Susa and Elam. Archaeological, Philological, Historical and Geographical Perspectives

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GEOARCHAEOLOGICAL RESEARCH IN LOWER KHUZESTAN: STATE OF THE ART*

V.M.A. Heyvaert,** P. Verkinderen† and J. Walstra††

1. Introduction

Up to now, geoarchaeological research in the Mesopotamian region has primarily focussed on the evolution of the floodplain of the 'twin rivers,' Tigris and Euphrates, and Upper Khuzestan, because remains of the great ancient civilizations have been discovered in these two areas. For the Lower Khuzestan plain such information is still lacking. Within the framework of the Belgian Interuniversity Attraction Pole 'Greater Mesopotamia: Reconstruction of its Environment and History' (IAP 6/34, and its predecessor IAP 5/14), research was initiated on the landscapes of Lower Khuzestan (Fig. 1). The main goal of this research project is to investigate the history of human-environmental interactions, i.e. how humans adapted to and/or changed their environment. The multidisciplinary team covers a wide range of research fields, including geology, archaeology, history and remote sensing.

In 2004, with the cooperation of Iranian colleagues, two field campaigns in the Lower Khuzestan plain were undertaken to collect geological and archaeological data. In addition, field control was done to verify the remote sensing data. The data from these surveys were published in a number of progress reports in the journal *Akkadica* (Baeteman et al. 2004/2005; Gasche/Paymani 2005). This paper presents an overview of the research carried out since then, including new evidence on the Holocene palaeoenvironmental evolution of the plain, in particular the positions of the Persian Gulf coastline and the main rivers. The reconstruction is based on the analysis of the geological and archaeological data collected during the field campaigns in 2004, and new evidence derived from textual sources, maps, satellite images and aerial photographs. It concerns mainly the integration of the results of three recently completed PhD studies (Heyvaert 2007; Ooghe 2007; Verkinderen 2009) and additional remote sensing data (Walstra et al. 2011). By means of a number of case-studies, the different datasets were integrated with a recently completed geomorphological map (Walstra et al. 2010a–b; Heyvaert et al. 2012). The case-studies provide new insights into the complex human-environmental interactions in the plain, and demonstrate the added value of a multidisciplinary approach in such studies.

* The research was undertaken within the framework of the Interuniversity Attraction Pole "Greater Mesopotamia: Reconstruction of its Environment and History" (IAP 6/34), funded by the Belgian Science Policy. All Landsat and CORONA data are available from the USGS; the CORONA imagery of mission 1045–2 was provided by the Center for Ancient Middle Eastern Landscapes, University of Chicago; the SPOT5 images were provided by the Belgian Earth Observation Platform. Mina Alizadeh, Beshad Askari, Dariush Baratvand and Abdol Reza Paymani of the Iranian Culture Heritage Organization in Ahwaz, and Hermann Gasche are thanked for their support during the two field surveys in 2004. Mark Van Strydonck has provided the calibration of the radiocarbon datings. Cecile Baeteman and Henk Weerts are thanked for the many discussions. Olivier Wambacq is thanked for the skillful production of Figures 7 to 11. This paper is a contribution to the INQUA Commission on Coastal and Marine Processes.

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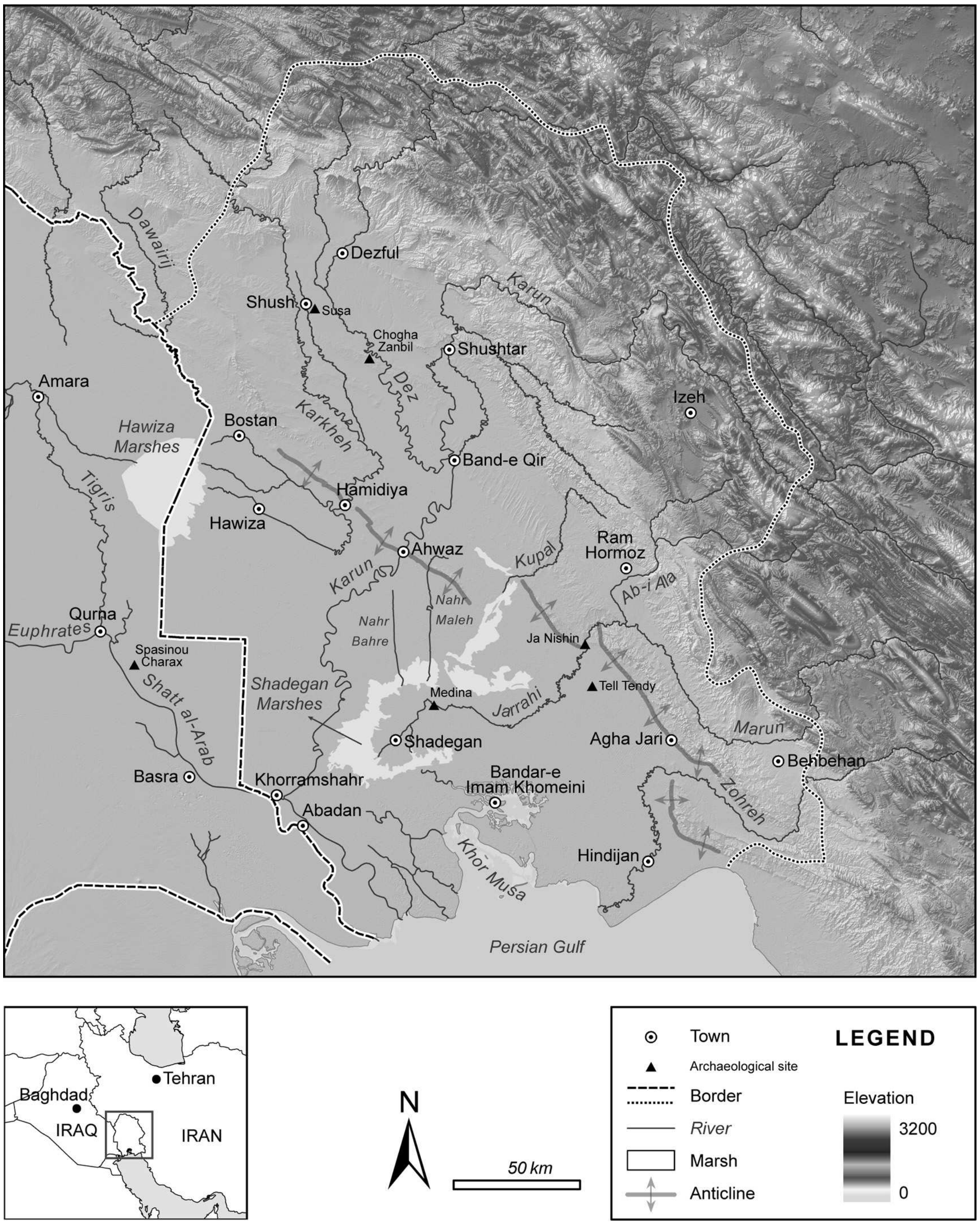


Fig. 1. Location map of the Khuzestan plain.

2. Regional Setting

The Khuzestan plain is located in southwestern Iran and geologically forms the southeastern extension of the Mesopotamian sedimentary basin. In the north and east the plain is bordered by foothills of the Zagros Mountains, in the south by the Khor Musa tidal inlet and Persian Gulf, and in the west by the Tigris and Shatt al-Arab estuary (Fig. 1) Subsidence of the Mesopotamian basin and uplift of the Zagros Mountains are associated with the collision of the Arabian and Eurasian tectonic plates (Haynes/McQuillan 1974; Audley-Charles et al. 1987; Vita-Finzi 1979). The orogenesis started during Late Miocene and is still ongoing (Hessami et al. 2006).

The Khuzestan plain is bisected from northwest to southeast by a series of anticlines: the Ahwaz, Marun, Agha Jari and Rag-e Safid anticlines. This paper focuses on the extremely flat lower half of the plain (c. 28,500 km^2). Five perennial rivers coming down from the Zagros Mountains drain into the lower plain: the Karkheh, Karun, Kupal, Jarrahi and Zohreh. Only the Karun and Zohreh reach the Persian Gulf, while the others empty into the Hawiza and Shadegan Marshes. The rivers receive most of their discharge from autumn and winter rains in the mountains, which cause extensive seasonal flooding of the marshes and changes in vegetation density.

The present coastline of Lower Khuzestan is shaped by a tidal regime. The tidal range averages c. 3–4 m along the coastline, increasing up to 5–6 m inside the Khor Musa tidal embayment (Höpner 1999; Admirality Tide Tables 2005). At the city of Khorramshahr, located 50 km upstream on the Shatt al-Arab estuary, the tidal amplitude averages c. 1 m. The coastline is fringed by large tidal flats, salt marshes and sabkhas. There is no freshwater inflow in the intertidal area, except in the case of extreme flood events.

The climate of Khuzestan is generally hot and arid, but some climatic division can be made in relation to the general relief. Lower Khuzestan falls within the arid zone with annual rainfall below 200 mm; towards the north and east rainfall amounts rapidly increase with height (Potts 1999). In summer temperatures may rise up to 58.9°C, while in winter they may fall below zero (Johnson 1973: 19–20; Potts 1999).

3. Previous Palaeogeographical Research

3.1. *Position of the Persian Gulf Coastline*

Since the early nineteenth century, historians and geomorphologists have debated the Holocene evolution of the Lower Mesopotamian plain, based on archaeological data, historical sources and surface observations. These early investigators were interested in the changes in the position of the Persian Gulf shoreline as a result of the postglacial sea-level rise.

The earliest theories claimed that the head of the Gulf shifted far north of its present position, followed by a gradual retreat of the Gulf caused by delta progradation*[1] during prehistoric and historic ages. Beke (1835) placed the northern limits of the Persian Gulf inland of the Mesopotamian plain as far as Samara (100 km north of Baghdad). Ainsworth (1838) presented reports of a geological reconnaissance in southern Mesopotamia and suggested that the front of the delta had prograded over a distance of 112 km to its present position. De Morgan (1900) produced two maps (325 BC and 696 BC) based on accounts and reports from historical sources (cf. Fig. 38 A and B in Baeteman et al. 2004/2005). The maps show the presumed position of the former coastline of the Persian Gulf between the cities of Basra and Amara.

Lees and Falcon (1952), on the contrary, challenged the nineteenth century concepts, and claimed that there was no evidence for the occurrence of an extensive marine flooding followed by delta progradation since the early Pliocene. The authors suggested a delicately balanced system between subsidence (neotectonic effects) and sedimentation on occasion of local marine inundations. Nevertheless, they reported sediments containing marine and estuarine shells found in the subsoil of the plain as far inland as Amara. The same authors also invoked subsidence caused by neotectonic movements to explain the flooding of the Sasanian (220–640 AD)

[1] Geological and geomorphological terms marked with * are explained in the appendix.

and Abbasid (758–1258 AD) irrigation canals nearby the present-day Khor Zubair (Iraq) and Khor Musa tidal embayments (Fig. 1). The formation of the Khor Musa tidal area was attributed to local subsidence and interpreted without further precision as being very young. Hudson et al. (1957) agreed with the views of Lees and Falcon (1952), contradicting their own identification of a landward extending Holocene marine unit (Hammar Formation) underlying the fluvial deposits of the Shatt-el Arab region.

The tectonic scenario as claimed by Lees and Falcon (1952) has been strongly criticised in the 1970's (Purser 1973; Larsen/Evans 1978; Evans 1979). These authors asserted that the Shatt-el Arab region has been more influenced by eustatic sea-level changes and deltaic progradation than by tectonic events. Macfyden and Vita-Finzi (1978) suggested on the basis of faunal evidence and the presence of the Hammar Formation that a marine embayment extended as far inland as Amara, followed by an overall delta progradation over a distance of about 150 to 180 km during historical times. Later research carried out in the Persian Gulf area also supported the view that Holocene sea-level changes controlled the evolution of the Shatt-el Arab region, rather than tectonics (Rzoska 1980; Ya'acoub et al. 1981; Purser et al. 1982; Al-Zamel 1983; Al-Azzawi 1986; Sanlaville 1989; Baltzer/Purser 1990; Aqrawi 1993; Aqrawi/Evans 1994; Lambeck 1996; Aqrawi 2001; Sanlaville 2002; Dalongeville/Sanlaville, 2005).

In literature, little is known about the post-glacial evolution of relative sea level (RSL) in the Persian Gulf. According to the RSL curve of Dalongeville and Sanlaville (1987) it is assumed that sea level rose progressively in the Gulf basin from 14,000 years BP onwards. Their reconstruction shows a particularly rapid rise between 9000 BP and 6000 BP, reaching a maximum at c. 4300 BP of at least one or two meters above the present-day level, followed by a gradual sea-level fall, upon which some oscillations are superimposed. Dalongeville and Sanlaville (1987) identified four sea-level highstands (transgressions*) during the period 6000–1000 cal years BC and four sea-level lowstands (regressions*) during 4500–200 cal years BC. Moreover they suggested that the maximum amplitude of RSL change in the period 6000–1000 cal years BC averages 2.5 to 3 m. The indicative meaning and age of the sea-level index points used by Dalongeville and Sanlaville (1987) for the reconstruction of the fluctuating RSL curve has been critically reviewed by Heyvaert and Baeteman (2007).

Sanlaville (1989, 2002) and Dalongeville and Sanlaville (2005) proposed a new general scheme for the evolution of Lower Mesopotamia on the basis of their previously published RSL curve. The authors produced three palaeogeographical maps showing the position of the Persian Gulf shoreline at c. 4300 BC, during the Hellenistic period (c. 323 BC) and the Medieval period (10th century AD), respectively. They concluded that the presumed shoreline of the Persian Gulf at the post-glacial maximum (4300 BC) extended as far as the present-day towns of Nasiriya, al-Amara and Ahwaz; in Lower Khuzestan the marine transgression was halted by the series of anticlines. They suggested that the post maximum sea-level period was marked by a rapid progradation of the Tigris-Euphrates-Karun delta, but they also mentioned that they did not know when the Gulf reached the position of its present shoreline. They proposed that during the Hellenistic period (323–140 BC) the coastline was located south of the present-day one, with a RSL at about one meter below the present-day level as demonstrated in Bahrein and Failaka (Dalongeville, 1990). Based on the latter, Sanlaville and Dalongeville rejected the map (325 BC) proposed by De Morgan (1900). Already in 1978, Hansman (1978b) contradicted De Morgan (1900) and considered that the southern limit of the Mesopotamian delta was very near to the present one during Hellenistic period. Hansman (1978b) claimed, on the basis of historical texts, that the Persian Gulf coastline has not changed appreciable since the Hellenistic period. On the contrary, Sanlaville (2002) and Dalongeville and Sanlaville (2005) claimed that since the Hellenistic period the coastline did not remain stable and proposed a Medieval (10th century AD) RSL high stand, which implies an inland extension of the Gulf as far as the present-day city of Abadan. Between Basra and Kufa, the authors drew an extensive marsh, which developed due to a rising groundwater table, associated with the RSL rise. The extent of this marsh and the landward limit of the Gulf are based on Arabic texts, as analysed by Le Strange (1905).

It should be mentioned that for Lower Khuzestan, the reconstruction of the coastline by Sanlaville (2002) and Dalongeville and Sanlaville (2005) is not based on geological data. Therefore, the lateral extent of the Holocene marine deposits in the subsoil of the vast plain was not accurately known. The only indication of marine deposits was reported by Thomas (quoted in Lees and Falcon 1952: 34) who found marine and estuarine deposits north of Bandar Shahpur (now Bandar-e Imam Khomeini).

3.2. *Position of the Rivers*

In previous studies, relatively little attention has been paid to the evolution of the alluvial systems of Lower Khuzestan. A first notion comes from Lees and Falcon (1952), who during their geological investigations in Khuzestan noted a "large deltaic fan", which was deposited by the Jarrahi river before it was deflected westwards into the Shadegan Marshes. From aerial photographs they also observed old irrigation networks (described as "long fingers" and "herringbone patterns") extending into the tidal flats of the Khor Musa embayment.

Based on aerial photographs and field observations, Hansman (1967, 1978a) used the position of (former) river courses and archaeological sites to identify the position of major settlements recorded in historical sources. He was the first one to describe meander patterns of an abandoned river across the plain between Ahwaz and the Shatt al-Arab. Hansman attributed the meanders to a former course of the Karkheh and used it to identify the ancient city of Spasinou Charax (Fig. 1), which according to classical sources was located at the junction of the Karkheh and the Tigris.

