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Aspects of floodplain deposition in semi-arid ephemeral rivers, examples from the Kuiseb river valley, central Namibia†

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Topographic and sediment work in the Kuiseb river, currently an ephemeral stream in central Namibia, has shown that floodplain deposition took place mainly downstream from zones of significant external sediment input. Two floodplain types are identified as floodplain islands which developed as braided river deposits in the midstream section of the river, and infill deposits developed from anastomosing streams in the downstream section. The two types are dependent on the geometry of the river cross section and the amount of sediment available. The topography, sediment content (fine sand and silt units) and structure all imply the deposition of floodplain deposits under wetter conditions. Particle size analysis of floodplain silts in relation to river bed and sand dune silt, indicates a closer association between the floodplains and Quaternary Homeb deposits. These data suggest that the floodplains likely formed under locally wet conditions which eroded the Quaternary Homeb deposits during the early-mid Holocene.

Keywords: braided river sediments, anastomosing river sediments, Holocene climatic events

INTRODUCTION

The ephemeral Kuiseb river in west central Namibia has been described as endoreic as presently the river infrequently reaches the Atlantic Ocean. The regional and local contexts of the river have been previously described at length in Jacobson *et al*. (2000a), Jacobson *et al*. (2000b) and Yamagata & Mizuno (2005). The river has a highly variable flood regime at present and often both clastic and dissolved loads are deposited throughout the lower reaches (Jacobson *et al*. 2000a). The river flows intermittently for about 600 km from the Khomas Hochland highlands to the Atlantic Ocean (Figure 1). The Kuiseb is incised into mica-schist and granitic outcrops of variable lithologies prior to traversing weathered desert sediments on the coastal plain (Ward, 1987). Whereas the early (pre-Holocene) evolution of the Kuiseb has been described in the literature (e.g. Ward, 1987; Smith *et al*., 1993), little discussion is available on later stage (Holocene) events (cf. Yamagata & Mizuno, 2005). Background literature dealing with floodplain development *per se* pertains to perennial streams or streams with a much longer flood duration than the Kuiseb. However as indicated in Nanson *et al*. (2002), the physics governing hydraulic processes are the same, irrespective of flow periodicity or duration. A major difference between ephemeral and perennial streams includes the abundance of suspended sediment due mainly to large quantities of fine grained material being available. This can lead to sediment loads being several orders of magnitude higher in ephemeral relative to perennial rivers (Laronne & Reid, 1993). Other important aspects of ephemeral rivers include high width to depth ratios and a tendency towards braiding (Bull & Kirkby, 2002).

This work considers key aspects of floodplain deposition in the Kuiseb river valley. The aim is to develop an understanding of former floodplain depositional processes in current ephemeral (arid to semi-arid) streams while providing insight into the possible age and origin of Kuiseb floodplain sediments.

METHODS

Elevation profiling on the mid-lower Kuiseb river (Figure 2) was undertaken using Shuttle Radar Topography Mission (SRTM) data augmented by Google Earth images. The altitude data were derived by pinpointing enlarged portions of the river bed (a total of 38 locations) occurring at five km intervals from KAN (the Schliesen M35 road crossing) southwards and then northwestwards to within 20 km of the Atlantic Ocean. Long profile data were obtained along the active channel by using an average of three elevation points at each of the 38 locations to give the final river bed elevation. Width data across the channel and adjacent floodplain were obtained at the same locations. Fieldwork undertaken during March 2011 involved topographic and sediment data collection along specifically selected transects chosen to correspond to inflexion points and/or major variations in the long profile (Figure 2). Samples were taken from 50 to 200 cm deep pits dug into the floodplains along each transect. In addition samples were taken from the basal slopes of adjacent sand dunes and the current river bed along each transect. The Quaternary Homeb deposits were also sampled. Sampling typically took place at 10 cm intervals but was increased to accommodate rapid bedding changes,

