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5 authors, including:

Vanessa Mary An Heyvaert
Royal Belgian Institute of Natural Sciences

Jan Walstra
Royal Belgian Institute of Natural Sciences

Peter Verkinderen
University of Hamburg

H.J.T. Weerts
Rijksdienst voor Cultureel Erfgoed


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The role of human interference on the channel shifting of the Karkheh River in the Lower Khuzestan plain (Mesopotamia, SW Iran)

Vanessa M.A. Heyvaert [a,*], Jan Walstra [b], Peter Verkinderen [b,c], Henk J.T. Weerts [d], Bart Ooghe [b]

[a] Geological Survey of Belgium, Jennerstraat 13, 1000 Brussels, Belgium
[b] Department of Languages and Cultures of the Near East and North Africa, Ghent University, Belgium
[c] The Netherlands-Flemish Institute in Cairo, Egypt
[d] Cultural Heritage Agency, Amersfoort, The Netherlands

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ABSTRACT

This study is concerned with the Late Holocene floodplain history of the Karkheh River in Lower Khuzestan, and in particular with the role of human action upon its channel shifts. The research was conducted in a multidisciplinary way, in which resources and approaches from different research fields were combined: (1) geomorphological mapping based on the interpretation of Landsat and CORONA satellite imagery, (2) analyses of geological sequences, including the identification of sedimentary facies and radiocarbon dating of organic material, (3) an archaeological field survey of ancient settlements, and (4) consultation of historical documents, mainly Arabic texts from the 9th–14th century and European travel literature from the 16th-early 20th century. Three main channel belts of the Karkheh were identified (labelled Kh1, Kh2 and Kh3), corresponding to successive stages in the evolution of the floodplain. Two river shifts are documented in the datasets, both taking place within the last 2000 years. The first avulsion regards a shift from channel belt Kh1, once a tributary of the Karun, to the straight river bed of Kh2, taking place at least after 1240–1310 cal BP/710–640 AD. The second avulsion, from Kh2 to Kh3, is clearly documented in historical sources and happened in a single night event in the year 1837/113 cal BP. Reactivation of the Kh2 river bed and its irrigation canals can be attributed to the recent construction of an artificial canal bypassing the second avulsion point. Both river shifts were strongly influenced by human interference, whereby an artificial irrigation canal took over the entire river flow from the main channel belt. Most likely, a combination of human-induced factors, such as weakening of the river levees, high sedimentation rates and disadvantageous channel gradients, led to a situation prone to avulsion.

1. Introduction

River channel avulsion occurs when a river diverts from its established course to follow a new course (Allen, 1965; Slingerland and Smith, 2004). In many cases avulsion is not the result of a single factor (Waters and Nordt, 1995). It represents the response of a river system to a wide range of autogenic factors, such as river meandering and vertical accretion, and allogenic controls, such as tectonics, climate change and sea-level change. Among the possible factors promoting river instability, human interference plays an important role (Stouthamer and Berendsen, 2000; Hudson et al., 2008).

Since early civilizations settled upon riverbanks in the Mesopotamian region, they altered the fundamental hydrological and sedimentary processes that control fluvial systems through the application of flood management and water supply techniques (e.g. construction of canals, dikes, dams, bypass corridors) (Graad van Roggen, 1905; Baeteman, 1980; Cole and Gasche, 1998; Wilkinson, 2003; Alizadeh et al., 2004; Heyvaert and Baeteman, 2008). These actions can trigger unintended geomorphic responses such as avulsion (Adams, 1981; Morozova, 2005; Heyvaert and Baeteman, 2008). At least since Parthian times (ca. 160 BC–221 AD), the Lower Khuzestan plain (Fig. 1) was the focus of huge irrigation and settlement programs, attributed to enormous investments and technical innovations (Baeteman et al., 2004/2005; Gasche and Paymani, 2005; Walstra et al., 2010a, b).

The objective of this paper is to investigate the role of human interference on the Late Holocene floodplain history of the Karkheh river, located in the northern part of the Lower Khuzestan plain (Fig. 1). In this study geological, remote sensing, historical and archaeological data are combined and interpreted with particular

* Corresponding author.
E-mail address: vanessa.heyvaert@naturalsciences.be (V.M.A. Heyvaert).

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regard to the large-scale impact of human action upon river shifting.

2. Study area

The Lower Khuzestan plain, forming the eastern extension of the Mesopotamian Plain, is bordered in the north and east by the foothills of the Zagros Mountains (Fig. 1). Both in relief and climate, there is a strong contrast between the semi-arid flat plain and the more humid Zagros Mountains. Three major rivers drain the plain: the Karun, Karkheh and Jarrahi. The present study is restricted to the northern part of the plain including the Karkheh and its (palaeo)channel belts. The Karkheh rises in the Zagros Mountains and, after entering the plain in the northwest, crosses the Ahwaz anticline near the village of Hamidiya. A little further downstream, the river turns into two parallel channels, both ending in the Hawiza Marshes near the Iraq–Iran border. Both channels show a distinct southeast-northwest direction parallel to the Ahwaz anticline (Fig. 1).

3. Previous work

3.1. River systems

Until now, relatively little attention has been paid to the reconstruction of river systems in the Lower Khuzestan plain. Meander patterns of an abandoned river across the plain between Ahwaz and the Shatt al-Arab were briefly mentioned by Hansman (1967) and Kirkby (1977), both using aerial photographs. Hansman attributed the meanders to a former course of the Karkheh. Kirkby, on the other hand, attributed the meanders to the Karun, or a combined Karun-Karkheh channel, based on the relationship between meander wavelength and bankfull discharge.

Recent geological work showed that the Late Holocene sedimentary infill of the Lower Khuzestan plain was controlled by the interplay between fluvial sediment input by the rivers Karun, Karkheh and Jarrahi and a decelerating rate in sea-level rise (Heyvaert and Baeteman, 2007). Moreover, it was demonstrated that the present-day Karun channel is the main channel of a large