Kirkby (1977) was mainly interested in the palaeorivers of Upper Khuzestan as indicators for past water resources and included the northern part of Lower Khuzestan in his analyses. He credited Hansman's meander traces to a combined Karun-Karkheh flow, based on the relationship between meander wavelength and bankfull discharge (though Hansman's identification of Spasinou Charax remained undisputed). Without further reference, Kirkby dated the river course at some period between 1500 BC and 1200 AD, after which the Karun shifted to a position at or near the present one and the Karkheh shifted twice towards positions further north. Hansman and Kirkby both mentioned traces of extensive irrigation canals, which apparently derived water from the abandoned river course, and dated them to the Sasanian and Early Islamic periods.

Although strictly outside our area of interest, some of Kirkby's work in Upper Khuzestan may be of significance to this study as well. At least for the Karkheh, Karun and Dez rivers in Upper Khuzestan he provided evidence for a phase of continuous river aggradation* (since c. 8000 BC) followed by a phase of down-cutting (after c. 2000 BC). His evidence was based on a series of dated levels of cultural material in excavated mounds, which were (partially) buried beneath alluvium and subsequently incised by rivers. Although this same sequence of events was previously used as an argument for tectonic movements (Lees/Falcon 1952), Kirkby attributed it to increasing aridity and grazing intensity throughout the Holocene.

In more recent work, the present-day Karun channel was recognized as the main channel of a large alluvial fan with a radius of about 100 km. It is one in a series of many alluvial fans flanking the external parts of the Zagros Mountain belt (Baltzer/Purser 1990).

Final contributions were presented in the *Akkadica* progress reports. A preliminary analysis of satellite imagery confirmed the presence of the (known) former Karun and Karkheh river courses and irrigation canals in the central plain. In addition, three detected alluvial fans were attributed to the Jarrahi; two being relict and the other currently active (Baeteman et al. 2004/2005). A thorough review of pre-Islamic historical sources by Cole and Gasche (2007) resulted in the attribution of many ancient toponyms to current or abandoned river courses. Interestingly, they embraced Kirkby's idea of a combined Karun-Karkheh flow, as it provided the perfect explanation for the persistent confusion between Karun and Karkheh nomenclature throughout history.

4. Current Work: Methodology and Datasets

The present research follows a multidisciplinary approach, drawing on data from different research fields, including remote sensing, geology, archaeology and historical geography. Based on the interpretation of satellite data, a geomorphological map was drafted (Fig. 3), presenting the distribution of past and present landforms and providing a spatial framework for the information derived from the other disciplines.

The geological dataset is based on fieldwork carried out during two Belgian-Iranian field campaigns in 2004 (cf. Baeteman et al. 2004/2005; Heyvaert 2007), which involved the facies analysis of the sedimentary sequence of hand-operated boreholes and outcrops. During the same missions archaeological fieldwork was carried out, encompassing the survey of ancient settlements and resolving their age based on datable ceramics. The results of the archaeological field campaign, combined with an overview of earlier archaeological data, were published by Gasche and Paymani (2005) and are summarized below for convenience. 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. 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 (Verkinderen 2009) and (2) European travel literature and cartography, dated between the 16th and the early 20th century AD (Ooghe 2007; Verkinderen 2009). Throughout the research, a Geographical Information System (GIS) was used for integration and interpretation of the project data.

4.1. *Remote Sensing Data and Methodology*

Given the vast size and limited accessibility to the study area, the use of remote sensing data is crucial for obtaining a full appreciation of the landscape. A variety of resources was exploited, differing in terms of footprint, ground resolution, spectral capability and acquisition time. Although aerial photographs provided guidance in the field, an attempt to use them for systematic archaeological prospection proved not very fertile (unpublished data Dupin). The available satellite imagery provided insufficient spatial detail for the detection of archaeological sites, but on the other hand proved very helpful for creating a geomorphological map and as a tool for quantifying (short-term) landscape changes. All image processing tasks were performed using standard functions in ERDAS IMAGINE software; image interpretation and mapping procedures were carried out in ArcGIS.

Table 1: Remote sensing data used in this study.

Sensor	Acquisition date	Scene IDs	Number of bands	Resolution	Comments
CORONA KH-4A: mission 1035–1	23/9/1966	Revolution 040D, frames F10–22	1	c. 3 m	Acquired from USGS
CORONA KH-4A: mission 1039–1	27/2/1967	Revolution 072D, frames A63–65	1	c. 3 m	Acquired from USGS
CORONA KH-4A: mission 1045–2	5/2/1968	Revolution 182D, frames A69–72, F75–84	1	c. 3 m	Provided by CAMEL
HEXAGON KH-9: mission 1216–5	15/9/1980	Operation 359, frame 4	1	6–9 m	Acquired from USGS
Landsat MSS	3/6/1973 & 26/7/1975	Path 178, row 38/39	4	60 m	Multispectral Scanner
Landsat TM	31/8/1990	Path 165, row 38/39	7	30/60 m	Thematic Mapper
Landsat ETM+	28/7 & 4/8/2001	Path 165/166, row 38/39	8	15/30/60 m	Enhanced Thematic Mapper Plus; wet season
Landsat ETM+	20 & 27/1/2002	Path 165/166, row 38/39	8	15/30/60 m	Idem; dry season
Landsat ETM+	12 & 28/3/2009	Path 166, row 39	8	15/30/60 m	Idem; combined SLC-off images
SPOT5	21/8/2004 & 22/6/2006	Path 146 & 147, row 287	3	2.5 m	Provided by BELSPO
Google Earth (QB) Google Earth (SPOT)	2003–2007 2008–2009		3 3	0.6 m 2.5 m	Variable quality & acquisition date
Aerial photographs	1950s/1993	2/73 frames	1	c. 0.4/1.6 m	No stereo-pairs
SRTM	11–22/2/2000	Tile 46_06	N/A	90 m	DEM

4.1.1. *Data Sources*

The multispectral Landsat missions are particularly suited for geomorphological mapping at a regional scale. In spite of recent developments in satellite sensor technology Landsat remains a significant resource for geomorphologists due to its repeat coverage, large scene size and low cost (Smith/Pain 2009). Drainage and vegetation patterns are important indicators to distinguish between landform units and these can be best accentuated in the near infrared region of the electromagnetic spectrum (Lillesand/Kiefer 1994). Therefore, false-colour composites were created from the raw image files. The ETM+ scenes were subject to further processing—using the panchromatic band the image ground resolution was enhanced to 15 m. Because the images have a high level of geometric accuracy (Gutman et al. 2008), no additional corrections needed to be applied.

CORONA images were acquired by the first generation of US photo-reconnaissance satellites between 1959 and 1972. They were declassified in 1995 and have been successfully used in geoarchaeological studies throughout the Near East (e.g. Philip et al. 2002; Ur 2003; Hritz 2010). Their main advantage is to provide a record of the landscape before many elements were destroyed by modern, large-scale cultivation. Drawbacks are the large image distortions due to the oblique and panoramic camera geometry. Because GPS surveying for precise ground control is not a realistic option in Lower Khuzestan due to security restrictions, a rigorous geometric correction of the images could not be carried out. Instead, CORONA image patches of 5.5 × 10.5 cm (corresponding to c. 18 × 36 km on the ground) were individually geo-referenced, based on control points obtained from the Landsat imagery. The CORONA images used in this study are from KH-4A missions, with a best ground resolution of c. 3 m. An image from a later photo-reconnaissance program (HEXAGON, mission KH-9), with lower ground resolution, was also acquired.

The acquired high-resolution imagery includes a set of digitally scanned aerial photographs and two SPOT5 scenes. The aerial coverage consists of black-and-white photographs with a scale of c. 1/39,000, scanned at 600 dpi (resulting in a ground resolution of c.1.6 m); unfortunately no stereo-pairs were available and the coverage is rather limited. The SPOT5 scenes are false-colour near infrared composites with a ground resolution of 2.5 m. As an additional source, Google Earth provides free imagery of the study area; although the imagery has (at least partly) a high resolution, the image quality is inferior to original source data.

A last relevant data source consists of elevation data produced by the Shuttle Radar Topographic Mission (SRTM). This is the best resolution digital elevation model (DEM) with worldwide coverage (ground resolution is 90 m), and the most reliable elevation data available for the study area. SRTM data have been used previously for the detection of alluvial ridges in the Central Mesopotamian plain (Hritz/Wilkinson 2006).

4.1.2. *Geomorphological Mapping*

A geomorphological map presents information about the form, origin, age and distribution of landforms and their formative processes, rock type and surface materials (Brunsden et al. 1975). It helps the understanding of individual landforms and the landscape as a whole.

A geomorphological survey traditionally involves a preliminary interpretation based on aerial photographs, followed by "groundtruthing" in the field. Photo-interpretation involves the identification of surface features based on their characteristic morphology, vegetation and drainage conditions. Due to restrictions of available material and field access (observations were done during the two field campaigns, but not in a systematic way), an unconventional approach was adopted, based on the interpretation of a variety of remote sensing data that are easily accessible and inexpensive (notably Landsat & CORONA imagery).

A standardized working procedure was developed for the consistent mapping of the alluvial landscapes of Lower Khuzestan (Walstra et al. 2011). In line with the motivations for this research project, the map legend distinguishes at the highest levels on the basis of landform genesis and chronology. As the landscapes have been subject to prolonged human activity, man is considered as an important agent. The original map sheets were produced at a scale of 1/100,000 but a downscaled version is included here.

4.2. *Geological Data and Methodology*

During two fieldwork campaigns in 2004, 52 hand-operated cores were collected to a depth of 5–10 m below the surface and 3 shallow outcrops were investigated (Fig. 2). The location of individual boreholes was recorded with a handheld GPS device. Elevations were derived from topographical maps and site-specific measurements obtained at the regional topographic institute. In the field, a detailed facies description was done on the basis of lithology, sedimentary structure (massive, tidal bedding, laminated, bioturbation, sharp or gradual contacts), presence of plant remains, gypsum and salt crystals, and macrofossils. A limited number of subsamples were taken for laboratory analyses, i.e. palaeoecological analyses (foraminifera and diatoms*) and radiocarbon dating (organic material and shells).

The facies interpretation (i.e. at environmental level) was done on the basis of its context (in relation to neighbouring facies) along geological transects. Knowledge of the context of a facies, that is, the relationship of one facies to another, is essential before proposing an environmental interpretation as a single facies can occur in different sedimentary environments. The facies analysis of the Holocene sequence enabled identification of three sedimentary units: fluvial (unit 1), coastal (unit 2; sub/intertidal*[2] and supratidal* subunits) and brackish-freshwater marsh (unit 3). A more detailed description of the lithological and palaeoecological properties of these units is given in Heyvaert (2007) and Heyvaert and Baeteman (2007).

Radiocarbon dates were obtained from organic material (Table 2) and provide a chronological framework for the palaeogeographical reconstruction. Calibrated dates are given with a 2 sigma error range in calendar years before present (cal BP*). Calibration was completed using the calibration programme of Stuiver and Reimer (1993).

Table 2: AMS radiocarbon data and calibrated ages.

Site	Geographical coordinates	Laboratory code	Age ^{14}C yrs BP	Calibrated age yrs cal BP	Sample altitude	Dated material
B5	31°20'43" 47°53'04"	KIA-24461	3270±30	3580–3390	+0.65	organic gyttja
B6	31°01'11" 48°12'31"	KIA-24465	1655±25	1510–1630	+3.95	organic gyttja
B24	30°38'41" 48°41'50"	KIA-24490	155±25	60–230	+3.35	organic material (reworked)
B24	30°38'41" 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	peaty mud
B34	31°41'50" 48°01'45"	KIA-26474	95±20	20–140	+6.40	vegetation remnant
B39	31°34'37" 47°57'59"	KIA-26481	1350±25	1240–1310	+1.10	organic gyttja
B44	31°24'43" 47°53'18"	KIA-26719	7935±35	8980–8630	+0.90	peaty mud
B49	31°18'07" 47°58'45"	KIA-27131	450±25	483–530	+4.75	peaty mud
B51	31°39'59" 48°37'19"	KIA-26480	280±20	350–430	+2.75	organic gyttja
B54	30°47'44" 48°12'00"	KIA-26482	6980±35	7710–7880	-3.70	roots
B54	30°47'44" 48°12'00"	KIA-26746	7275±35	8170–8010	-3.80	fine roots
B54	30°47'44" 48°12'00"	KIA-26747	7085±35	7980–7840	-5.40	peaty mud

[2] Geomorphological and geological terms marked with * are explained in the appendix.

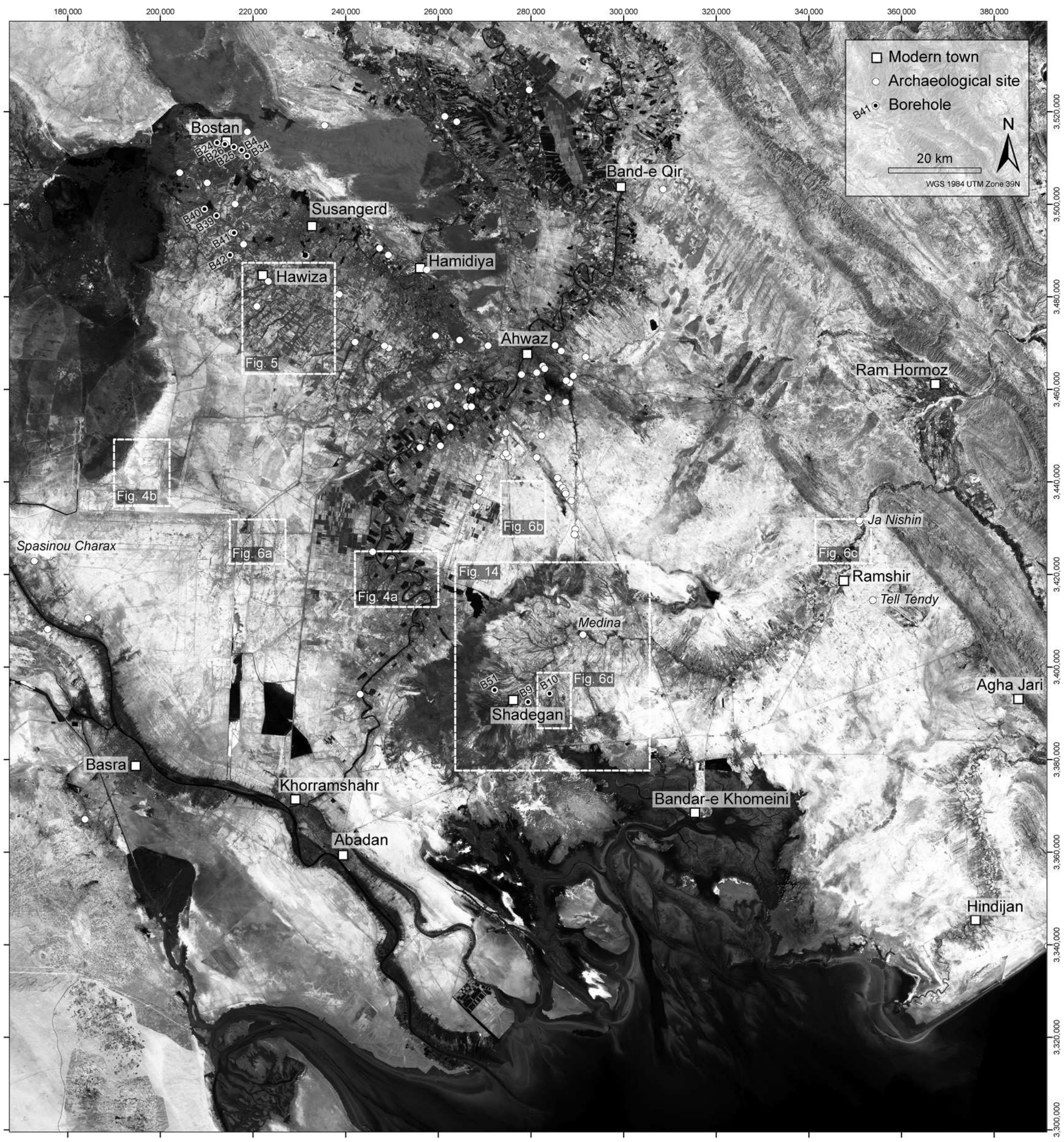


Fig. 2. Landsat ETM+ image mosaic of Lower Khuzestan with the location of archaeological sites, geological boreholes and areas covered by Figures 4–6 and 13. The imagery was acquired in July/August 2001 and is displayed as a near-infrared colour composite (band combination 4/3/2, converted to greyscale).

