhahran Al Janoub area (17° 39.322′ N, 43° 28.454′ E). **e** Slump fold in the Khusayyan Formation. Habala area (18° 0.317′ N, 42° 52.433′ E). **f** Large-scale herringbone cross stratification at the base of the massive upper unit of the Khusayyan Formation in the Habala area (18° 1.931′ N, 42° 51.248′ E). Outcrop is approximately 10 m high. **g** The entire succession of the Wajid Group in the Habala area (18° 0.317′ N, 42° 52.433′ E). Above the basement (covered with scree), mainly medium bedded, light-colored sandstones are present. Above this is a succession of thin-bedded to medium bedded, almost white sandstones, which are overlain by thick-bedded and massive beige sandstones typical of the majority of the Khusayyayn Formation. **h** Base of the Khusayyayn Formation. Here, it overlies weathered and bleached sediments of the red succession. Note the absence of conglomerate. Ahad Rufaidah area (18° 5.932′ N, 42° 50.807′ E)

bedforms are rare. All bounding surfaces are sharp; reactivation is prominent. Repeatedly, the siltstones and some shales are reworked to form intraclast layers (Fig. 7c).

The formation of 2D dunes requires strong currents (Ashley 1990). Unidirectional currents create foresets with dips >25°; bi- or multidirectional currents show slip faces with regularly <20° (Flemming 1982; Harms et al. 1982). For the red succession, the non-uniform cross-bed directions plus the shallowly dipping foresets indicates non-unidirectional currents.

Architectural elements within the association include both lateral and downstream accretion with the latter being dominant. Beds and bed sets of the latter may achieve several meters in thickness. Locally, siltstones and shales terminate with the stacking of the beds. The most prominent example of a downstream accretionary complex is shown in Fig. 6e, f. Additionally, chute channels are present in the succession that are filled with a basal conglomeratic layer passing upward into coarse sandstone (Fig. 5e).

The entire set of observations points to a fluvial depositional environment dominated by upper flow regime conditions. Lower flow regime conditions are only indicated by the fine-grained sediments and the ripple drift cross-bedded sandstones. The architecture of the sediments points to a shallow braided river system (Miall 2006). Stacking of nested trough cross-beds, which would indicate wider and deeper channels of a major braided river system, has not been observed. Sandstones with their different internal geometry reflect different energetic conditions with the corresponding formation of different ripples, bars, and dunes. Intensive weathering in the hinterland is documented by the absence of feldspar and other clasts and by abundant kaolinitic layers. Kaolinite is also present as a detrital component in many of the siltstones and some sandstones. The finer grained sediments reflect abandonment of individual channels or locally overbank deposits.

Migration of the subsequent bedform led to erosion and reworking of these sediments and their incorporation into the younger bedform as a basal intraclast layer.

AKM-4: 2D–3D dunes complex association

As stated by Al Ajmi et al. (2015), this is the most spectacular association of the Wajid Group and constitutes almost the entire beige succession. Its macro-scale to giant cross-beds is typical of this association, which is recognized even from some distance (Fig. 5f). The cross-beds regularly dip with angles >25°. The association is composed of tabular-bedded sandstones, 2D dunes and some 3D dunes. Each bed is bounded by a sharp base and a sharp top, indicating non-continuous sedimentation and reworking at the top of the dunes. Sedimentary structures include large-scale herringbone cross stratification and slumping (Fig. 7e, f).

The formation of 2D (and 3D) dunes requires strong currents (Ashley 1990), where strong unidirectional currents create foresets with dips >25° and bi-directional currents show slip faces with regularly <20° (Flemming 1982; Harms et al. 1982).

As large dunes may be stationary for extended periods (Bokunewiecz et al. 1977; Allen and Collinson 1979; Allen 1980), fine-grained material can accumulate in the protected interdune areas. Through scouring in front of the overriding dune, this material is worked up and incorporated into the succession as intraclast layers.