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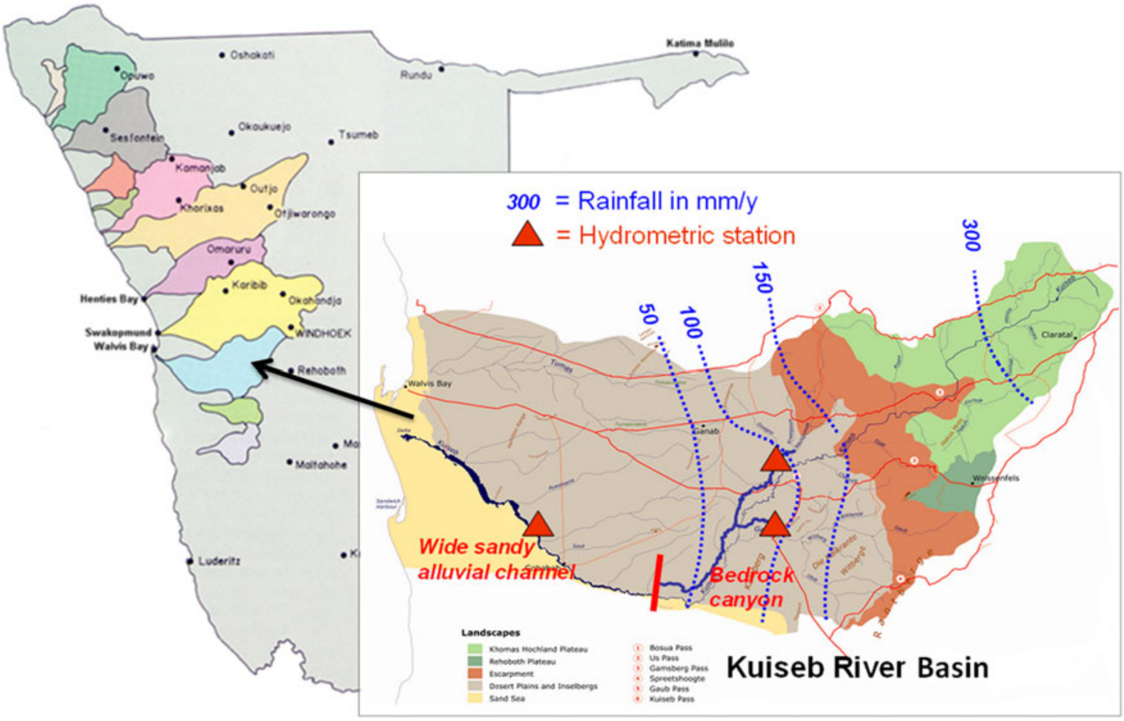

Figure 1. Location map (after DRFN) showing the location of the Kuiseb river in Namibia and the main physical features including the decline in average annual rainfall from the highlands (*c*. 300 mm) to the coastal plain (>50 mm).

particularly where sandy-silt and silt lie in close juxtaposition in the floodplains. Major floodplain characteristics were later analysed from the KAN, HOM, GBB, NAK and ROE fieldwork sites (Figure 2) while floodplains were absent at HYD. Particle size analysis was undertaken in the University of Botswana (ORI) laboratories, after preliminary assessment at the Gobabeb Research Station using standard sieving techniques (UCL, 1999–2014). Particle size distribution data of 46 sand-silt samples were subject to Pearsons Product Moment two-tailed correlation analysis using SPSS software.