4.3. *Archaeological Data*

Only limited archaeological information about the Lower Khuzestan plain is available (Fig. 2); archaeological research in Khuzestan has tended to focus on the upper part of the plain, where the older settlements can be found.

The Dutch engineer Graadt van Roggen (1905) surveyed the water works of Khuzestan in preparation of an (aborted) Persian government project that aimed at restoring agricultural wealth to the impoverished province. Most of these were located in the northern part of the plain, the southernmost being the dam at Ahwaz.

The most extensive settlement survey in the lower plain was carried out by McCown in 1948, who recorded 44 sites in the vicinity of Ahwaz and Hawiza. These consisted only of sites visible from motorable roads, and the material was left unpublished for almost four decades (ultimately published by Alizadeh 1985). Based on surface finds of pottery most sites were attributed to Sasanian (c. 221–640 AD) or Islamic (after c. 640 AD) times, and a few to the Seleucid (c. 312–140 BC) and Parthian (c. 160 BC – 221 AD) periods.

Further significant information is provided by Hansman, who surveyed the region of the Jarrahi river (Hansman 1978a), and identified the ruins of Naisan with the ancient city of Spasinou Charax along an abandoned course of the Karun and the Tigris (Hansman 1967). Kirkby (1977) mentioned extensive canal systems of Sasanian or Early Islamic age extending from the same former Karun course.

The sum total of these investigations provides a rather limited and geographically biased distribution of archaeological sites. In the course of this project, a limited survey of Lower Khuzestan was conducted which revisited some of McCown's sites and noted another 15 "new" sites (Gasche/Paymani 2005). These sites were all occupied between the Seleucid and Islamic periods, corroborating earlier findings suggesting that the plain had its heyday during the Sasanian and Early Islamic periods and earlier sites are rare (Adams 1962; Alizadeh 1985). A comprehensive and systematic survey of the Lower Khuzestan plain is still wanting.

The geomorphological map (Fig. 3) shows the location of the archaeological sites surveyed in the framework of this project (after Gasche/Paymani 2005).

4.4. *Texts and Historical Maps*

Textual information on the alluvial landscapes of Lower Khuzestan is very sparse before Islamic times. No textual data exist prior to 1200 BC, and between this date and the Islamic conquest, most of the information derives from two short periods of external military expeditions into Khuzestan.[3] These pre-Islamic sources have been studied numerous times, most recently by Cole and Gasche (2007). Limited additional information, from the 3rd century AD onwards, is furnished by the records of the Oriental Syrian churches (Fiey 1969, 1970) and a number of Sasanian seals (Gyselen 1989, 2002).

From the 9th century AD onwards, these sources are overshadowed by a large corpus of Arabic texts (more than 100 works have been used in our research) from different genres that provide information about the landscape of Khuzestan, among others:

- "Road books": geographical works that focus on routes and imperial geography
- works of mathematical geography, continuing the Hellenistic tradition of Ptolemy
- "marvel literature" that focus on wonders, from strange creatures like unicorns and elephants to volcanoes
- geographical dictionaries commenting on place names mentioned in the most famous Arabic literary works
- travellers who describe their journeys in varying detail; often first-hand information
- historiographical works; wars and rebellions prove to be especially fecund grounds for the survival of geographical information

[3] The regular military campaigns by the Neo-Assyrian empire against Chaldean and Aramean tribes in Southern Iraq and Khuzestan (744–694 BC), as known from Assyrian inscriptions, and the activities of Alexander the Great and the war between his successors, Eumenes and Antigonus (331–316 BC), as documented in the works of Diodorus Siculus, Quintus Curtius Rufius, Plutarch and Arrian. For a full survey of sources see the appendix in Cole/Gasche 2007.

– prosopographical works, giving details about generations of scholars, poets, etc., including the places where they were born, lived and died, often with dates that can help us prove the existence of a certain place at a given time
– juristic works that contain references to places, watercourses and practices in the first century after the Islamic conquest, a period underrepresented in other sources
– collections of poems and anecdotes, and other genres

A number of these sources have been used in the past to reconstruct the lands of the eastern Caliphates (Le Strange 1905) and Iran (Schwarz 1896), but these reconstructions suffer from a number of shortcomings, which render them all but useless for scientific purposes. The most important problem is the fact that they are very superficial and do not take into account the shortcomings of these sources:

– *uneven distribution of the sources over time*: a few of the earliest works date from the 8th century, but the bulk of our knowledge comes from 10th-century works. After the 13th century, very few important sources were found. Information from these sources can be extrapolated to earlier and later times under some conditions. This is made more difficult by the
– *authority-based structure of early Islamic science*: information from trusted sources is quoted time and again for centuries, regardless of the question whether the information was still valid or not. This problem becomes more and more pronounced in the later centuries, because layer after layer is added to the accumulation of "knowledge". This often gives rise to
– *contradictory reports, both inside one work and between contemporary works*: these contradictions can point to an evolution in the landscape, or to misinterpretations in the information chain; sometimes, however, apparently contradictory reports can be reconciled and proven to be complementary rather than mutually exclusive;
– *lack of documentary sources*: the descriptive nature of the Arabic sources is not only a blessing, but also a curse: in contrast to other periods in the history of Khuzestan, and other areas in the world, almost no real-life written documents from early Islamic Iraq have survived. We only have information that was filtered through the mind of a medieval author, with all the restrictions this entails.
– *selectivity*: the corpus is largely urban-centred, and contains little information about rural areas

A number of European travellers and explorers visited the wider region from the 16th century onwards, but it is only in the 18th century that these provide useful information about Khuzestan, with the rise of interest in Persia of European imperialist powers, especially Great Britain (Ooghe 2007; Verkinderen 2009).

A variety of historical maps were used in this study. The oldest are the 10th-century regional maps of the so-called Islam Atlas (al-Istakhri c. 950; Ibn Hawqal c. 970; al-Muqaddasi c. 990), which are extremely schematic, and cannot be interpreted without reference to the accompanying text. A second set of maps was made by the 12th-century geographer al-Idrisi (c. 1165) for the Norman kings of Sicily and these are equally schematic (for reproductions of all these maps, cf. Miller 1927). More detailed are the maps used by European ships on the way to India, although depictions of the study area did not become very realistic until the early 17th century, even as these maps only show the coastal strip (reproductions and commentary: Sahab et al. 2005; Couto et al. 2006). The first reliable European maps of mainland Khuzestan appear in the 19th century. A British expedition surveyed the Euphrates, Tigris and Karun rivers between 1835 and 1837 in order to assess their suitability as trade routes (Chesney 1850; Ainsworth

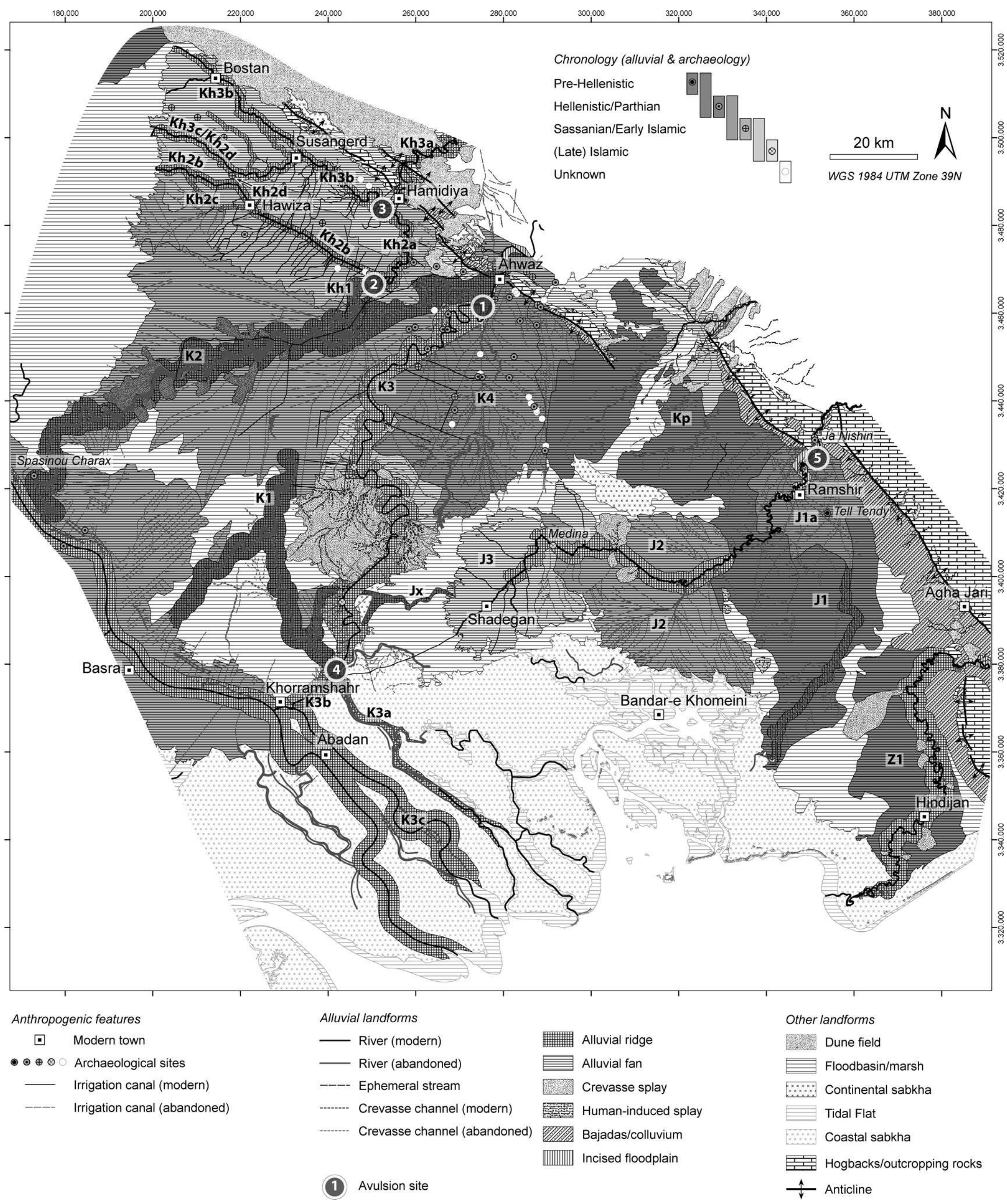


Fig. 3. Geomorphological map of the study area. The chronological order of the alluvial units is attributed according to their final stage(s) of activity. Also shown are the locations of archaeological sites and avulsions. The labels of the main river belts and fans refer to the units described in the text.

1888) and produced a detailed map of these rivers. The border area between Iraq and Iran (then the Ottoman and Persian empires) was the subject of two major international survey campaigns (in 1848–1852 and 1913–1914) in an attempt to solve border conflicts (Ryder 1925).[4]

[4] For a full overview of the textual sources and historical maps of the area used in this research, see the bibliography in Verkinderen 2009.

5. Results

5.1. *The Geomorphology*

5.1.1. *General Relief*

The Lower Khuzestan plain is extremely flat, in contrast to the rugged terrain of the adjacent anticlines. Elevation of the plain ranges from sea level to +32 m along its northeastern limits, over a distance of 60–110 km. The gentle relief is mainly the result of spatial variation in river sedimentation, with alluvial fans and ridges forming the higher grounds and floodplains representing the lower areas. All major rivers draining into the plain, except for the Kupal, have developed distinct alluvial ridges. The large brackish-freshwater marshes are positioned in the lowest parts of the plain, representing flood basins enclosed by alluvial ridges and coastal sabkhas. The main landforms are further described below.

5.1.2. *Structural Landforms*

In the northeast the plain is bordered by series of hogbacks* formed as a result of steep dipping anticlines (15°–80° according to the geological map sheets). The ridges are dissected by erosion gullies and valleys of mostly ephemeral streams, while their piedmont consists of a more or less continuous alluvial apron or bajadas*.

5.1.3. *Aeolian Landforms*

Along the entire anticlinal front sand dunes occur. They are mostly limited to small, local dune fields, except for northwest of Ahwaz, where some very large dune complexes are present. From field evidence they are known to consist of silty fine sand (Baeteman et al. 2004/2005; Heyvaert 2007). The material either derived from the nearby alluvial plain, or was blown in by dust storms from the Arabian deserts. It is yet unknown whether the dunes formed under current environmental conditions or represent relics from past times (e.g. Pleistocene), but the dune field northwest of Ahwaz is already mentioned in a 10th-century geographical work (al-Muqaddasi: 408).

Table 3: Morphological characteristics of the alluvial fans in Lower Khuzestan.

Alluvial fan	River type	Fan area (km2)	Average gradient
Jarrahi J1	Meandering	>2,500	0.0005
Jarrahi J2	Meandering/distributary	>1,200	0.0004
Jarrahi J3	Distributary	800	0.0002–0.0004
Karkheh	Anabranching	2,300	0.0003
Karun	Meandering	7,600	0.00012
Kupal	Sheetflow, meandering in past	1,200	0.0007
Zohreh	Meandering	1,500	0.0003

5.1.4. *Alluvial Landforms*

The Lower Khuzestan plain essentially consists of a series of large alluvial fans* (Baeteman et al. 2004/2005; Heyvaert 2007; Heyvaert/Weerts 2007; Table 3); based on the large size and low gradient they may be classified as megafans* (cf. DeCelles/Cavazza 1999; Leier et al. 2005). The fans are characterised by meandering river belts that episodically shift across the fan surface (a process known as avulsion*), thereby creating distinct, diverging alluvial ridges that correspond to different evolutionary stages of the fan. Meandering river belts exhibit

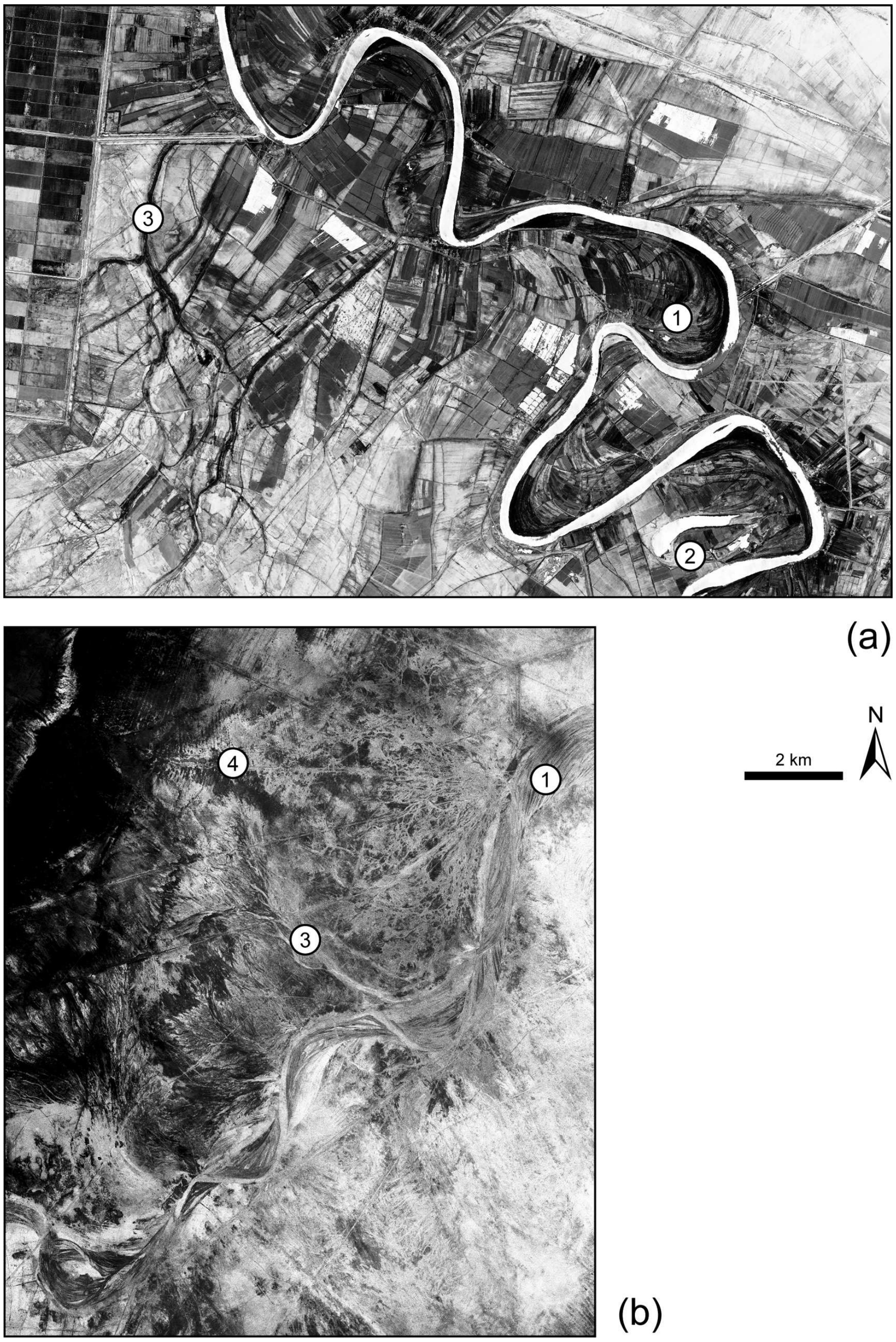


Fig. 4. SPOT5 (a) and CORONA (b) image showing characteristic elements of a meandering river, belonging to the K3 and K2 channel belts respectively: scroll-bars (1), an oxbow lake (2) and crevasse channels (3); in addition, nearby palaeochannel K2 are patterns of ancient irrigation canals visible. The SPOT5 image is a near-infrared colour composite, acquired on 22 June 2006 (scene 146–287/8, © CNES 2006, Distribution Spot Image S.A., France, all rights reserved), while the CORONA image dates from 27 February 1967 (frame DS1039–1072DA064).

some typical geomorphological elements, resulting from spatial variations in flow velocity and deposition, e.g. scrollbars*, meander cut-offs*, levees*, crevasse splays* and floodplains* (see Fig. 4).

