Bank pull or bar push: what drives scroll-bar formation in meandering rivers?

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Abstract

One of the most striking features of meandering rivers are quasi-regular ridges of the point bar testifying of a pulsed lateral migration of meander bends. Scroll bars formed on the inner bend are preserved on the point-bar surface as a series of ridges as meanders migrate, and in the subsurface of the point bar as inclined heterolithic stratification with lateral accretion surfaces. It is necessary to understand the formation and sedimentary architecture of these point bars which are fundamental geomorphic building blocks of meandering rivers and are potential reservoirs for water, oil and gas. However, it remains unresolved whether the scroll-bar pattern forms in response to outer-bend bank erosion during floods, i.e., bank pull, or is forced by bank progradation, i.e., bar push. Here we use experimentally formed meandering rivers with a set of static and migrating bends to isolate the effects of sediment supply to the point bar, bank protection and forced bank retreat. We find that channel widening caused by bank retreat near the bend apex causes deposition of new scroll ridges along the inner-bend point bar, whereas scroll bars cannot be forced by sediment pulses. Thus channel width variations along meander bends cause bank pull, which is necessary for scroll-bar formation. Furthermore, we find that each newly attached scroll bar overlies a non-permeable layer of finer-grained sediment caused by the temporary flow expansion, which explains the fining upward tendency of point bars.

1. Introduction

Point bars are major depositional bodies of meandering rivers (Miall, 1985). They have a characteristic ridge-and-swale topography, which is visible on airborne scanning laser altimetry images (Fig. 1A) and often expressed in the distribution and succession of vegetation (Fig. 1B). The ridges are formed as scroll bars parallel to the curved channel and separated from the inner bank by a swale (Jackson, 1976; Nanson, 1980). The low-lying swales are preferential pathways for cutoffs rather than the elevated ridges (Zinger et al., 2011). A key unresolved problem is whether scroll bars are formed as a consequence of bank pull, i.e., erosion of the outer bank, or prior to bank erosion due to quasi-periodic variations in local sediment supply, after which the flow is ÓřushedÒătoward the outer bank by the bar. Several studies suggested that each scroll bar is formed during one flood event (Nanson, 1980; Nanson and Hickin, 1983), but no previous study has documented whether these scroll ridges are triggered by outer-bank retreat or cause the flow to scour the outer bank.

Understanding the formative conditions for scroll bars is essential to explain fundamental meandering morphodynamics and to characterize the internal three-dimensional sedimentary architecture of point-bar deposits. Point-bar deposits are predominantly coarse-grained, i.e., sandy to gravelly, which makes them excellent reservoirs of natural resources. Yet, depending on the formative mechanism, lithologic heterogeneities within these depositional bodies determine the hydraulic properties (Bierkens and Weerts, 1994; Huggenberger and Ainger, 1999), which is relevant to predict the internal fluid-flow behavior (Gibling and Rust, 1993; Labrecque et al., 2011) and to assess groundwater contamination and remediation (Wagner and Gorelick, 1989; Rauber et al., 1998). The lithologic heterogeneities are often expressed as fining-upward lateral-accretion deposits (Miall, 1985) but how these characteristic sedimentary features are related to meander bend migration and the hydrodynamics along meander bends is poorly understood. A detailed understanding of the mechanisms of channel bend migration and the controls on erosion and deposition along meander bends is therefore of great interest to geomorphologists, engineers as well as to sedimentologists and petroleum geologists.

In this paper, we present a series of systematic flume experiments to test the bar push and bank pull hypotheses for formation of individual scroll bars and the consequences for the resulting point-bar stratigraphy. Multiple flume experiments (Pyrce and Ashmore, 2005; Van Dijk et al., 2012; Van de Lageweg et al., 2013) showed that typical point-bar ridge-and-swale topography developed under constant discharge (Fig. 1C) and an individual flood event did not cause a single scroll bar (Van Dijk et al., 2013, Fig. 1D). We present detailed data of a series of controlled flume experiments in which the essential conditions to form the characteristic ridge-and-swale topography and associated lithologic heterogeneities in point-bar deposits are isolated. We compared bends that migrated with static bends, fixed outer banks, attempted to force bar-push by adding sediment just upstream of bends and attempted to