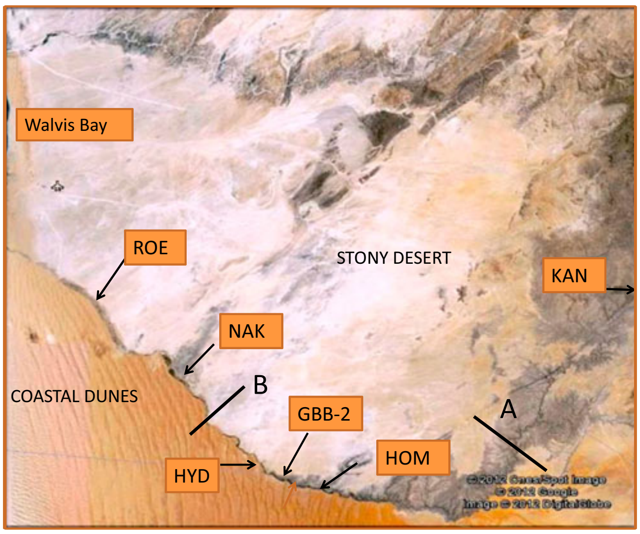

Figure 2. Names and location of cross-river transects (indicated by arrows). Line A indicates the end of the canyon section and the beginning of the midstream section. Line B marks the end of the incised midstream section and the beginning of the downstream section.

RESULTS

The entire Kuiseb river long profile has been previously documented in Jacobson *et al*. (2000b). Here we examine the lower 200 km from the Schliesen bridge to the Atlantic Ocean (Figure 2). The partial long profile is quasilinear (gradient 0.0025) and characterised by intermittent convexities and concavities until *c*. 100 km from the Ocean. The profile then develops a convex slope prior to merging with coastal dunes (Figure 3A). The upper section (above HYD, Figure 2) shows most irregularities resulting from a high degree of bedrock control. The lower convex section is characterised by broad alluviation (aggradation) on the coastal plain. Floodplain width in relation to long profile elevation (Figure 3B) provides a basis for dividing the river into three sections (a) canyon section, where channel width is constant (*c*. 200 m) between 800 and 500 m asl: (b) mid-section where the bedrock incised channel width increases from 200 to 700 m inversely downstream and (c) downstream section where wider floodplains (to 2400 m) are associated with an open, stony desert periphery comprising more erodible bank sediment.

Floodplain landforms and sediment content are described from field transect data (Table 1). In the canyon section the incised Kuiseb valley is characterised by low lying sand and gravel/cobble bars which appear to relate to the present day flood regime (Figure 4A). No remnant floodplains have developed as the entire channel is submerged during flood events reforming the in-channel sediments into various bedforms. Midstream floodplain features form islands of sand and silt standing initially at 1–2 m above the current channel. These increase and decrease in elevation between the landward margin and the present river channel and have been described as separate terrace features in Yamagata & Mizuno (2005). However aerial analysis shows that incipient floodplain islands have accumulated close to the river banks and begin extending into the channel as long ridges interspersed by narrow anabranches (cf. Nanson *et al.*, 2002). Being semi-continuous, the ridged pattern enhances the quasi-meandering trace of the main channel. Large floodplain islands become prominent in terms of size and spatial extent at Homeb (HOM site, Figure 4B), where they are *c.* 470 m wide and densely vegetated except in the vicinity of anabranch channels. Downstream from Homeb (at GBB) floodplain islands are smaller (*c.* 270 m wide) and less well vegetated (Figure 4C). A schematic cross section based on the HOM transect illustrates floodplain islands as silty backwater deposits crossed by infrequent, shallow, anabranch channels. These resemble a former braided system which is currently fringed by channel curvilinear overbank sand bars which are active during high floods (Figure 4D).

In the downstream reach (Figure 2) the river banks are formed of more easily erodible desert weathered sediment and the floodplains widen out to *c.* 2.0 km (Table 2). Here sediment depth varies between 20 and 40 m (Namwater, 2010) with drill-logs showing major sedimentological variations between riverine and dune sand interspersed with finer silt and clay beds. Valley widening is locally intermittent and mainly takes place on northwest oriented reaches. Two similar northwest oriented reaches were examined at NAK and ROE which are both intermittently vegetated. At ROE (Figure 5A) wide recently active channels comprise extensive sand beds interspersed with linear silt shoal bars. Remnant floodplains extend laterally (northeastwards) from the main channel and consist of extensive flat topped deposits comprising finely interbedded fine sand and silt. These deposits support a network of relict anabranch channels resembling former anastomosing patterns (e.g. Makaske, 2001; Smith, 2009). Beyond the sand-silt beds extensive areas of sand suggest widespread overbank deposition, possibly resulting from former channel avulsion. Much of the uppermost sand has been reformed into aeolian dunes up to 4–6 m high. The depth and extent of remnant deposition suggest extended