The central Lower Khuzestan plain is occupied by the Karun megafan with its apex at Ahwaz, where the river enters the plain, and its toe 110 km downstream at the confluence with the Shatt al-Arab. Besides the present-day Karun (K3) two palaeochannel belts (K1 and K2) were identified and mapped (Baeteman et al. 2004/5; Heyvaert 2007; Heyvaert/Weerts 2007; Walstra et al. 2010b):

- Palaeochannel belt K1 is located in the south-central part of the plain and splits into two branches. It is unclear whether both K1 branches were active simultaneously or one after the other. As the traces of K1 are less distinct than K2, it is assumed to be older, but this could also be the effect of soil degradation due to frequent flooding and salinization.
- Palaeochannel belt K2 crosses the plain in west-south-western direction from the city of Ahwaz to its confluence with a former Tigris/Shatt al-Arab channel, nearby the archaeological site of Spasinou Charax. Its upper section is obscured by the urban sprawl of Ahwaz, but further downstream scrollbars and crevasse splays are clearly visible and suggest that the river was subject to dynamics similar to the present-day river (cf. Kirkby 1977).
- The upper and middle sections of the present channel (K3) display a dynamic morphology with winding meanders, abundant scrollbars and meander cut-offs (Fig. 4). Large crevasse splays occur in the middle section (and only there); their absence in the upper section may be related to the slight entrenchment of the channel. The lower section of the river consists of relatively straight segments and eventually bifurcates into two branches: the main channel, Shatt al-Haffar (K3b), discharges into the Shatt al-Arab near Khorramshahr, while the Shatt Bamishir (K3c) enters the sea independently. The "Blind Karun" (palaeochannel K3a) also branches off in south-eastern direction, parallel to the Shatt Bamishir; this channel lines up remarkably with one of the K1 branches on the other side of the present-day river channel.

It should be noted that more palaeochannel belts may be present in the subsurface, which were not detected from the satellite imagery. For example south of Ahwaz, along the Nahr Bahre, some individual meander traces were noted, largely covered by irrigation patterns and therefore without any context, which may belong to a third Karun palaeochannel (K4).

The northwestern part of the plain is dominated by the Karkheh river, entering the plain near Hamidiya. Three main channel belts (Kh1, Kh2 and Kh3) were distinguished, two of which are currently active (Baeteman et al. 2004/2005; Heyvaert 2007; Heyvaert et al. 2012):

- Traces of palaeochannel Kh1 are clearly visible before it merges with the K2 channel belt, indicating that in the past the Karkheh flowed southwards and was a tributary of the Karun (cf. Kirkby 1977).
- Another channel belt, known since its abandonment in the 1830s as the "Blind Karkheh" (Karkheh Kur, Kh2), represents a previously abandoned river course that was recently reactivated through the construction of a bypass canal near Hamidiya. Upstream it follows a meandering course (Kh2a—lined up with the earlier Kh1), but after a sharp turn it continues along a rather straight line (Kh2b) in north-western direction towards Hawiza. Traces of two abandoned channels diverting from the Kh2b are noteworthy: the Kh2c and Kh2d.

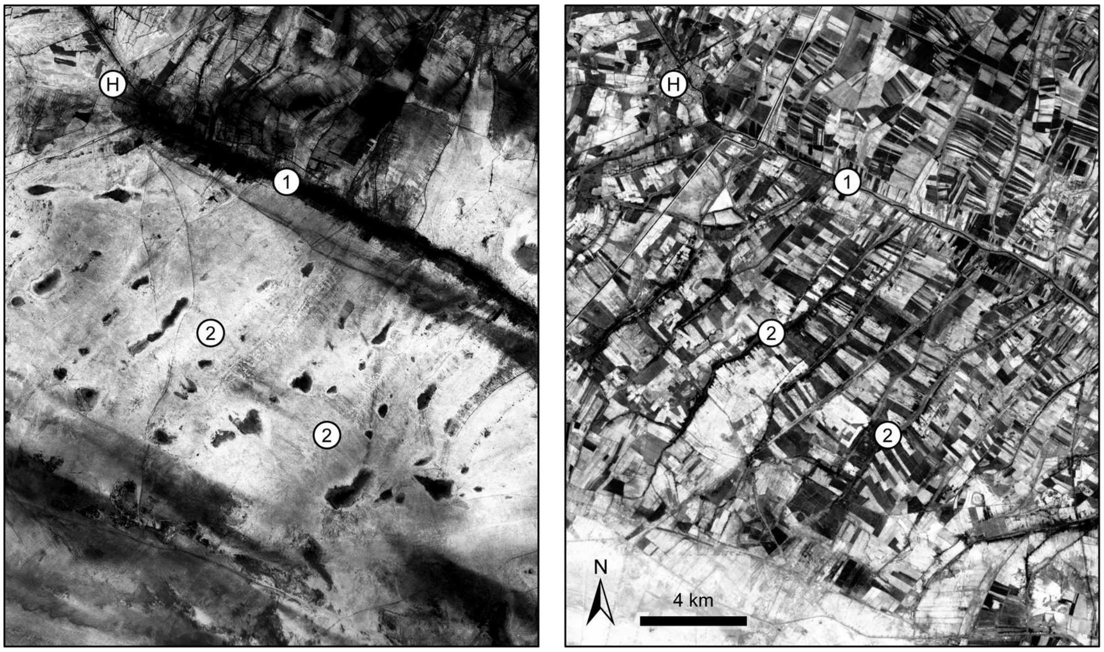


Fig. 5. Comparison of satellite imagery, revealing the reactivation of irrigation canals (2) along the Karkheh Kur/Kh2b channel (1) upstream of Hawiza (H). The image on the left shows a mosaic of CORONA scenes (mission DS1035–1040, acquired on 23 September 1966); the image on the right is a near-infrared colour composite Landsat ETM+ scene (166/38, acquired on 4 August 2001).

– The present main channel of the Karkheh (Kh3a, b) turns in north-western direction shortly after entering the plain and follows a course parallel with Kh2b and the anticlinal front, towards Bostan. Many channels/canals (both active and abandoned) branch off from the main channel, most notably the Kh3c at Susangerd. The latter seems to have reoccupied the Kh2d channel.

Further downstream many channels/canals branch off from the two main streams Kh2 and Kh3, eventually discharging into the Hawiza Marshes.

The eastern part of the plain is dominated by three alluvial fans that were successively deposited by the Jarrahi river (J1, J2 and J3). Distinction between the fans is primarily based on the layout of the river channel and irrigation patterns (Baeteman et al. 2004/2005; Walstra et al. 2010a):

– The first and largest fan (J1) stretches from the location where the Jarrahi enters the plain to the tidal flats of Khor Musa. A southwards orientated alluvial ridge can be linked to traces of a palaeochannel that continues into the tidal flats. Towards the northwest and southeast the fan merges into the adjoining fan surfaces of the Kupal and Zohreh rivers. In the upper fan section the present river has cut a 1.5 km wide valley, up to 8 m deep into the fan surface. Within this valley the Jarrahi flows through a highly dynamic anastomosing river bed, with several meander cut-offs alongside the main channel.
– The second fan (J2) is located immediately downstream of the first one. Here the river has emerged from its entrenchment and continues over an elevated alluvial ridge, raised 2–3 m above the fan's surface.
– The third and presently active fan (J3) displays a typical distributary channel system, with many bifurcating outlets branching off from the main channel. These branches ultimately

split up into small ditches, separating extremely narrow elongated fields, before draining into the Shadegan Marshes. Several crevasse splays have been identified alongside the Jarrahi, in particular near the apex of fan J3; some of them have been transformed into irrigation networks.

- To the west of fan J3 a meandering palaeochannel (Jx) crosses the Shadegan Marshes. Its levees are clearly raised above the water, but at both ends the channel is covered by recent alluvial deposits of the Jarrahi and Karun rivers.

The single meandering course of the Zohreh river is pushed to the very eastern limits of the plain, along the foot of the Rag-e Safid anticline. Besides the Karun it is the only river that reaches the Persian Gulf.

The Kupal river has created a modest alluvial fan (Kp) at its entrance to the plain between the Ahwaz and Marun anticlines. On the plain itself the river does not have a distinct channel, although some traces of palaeochannels were detected. During wet seasons the Kupal drains superficially via a broad marshy zone into the Shadegan Marshes. A similar marshy zone is present in the area between the Jarrahi and Zohreh fans, fed by ephemeral streams issuing from the Agha Jari anticline.

Towards the southwest the plain is bordered by the Shatt al-Arab estuary, which receives the bulk of sediment from the Karun river (Lees/Falcon 1952). In addition to the active channels of the Shatt al-Arab and the Shatt Bamishir, several palaeochannels are located further to the east, most notably the Blind Karun (K3a). The lower parts of these outlets now act as intertidal channels.

Throughout the plain, extensive patterns of relict irrigation systems were mapped, superimposed on the alluvial fans (Walstra et al. 2010a–b; Heyvaert et al. 2012):

- The most impressive network consists of diverging canals on both sides of the present Karun channel, south of Ahwaz. The canals radiate from two huge feeder canals, and extend up to 40 km across the plain before ending in distinct "herringbone" field patterns (Fig. 6). The traces of this network clearly intersect the K2 and Kh1 palaeomeanders (in contrast to Kirkby's interpretation who rather described them as branching off from the meanders), and completely obscure the upstream part of K1. A somewhat different layout of parallel canals is branching off at sharp angles from the eastern feeder canal (named Nahr Bahre), apparently overlying "herringbone" patterns.
- A similar, radially diverging network of canals with "herringbone" patterns covers Jarrahi fan J2.
- Dense networks of relict irrigation canals were also identified across fan J1, diverging from its apex on both sides of the incised river valley.
- The Karkheh Kh2b channel belt is characterised by irrigation canals orientated perpendicular to the main channel and typically extending over a distance of 10–13 km. This system was previously abandoned, but has been reactivated in recent times due to the construction of a bypass near Hamidiya).
- A broad zone with regular patterns of ridges at 100–120 m intervals flanks the Shatt al-Arab. Concordant field patterns are present further inland, although less distinct, maybe due to frequent flooding and soil salinization.

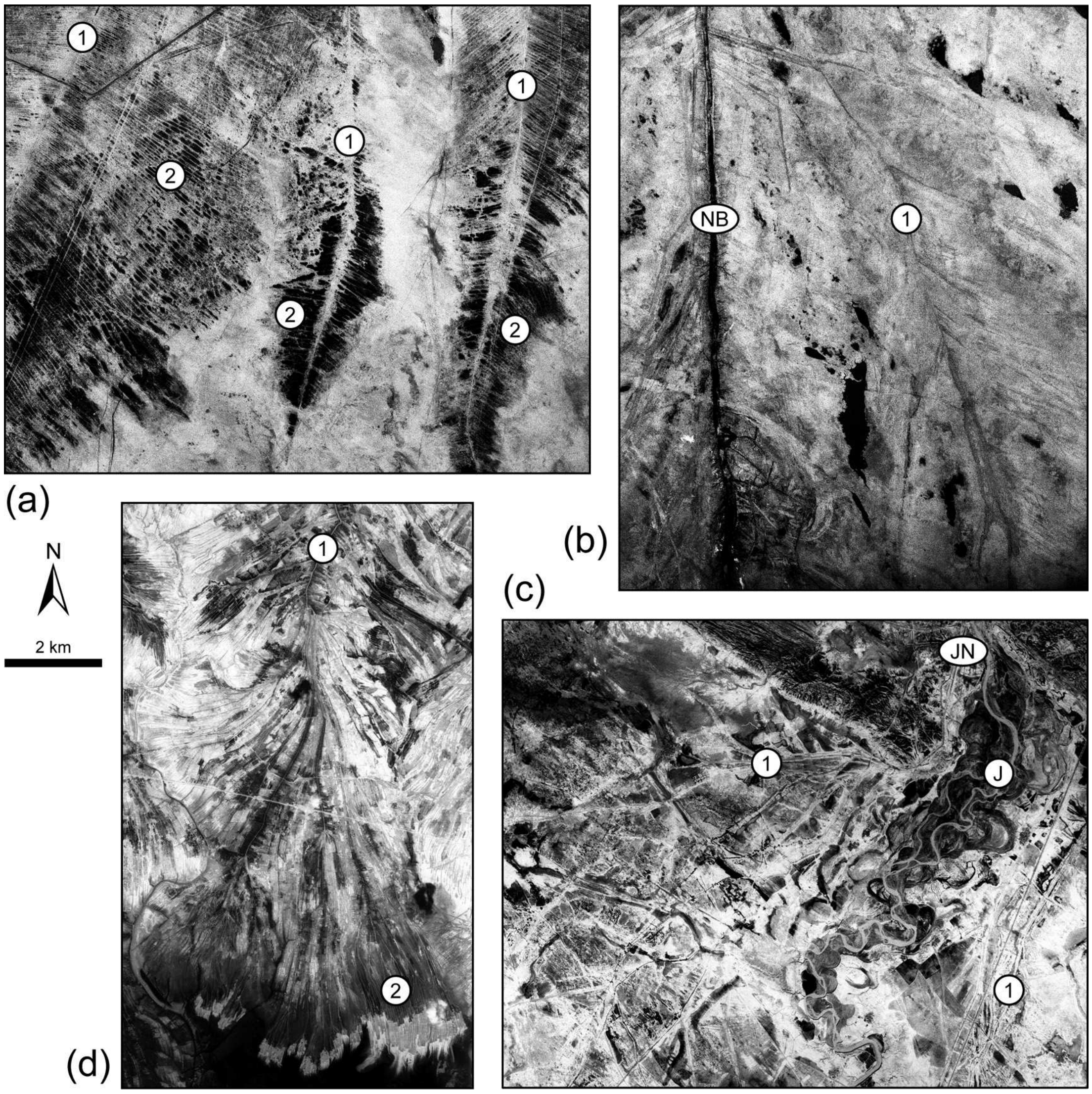


Fig. 6. CORONA images displaying different patterns of ancient to modern irrigation systems: (a) "herringbone" field patterns south of channel belt K2, (b) large parallel canals branching off from the Nahr Bahre (NB), (c) traces of canals on both sides of the incised Jarrahi valley (J) downstream of Ja Nishin (JN), and (d) the present-day distributary channel system of the Jarrahi. Main feeder canals are indicated by (1) and field patterns by (2). (CORONA scenes: DS1039–1072DA065, acquired on 27 February 1967 (a and b), DS1045–2182DF080 (c) and DS1045–2182DF078 (d), both acquired on 5 February 1968).