This association records strong current activity with alternating transport conditions and directions. 2D and 3D dunes are the products of unidirectional flow (Ashley 1990) although of different intensities. The facies association may have originated either in a fluvial environment or on a vast shallow-marine siliciclastic shelf. Even in outcrops extending over several 100 m or even kilometers, nowhere structures have been observed that would indicate a channel margin. Together with the absence of any other lithofacies that might indicate fluvial environments, this indicates deposition of single bed forms across extremely wide areas. Hence, a shallow-marine environment is the most likely depositional setting. On epicontinental shelves, the strong currents may be invoked of geostrophic, of tidal, or of storm origin. As no indications of storm activity have been observed, this association records an alternation of tidal-dominated and of wave-dominated episodes.

Hitherto, little is known about the interactions between relative sea-level changes and sediment input on to the shelf in this part of Gondwana. Hence, the observed alternations of facies within the beige unit either record different volumes of sediment delivered per time or relative fluctuations of sea level leading to migrations of facies belts.

Close to the base and locally directly resting on the underlying red succession is the massive sandstone. As this sandstone is intercalated in a marine succession, it is likely that it is also of marine origin. Following Eschner and Kocurek (1986), this massive sandstone may represent a singular storm event of unusual dimensions in an otherwise tide-dominated environment. Alternatively, the triggering effect for the collapse of submarine dunes may have been a major earthquake.

Discussion

In the Abha/Khamis Mushayt area, the Wajid Sandstone comprises two distinct lithostratigraphic successions (Figs. 4 and 7a, g). The lower red succession (maximum preserved thickness is about 40 m to 50 m) is composed of the regolith association and the shale–siltstone–2d dunes association. The upper beige succession (>240 m) is composed of the white sandstone–shale–conglomerate association and the 2D–3D dunes association. In the type area, the regolith association is known from wells, the white sandstone–shale–conglomerate association from the base of the Khusayyayn Formation; however, both associations have not been distinguished as individual facies associations by Al Ajmi et al. (2015). The regolith association (AKM-1) was included in the basal association of the Dibsiyah Formation, whereas AKM-2 is not developed in the type Wajid area.

The red succession

Based on lithostratigraphic considerations, Babalola (1999) tentatively correlated the red succession with the Dibsiyah Formation of the type Wajid area (Fig. 3). This correlation was based on the gross sedimentological similarities and on the red color that distinguishes the Dibsiyah Formation from all other units of the Wajid Group. Three lithofacies associations are recognized in the Dibsiyah Formation; from bottom to top, these are conglomeratic 3D dunes association (LF-A1), 2D–3D dunes complex association (LF-A2), and 2D dunes–piperock association (LF-A3). From these, LF-A2 and LF A3 contain abundant horizons with “Tigillites” or *Skolithos* piperock, features that are entirely absent from the red succession (Table 1). In turn, these units do not contain any significant amount of fine-grained deposits. Hence, a lithostratigraphic correlation between these two associations and the red succession is unlikely.

The basal unit of the type Wajid is the conglomeratic 3D dunes association. Despite its coarse-grained nature and many fluvial characteristics (Kellogg et al. 1986), this is a marine unit as evidenced by its ichnofauna (Table 1; Al Ajmi et al. 2015). Many of its lithofacies are also present in the red succession of the Abha/Khamis Mushayt area. The latter, however, lacks this diagnostic ichnofauna. Other differences are the higher amount of fine-grained sediments in the latter in addition to a higher amount of kaolinitic sediments as described above (Fig. 4). Although there are lithological similarities, the red unit most probably was deposited in a shallow braided-river system. If both successions are time equivalent (what is not proven), the Abha–Khamis Mushayt sections might be the fluvio-terrestrial equivalent of the basal Wajid succession. In this scenario, the rivers provided the siliciclastic detrital sediments now found on the vast Wajid shelf.

In Saudi Arabia, however, there is a unit that lithologically more closely matches the red succession of the southwest: the Siq Formation exposed in the northern Kingdom (Fig. 3). The Siq Formation is the oldest unit in this area, locally preserved between the Neoproterozoic basement and the overlying Quweira or Saq formations (Janjou et al. 1998; Saudi Stratigraphic Committee 2013). Similar to the red succession, it has a patchy occurrence in paleo-depressions. The basal unit of the Siq Formation is a regolith as shown by the Saudi Stratigraphic Committee (2013; Fig. 3). Up section follows cross-bedded sandstones and red and white kaolinitic shales and siltstones of a braided river system. A few *Tigillites* horizons are present in the upper part of the formation indicating the transition to marginal marine environments.