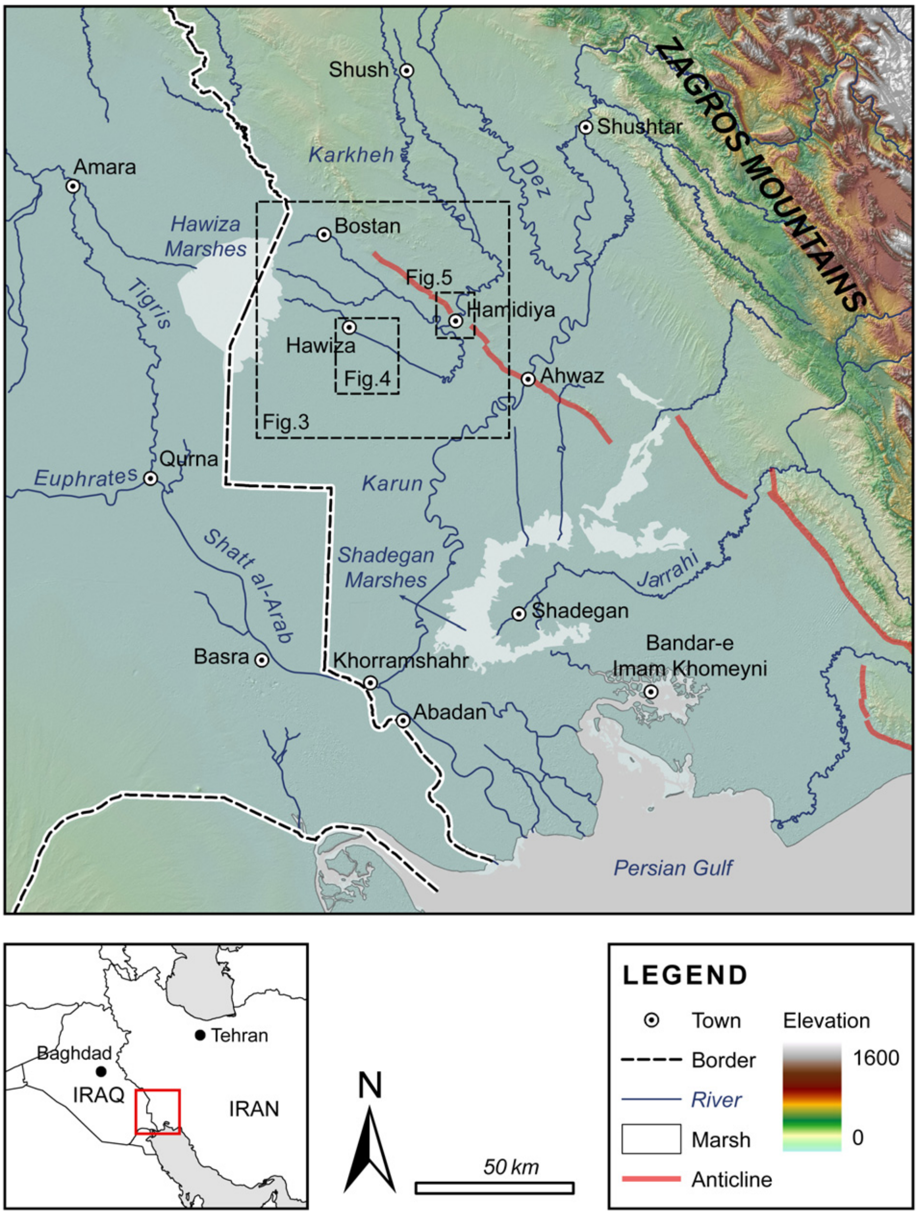

Fig. 1. Location map of the Lower Khuzestan plain (SW Iran). The inset shows the location of the map displayed in Figs. 3–5.

alluvial fan with a radius of about 100 km (Fig. 2) (Baltzer and Purser, 1990; Heyvaert, 2007). The evolution of this Karun 'mega-fan' is the product of repeated avulsions and also controlled the Late Holocene shifting of the rivers Jarrahi and Karkheh (Heyvaert, 2007; Heyvaert and Weerts, 2007).

Interpretation of satellite imagery (only Landsat) revealed the existence of three (palaeo)channel belts of the Karkheh (Fig. 2), including its present-day course (Kh3), an (abandoned) channel belt more or less parallel to it (Kh2), and another one (Kh1), apparently once a tributary of a Karun palaeochannel belt K2, as was already suggested by Kirkby (1977) (Baeteman et al., 2004/2005; Heyvaert, 2007; Heyvaert and Weerts, 2007). In addition, irrigation canals branching off at right angles from the Kh2b channel belt were identified on remote sensing imagery (Baeteman et al., 2004/2005).

3.2. Archaeology

Only very limited archaeological information for Lower Khuzestan is available. McCown carried out the most extensive survey in 1948 (ultimately published by Alizadeh, 1985), recording 44 sites in the vicinity of Ahwaz and Hawiza (Fig. 1). Most sites were attributed to the Sasanian (221–640 AD) or Islamic (after ca. 640 AD) times, and only a few to the Seleucid (312–140 BC) and Parthian (140 BC–221 AD) periods. This view was confirmed by a more recent survey (Gasche and Paymani, 2005) which noted another 15 sites, all occupied between the Seleucid and Islamic periods.

4. Methods

Geological, remote sensing, historical, and archaeological data were combined to study the Late Holocene development of the fluvial system of the river Karkheh. Remote sensing data provide the spatial framework for the information derived from other disciplines. Based on the interpretation of satellite imagery (notably from Landsat and CORONA missions) a geomorphological map of the study area was produced (cf. Walstra et al., 2011) for the first time. This map (Fig. 3) presents the distribution of past and present landforms, including traces of human activity. Archaeological fieldwork during two missions in 2004 included the survey of ancient settlements and resolving their age based on datable ceramics (cf. Gasche and Paymani, 2005). Geological fieldwork, which also took place in 2004, involved the analysis of the sedimentary sequence of 52 hand-operated boreholes and 3 outcrops. The detailed facies analysis of the Holocene sequence of Lower Khuzestan enabled the identification of three sedimentary units. Sediments belonging to these units were interpreted as being deposited in a fluvial (Unit 1), a coastal (Unit 2) and brackish-

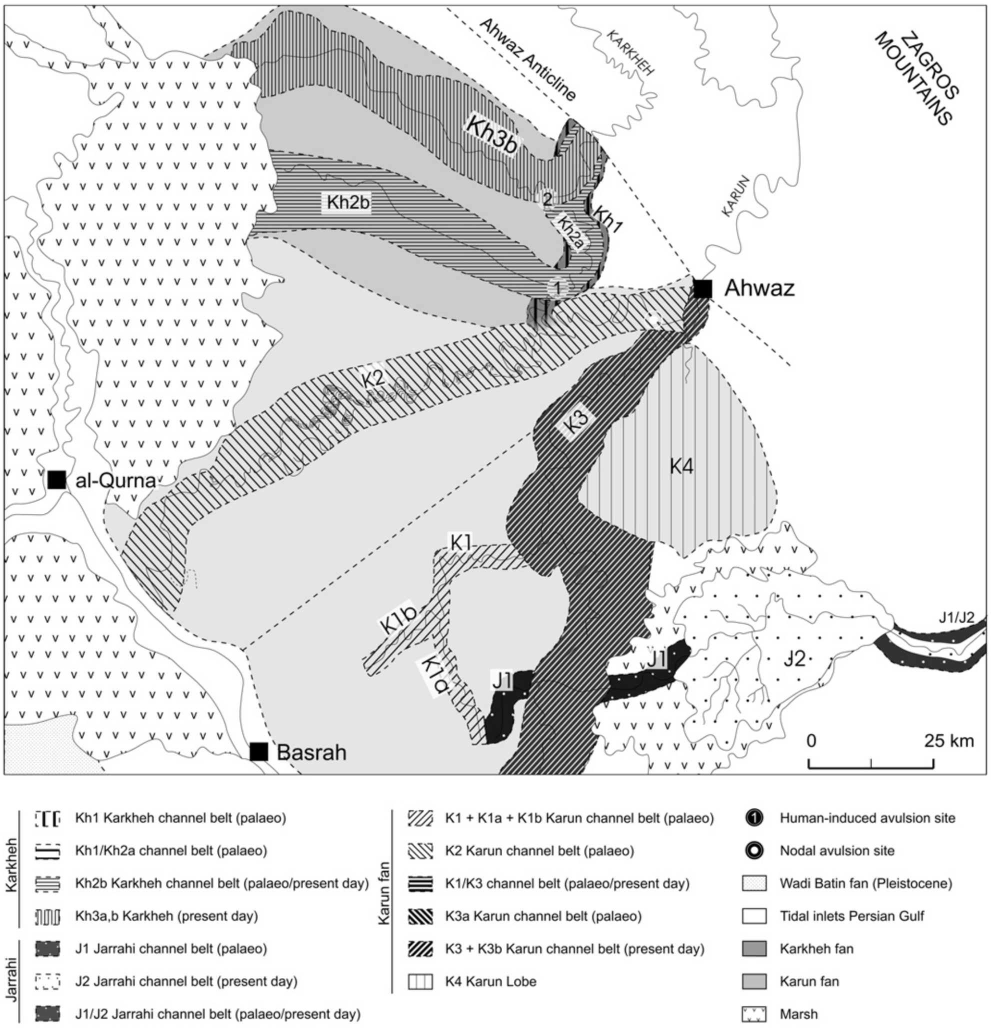

Fig. 2. Map of the Lower Khuzestan plain showing the Late Holocene fans and palaeochannel belts of the rivers Karun, Karkheh and Jarrahi. (Source: Heyvaert, 2007).