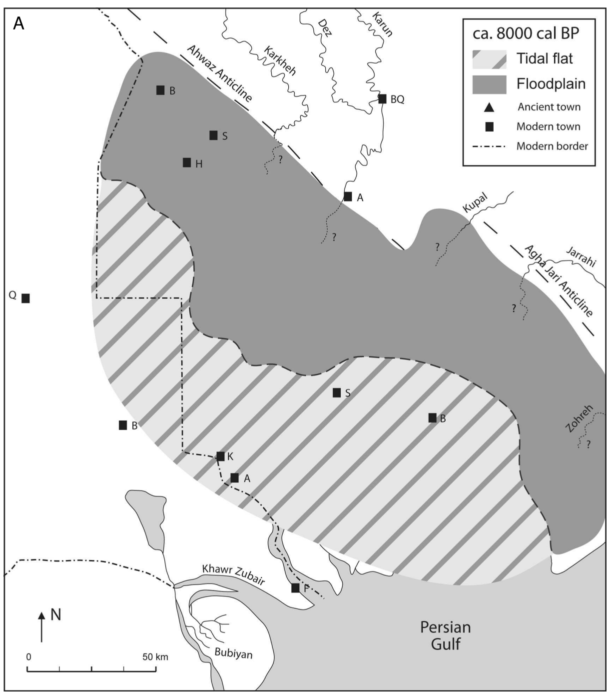
5.1.5. *Coastal Landforms*

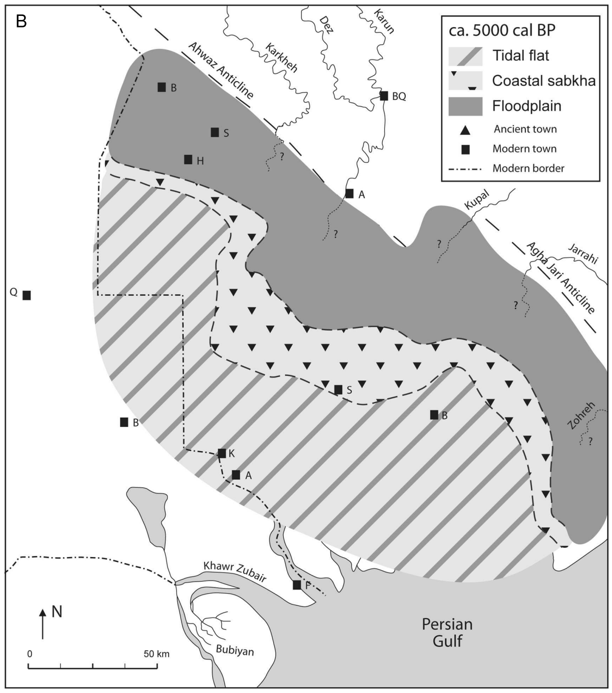
The tide-dominated coastline is fringed by a broad zone of tidal flats*, salt marshes and coastal sabkhas* with saltpans. The latter are inundated only by extreme high water and can be classified as clastic coastal sabkhas (Heyvaert/Baeteman 2007). The Khor Musa tidal embayment is partly protected from the open sea by spits* and barrier islands*.

5.2. *General Palaeogeography*

Considering the vast area of the Lower Khuzestan plain and the limited number of geological boreholes (Fig. 2) and radiocarbon-dates (Table 2), any attempt to describe the palaeogeographical evolution of the plain is constrained by the assumptions that are used to interpolate between dated samples through both time and space.

The infill of a drowned palaeovalley is controlled by many interacting factors, including rate of relative sea-level (RSL) rise, sediment budget, morphology of the pre-transgressive surface*, accommodation space*, neotectonic setting and sediment compaction. During the infill of a palaeovalley, initially caused by RSL rise, the relative importance of these individual factors changes in the course of time (Baeteman 1998; Beets/van der Spek 2000). Knowledge of these factors is very limited for the Lower Khuzestan plain, but a more detailed discussion is provided by Heyvaert and Baeteman (2008).




B
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Tidal flat
Coastal sabkha
Floodplain
Ancient town
Modern town
Modern border
Ahwaz Anticline
Karkheh
Dez
Karun
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Jarrahi
Agha Jari Anticline
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Persian Gulf
N
0
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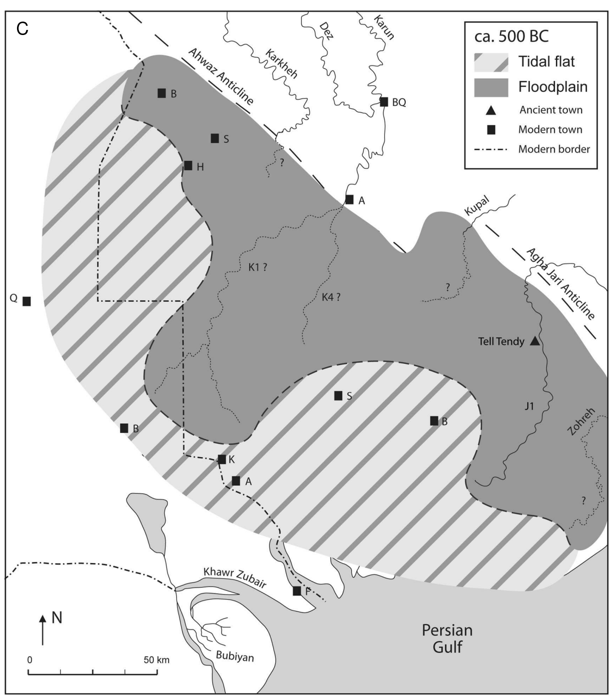
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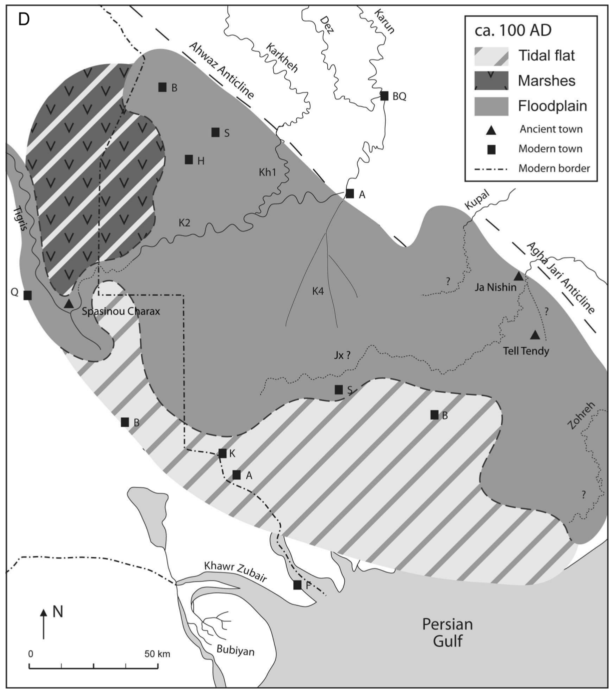
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Spasinou Charax
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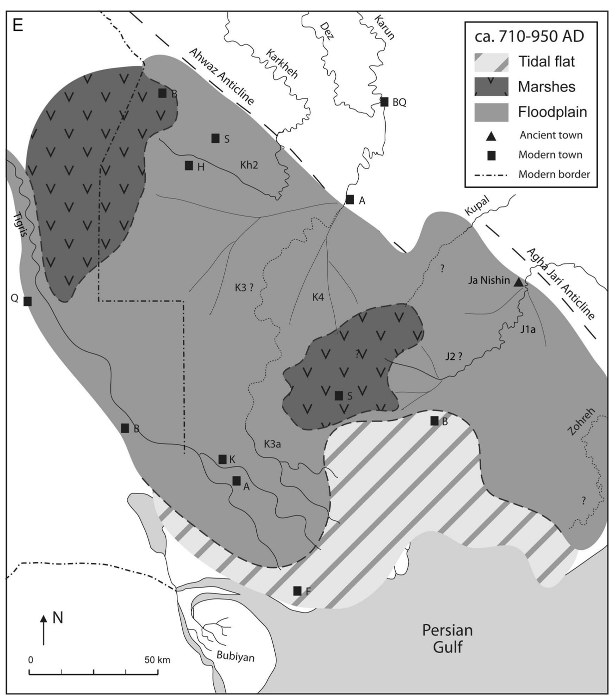
E
ca. 710-950 AD
Tidal flat
Marshes
Floodplain
Ancient town
Modern town
Modern border
Ahwaz Anticline
Karkheh
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K3 ?
K4
K3a
J2 ?
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Zohreh
Bubiyan
Persian Gulf
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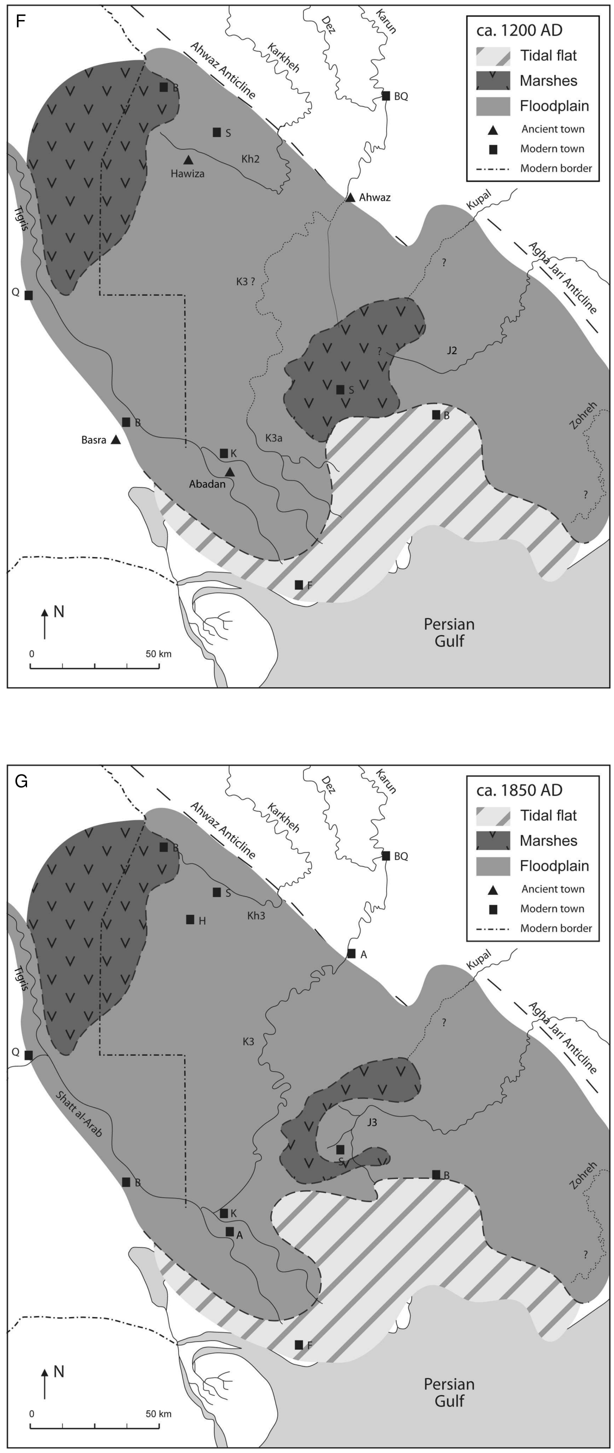

Fig. 7a–g. Reconstruction of the environmental setting of the Lower Khuzestan plain from 8000 cal BP to present (after Heyvaert/Baeteman 2007; adjusted in the light of new results, cf. case studies below).

A series of palaeogeographical maps, published earlier by Heyvaert and Baeteman (2007) and Heyvaert (2007), was further refined for the present paper on the basis of the integration of archaeological and historical data with geological data. The different time slices are chosen according to the available radiocarbon dates and to some major changes in the development of the plain.

During the early and middle Holocene, the Lower Khuzestan plain was a tidal embayment under estuarine conditions. In the early Holocene, the sea invaded the deepest parts of the antecedent valley of the Shatt-el Arab which changed into a tidal embayment. Our analysis of the geological data demonstrates a landward extension of the Gulf until at least 80 km north of its present-day shoreline at about 8000 cal BP (c. 6000 BC; Fig. 7a). Due to a high rate of RSL rise, the area was flooded rapidly and the tidal environments shifted landwards. Certainly until 7000 cal BP (c. 5000 BC), the low-lying areas were essentially wetlands on account of the proximity of the water table to the surface and/or their susceptibility to inundation by estuarine or riverine flooding and little evaporation. Salt marshes with reed growth developed, however, not for a time sufficiently long for peat to accumulate. This, together with the indication of various high intertidal silting-up phases with vegetation growth, indicate a high supply of coastal sediment and a rapid RSL rise. Deceleration of the rate of RSL rise after approximately 5000 cal BP (c. 3000 BC), together with probably more arid conditions, allowed coastal sabkhas to extend widely and to aggrade while the position of the coastline remained relatively stable. Instead of salt marshes, the coastal sabkhas developed directly landwards of the high intertidal flat (Fig. 7b).

Continued deceleration of the rate of RSL rise initiated the progradation of the coastline from c. 2500 cal BP (500 BC; Fig. 7c). The effect of sediment supply by the rivers became more important than the effect of the RSL rise and major parts of the sabkhas were gradually replaced by a floodplain. An avulsion-controlled Karun megafan developed under a decelerating rate of sea-level rise, controlling the shifting of the Karkheh and Jarrahi channels and their loci of sediment input. By approximately 2500 cal BP (500 BC), palaeochannels belt of the rivers Karun/Karkheh and Jarrahi started to fill the tidal environment in the southern part of the central plain causing progradation of the coastline. However, the tidal environment still continued to expand in the northern part of the plain, which hitherto had been out of the reach of marine influence. Between 2500 cal BP and 1240 cal BP (550 BC – 710 AD), the Karun shifted north (Fig. 7d) and started to reduce the initial width of the tidal embayment directly to the south of Qurna (Iraq). In the northern part of the plain, the tidal environment became gradually isolated and changed into a brackish-freshwater marsh environment by 1240 cal BP (710 AD). In the period between 1240–1000 cal BP (710–950 AD; Fig. 7e) the Karun avulsed to (or at least nearby) its present-day position, and started to control the progradation of the coastal area in the southern part of the plain. In the northern part of the plain, the brackish-freshwater marshes became locally filled up by the newly developed Karkheh palaeochannel nearby the village of Hawiza. By 450 cal BP (1500 AD; Fig. 7 f.), in the southern part of the plain, a brackish-freshwater marsh was present in the surroundings of the Jarrahi distributary system. The last avulsion of the Karkheh (Fig. 7g) happened in 1837 AD, as documented in historical texts (see case study Karkheh).

The palaeogeographical reconstruction of the plain presented above, represents a significant step forward with respect to earlier reconstructions. However, it only constitutes a broad scheme and provides a framework for further research. A more detailed discussion of the palaeogeographical reconstruction of Lower Khuzestan can be found in Heyvaert and Baeteman (2007) and Heyvaert (2007).

The reconstruction of the shifting of the palaeochannelbelts of the river Karun, Karkheh and Jarrahi and the development of an age model for the channel belts is based on the integration of multidisciplinary datasets; the case-studies below will illustrate this.

6. Human-Environmental Interaction: Case-Studies

6.1. *The Karkheh River System*

The objective of this case-study is to investigate the role of human interference in the late-Holocene floodplain history of the Karkheh river, located in the northern part of the Lower Khuzestan plain. Below, the main data and results are summarized. A more detailed discussion can be found in Heyvaert et al. (2012).

6.1.1. *Geomorphological Data*

As already mentioned above (cf. section geomorphological map, Fig. 3), three main Karkheh channel belts (Kh1, Kh2 and Kh3) and several diverting branches (e.g. Kh2d, Kh2c) were distinguished. These different courses can be attributed to successive stages in the development of the Karkheh floodplain.