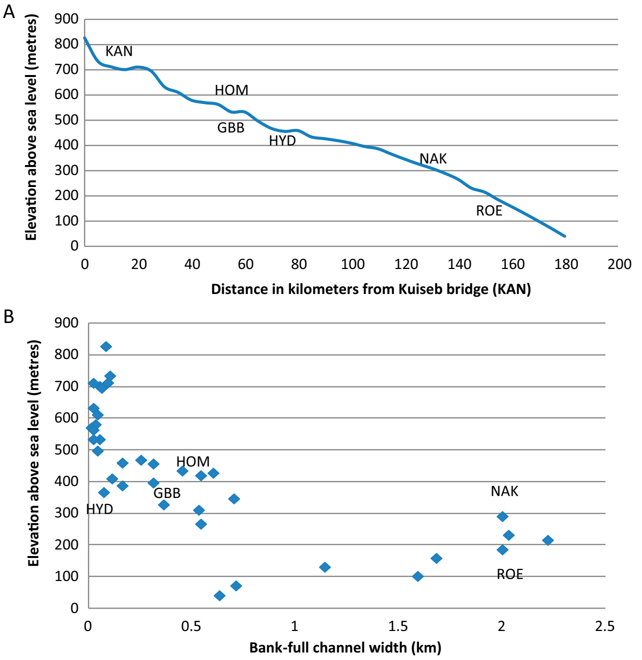

Figure 3. A. Kuiseb river partial long profile showing irregular height changes due to bedrock outcrops upstream from HYD and convexity relating to aggradation downstream. B. Elevation of Kuiseb river above sea level relative to bank full width during floodplain deposition. Decreased width of river downstream from ROE relates to (a) human induced channelling effects and (b) constrictions by sand dunes.

Table 1. Major Kuiseb river and floodplain characteristics at transect locations (see Figure 2).

Floodplain transect	Average elevation of main river (m asl)	Average floodplain width (km)	Average channel width (km)	Bank characteristics	Main floodplain and bank features (sand channel prevalent throughout)
KAN	827	0.10	0.10	Mica-schist rock walls (canyon)	Sand bars and gravel/cobble bars Rock embayments and rock outcrops
HOM	434	0.47	0.40	Alluvial wash and sand draped cliffs	Floodplain islands – sand-silt ridges Relict braided channels and lateral terrace deposits
GBB	396	0.32	0.40	Incised bedrock and sand draped cliffs	Floodplain islands Relict braided channels
HYD	366	0.18	0.14	Exposed bedrock and dunes	Rock outcrops Lateral terrace deposits
NAK	290	1.73	0.20	Weathered sediment banks and dunes	Rock outcrops Extensive floodplain sand/silt accretion Aeolian modification Anastomosing channels and lateral terrace deposits Old main channel features
ROE	185	2.38	0.57	Weathered sediment banks and dunes	Extensive floodplain sand/silt accretion Aeolian modification Anastomosing channels and lateral terrace deposits Old main channel features