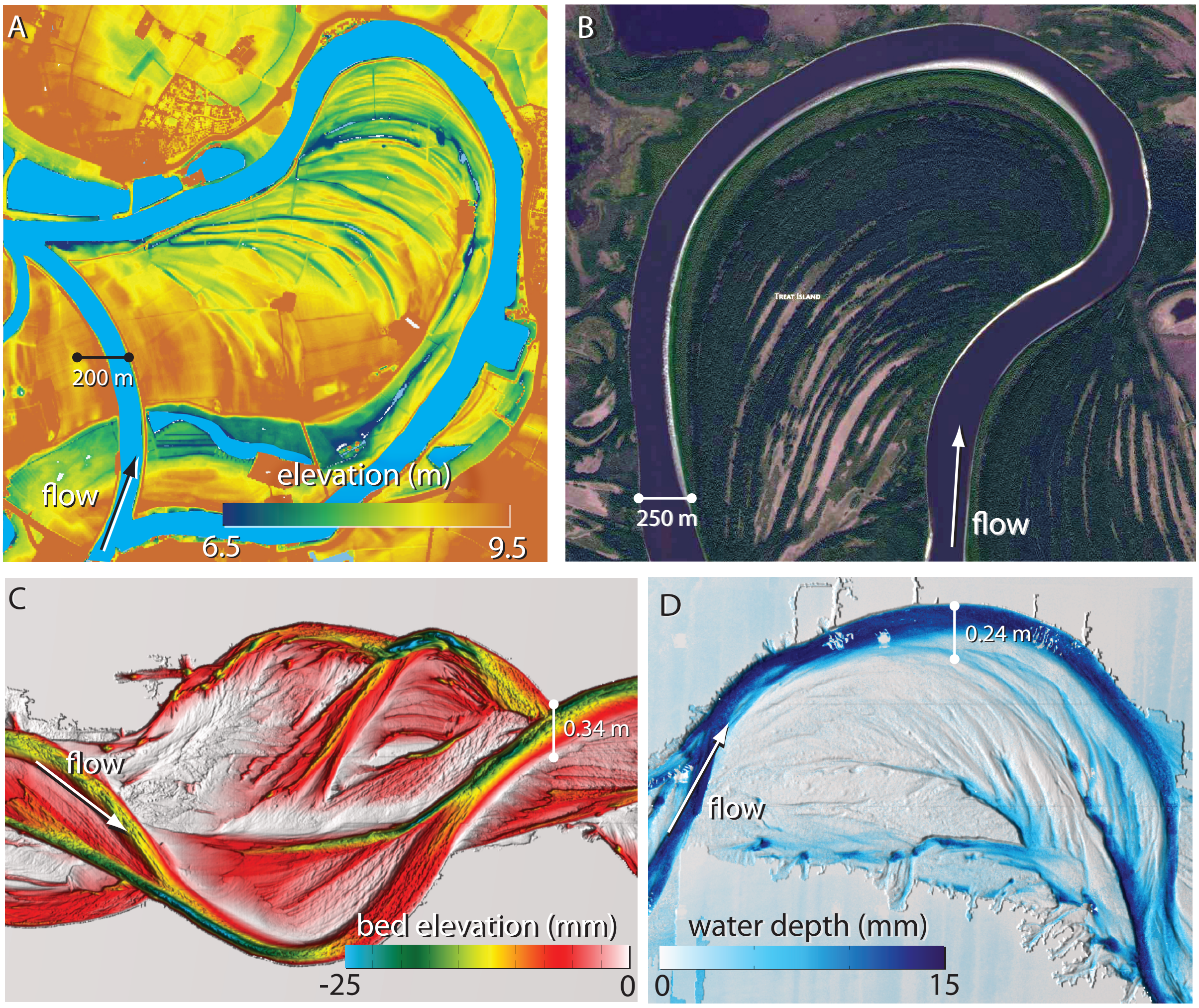

Figure 1: *Examples of natural and experimental point bars with a characteristic ridge-and-swale topography. a) Lidar images identify the ridges and swales on a point bar of the river IJssel, The Netherlands (source: http://ahn.geodan.nl/ahn/). b) The ridge-and-swale topography is highlighted by the distribution and succession of vegetation on the point bar of the river Koyukuk, Alaska (source: DigitalGlobe). c) Point-bar deposits with intact and cross-cut scrolls in an experiment with constant bankfull discharge (Van Dijk et al., 2012; Van de Lageweg et al., 2013). d) Well-developed point bar with alternating scroll ridges and swales in an experiment with fines and a varying discharge (Van Dijk et al., 2013).*

force bank-pull by removing bank material (Table 1).