6.1.2. *Archaeological Data*

The survey by Gasche and Paymani (2005) noted 16 sites in the area of the Lower Karkheh, 12 of which could be dated. Seven of these were founded only in the Early or Middle Islamic periods (c. 640–1500 AD).

The oldest archeological site discovered in the area is located in the eastern part of the town Hamidiya (Gasche/Paymani 2005: 38, no. 311), at the place where the river breaks through the anticline and enters the Lower Khuzestan plain; the site was inhabited from Achaemenid (539–331 BC) to Islamic times (c. 640 AD-).

No sites firmly associated with the Kh1 palaeochannel have been found; one site (Gasche/Paymani's no. 41) is located very close to both the Kh2b and Kh1 channels, and could have been linked with either one of them. Materials dating to the Seleucid/Parthian (c. 312 BC – 221 AD) and Islamic periods (after c. 640 AD) have been found here.

Two more pre-Sasanian sites (Gasche/Paymani's nos. 39 and 43) were found at some distance from the Kh2a and Kh2b channels, but most of the sites along the Kh2b-d channels date from islamic times. The most important of these are the ruins of the city Hawiza (Tell Hawiza), where Seljuq and Mongol pottery was found (c. 1050–1500 AD). No archaeological sites were found associated with the Kh3 channel.

6.1.3. *Historical Data*

The area of the lower Karkheh was a backwater and is rarely mentioned in historical sources. In Arabic sources, a town called Nahr Tira is mentioned in this area; the town was located along a river or canal of the same name, and one of the 7 *kuwar* (districts) of Khuzestan was named after it. The Nahr Tira channel/canal was most probably part of the Karkheh Kh1 system, and is last mentioned as an active watercourse in a description of a battle that took place in 702 AD (Verkinderen 2009: 422–426). Ninth- and tenth-century itineraries suggest that the place must have been located in the area of Hamidiya; Gasche/Paymani's site no. 311 is perhaps to be identified as Nahr Tira (Gasche/Paymani 2005: 38; Verkinderen 2009: 423).

From the mid-10th century onwards, the area became the center of a powerful tribe, the Banu Dubais. Their capital Hawiza (Fig. 2) was located on a land route from Shiraz to Baghdad and rose to prominence by the middle of the 12th century (Isfahani: 218; Ibn Battuta: II 93). Cash crops (corn, cotton and especially sugarcane) were cultivated around the town in the 14th century (Mustawfi: 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

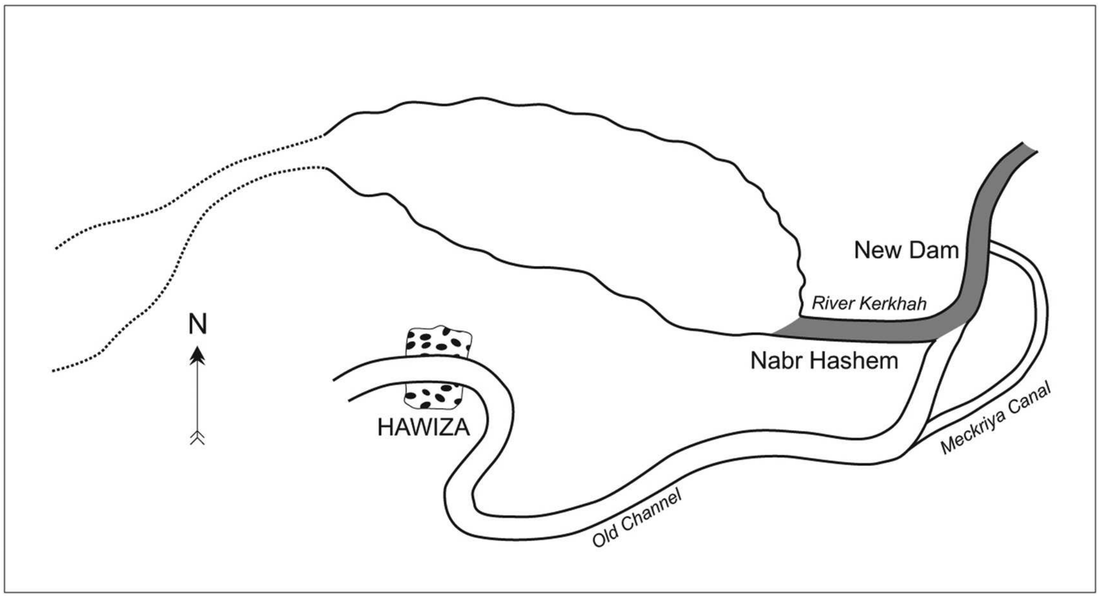

Fig. 8. Historical map showing the position of the Nahr Hashem irrigation canal upstream along the 'old channel' of the Karkheh (after Loftus 1857a).

of the province of Arabistan (Khuzestan) and the seat of its great dynasty of governors, the Mushaʿshaʿa (Layard 1846).

Few European travellers visited the region, and only from the nineteenth century onwards (Layard 1846; Loftus 1857a–b). Loftus 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. One canal, locally called Nahr Hashem, was dug 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 from the river. As a consequence, a dam was constructed at the bifurcation point to prevent the Karkheh of 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.

6.1.4. *Geological Data*

The geological data comprise of the facies analyses of 8 hand-operated boreholes and one outcrop, forming two transects along the Karkheh palaeochannel belts.

A first transect is located along the Karkheh palaeochannel belt (Kh2d) which at present time is fed by the Karkheh Kh3c channel (Fig. 9). The sedimentary succession along this transect consists mainly of fluvial deposits with a thickness of c. 5 to 6 m. These fluvial deposits are interpreted as channel belt/crevasse splay deposits or floodbasin deposits associated with the Karkheh (palaeo-) channel belt Kh2d/3c. Only in boreholes B39 and B40 the fluvial deposits (channel belt/ crevasse splay deposits and floodbasin deposits) were found overlying

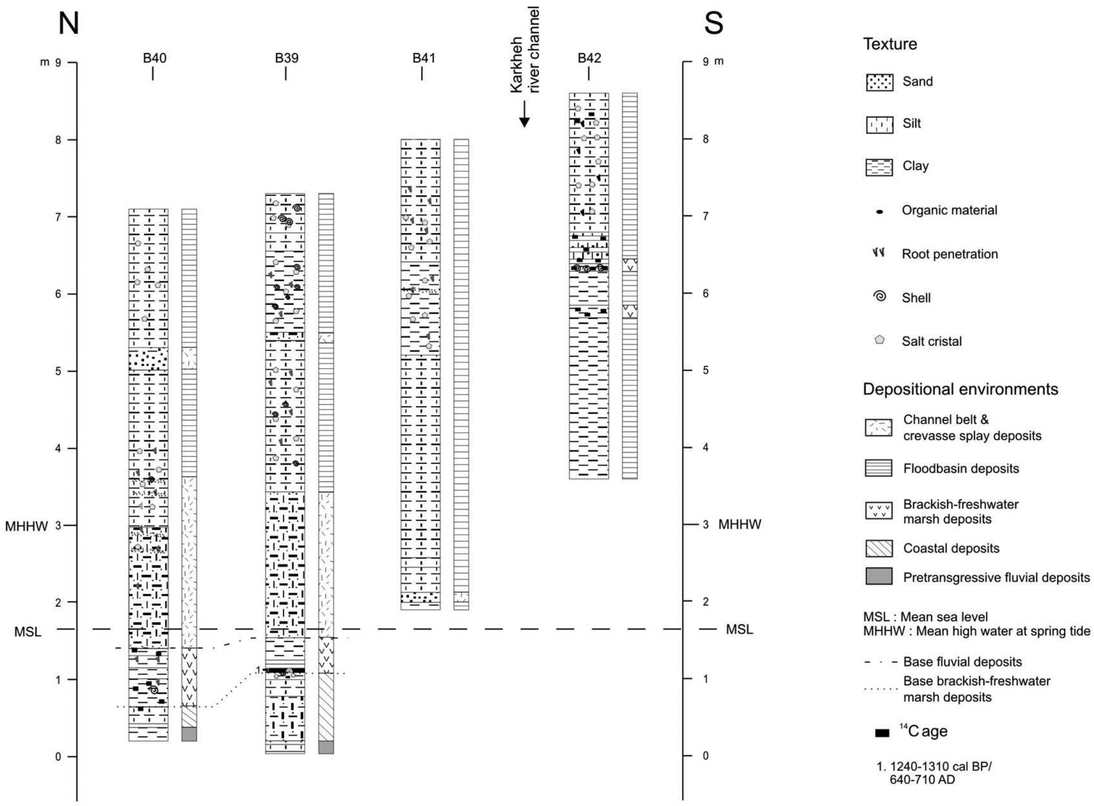

Fig. 9. Stratigraphic profile with indication of the depositional environments of cores along (palaeo)channel belt Kh2d/Kh3c. Sediment textures are based on field descriptions. (after Heyvaert et al. 2012). The location of boreholes is given in Fig. 2.

a 0.5 to 1 m thick layer of organic rich brackish-freshwater marsh deposits, covering coastal deposits. In borehole B39, organic material at the base of the marsh deposits was dated at 1310–1240 cal BP. This date indicates that a brackish-freshwater marsh, which can be attributed to a former extension of the present-day Hawiza Marshes, existed from c. 640–710 AD onwards, and that the sedimentation associated with (palaeo-) channel Kh2d/3c started later.

A second transect (Fig. 10) follows an east-west direction parallel with and south of the lower part of the currently active Karkheh channel belt Kh3b. The boreholes in this transect show a similar sedimentary succession to the one found along the first transect.

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 440–350 cal BP (1510–1600 AD) and 320–270 cal BP (1630–1680 AD), respectively (Table 2). The reworked organic material at the level of +3.35 m in B24 was dated at 230–260 cal BP (1720–1890 AD). 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 dated at 230–130 cal BP (1720–1820 AD) and 150–120 cal BP (1800–1930 AD), respectively. 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 to 4 m can also be linked to a former eastern extension of the Hawiza Marshes. The onset of the formation of the marshes at this location can be estimated at

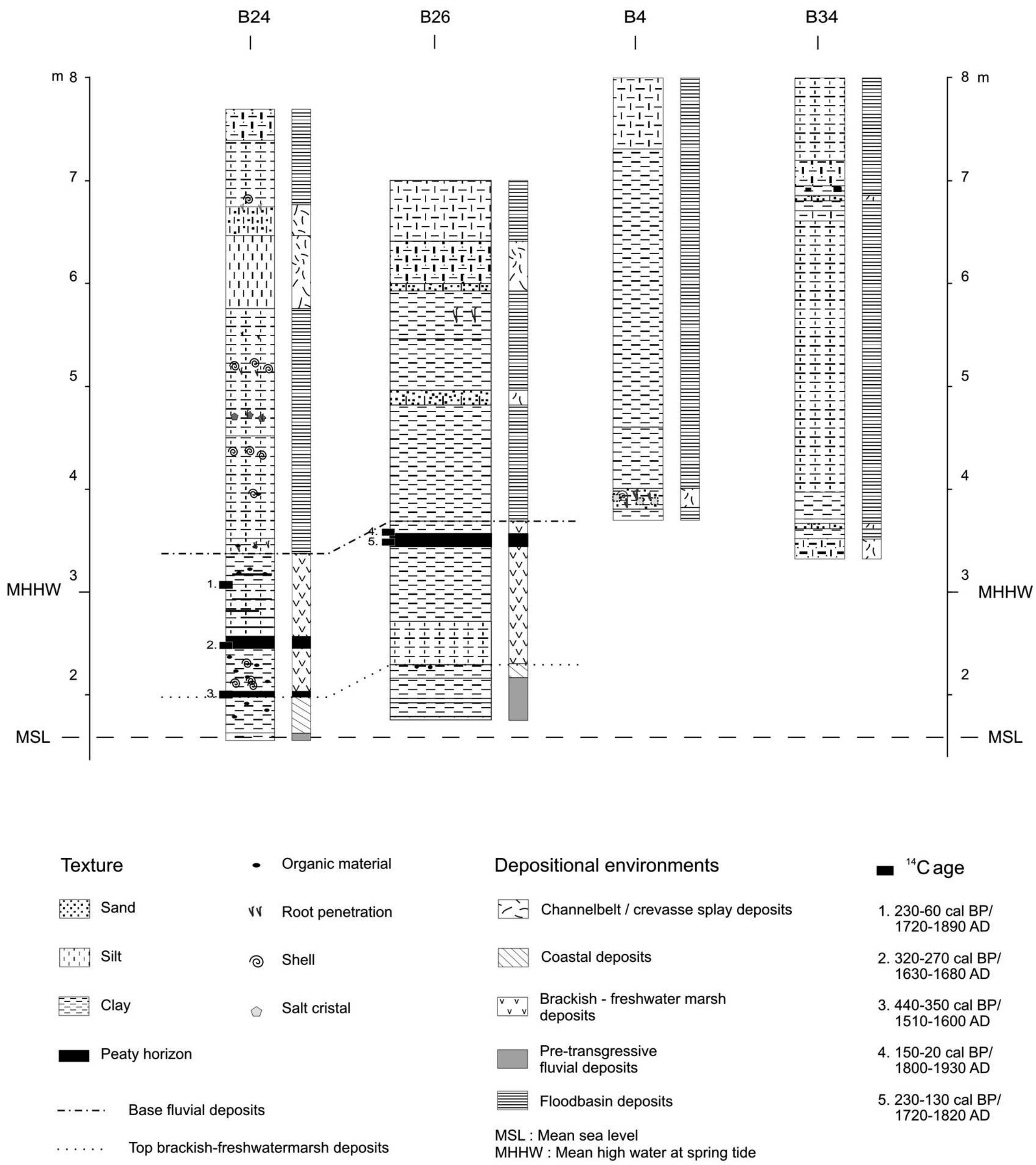

Fig. 10. Stratigraphic profile with indication of the depositional environments of cores located along the downstream part of channel belt Kh3b. Sediment textures are based on field descriptions. (After Heyvaert et al. 2012). The location of boreholes is given in Fig. 2.

c. 440–350 cal BP (1510–1600 AD). 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 very recently at this location, at the earliest at 1800–1930 AD.

6.1.5. *Correlating Datasets—Karkheh Floodplain History*

Based on the integration of geomorphological, geological, archaeological and historical datasets the floodplain history of the Karkheh can be reconstructed.

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. The K2 channel was active from at least the 2nd century BC onwards (see Karun case-study below, and Heyvaert 2007; Walstra et al. 2010b). Moreover, just like the K2, the Kh1 palaeochannel belt is intersected by irrigation systems that most probably date from Sasanian/Early Islamic times (Walstra et al. 2010b). The latter gives an indicaton for an end-date of activity of palaeochannel belt Kh1. It is possible that this Kh1 channel is to be identified with Nahr Tira, which was abandoned by the time that the first Arabic geographical works were written in the 9th century. Along the first transect (Fig. 9), 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 640–710 AD for the formation of palaeochannel belt Kh2d, which branches off from the palaeochannel belt Kh2b. Indirectly, this indicates that the abandonment of the predecessor of Kh2, i.e. palaeochannel belt Kh1, most likely did not occur long before 640–710 AD. 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 to Middle Islamic period (c. 640–1500 AD).

Historical sources indicate that the area of Hawiza was flourishing in the 13th and 14th centuries (Mustawfi: 109), and inform us that the palaeochannel belt Kh2b, and extensive irrigation networks connected to it, were fully active until 1837 AD. In that year, the channel (Kh2b) shifted to its present-day position (Kh3b) (Layard 1846; Loftus 1857, 1857b), leaving all of the irrigation canals connected to the Kh2b channel dry. The historical date of the avulsion event fits well with the geological data (second transect, Fig. 10), which show that near Bostan, sedimentation by palaeochannel belt Kh3b started after 1800 AD (borehole B26). Palaeochannel belts Kh2c and Kh2d, which branch off from Kh2b, must have been abandoned due to the same event in 1837 AD as well. Kh2d was later reoccupied by a channel (Kh3c) branching off from the Kh3b channel downstream of Susangerd. The Kh2b palaeochannel belt and its irrigation networks were reactivated by the late 1960s, after the construction of a canal bypassing Hamidiya (progress of construction works is clearly visible on CORONA images from 1968).