In northern Saudi Arabia, the Siq Formation is sandwiched between the basement below and either the Quweira or Saq formations. The former also has a patchy distribution and an unconformable upper contact to the Saq Formation. The Saq Formation is the first widespread, Cambrian sand sheet unit transgressing the Arabian Shield. In this, it is similar to the Dibsiyah Formation of the type Wajid area and regularly litho- and chronostratigraphically correlated to it (discussion and figures in Al Ajmi et al. 2015).

A three-dimensional architectural framework for Saudi Arabia during the lowermost Paleozoic would show a wide peneplain on top of the basement of the Arabian Shield. This peneplain was dominantly covered by regolith, although locally white kaolinitic sandstones and siltstones were deposited, probably in a fluvial environment. Subsequently, rivers draining the Arabian Shield intersected the peneplain and the valleys and channels were filled with fluvial and later with nearshore marine sediments as proposed by Janjou et al. (1998). This does not mean that the red succession and the Siq Formation are necessarily time equivalent; however, they represent the same tectono-stratigraphic setting. Subsequently, the global overall sea-level rise, which started during the Cambrian (Ross and Ross 1988, 1995; Miller et al. 2005), flooded large areas of the Arabian–Nubian Shield and large sheets of sand (Saq Formation, Dibsiyah Formation) covered the entire area and buried the Siq Sandstone (and the Quweira Formation) in the north and the red succession in the south. Whereas in the north, these relations can directly be observed in the outcrops, in the south, the outcrops of the successions have been detached from each other through subsequent erosion and a direct observation of the spatial relations is no longer possible.

The beige succession

The upper beige succession, whose outcrops can be traced from Abha and the Yemeni border to Najran and then into the type Wajid area, is definitely part of the Khusayyayn Formation (Fig. 3). This assignment is based on the lithologic and sedimentologic similarities between both areas (Table 1):

- They are composed of a 2D dunes–3D dunes association (Fig. 7f–h), LF-A2 of Al Ajmi et al. (2015).
- They show beige to ochre colors.
- They show dominantly mega-scale and giant dunes with subordinate meso-scale units.
- Certain intervals are dominated by mega-scale herring-bone cross stratification.
- Many of these units can be traced laterally over tens of meters or even hundreds of meters.

The only difference is that (Fig. 4) a bed similar to the massive bed with its erosional features close to the base of the Khusayyayn Formation (Fig. 8a, b) of the Abha/Khamis Mushayt has not been observed in the Wajid area, although massive sandstone is present there locally.

Conclusions

In the Abha/Khamis Mushayt area of southwestern Saudi Arabia, two distinct lithologic successions are present, here named the red succession and the (upper) beige succession. A regolith separates the basal red succession from the basement of the Arabian Shield. This regolith, found over vast areas of Arabia and adjacent Gondwana (Avigard et al. 2005; Kolodner et al. 2006; Gutiérrez-Alonso et al. 2004), marks a late Neoproterozoic/Early Cambrian episode of intensive weathering and peneplanation. The red succession itself consists of a shallow braided-river system (shale–siltstone–2d dunes facies association). The geometry and distribution of the sediments suggest that they were deposited in laterally discontinuous depressions on the old surface (Fig. 9).

The upper beige succession was also deposited above a regional surface of erosion (Fig. 9). This surface is characterized by a conglomeratic facies association with evidence of previous lateritic weathering (ironstone clasts, kaolinite). Large submarine 2D and 3D dunes testify to strong submarine currents, partly of wave and partly of tidal origin in the remainder of the unit testifying to the interplay between eustacy and sediment supply.

Whereas the "regular" facies associations are genetically intrinsic to the Wajid Sandstone, the regolith association is not. It invariably forms the basal deposit of the Phanerozoic succession in this part of Gondwana, e.g., at the base of the Wajid Group, the Siq Sandstone, the Quweira Sandstone, and the Saq Sandstone, among others. Its basal unconformity represents the end of the pan-African orogenic cycle. The regolith is absent only where it has been reworked and redeposited during younger events as at the base of the Khusayyayn Formation (Fig. 9).