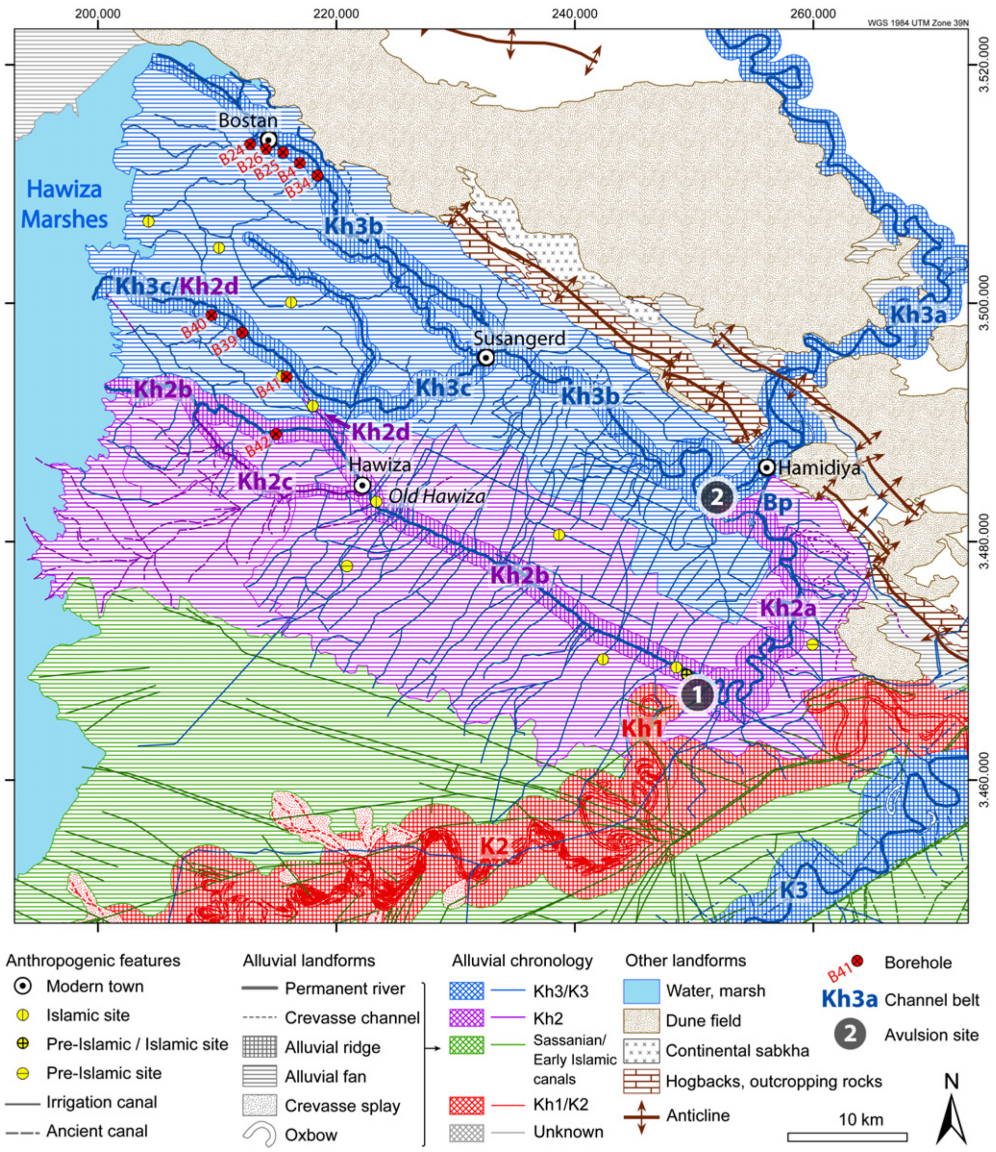

Fig. 3. Geomorphological map of the study area. Chronological order of the alluvial units is from Kh1/K2 (older) to Kh3/K3 (more recent), attributed in accordance to the final stage of activity. Also shown are the locations of archaeological sites and the boreholes described in this study.

freshwater marsh (Unit 3) environment, respectively. A detailed description of the lithological and palaeoecological properties of these units is given in Heyvaert (2007) and Heyvaert and Baeteman (2007). It is assumed that the coastal sediments were deposited during the Early and Middle Holocene when the Persian Gulf extended far north in to the Lower Khuzestan Plain (Heyvaert and Baeteman, 2007).

This study will focus on the lateral and vertical distribution of the upper fluvial sedimentary unit (1) and the brackish-freshwater marsh unit (2) in the sedimentary sequence of the Karkheh floodplain. A series of 8 boreholes and one outcrop, located along the mapped Karkheh (palaeo)channel belts, are investigated (Figs. 3, 6 and 7). The locations of individual boreholes were recorded by a handheld GPS device. Surface elevations were derived from topographic maps. Radiocarbon dates (listed in Table 1) were obtained from organic material to provide a chronological framework. Calibrated dates are given with a 2 sigma error range I calibrates (Calendar) years before present (cal BP). Calibration was completed using the calibration programme of Stuiver and Reimer (1993).

The last data set consulted for this study consists of historical documents, mainly in the form of (1) Arabic historiographical and geographical literature from the 9th to the 14th century and (2) European travel literature and cartography, dated between the 16th and the early 20th century AD. The use of historical sources for landscape research entails a rigorous critique of the individual source in terms of the limits of its information. Travel into this area of Khuzestan was rather limited as no main passageways ran through it. The available accounts often occur at intervals of several decades or even centuries. Moreover, they sometimes only contain information on the bordering regions, particularly the Tigris and Shatt al-Arab, and may include second-hand data (Ooghe, 2007; Verkinderen, 2009).

5. Results

5.1. Geomorphological mapping of the Karkheh alluvial plain

Based on the interpretation of satellite imagery, three main channel belts of the Karkheh were identified (Kh1, Kh2, Kh3 –

Table 1
AMS radiocarbon data and calibrated ages.

Site	Geographical coordinates	Laboratory code	Age ^{14}C(yr BP)	Calibrated age (yr cal BP)	Sample altitude	Date material
B24	30°38′41″ 48°41′50″	KIA-24490	155 ± 25	60–230	+3.35	Organic material
B24	30°34′41″ 48°41′50″	KIA-24480	250 ± 25	270–320	+2.50	Peaty mud
B24	30°38′41″ 48°41′50″	KIA-24481	280 ± 25	350–440	+1.98	Peaty mud
B26	31°43′10″ 47°58′53″	KIA-26488	80 ± 30	20–150	+3.55	Peaty mud
B26	31°43′10″ 47°58′53″	KIA-26745	160 ± 20	230–130	+3.50	Vegetation remnant
B39	31°34′37″ 47°57′59″	KIA-26481	1350 ± 25	1240–1310	+1.10	Organic gyttja

Fig. 3). These different courses can be attributed to successive stages in the development of the Karkheh. Evidently, the (palaeo) channels visible from space represent only their final position, at the end of each stage, and only as far as the traces were not subsequently removed by erosion or covered by later deposits. Therefore, the geomorphological map depicts the relative chronology of alluvial units based on their final stage of activity (i.e. a channel active during successive stages is attributed with the colour of its last stage).

At present, the Karkheh River enters the plain via channel Kh3a through a narrow breach in the Ahwaz anticline near Hamidiya (Fig. 3). It then turns (at avulsion point 2) in a southeast-northwest direction parallel with the Ahwaz anticline, and discharges through channel Kh3b into the Hawiza Marshes nearby the village of Bostan. Between Hamidiya and Bostan, many channels/canals (active as well as abandoned) branch off from the main channel, most notably the Kh3c that breaks away from the Kh3b at Susangerd.

From avulsion point 2, a second branch (named Karkheh Kur or "Blind Karkheh") initially follows a strongly meandering course (Kh2a, Fig. 3) to the south and then turns (at avulsion point 1) sharply into a southeast-northwest direction (Kh2b). Judging from the traces of palaeomeanders immediately south of Hamidiya, which link the channel upstream to the Kh3a, this once was the (only) natural course of the Karkheh. At present the channel is fed via an artificial canal bypassing Hamidiya and the palaeomeanders (labelled Bp in Figs. 3 and 5).