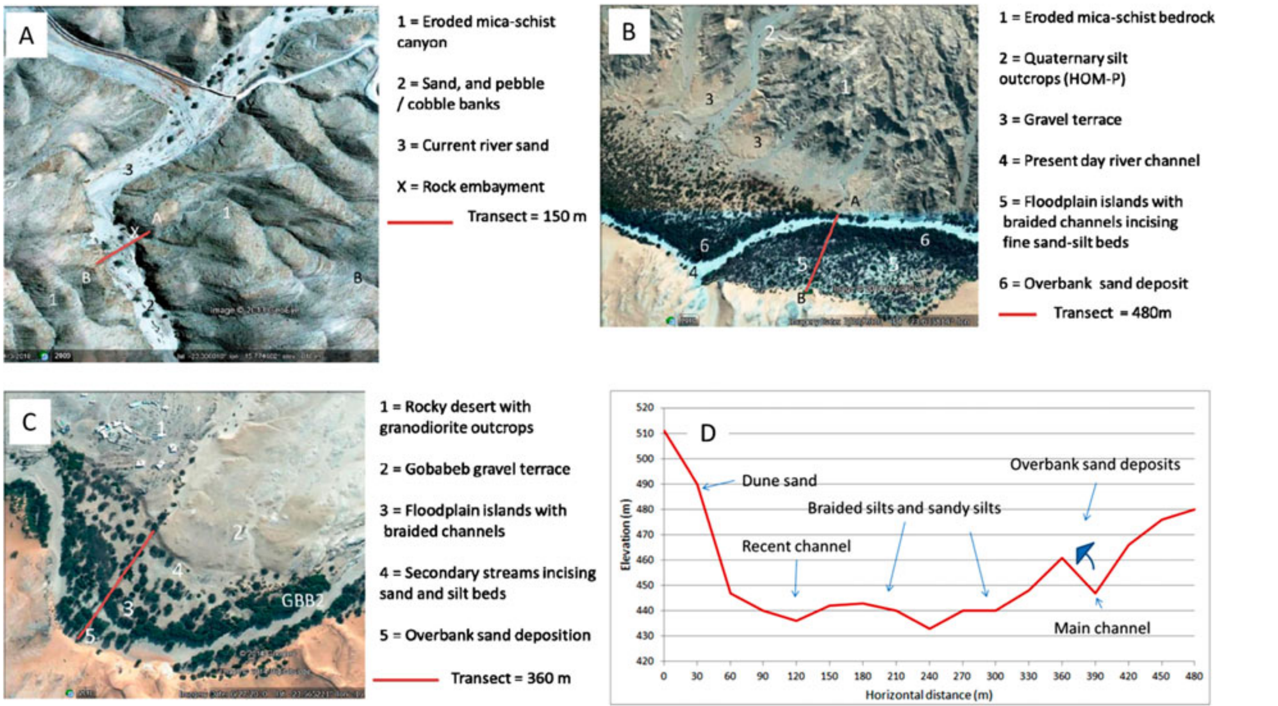

Figure 4. A. Characteristics of Kuiseb river south of bridge at Schliesen (M35). Note mainly in-channel depositional landforms and absence of remnant floodplain formation. B. Kuiseb river at Homeb in mid-incised section of river with significant floodplain island deposition and narrow main channel. Note the location of Quaternary Homeb silts towards the top of the image. C. Floodplain island and related features at GBB. D. Schematic cross section of floodplain islands showing former braided development now forming backwater silts and sandy silt. Note formation of overbank sand deposits peripheral to the main channel which is subject to present day aggradation, presumably leading to later diversions through the floodplain.

Table 2. Particle size data (Wentworth Scale) from Kuiseb floodplain sediments and associated features (percentages).

Sample	Granular fraction* (–2Ø–1Ø)	Medium sand (2Ø)	Fine sand (3Ø)	Very fine sand and coarse silt (4Ø)	Fine silt and clay (>4Ø)
*Canyon***	*KAN*	n=*7*			
Sand bank – river sand	13.74	33.38	**45.32**	6.64	1.9
Cobble/pebble bank	**62.62**	10.48	19.84	5.52	1.58
Midstream	*HOM*	n=*18*			
Floodplain island sandy-silt	6.98	11.5	23.36	**32.56**	25.5
Floodplain island silt	0	0.24	4.4	7.28	**88.08**
Quaternary Homeb-sandy silt	0.90	5.56	12.94	34.68	**45.92**
Quaternary Homeb silt	0	0.98	2.08	10.42	**86.52**
River sand	0.48	11.18	**68.06**	17.28	2.18
Lower dune slope sand	1.36	50.36	**43.7**	2.54	1.16
River terrace	**67.96**	11.06	12.43	5.8	2.04
Midstream	*GBB2*	n=*20*			
Floodplain island sand	2.3	21.5	**51.72**	17.78	6.36
Floodplain island fine sand and silt	1.38	14.46	23.18	**45.42**	15.46
Floodplain island silt		0.88	6.64	14.38	**78.10**
River sand	4.56	40.26	**48.2**	5.42	1.56
Lower dune slope sand	0.24	25.36	**66.2**	4.94	3.26
Downstream	*NAK*	n=*15*			
Aggraded silt	0	9.82	10.6	18.62	**61.96**
Aggraded sandy silt	0.24	15.18	**60.66**	20.72	2.76
River sand	1.28	35.36	**48.64**	11.4	2.05
Lower dune slope	0.06	**79.92**	19.4	0.44	0.06
Downstream	*ROE*	n=*18*			
Aggraded silt	0	0.96	2.26	19.58	**77.2**
Aggraded sandy silt	0.4	5.6	**58.74**	32.38	2.82
River sand	0.1	11.92	**71.46**	14.8	0.94
Lower dune slope	0.7	**54.98**	41.42	1.26	0.64