According to the present investigations, little doubt is left about the assignment of the upper beige succession of the Abha/Khamis Mushayt area to the Khusayyayn Formation in the type Wajid area (Fig. 3) as originally proposed by Babalola (1999). The attribution of the red succession, however, remains controversial. Lithologically, it certainly does not correspond to the middle and upper part of the Dibsiyah Formation with its well-developed *Tigillites* fauna. It may be a lateral, fluvio-terrestrial facies equivalent of the lower unit of the Dibsiyah Formation as described by Al Ajmi et al. (2015) and, hence, maybe an integral part of the Wajid Group. However, the red succession shares many lithologic characteristics with the Siq

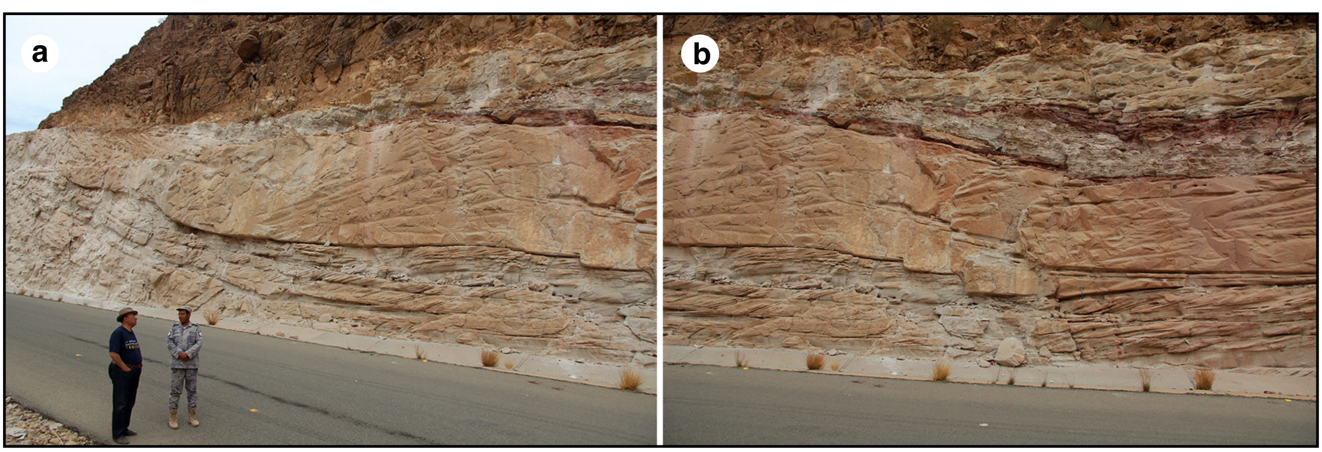

Fig. 8 **a** Massive channeled Khusayyayn sandstone approximately 60 m wide. Fill is about 4 m thick. Dhahran Al Janoub area (17° 30.819′ N, 43° 31.961′ E). **b** Step-like incision of the basal sandstone into the underlying rocks, probably enhanced by loading. Locality as in **a**

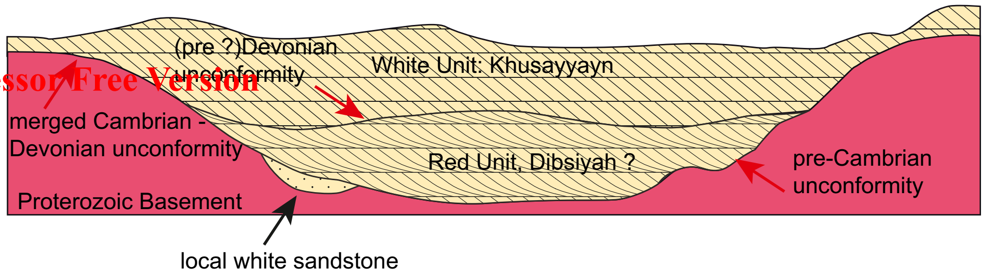

Fig. 9 Model of the generalized spatial architecture of the red succession and the beige succession in the Abha/Khamis Mushayt area and their bounding unconformities. Not to scale

Sandstone of northern Saudi Arabia. Hence, the question is raised here, whether the red succession may represent a yet in the Abha/Khamis Mushayt area unidentified lithostratigraphic unit older than the Wajid Group (Fig. 3).

Acknowledgements We would like to express our thanks to the anonymous reviewer, whose meticulously worked out comments helped to improve the manuscript considerably.

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