The Kh2b channel shows a remarkably straight course towards the village of Hawiza. Traces of two large abandoned channels diverting from the Kh2b are noteworthy. The first one (Kh2c), branches off southwest of Hawiza and is indicated on contemporary Russian topographical maps as Karkheh Kur, hence suggesting it once was the main channel. The second channel (Kh2d) is called Shatt Naysan on topographical maps and branches off northwest of Hawiza. After Kh2c and Kh2d branch off from the main channel of the Kh2b, the latter continues as Nahr Lawi. It seems that the Kh2d palaeochannel was reoccupied by the Kh3 channel network, as nowadays the lower part receives its flow from the Kh3c branch. At this incident, the entire Kh3c channel must have taken over its name (Shatt Naysan), up to the place where it branches off from the Kh3b and down to the point where it discharges into the Hawiza Marshes. These observations suggest that the downstream branches of the Karkheh commonly shifted and sometimes reoccupied older channels.

Patterns of palaeomeanders associated with the Kh1 channel belt were detected perfectly aligned with the meanders of the Kh2a branch (south of avulsion point 1). The traces merge with those of a Karun palaeochannel belt (K2), thereby indicating that once, the river Karkheh was a tributary of the Karun. Both palaeochannel belts are intersected by large, abandoned irrigation canals originating from the present-day Karun channel belt (K3).

The Kh2b channel belt is characterised by the presence of irrigation canals, typically orientated perpendicular to the main channel and some 10–13 km in length. Although still abandoned and amidst wasteland in the late 1960s, recent satellite imagery (Figs. 4 and 5) show that these canals are back in use after discharge through the Kh2b branch resumed via the artificial canal bypassing Hamidiya. Some more canals branch off from the Karkheh at the same location upstream of Hamidiya. During the late 1960s these canals were still under construction, but satellite imagery clearly show that in the following decades the area between the Kh3b and Kh2b has become gradually intersected by large-scale irrigation works fed by them.

5.2. Alluvial architecture and chronology

5.2.1. Zone 1: Karkheh (palaeo)channel Kh2d/3c

Transect 1 (Fig. 6) is located along the Karkheh palaeochannel belt (Kh2d) which at present time is fed by the Karkheh Kh3c channel. The sedimentary sequence along this transect consists mainly of fluvial deposits with a thickness of ca. 5–6 m. Only in boreholes B39 and B40 these fluvial deposits were found overlying a 0.5–1 m thick layer of organic rich brackish-freshwater marsh deposits, covering coastal deposits. The tidal flat deposits are characterised by bluish-grey soft clay. The brackish-freshwater marsh deposits are characterised by greenish-blue soft clay with fine rootlets, mollusc shells (*Corbicula sp. Melanoids sp. and Menalopsis sp.*) and thin layers of black peaty mud or organic gyttja. In B39 the base of the peaty mud was dated at 1240–1310 cal BP (Table 1). Above ca. +1.40 m, a 2 m-thick grey brown fine sandy clay was found in B39 and B40. These deposits are interpreted as channel-belt/crevasse-splay deposits associated with the Karkheh (palaeo) channel belt Kh2d/3c The upper part of the sedimentary sequence along transect 1 consists of a compact greyish brown silty clay and brownish grey clay with salt crystals, fragments of freshwater shells and fine root penetrations scattered all over. The latter is interpreted as a floodbasin deposit of the Karkheh (palaeo)channel Kh2d/3c. The brackish-freshwater marsh deposits, which underlie the fluvial deposits of the Karkheh Kh2d/3c at a level of ca. +1.40 m, can be attributed to a former extension of the Hawiza Marshes and developed from ca. 1240–1310 cal BP in this area. This date also indicates that onset of sedimentation associated with (palaeo)channel Kh2d/3c started at least after 1240–1310 cal BP. In view of this very young age and the 5–6 m thick fluvial deposits, fluvial sediment input and sedimentation rate were very high at this location.

5.2.2. Zone 2: Karkheh channel belt Kh3b

Transect 2 (Fig. 7) follows an east-west direction parallel with and south of the lower part of the present-day active Karkheh channel belt Kh3b. The boreholes in this transect show a sedimentary sequence similar to the one found in zone 1.

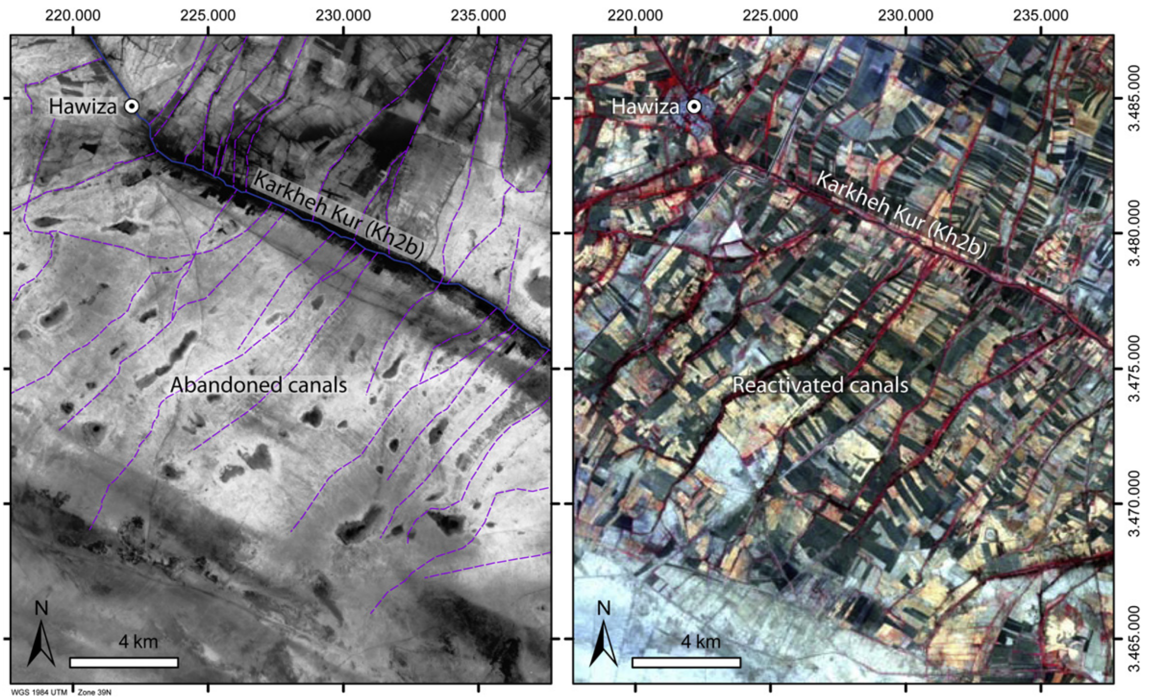

Fig. 4. Comparison of satellite imagery, revealing the reactivation of irrigation canals along the Kh2b channel: a mosaic of CORONA images (mission DS1035-1/040, acquired 23 September 1966) and a near-infrared colour composite Landsat ETM+ scene (path 166/row 38, acquired 4 August 2001). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Coastal deposits, covering the pre-transgressive surface, are gradually overlain by brackish-freshwater marsh deposits and fluvial deposits. Only in core B24 and outcrop B26 datable organic material was encountered in the brackish-freshwater marsh deposits. In borehole B24, two peaty horizons at +1.98 m and +2.50 m were dated at 350–440 cal BP and 270–320 cal BP, respectively (Table 1). The reworked organic material at the level of +3.35 m in B24 was dated at 230-60 cal BP. In outcrop B26, a peaty horizon was found in the brackish-freshwater marsh deposits on a level of +3.55 m. The base and the top of the peaty horizon were