*Pebbles, granules and coarse sand. **No floodplains in canyon.
Figures in bold show the highest grain size proportions per sediment type.

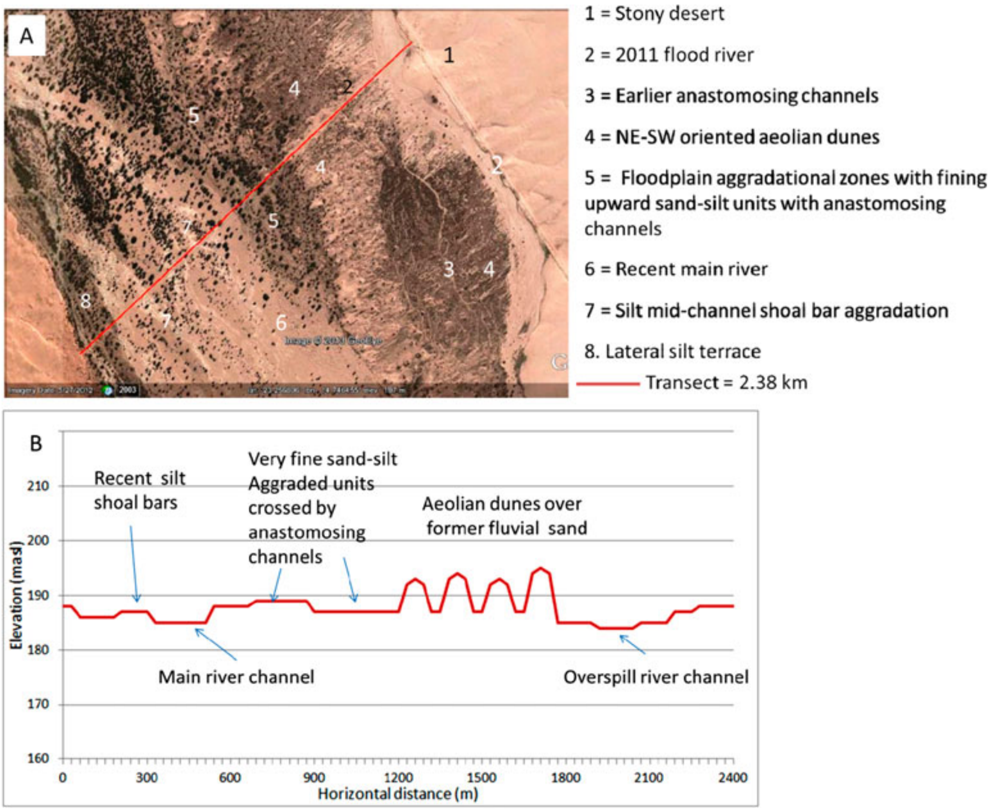

Figure 5. A. ROE transect – in valley sand-silt deposition showing diverted flood channel (2) and main alluviation features comprising sand-silt floodplain aggradational zones (5) intermittently covered by either aeolian or fluvial sand reforming into present day dunes (4). Linear sand/silt banks (7) occur within and peripheral to the recent main river which is flanked by lateral silt deposits (8). B. Schematic cross section showing upper portion of downstream floodplain aggradation comprising flat topped sandy-silt beds crossed by anastomosing channels. Additional features include reworked dunes over former fluvial sand. Profile drawn to highlight reactivated dunes.

periods of aggradation leading to the convex profile in this section (cf. Jacobson *et al*., 2000b).