6.1.6. *Human Impact*

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 channel was dug for irrigation purposes. Moreover, a network of irrigation canals perpendicular to the channel Kh2b was identified (Fig. 5), suggesting human interference. Our historical data (Layard 1846; Loftus 1857, 1857b) firmly attribute the second avulsion event (Kh2b to Kh3b—avulsion site 2) in 1837 to human interference. For a broader discussion on human-interference on the Karkheh floodplain evolution, we refer to Heyvaert et al. 2012.

6.2. *The Karun River System*

The aim of this case-study is to reconstruct the evolution of the Karun alluvial megafan. As shown on the geomorphological map, three Karun palaeochannel belts were detected: K1, K2, and K3, of which the latter one is in use today. Older channel belts may be present in the plain but are not visible on satellite imagery. Complementary evidence from texts and geological and archaeological field data allowed the elaboration of a chronology of the channel belts and canal systems.

6.2.1. *The Ahwaz Dam and Irrigation System*

At its entrance to the Lower Khuzestan plain in Ahwaz, the river breaks through the anticline, reducing the high ridge to a number of rocky shoals in the river bed. On these rocks, traces of an ancient dam have been found (Graadt van Roggen 1905). Based on Graadt van Roggen's sketch map of the dam area, huge feeder canals were identified on aerial photographs and satellite imagery [from the 1950s and 1960s, before the area was absorbed by the modern city], and linked to the vast irrigation network extending on both sides of the present-day Karun. Since the radially diverging canals clearly cross the palaeochannels, they must postdate channel belts K2 and Kh1. The "herringbone" field patterns also cover the upper part of palaeochannel belt K1.

Most of the canals belonging to the system east of the K3 channel do not exhibit the same typical herringbone field patterns observed to the west, which might indicate their lifetimes did not completely overlap. Likewise, one of the east bank canals is cut by the K3 channel. It therefore seems possible that only part of the canal system predates the present-day channel belt, while part of it remained/became active during the early days of K3. Both networks appear to have been in use for a long time, since numerous bypasses that point to restorations have been identified on satellite images (those on the east bank of the Karun were already noted by Gasche/Paymani 2005: 24–30).

The exact age of the ruined dam has not been established. Traditionally, irrigation works of this scale are attributed to a major colonization program in Sasanian times (Christensen 1993), but there is no material proof for this date. Although archaeological surveys indeed suggest that the settlement in the plain had its heyday during the Sasanian and Early Islamic periods, the canals to the east of K3 are in fact associated with sites from Seleucid/Parthian to Islamic times (Gasche/Paymani 2005: 24–31), suggesting that at least a precursor of the irrigation system existed before.

At the end of the 10th century, the travellers al-Muqaddasi (410) and Ibn al-Muhalhil (28) still refer to the dam in Ahwaz and at least 2 important irrigation canals feeding from it: "the dam holds back the water (of the Karun), and divides it into three streams, which flow to their agricultural estates and irrigate their fields. They say that without the dam, Ahwaz would not be inhabited, and its rivers would be of no use", al-Muqaddasi (411) writes. A careful comparison of the 10th-century descriptions by al-Muqaddasi and Ibn al-Muhalhil with the archaeological observations of Graadt van Roggen near the dam of Ahwaz proves that at least the east bank feeder canal was still in use in the 10th century (Verkinderen 2009: 306–311). For the west bank canals, the texts are more ambiguous, but the references to major canals and investments in irrigation in this area at least until the 9th century suggest that the canal system was active in the Early Islamic period (Verkinderen 2009). It is unknown when exactly these irrigation systems fell into disuse.

6.2.2. *Channel Belts and Embouchure*

No archaeological sites or other direct age indicators associated with the K1 palaeochannel belt have been surveyed (although some potential sites have been found on topographical maps and satellite imagery), and no geological corings along this river bed were carried out to this day. The K1 system obviously predates at least the latest phase of the large (Sasanian/Early Islamic) irrigation systems, as its upper section is covered by the "herringbone" patterns. The channel belt is probably also older than K2, although this is less sure.

The founding and abandonment of the ancient city of Spasinou Charax (Naisan) provides strong evidence for dating channel belt K2: Pliny (c. 79 AD) writes that the city was located at the confluence of the Tigris and the Karun, which implies the K2 channel belt was active from at least the 2nd century BC (at which time the area was ruled by the Spasines after whom the city was named), and perhaps even earlier, if Pliny's attribution of an earlier founding of the city to Alexander the Great is correct (Hansman 1967). The city was probably abandoned by the early 7th century AD, as its Arabic name Karkh Maisan figures in the accounts of the Muslim conquests only as a *kura* (district), not as a city anymore (Schuol 2000; Verkinderen 2009). Also, the channel belt is intersected by canals of the large (Sasanian/Early Islamic) irrigation system, thereby providing a terminus ante quem.

McCown's survey identified a number of archaeological sites from the Seleucid/Parthian period close to the present-day Karun channel (K3) in the vicinity of the city Ahwaz (Alizadeh 1985). Unfortunately, the recent survey by Gasche and Paymani was not able to localize these sites more accurately (Gasche and Paymani 2005: 23), and therefore they cannot be firmly associated to either the K3 channel belt, to one of the large canals that derive from the dam at Ahwaz, or to the K1 channel belt, all of which pass through the same corridor in this area. The only archaeological sites securely associated with the K3 bed are 2 imamzadehs (local saints' tombs) on the lower part of the K3 channel that were described by 19th century travellers, but are lost today (Gasche/Paymani 2005: 35–37). Gasche and Paymani suggest a date between the 12th and 14th century for these shrines, based on their characteristic "sugarbread" or "pinecone" domes, but this date is far from certain, since domes of this type were constructed on new imamzadehs in Khuzestan at least until the 1920s (Unvala 1929: 590). There is little textual evidence about the upper course of K3; only in the 19th century is there positive evidence that the Karun flowed in its K3 bed. The geological information gathered about the K3 channel is also not conclusive.

The earliest evidence for the K3a (Blind Karun) can be attributed to 10th-century Arabic sources, which depict the Karun entering the sea independently near Abadan (i.e. instead of discharging into the Shatt al-Arab). The distances cited by the Arabic geographers point to the K3a as the most probable early Islamic Karun outlet (Verkinderen 2009: 327–354; Walstra et al. 2010b). A number of canals between the K3a and the Tigris outlet were constructed in the 9th and 10th centuries, and one of these canals (the Haffar canal) eventually became the main outlet of the Karun as a result of the destruction of a dam on the Karun in 1763 AD, which led to the abandonment of the K3a branch (Verkinderen 2009: 334; Walstra et al. 2010b: 123). The Haffar (or a similar canal that connected the Karun to the Shatt al-Arab) appears to have functioned as the main outlet of the Karun at least, in the 14th century (Mustawfi 207). By the mid-17th century, the Haffar (for the first time called by this name) is described by the French traveller De Thévenot as a narrow snaking canal, only a few meters wide, that connected the Tigris to the main outlet of the Karun, the K3a branch at that time (de Thévenot 1727; Verkinderen 2009; Walstra et al. 2010b).

To conclude, we can say that the exact course of the Lower Karun before the early Parthian period is not known. The river flowed in its K2 bed at least from the 2nd century BC onwards.

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At the time, the Karkheh was a tributary to the Karun, by way of its Kh1 channel, which joined the Karun west of Ahwaz. Sometime before the mid-7th century, the Karun shifted its bed eastward, most likely to the K1 or K3 channel. After the eastward shift of the Karun, the area previously occupied by the K2 channel was irrigated by long irrigation canals that derived from a single feeder canal, which ultimately appears to have taken off from the Karun at the Ahwaz dam. The huge size of this irrigation system implies that it was constructed in the heyday of the plain, i.e. in the Sasanian or Early Islamic period. The fact that the upper part of the K1 channel is covered by the herringbone patterns of the irrigation system, suggests that the K1 either predates this shift away from the K2 (and therefore, the K2 channel itself) or was active in the period between this shift and the construction of the irrigation system. Since there is evidence of numerous bypasses and repairs to the irrigation system, it cannot be ruled out that the K1 was contemporary to an early phase of the irrigation system. Only in the 19th century we have conclusive proof that the Karun flowed in its K3 bed. More information is available for the final stretch of the river. From the 10th century onwards, we have proof that the Karun discharged into the Persian Gulf by way of (or nearby) the Blind Karun (K3a) channel. It is not clear if the river was flowing in its K1 or K3 bed at that time, since both seem to have been connected to the K3 channel. Sometime between the end of the 10th and the middle of the 14th century, the Karun shifted its bed to discharge into the Shatt al-Arab by way of the Haffar (or similar) channel. By the 17th century, it flowed into the Persian Gulf independently again, by way of the Blind Karun (K3a) channel. In the 1760s, a dam break caused the final shift of the river from the K3a to the Haffar channel.

6.3. *The Jarrahi River System*

The aim of this case-study is to reconstruct the development of three alluvial fans successively deposited by the Jarrahi river (Walstra et al. 2010a).

Initially, the Jarrahi built up a large alluvial fan (J1) at the foot of the Marun and Agha Jari anticlines. An important archaeological site, Tell Tendy, is located along an abandoned palaeochannel belt and provides an indication for its age of activity. The site was populated at least between the Achaemenid (539–160 BC) and Parthian (160 BC – 221 AD) periods, but probably had a much longer history before (Hansman 1978a). Abandonment of the site may be related to the avulsion of the Jarrahi to its present position and the incision (Fig. 12) that followed. An extensive irrigation network that derived water via intake canals from a dam nearby the site of Ja Nishin can be considered as an effort to revive water supply across the fan (unit J1a). The foundation of Ja Nishin was dated by Hansman to Hellenistic times, and the site was inhabited until the 10th century (Hansman 1978a). The dam has been attributed to Sasanian times (Hansman 1978a), although an earlier date cannot be ruled out.

During a later phase, which may have started together with the down-cutting in the first fan, a second fan (J2) developed downstream. The surface of this fan is characterized by radially diverging canals with "herringbone" field patterns. No known archaeological sites are associated with the system, but the size and layout are very similar to the patterns identified along the Karun river (see case-study Karun), and therefore a Sasanian or Early Islamic origin is suggested.

The last phase regards the deposition of the present-day fan (J3), again further downstream and westwards. Organic material from the marsh deposits underlying the alluvium was radiocarbon dated at 350–430 cal BP (1520–1600 AD), thereby providing a terminus post quem for the onset of alluvial deposition (Heyvaert/Baeteman 2007; cf. Fig. 11).

The earliest historical evidence for the J3 fan is the founding of Fellahiyah/Shadegan in the 1740s (Layard 1846), while archaeological remains of the previous capital town Medina/Dawraq were dated to the 17th–18th century AD (Hansman 1978a). These data all suggest a

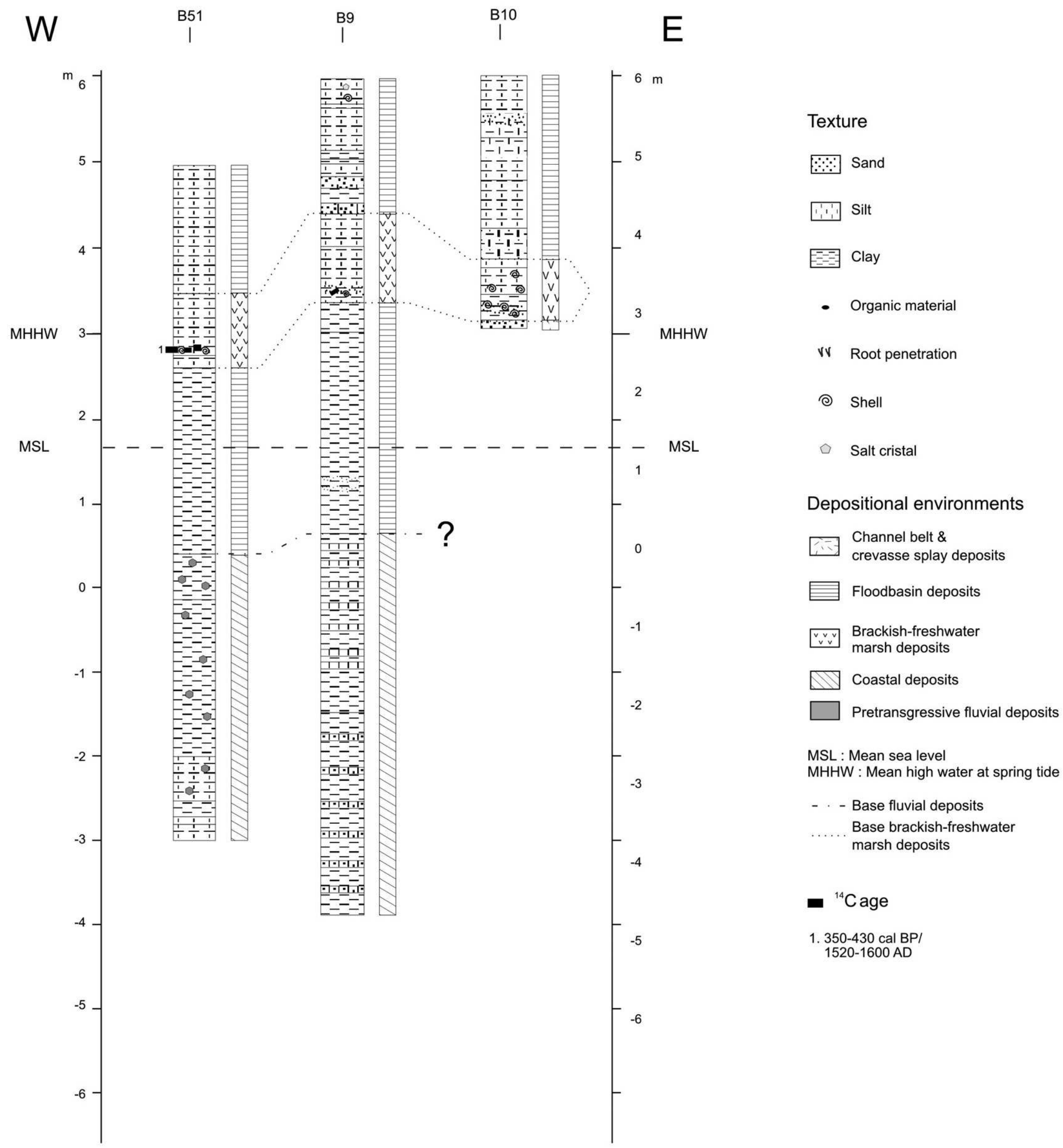

Fig. 11. Stratigraphic profile with indication of the depositional environments of cores located in de Jarrahi fan J3. Sediment textures are based on field descriptions. The location of boreholes is given in Fig. 2.

very rapid fan formation, which was confirmed by observations from recent satellite imagery (see Fig. 13).

There is no direct evidence for the age of palaeochannel belt Jx, but it may be associated with fluvial deposits underlying the dated marsh deposits underneath fan J3. The palaeochannel is intersected by the present-day Karun; unfortunately, the date of the shift of the Karun to its present-day bed is still unknown (see case-study Karun).

Early Islamic texts do not mention the Jarrahi river itself. 9th- and 10th-century sources make clear that the area of the present-day lower Jarrahi was very water-rich; it was easier to travel there by boat than on horseback, one of the way stations that was located on the route that crossed the area is described as "located in the middle of the water", and the area was known as

Fig. 12. Jarrahi channel incision of fan J1 (photo by V.M.A. Heyvaert, 2004)

the place where the water of all of Khuzestan gathered (e.g. al-Istakhri: 33; al-Masʿudi: II 288; cf. Verkinderen 2009). This water probably formed a large marsh area, which drained into the Karun river and the sea. It is not clear if the Jarrahi had a distinguishable channel through these marshes, and which could be identified with the Jx paleaochannel. The maps accompanying the works of al-Istakhri, Ibn Hawqal and al-Muqaddasi (Miller 1927) do indicate a waterway that joins the Karun at the place where we would expect the Jarrahi. On the other hand, the same maps also depict a waterway through the marshes of lower Iraq, where no noticeable river channel existed, and boats navigated through a series of corridors through the reeds linking bodies of open water (Ibn Rusta: 161; Ibn Sarabiyyun: 135). Moreover, two canals identified with present-day Nahr Bahre and Nahr Maleh are said to have reached the sea, which seems to preclude a Jarrahi channel that reached the Karun (Verkinderen 2009).