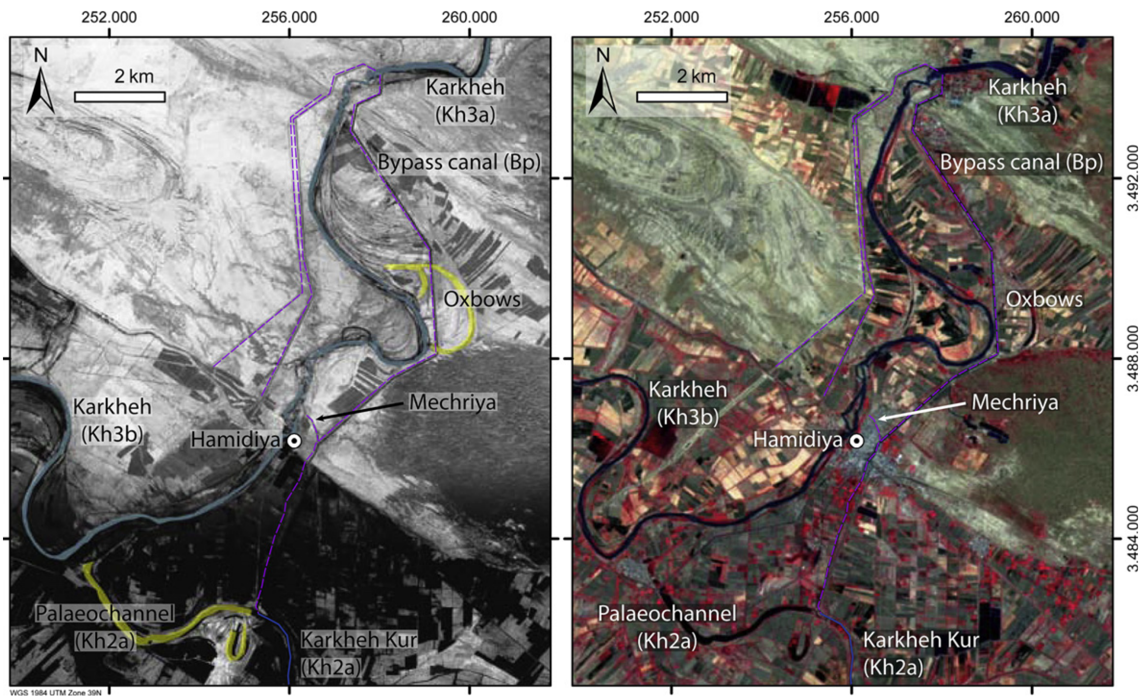

Fig. 5. Satellite imagery showing the large bypass canal near Hamidiya and traces of its 19th century counterpart (Mechriya, see Section 4.3), both constructed to restore discharge through the Kh2 channels: a mosaic of CORONA images (mission DS1035-1/040, acquired 23 September 1966) and a near-infrared colour composite Landsat ETM+ scene (path 166/row 38, acquired 4 August 2001). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

dated at 230–130 cal BP and 150–20 cal BP. In all boreholes the upper part of the sedimentary succession consists mainly of a compact greyish brown silty clay and brown clay with red-brown laminae, salt crystals, fine root penetrations, oxidation spots and fragments of freshwater shells scattered all over. These sediments are interpreted as floodbasin deposits of the present-day Karkheh (Kh3b) fluvial system. Thin layers of greyish brown silty sand, interpreted as channel-belt/crevasse-splay deposits, are found intercalated within these floodbasin deposits. It is suggested that the brackish-freshwater marsh deposits, which underlie the fluvial deposits of the present-day Karkheh river system at a level of +3.5–4 m can again be linked to a former eastern extension of the Hawiza Marshes. The onset of the formation of these marshes at this location can be estimated at ca. 440–350 cal BP. The date of the peaty layer in B26, covered by the fluvial deposits, suggests that sedimentation by the river (Kh3), filling in theses marshes, started at the earliest at 150–20 cal BP at this location. In view of the thickness of the fluvial deposits (ca. 3–4 m) and the short-time span of deposition (max 150 years), sedimentation rates must have been very high. This high sedimentation rate is probably caused by deforestation and intensified land-use in the catchments over the years causing annual sheet-like flooding over the entire Karkheh plain.

5.3. Archaeological and historical data

5.3.1. Archaeological data

Because of the dry climate in the region, societies have always depended on the position of river channels for their economic survival (Adams, 1981; Cole and Gasche, 1998). This makes that the presence of archaeological sites in the surroundings of palaeochannels is a useful tool to obtain a reliable chronology of channel belts. In principle, the presence of an archaeological site nearby a channel belt gives an indication of a minimum age for that channel belt. A number of archaeological sites founded during the Early and Middle Islamic periods (1313–450 cal BP/637–1500 AD) were identified by Gasche and Paymani (2005) along the palaeochannel belt Kh2b (Fig. 3). Moreover, they found the 14th-century ruins of the Islamic city of Hawiza (Tell Hawiza) directly south of the present-day town of Hawiza. This suggests that the palaeochannel belt must have been active from at least the Middle Islamic period onwards. It is remarkable that along the Kh3b channel no archaeological sites have been identified.

5.3.2. Historical data

The area of the lower Karkheh was a ‘political backwater’ until the 13th century; it is not mentioned in sources that predate the Islamic conquest of the area in the mid-7th century. A pre-Islamic city called Nahr Tīrā is mentioned in this area during the first centuries of Islam, but had apparently disappeared by the time the major geographical works were written in the 9th and 10th centuries (Verkinderen, 2009). In the 11th century, an Arab tribe called the Banu Dubais took control over the area between the lower Tigris and Karun, which was consequently called Jazirat Bani Dubais (“Island of the Sons of Dubais”) (Yaqut, 1955: II 326; Zabidi, 1889 s.v. *al-Hilla*; Rudhrawari, 1920–1921: 266f.; Ibn al-Athir, 2006: VIII 64, 83f., 167, 348; Ibn Khaldun, 2006: IV 331–335; cf. Verkinderen, 2009). From the 12th century onwards, the main town of the area, Hawiza (Fig. 3), became an important center, located on