To obtain insight into their origin, particle size data of floodplain sands and silts are compared to local dune and present day river bed sediments. Comparisons are also drawn between floodplain sediments and up-stream channel sands (from KAN, Figure 4A) and Quaternary Homeb silts in an attempt to establish source material (Figure 4B). In the midstream section at HOM (Table 2), fine silts (and clays) predominate in silt rich cross laminae while fine sand and coarse silt are prevalent in sandy inter-beds. The floodplain beds are similar in grain size to Homeb silts and appear more inherently fluvial than aeolian in origin (cf. Garzanti *et al*., 2012). In contrast, both upstream and nearby river and dune sands are coarser than floodplain island deposits. In downstream sections at NAK and ROE, results show higher overall median proportions of fine sand, suggesting that the downstream aggraded floodplains are slightly coarser than the midstream floodplain islands (Table 2). However at both locations the fine silt and clay content remains high. Results show no grain size similarity between floodplain deposits and the Kuiseb canyon (KAN) fluvial sediment (Table 2). The results of correlation analysis on particle size data (Table 3) show that while the HOM transect floodplain sand might have been derived from adjacent river sand, the silt-rich portion of the floodplain sediment was most likely derived from the Quaternary Homeb silt beds. A similar result pertains for GBB2 floodplain sediments where again the

Table 3. Pearson's product moment correlation coefficients for Kuiseb floodplain deposits in relation to possible source sediments (*n*=46).

Location of field transect (Figure 2)	Quaternary Homeb sand	Quaternary Homeb silt	KAN river sand	Adjacent dune sand	Adjacent river sand
HOM Floodplain sand	0.927 **	0.989 **	N/C	N/C	0.951 **
HOM Floodplain silt	0.915 **	0.977 **	N/C	N/C	0.867**
GBB2 Floodplain sand	0.797 *	N/C	N/C	0.935 **	0.998 **
GBB2 Floodplain silt	0.851 **	0.912 **	N/C	N/C	N/C
NAK Floodplain sand	0.965 **	0.958 **	N/C	N/C	0.773 *
NAK Floodplain silt	0.951 **	0.984 **	N/C	N/C	0.773 *
ROE Floodplain sand	0.957 **	0.998 **	N/C	N/C	0.813 *
ROE Floodplain silt	0.839 **	0.754 *	N/C	0.916 **	0.991 **

*Coefficient significant at 95% level. **Coefficient significant at 99% level. N/C = no significant correlation.

silt-rich beds are strongly correlated with Quaternary Homeb sands and silts. Comparable results were obtained for the downstream NAK transect (Table 3). The situation is reversed for the ROE floodplains which are much further downstream. At this location the floodplain deposits, in terms of their particle size, more closely resemble local river and dune sands. Hence most silt-rich floodplain sediment is significantly correlated (in terms of particle size) with samples taken from the Quaternary Homeb silts. While more work is needed, this infers that transported Homeb silt washed down from tributary valleys (Figure 4B) likely played a role in contributing sediment to the Kuiseb river in the past. This silt addition is particularly apparent in the vicinity of Homeb where the floodplain islands are locally enlarged in the midstream section of the river.

DISCUSSION

Kuiseb floodplain development is not apparent in the upstream (canyon) portion of the river and importantly floodplains only begin to form downstream from external sediment inputs. Different sources of floodplain sediment potentially include fluvial deposits directly derived from weathering within the Kuiseb catchment, sediment derived from the northward moving dunes (Namib sand sea) and previously deposited fluvial sediment found within tributary systems. The floodplains comprise laterally constrained floodplain islands in the incised midstream section and unconstrained (laterally extensive) aggraded valley infills in the downstream section of the river. Sedimentation within these two sections is controlled initially by their bank material. Their topographic response suggests that differing fluvial depositional environments pertained during wetter periods in both parts of the river. In both cases the floodplains are mostly remnant deposits which are only slightly modified during present day floods. Based on their topography, sediment content and associated structures the midstream floodplain islands and downstream anastomosed valley infills were formed under wetter conditions than today, which led to higher average discharge rates possibly over the entire Kuiseb catchment.