It is interesting to note that the district capital was relocated stepwise in downstream/westwards direction, apparently synchronous with phases in the evolution of the Jarrahi:

- The Sasanian and Early Islamic capital, named Dawraq (Fiey 1969, 1970; Gyselen 1989, 2002), was probably located at Ja Nishin, where pottery from these periods was found (Hansman 1978a). The same site has also been identified as the Hellenistic city Seleucia-on-the-Hedyphon, but this is more tentative—another candidate is Tell Tendy, located along a previous course of the same river (Hansman 1978a; Verkinderen 2009).
- Early Islamic texts suggest that Dawraq had moved downstream by the 10th century, as they mention a clear connection between the town, marshes and the sea, which cannot refer to Ja Nishin (Verkinderen 2009).

– In the 17th–18th century the capital was located at Medina and eventually it moved to Fellahiyah/Shadegan, which was founded in the 1740s (Hansman 1978a; Layard 1846).

6.3.1. *Human Impact—River Incision*

The channel incision of fan J1 (Fig. 12) may simply be the result of an avulsion and internal adjustment of the river to its new gradient, a common process on alluvial fans known as fan-head entrenchment (Bridge 2003; Blair/McPherson 1994; Harvey et al. 2005). On the other hand, it can also be explained by several external factors, such as tectonic activity, changes in base-level, or changes in river discharge and sediment load (cf. Blair/McPherson 1994; Jones/Schumm 1999). Kirkby provided evidence for a similar phase of down-cutting river systems in Upper Khuzestan after c. 2000 BC, and suggested this was a regional rather than local phenomenon. Indeed, the construction of the dam at Ja Nishin can be considered as an effort to restore water supply after it had been cut off by river incision. Remnants of similar dams, built to raise water up to the level of intake canals, have been attested throughout Khuzestan (Graadt van Roggen 1905) and are traditionally attributed to Sasanian times (although some predecessors might actually predate this period, see case-study Karun). The requirement of such dams across all rivers in Khuzestan strongly supports Kirkby's case.

6.3.2. *Human Impact—Crevasse Splays*

It is known from ancient times that natural levee breaks and their associated crevasse splays formed the ideal loci for irrigation (Wilkinson 2003; Morozova 2005; Heyvaert/Baeteman 2008). The same principle is still being applied today across fan J3, where levee breaks are transformed into outflow points and the naturally elevated position of the alluvial ridge facilitates gravity-flow. Maintenance of the resulting distributary channel system prevents avulsions taking place and spreads out the sediment load over a large area. As a consequence, deposition takes place at very high rates and along extremely low gradients: the average fan progradation rate equaled 2.6 $km^2\ a^{-1}$ over the last 68 years (based on analysis of satellite data and map sources, cf. Fig. 13), while the vertical aggradation rate was estimated at 3–5 mm a^{-1} for the last four centuries (based on geological coring B51); surface gradients range from 0.0002–0.0004, which is exceptionally low.

7. Conclusion

In this paper the geographical evolution of the Lower Khuzestan plain was reconstructed based on the integration of geological, textual, archaeological information and remote sensing imagery.

Geological data show that during the early and middle Holocene the Lower Khuzestan plain was a low-energy tidal embayment under estuarine conditions. In the Early Holocene, a high rate of relative sea level rise caused the land to be flooded by sea water, and the coastline moved up to 80 km further landward than the present-day shoreline, reaching its peak about 6000 BC. A large part of western Lower Khuzestan was covered with supra- and intertidal flats and salt marshes, where coastal sediments were deposited at a high pace, resulting in aggradation of the plain. Due to a decreasing rate of relative sea level rise and perhaps more arid conditions after 3500 BC, coastal sabkhas developed along the now more stable coastline.

From c. 550 BC onwards, sediments supplied by the rivers became more important than the effect of the relative sea level rise, resulting in the progradation of the plain and reducing the extent of the sabkhas. The Late Holocene progradation of the plain was controlled by the

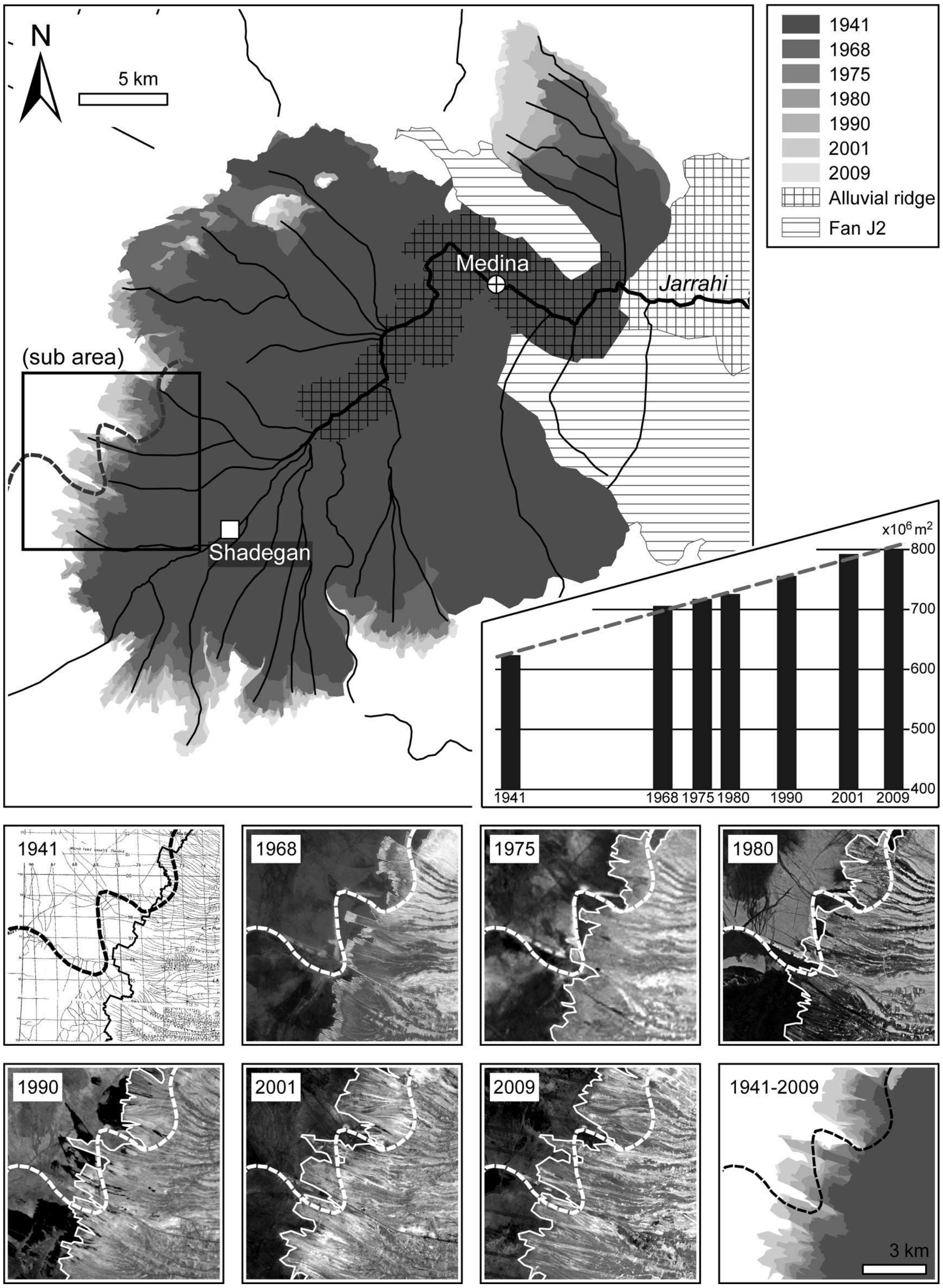

Fig. 13. Progradation of the present-day Jarrahi fan (J3) between 1941 and 2009, based on a sequence of satellite images and maps. The dashed line represents Jarrahi palaeochannel Jx, which is gradually buried by fan deposits. The graph (inset) shows the increase of areal extent through time. Source data: K701 map (1941, © Crown copyright, reproduced with permission of the Controller HMSO), CORONA (1968), Landsat MSS (1975), HEXAGON (1980), Landsat TM (1990), Landsat ETM+ (2001 and 2009).

development of a Karun megafan. This megafan was formed by successive avulsions of the Karun. Two abandoned Karun channels (K1 and K2) have been detected west of the present-day Karun bed (K3); traces of what might be a third Karun palaeochannel (K4) are visible underneath the irrigation canals east of K3. The exact order of these palaeochannels is not clear. K2 was active at least from the Parthian period (160 BC–221 AD) onwards. Its meanders are crossed by an extensive canal system (linked to the dam at Ahwaz) that most probably dates from the Sasanian or Early Islamic periods, which gives an end-date to the activity of K2. The upper part of K1 is also crossed by these same canals. K1's more faded appearance suggests it is older than K2, but the lower visibility of its traces might be the result of different erosional circumstances rather than older age. It is not clear when the Karun shifted to its present-day position; only from the 19th century onwards we have definite proof that the Karun was flowing in its K3 channel.

The avulsive shifting on the Karun fan probably influenced the changing positions of the Karkheh and Jarrahi channels. The first known Karkheh palaeochannel (Kh1) is synchronous with the K2 Karun channel. The formation/extension of the Hawiza Marshes between 640–710 AD may be linked with the avulsion of the Karkheh to its Kh2 bed. Later, in a single night event in 1837 AD, the Karkheh left its Kh2 channel, and took to its present-day position (Kh3). A number of attempts to revive the Kh2 branch have been executed, the latest being a bypass canal dug in the late 1960s.

Three successive fans formed by the Jarrahi have been detected. The first one (J1), associated with the earliest detectable Jarrahi channel, is linked to the archaeological site of Tell Tendy, which dates back at least to the Achaemenid period (539–160 BC). The river avulsion to its present bed, situated further to the north, took place before or during Sasanian times (221–640 AD) and was followed by a period of river incision. The dam at Ja Nishin existed at least from Sasanian times onwards, probably to secure water supply across the fan. A second fan (J2) is characterized by canals that resemble the canal systems west of the K3 channel, and is therefore assumed to date from late Sasanian or Early Islamic period. The third Jarrahi fan (J3) is formed by a distributary canal system and has expanded rapidly into the surrounding Shadegan marshes. An abandoned western extension of the present-day Jarrahi channel has been detected on satellite imagery (palaeochannel Jx). The development of the Shadegan marshes may have been triggered by the shifting of the Karun to its K3 bed that cut the Jx channel.

Given the limited accessibility to the study area, the paucity of data makes that this reconstruction of the coastal-fluvial evolution of the Lower Khuzestan plain should be regarded as preliminary results. Further detailed fieldwork and dating of the palaeochannels is necessary to refine the present knowledge and to assess the interplay between sea-level change, fluvial variability and human interference.

Appendix: Geomorphological and Geological Terms

Accommodation space: refers to the volume available in a depositional system for sediment accumulation to occur. It is a function of, among others, antecedent topography and relative sea-level change.

Aggradation: increase in land elevation due to the deposition of sediment.

Alluvial fan: cone-shaped depositional landform, typically located at the mountain front where a river is released from its confinement and discharge conditions promote frequent avulsions (Bridge 2003).

Avulsion: shift of a river channel to a new course on the floodplain. It is the combined result of vertical accretion of a channel system above the floodplain and external factors such as tectonic movements, changes in base level, discharge conditions and human interference. Avulsions may be initiated by the development of a crevasse channel, which eventually takes over the entire river flow, or by reoccupation of a previous river channel. The abandoned river belt remains visible in the landscape due to traces of its channel fill, scrollbar patterns and/or elevated topography. These traces represent the final stage of activity of the abandoned river belt and eventually will be removed by erosion or covered by subsequent deposition (Berendsen 1997; Goudie 2004).

Bajada: zone of a more or less continuous alluvial apron lying between the mountain front and the basin floor (Goudie 2004).

cal BP: calibrated radiocarbon age, in calendar years before 1950. It is based on calibration curves that correct for the natural deviations of atmospheric radiocarbon (14C) through time (Gornitz 2009).

Coastal sabkhas: develop in the supratidal zone along arid coastlines and are inundated only by high water levels (e.g. during spring tides and storm surges). They are characterized by a surface crust of carbonates and sulphates, which has formed through precipitation from seawater and/or groundwater due to evaporation (Bird 2008; Goudie 2004).

Crevasse splay: fan shaped deposit, resulting from floodwater breaking through a breach of a river levee. Crevasse channels are typically distributive and/or anastomosing in planform and wash material onto the floodplain (Goudie 2004).

Diatoms: unicellular algae, one of the most abundant groups of phytoplankton in a variety of marine and freshwater environments. Their siliceous cell walls are taxonomically diagnostic, often well preserved in the fossil record and therefore helpful in palaeoenvironmental studies (Gornitz 2009).

Floodplain: the low-lying parts of the alluvial plain at some distance from the river channel, which are regularly flooded and remain submerged for prolonged periods. Due to the slow flow conditions, the fine suspended particles (clay) finally settle here (Berendsen 1997).

Hogback: sharp ridge of hard rock, formed as a result of the steep dipping and differential erosion of alternating hard and soft strata (Goudie 2004).

Intertidal: coastal zone situated between the mean high water and mean low water levels, that is daily inundated by seawater.

Levee: wedge-shaped ridge (usually several decimetres or meters high) bordering the river channel and the result of overbank deposition. Levees gradually build up as sediment deposited nearby the channel tends to be coarser and thicker than further onto the floodplain. During high flows that do not exceed bankfull discharge, sediment is deposited in the river bed, resulting in the river surface gradually rising above the surrounding floodplain level (Berendsen 1997; Goudie 2004).

Meander cut-off: a U-shaped bend, cut-off from the main stream; a result of lateral river bed migration. Initially, the cut-off forms a lake (oxbow lake), which slowly fills up with sediment, although even then it may remain visible in the landscape for a long time (Berendsen 1997).

Megafan: a very large alluvial fans ($>10^3$ km^2) with extremely low gradient (<0.002), dominated by fluvial deposition processes. Usually, it is characterised by meandering river belts that episodically shift across the fan surface, thereby creating distinct diverging alluvial ridges that correspond to evolutionary stages of the fan (DeCelles/Cavazza 1999; Leier et al. 2005).

Pre-transgressive surface: top of the Pleistocene (or older) deposits, subsequently flooded by the Holocene transgression.

Progradation: seaward extension of a coastal area.

Regression is the retreat of a shoreline, exposing previously submerged seafloor above sea-level. In a vertical succession of sedimentary strata it is characterized by a shift from deeper marine sediments to terrestrial and fluvial sediments. The position of a shoreline is determined by many interacting factors, including sea-level change, tectonic movement and changing rates of sediment supply, deposition and erosion (Lerner/Wilmoth Lerner 2003).

Scrollbars: distinct patterns of concentric ridges and swales on the inside of river bends. It is related to the continuous migration of the river bed, with erosion on the outside of river bends and sedimentation on the inside (Goudie 2004).

Spit and barrier island: both landforms result from the transport and deposition of sand by longshore currents. Their outlines above high tide level are shaped largely by the dominant patterns of wave action. A spit is attached at one end to the mainland while barrier islands are formed offshore across the mouth of the embayment (Bird 2008; Goudie 2004).

Subtidal: coastal zone situated below the intertidal zone, permanently covered by the sea.

Supratidal: coastal zone situated above the mean high water level, only flooded by the sea during spring tide and storm surges.

Tidal flats: occur along tide-dominated shorelines with high sediment supply, in particular estuaries and deltas. Most of the sediment of such environment is in the intertidal zone, i.e. submerged and exposed twice daily. The lower zone is characterized by sandy tidal flats, the middle zone consists of muddy flats and the upper zone includes (vegetated) saltmarshes (Goudie 2004).

Transgression is the advance of the sea across previously exposed land surface, accompanied by a landward displacement of coastal and marine sedimentary environments. In a vertical succession of sedimentary strata it is characterized by a shift from shallow water and terrestrial sediments to deeper coastal water sedimentary facies (Lerner/Wilmoth Lerner 2003).

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