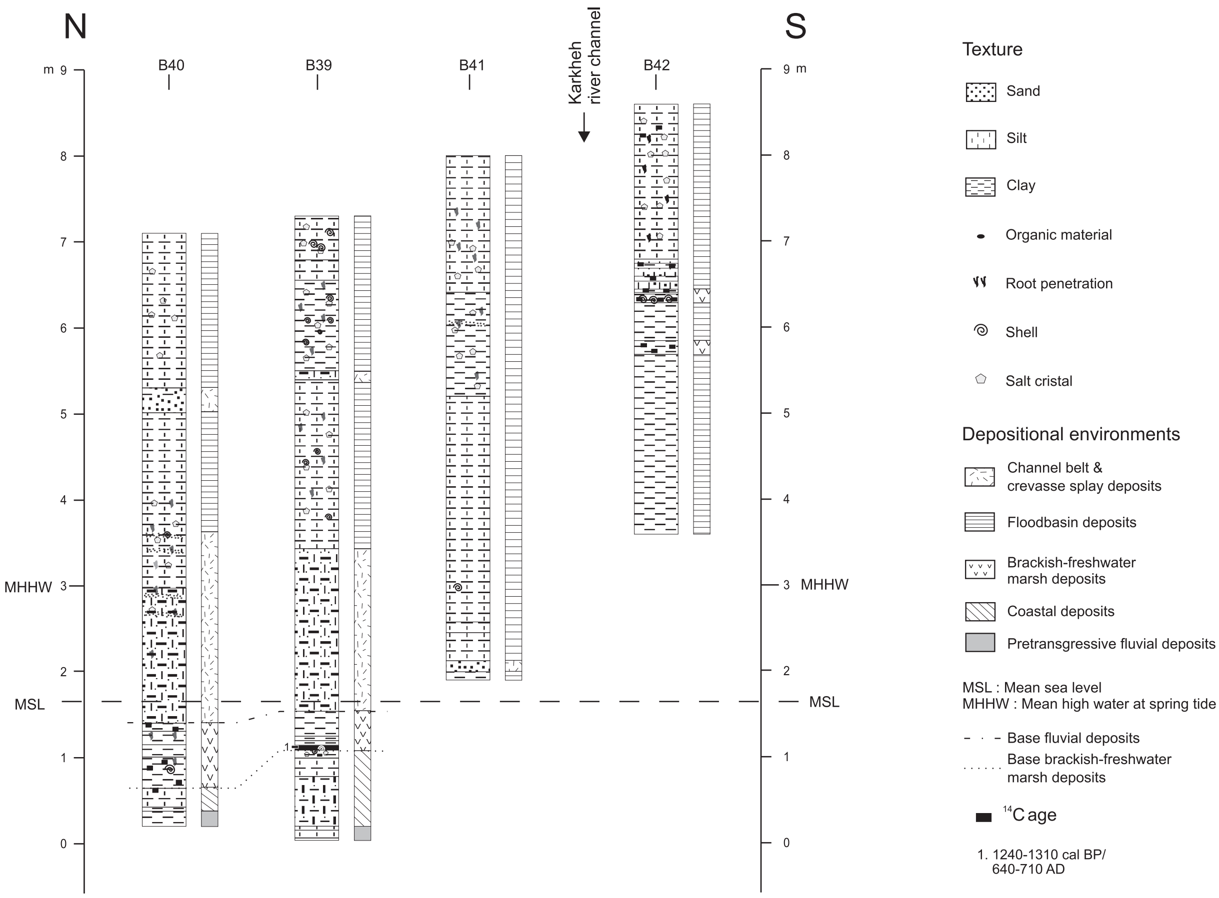

Fig. 6. Stratigraphic profile with indication of the depositional environments of cores along (palaeo)channel belt Kh2d/Kh3c. Sediment textures are based on field descriptions. The location of boreholes is given in Fig. 3.

a trade route from Persia to Basra and Baghdad (Isfahani, 2001: 218; Ibn Battuta, 1853–1858: II 93). Cash crops (corn, cotton and especially sugarcane) were cultivated around the town in the 14th century (Mustawfi, 1915–1919: 109), which indicates abundant water supply was available at the time. The importance of the city increased further in the following period: it became the capital of the province of Arabistan (Khuzestan) and the seat of its great dynasty of governors, the Musha'sha'a (Layard, 1846).

The exact course of the lower Karkheh is not described in the Islamic sources. At least three different branches are mentioned that discharged into the Dujail (Karun) river, both upstream and downstream of Ahwaz (Verkinderen, 2009). Mustawfi, writing in the 14th century, says the Karkheh flowed down to the area of Hawiza before joining the combined waters of the Karun and the Dez, which finally ended in the Shatt al-Arab (Mustawfi, 1915–1919: 211).

Few European travellers visited the region, and only from the nineteenth century onwards. Loftus (1857a, b) describes a major landscape change in the surroundings of the Arab city of Hawiza. Prior to 1837 the river Karkheh had flowed along Hawiza (i.e. in its Kh2b channel), and the region had been intersected by irrigation canals connected to the Karkheh (Loftus, 1857a, b; Layard, 1846). One canal, locally called Nahr Hashem, branched off from the river at some 15 miles north of Hawiza (Fig. 8). Because the lands irrigated by the Nahr Hashem canal lay topographically lower than expected, the canal gained importance and started to carry off exceeding amounts of water. As a consequence, a dam was constructed at the bifurcation point to prevent the Karkheh from

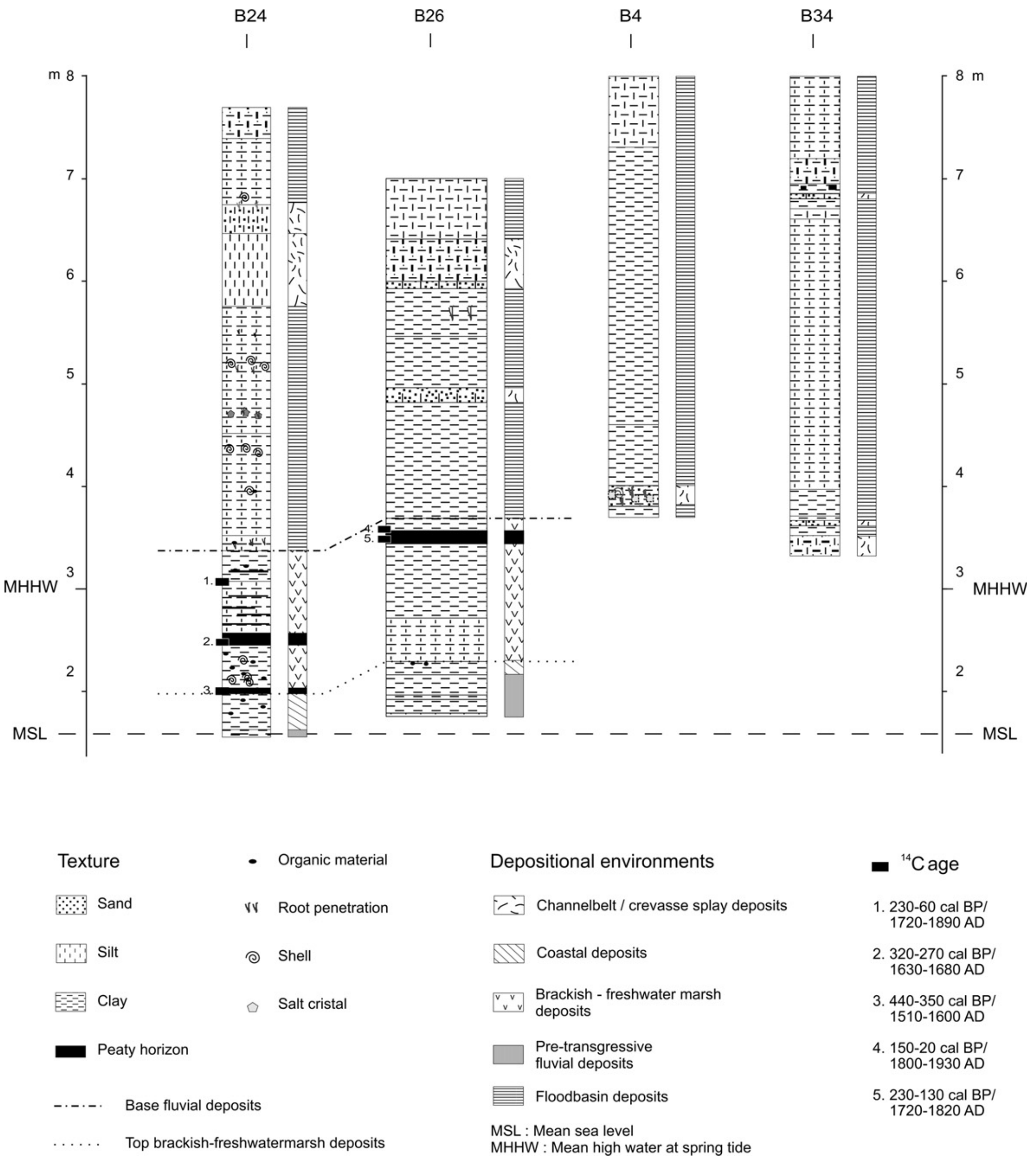

Fig. 7. Stratigraphic profile with indication of the depositional environments of cores located along the downstream part of channel belt Kh3b. Sediment textures are based on field descriptions. The location of boreholes is given in Fig. 3.

abandoning its original course along Hawiza. This dam was damaged in a flood event, and a new, stronger dam was built. Finally, in 1837, this dam was washed away, and during a single night the entire river changed its course, leaving its original bed to flow into the Nahr Hashem canal. The area irrigated by the Hawiza channel became largely abandoned, as was the city of Hawiza itself. Efforts were made to rectify this situation and a new canal, called the Mechriya, was dug above and opposite to the Nahr Hashem, but had little effect (Layard, 1846; Loftus, 1857a, b). The Karkheh shift was near contemporary with the breaking of the stone dam/bridge across the Karun at Shustar, perhaps indicative of similar unusual flood conditions, and a plague epidemic that decimated the population of Khuzestan (Rawlinson, 1839). These circumstances must have rendered direct intervention to rectify the shift less feasible.