Results indicate that the floodplain islands were formed as braided river deposits due to heavy influxes of external sediment, particularly older silt (Figure 4B). Braided rivers, similar to those which occur in the mid-incised section, often consist of a series of broad, shallow channels and bars, with elevated areas active only during floods, and dry islands (Maill, 1977). Important in-channel sediment depositional processes include point bar formation, channel-floor dune migration, low-water accretion and overbank sedimentation similar to that envisaged during earlier Kuiseb floodplain island formation. In addition Schmidt (1990) describes deposition within confined bedrock walls as resulting from recirculating currents which develop just downstream from sharp meander bends or near bank irregularities. Fine sediment accumulates under an extended helical current initially at a point of separation (from the main current), through the controlling recess and back to a reattachment point upstream. Deposition occurs under primary eddies within the recess as flow decelerates. This kind of helical flow was observed along the Kuiseb banks during the last (2011) flood. An extended version of helical flow may have contributed to floodplain island formation in the past.

In contrast, downstream floodplain deposits are characterised by complete valley infills resembling the depositional effects of broad, anastomosing rivers which assume multichannel systems such as those brought about by avulsion processes (Slingerland & Smith, 2004). Rapidly aggrading rivers worldwide result from high sediment loads in wide valleys where climate is not a controlling factor. According to Knighton and Nanson (1993) and Makaske (2001) aggrading rivers of this size are characterised by (a) rapid vertical accretion, often in very low gradient subsiding basins, (b) crevasse splay development (avulsion) and levee formation with associated overbank deposition, (c) overbank fine sand and silt development into flat topped beds, similar to those observed in downstream Kuiseb profiles. Vertical aggradation in the downstream Kuiseb continued as flow velocity dropped below the river's ability to transport the fine sand and silt bedload.

Particle size data suggests that a proportion of sandy-silt in both the floodplain islands and aggradation infills was derived from the Quaternary Homeb silt beds which have been repeatedly age-dated (as summarised in Stone & Thomas, 2013) and shown in Srivastava *et al*. (2006) to have been deposited in two sequences centred around 15 ka and 6 ka. This compares favourably to calibrated 14C dates reported in Chase *et al*. (2009), implying that wet/humid conditions were likely prevalent over the Namib coastal plain around 7000 BP, 6800 BP, 5300 BP and around 4800 BP. Hence we are suggesting that following the deposition of the Homeb silts, the tributary systems feeding into the Kuiseb river were intermittently active. This tentatively suggests that the Kuiseb floodplain islands and aggradation infills received large quantities of sediment during the early–mid Holocene. Additional dating work is however required to corroborate this possibility.

CONCLUSIONS

This work has shown that:

- Floodplain deposition in the Kuiseb river took place predominantly downstream from zones of significant external sediment input.
- Two floodplain types are identified – floodplain islands which developed as braided river deposits in the midstream section of the river and aggradational infill deposits which developed from anastomosing streams in the downstream section. The two types were dependent on the geometry of the river cross section and the amount of sediment available during the Holocene.
- The topography, sediment content (fine sand and silt units) and structure all imply that the deposition of floodplain deposits took place under wetter conditions than those recently prevalent.
- Particle size analysis of floodplain silts in relation to river bed and sand dune silt indicates a close association between the floodplains and Quaternary Homeb deposits.
- The floodplains likely formed under wet conditions in the early–mid Holocene following Quaternary Homeb silt deposition when the tributary valleys were actively flowing. For the tributaries to flow, intermittent rainfall was needed along the coastal plain during the Holocene.

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