Maps drawn by an international commission charged with defining the border between the Ottoman and Persian empires (Great Britain, Public Record Office MFQ 1/78, maps 1, 5 and 6) show that in 1912, the Kh2b channel was dry up to a place ca. 3 km upstream of Hawiza, where water from the marsh that had formed between the Kh2b and Kh3b entered the old bed. Ca. 4 km west of Hawiza, both the Kh2b (Nahr Lawi) and Kh2d (Shatt Naysan) carried water, which finally flowed out into the Hawiza Marshes.

6. Discussion

6.1. Correlating datasets – floodplain history

Based on the integration of geomorphological, geological, archaeological and historical datasets the floodplain history of the Karkheh can be reconstructed (schematic diagram Fig. 9). The Karkheh was once a tributary of the Karun as is clearly indicated by the joining of palaeochannel belts Kh1 and K2 west of Ahwaz. On the basis of historical sources, it has been suggested that the K2 channel was active from ca. the 2nd century BC (Walstra et al., 2010a). However, the exact starting date of channel activity of the K2, and as a consequence also the Kh1, is still under discussion. However, just like the K2, the Kh1 palaeochannel belt is intersected by irrigation systems that most probably date from Sasanian/Early Islamic times (Hansman, 1967; Kirkby, 1977; Walstra et al., 2010a). The latter thus provides an end-date of activity of palaeochannel belt Kh1.

Along transect 1 (Fig. 6) located along the palaeochannel belt Kh2d/3c, brackish-freshwater marsh deposits dated at 1240–1310 cal BP were found covered by fluvial deposits. The latter sets a maximum age of 1240–1310 cal BP for the formation of palaeochannel belt Kh2d, branching off from the palaeochannel belt Kh2b. This is in agreement with the distribution of archaeological sites, which suggests that the palaeochannel belt Kh2b was active at least from the Early Islamic period (1310 cal BP/640 AD). Indirectly, this indicates that the abandonment of the predecessor of Kh2, i.e. palaeochannel belt Kh1, most likely did not occur before 1240–1310 cal BP/710–640 AD.

Historical sources indicate that the area was flourishing in the 13th and 14th centuries (Mustawfi, 1915–1919: 109), and indicate that the palaeochannel belt Kh2b and extensive irrigation networks connected to it were fully active until 1837 AD/113 cal BP. In that year, the channel (Kh2b) shifted to its present-day position (Kh3b) (Layard, 1846; Loftus, 1857a, b), leaving all of the irrigation canals connected to the Kh2b channel dry. This also means that palaeochannel belts Kh2c and Kh2d, branching of from Kh2b, became abandoned in 1837 AD/113 cal BP.

The historical date of the avulsion event fits well with the geological data (transect 2 Fig. 7), showing that near Bostan, sedimentation by palaeochannel belt Kh3b started at the earliest in 150 cal BP/1800 AD. This also means that the present-day still active Kh3c channel, branching off from the Kh3b channel downstream of Susangerd, reoccupied the old bed of the Kh2d channel somewhere after 1837. Maps of the Turco-Persian Frontier Commission show that in 1912 the lower part of the Kh2b (starting from a point ca. 3 km upstream of Hawiza) and Kh2d were filled only by water coming in from the marshes in the area between the Kh2b and Kh3b branches. The same maps depict the upper part of the Kh2b as the dry, old river bed of the Karkheh. Satellite imagery shows that the palaeochannel belt Kh2b and its irrigation networks became reactivated some time after 1968 due to the construction of a canal bypassing Hamidiya.

To conclude, the period of activity of (palaeo)channel belt Kh2b and Kh3b, i.e. the period between beginning and end of overbank sedimentation by the river channels, can be estimated at ca. 1127–1197 y and 113 y, respectively (ref. 1950).

6.2. Human-induced avulsion

The Karkheh avulsion sites 1 and 2, indicated on the geomorphological map (Fig. 3), are human-induced avulsion sites and represent the loci of shifts from palaeochannel Kh1 to a more northern position Kh2b, and from palaeochannel belt Kh2b to position Kh3b, respectively.

The straight course of the palaeochannel Kh2b and the absence of palaeomeanders along its course indicate that most probably the

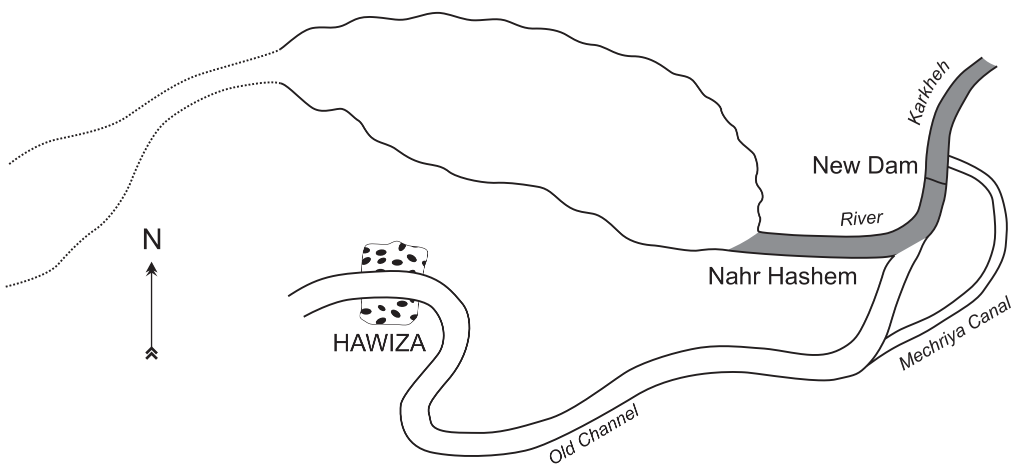

Fig. 8. Historical map showing the position of the Nahr Hashem irrigation canal upstream along the 'old channel' of the Karkheh. (after Loftus, 1857a).

channel was dug for irrigation purposes. Moreover, a network of irrigation canals perpendicular to the channel Kh2b was identified (Fig. 4), suggesting human interference. Mesopotamian farmers used the natural floodplain to their own advantage. In a single meander channel belt, natural levee-breaks and crevasse channels were ideal loci for irrigation, transforming levee-breaks into outflow points for irrigation water (Wilkinson, 2003; Morozova, 2005; Walstra et al., 2010b). Human control obstructed the natural development of the crevasse splays, which would normally enlarge during subsequent floods and develop progressively into a new avulsion belt (Smith et al., 1989; Makaske, 1998) (Fig. 10). Human control fixed the location of the main channel, thereby preventing the channel to migrate. Sometimes human management even transformed natural crevasse splays into rapidly

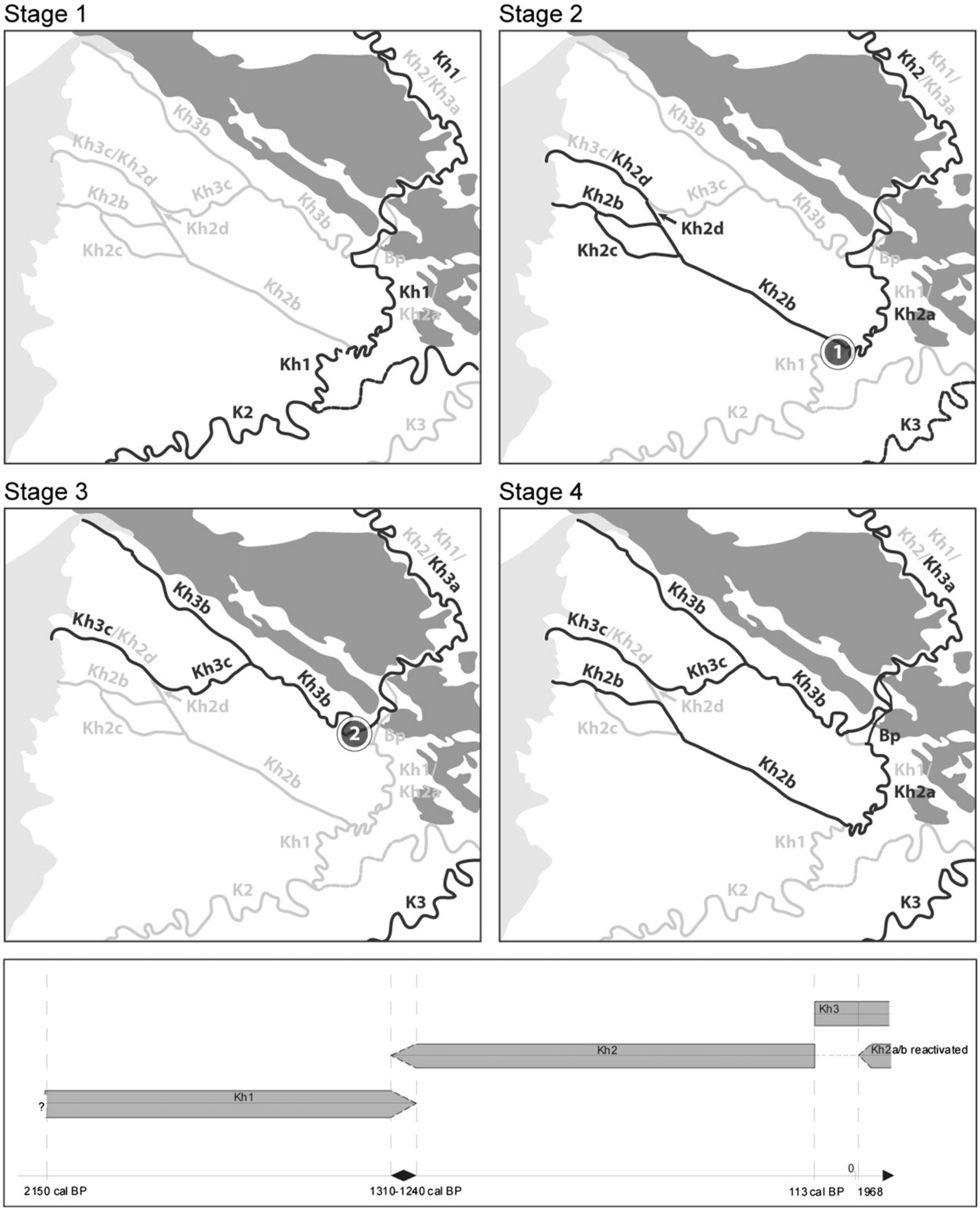

Fig. 9. Palaeogeographical scheme and estimated periods of channel activity of the (palaeo) channel belts of the river Karkheh. Stage 1: ca. 2150–1310/1240 cal BP, Stage 2: ca.1310/1240–113 cal BP, Stage 3: ca. 113 cal BP – 1968, Stage 4: ca. 1968 – present.

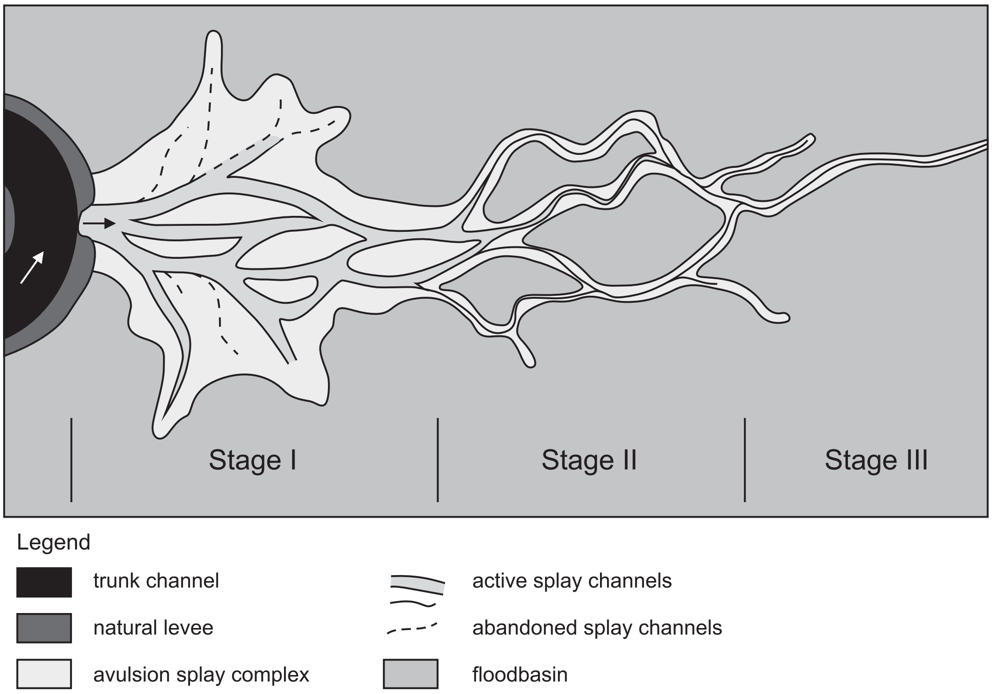

Fig. 10. Formation of a crevasse complex and an avulsion belt (after Smith et al., 1989; Makaske, 1998, 2001).

prograding irrigation lobes with very low gradients, as happened with the development of present-day Jarrahi fan in the southeast of the Lower Khuzestan plain (Walstra et al., 2010b).

Whether the levee-cut at avulsion site 1 has 'a truly natural origin' and later was converted in an irrigation outflow point remains questionable as cuts through levees may also be fully human-made. For the Khuzestan plain there is evidence from past and present times, of the creation of canals used for diverting annual excessive floodwater from the Karun and Jarrahi to marsh areas or even to the sea (e.g. the Nahr Malih and Nahr Bahre, south of Ahwaz) (Walstra et al., 2010b).

Historical data (Layard, 1846; Loftus, 1857a, b) firmly attribute the second avulsion event, in 1837, to human interference. This event eventually led to the abandonment of Kh2b and the creation of a new channel Kh3b, at present-day still active. Originally an irrigation canal, the channel now carries the entire discharge (until bankfull capacity) generated by its catchment. Avulsion was caused by a combination of land layout (i.e. a downward slope), weakening of the main river levee through artificial breaching for irrigation purposes, widening of the head of the Nahr Hashem canal due to high seasonal discharges and the high sedimentation rates. The latter resulted from an increasing gradient disadvantage of the existing channel environment compared to its surroundings. Finally a flash flood caused a total, instantaneous avulsion during one single night.

7. Conclusion

Given the limited accessibility to the study area, the paucity of data makes that any reconstruction of the Karkheh floodplain or study of avulsion threshold conditions and triggers presented in this study should be regarded as preliminary results. Nevertheless, the combination of geological, geomorphological, archaeological and historical data indicated that human activity (i.e. the construction of irrigation canals) next to discharge variations, aggradation rates and gradient advantages, must have played an important role on the floodplain history of the Karkheh.

In this study it is documented that during the past 2000 years the river Karkheh shifted at least two times. The first avulsion represents the shift from the Karkeh channel Kh1, a tributary of a Karun palaeochannel, to a more northern position Kh2b, flowing in a direction parallel with the Awaz anticline. This avulsion did not occur before 1240–1310 cal BP/710–640 AD. The second avulsion of the Karkheh, to its present-day position Kh3b, is clearly documented in historical sources. The avulsion took place during a single night event in 1837 AD. Recently (shortly after 1968), the abandoned palaeochannel belt Kh2b and its irrigation canals became reactivated due to the construction of a bypass canal.

Avulsion in the Lower Khuzestan plain was strongly influenced by human interference. However, other autogenic and allogenic factors such as tectonics, substrate composition, climate change etc. also may have played an important role. Unfortunately, there is insufficient data available to evaluate the effects of all factors. Further studies on the avulsions in Lower Khuzestan need to take a broader approach and should incorporate also these factors. A more thorough understanding of these factors will help to study the significance of the Karkheh channel changes on the development of regional river system in this part of the world.

This multidisciplinary study provides an important asset to Near Eastern landscape research and gives insights into short-time river variability within semi-arid regions.

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