2. Experimental methods

We conducted eight experiments in the Eurotank basin measuring 11 m x 6 m to form dynamic meandering rivers with scroll-bar formation (Van Dijk et al., 2012; Van de Lageweg et al., 2013). We systematically measured and manipulated a set of developing point bars with a range of dynamics to investigate if the typical ridge-and-swale topography and associated subsurface expression are caused by inner-bend sediment pulses (i.e., bar pushing) or outer bank erosion (i.e., bank pulling). In our experiments we cause ongoing lateral development of meanders on average by a sustained perturbation of the upstream inflow location of water and sediment in the flume (Van Dijk et al., 2012). As a result bend migration varied both spatially and temporally from nearly static bends to rapidly migrating bends, which allowed us to select a set of point bars with a wide range of dynamics for measurement and systematic manipulation. Details on the experimental setup and approach are provided in the GSA Data Repository1.

We used five different bends to study the effect of forced sediment pulses and forced or stalled outer-bend erosion on the development of scroll ridges in migrating or non-migrating meander bends (Table 1). Cases 1 to 3 served as control experiments for both migrating and non-migrating static bends. The bar push mechanism was tested by adding sediment pulses upstream of the bend (cases 4 and 5). Pulse volume (200 ml) was equal to the volume of a single scroll bar. The bar push mechanism was tested on a migrating channel bend and on a bend that was not migrating (static). The bank pull mechanism was tested on two migrating bends for which we either fixed the outer bank (case 6), or we manually removed sediment from the outer bank (case 7). In this latter case, the outer bank was displaced each time by at least a tenth of the channel width. Cases 1 to 7 had a constant discharge of 0.5 l/s and no silica flour was added. A specific experiment (case 8) was conducted to study the relation between the migration of meander bends, deposition of fine sediment and the formation of fining-upward lateral-accretion packages within point bar deposits. Case 8 had a stepped hydrograph with a low discharge of 0.25 l/s for 2.5 hours and a high discharge of 0.5 l/s for 0.5 hours. We added 0.5 l of slightly cohesive silt-sized silica flour during the high discharge stages.

The surface was recorded by a high-resolution ($<$ 0.5 mm) line-laser scanner for digital elevation models and a digital single lens reflex camera on an automated gantry for (1) channel-floodplain segmentation from water color intensity and (2) silt surface cover from normalized image luminosity (Fig. DR1, Van Dijk et al., 2013). The effect of bar push and bank pull are quantified by measuring the displacement of the inner and outer banks compared to their initial location. A transverse bed slope predictor (Eq. 1 in DR1, Struiksma et al., 1985) was used to predict the dip angle of lateral-accretion deposits. Furthermore, sequential digital elevation models of the meander morphology were used to generate a synthetic stratigraphy verified by lacquer peels that records deposit age and erosional surfaces (Van de Lageweg et al., 2013).

3. Results and discussion

3.1. Scroll-bar formation

Point-bar deposits are built up by successive attachment of individual scroll bars as the outer bank retreats. Previous studies suggested that these scrolls formed by oblique dunes (Dietrich and Smith, 1983) or by transverse bars (Sundborg, 1956). We observed trains of oblique sediment sheets migrating along the inner bend at a higher frequency than that at which scrolls formed (Fig. 2). The ridges of these sediment sheets shoaled and migrated upslope onto the point bar downstream of the bend apex. Deposition of several of these bedforms resulted in a single scroll ridge. Net movement of bedforms toward the inner bend is caused by helical flow forced by bend curvature (Nanson, 1980) and deposition is determined by flow expansion forced by width variations along the bend (Zolezzi et al., 2012; Frascati and Lanzoni, 2013). The experimental point bars migrate mostly by downstream translation, which is consistent with typical field (Fig. 1) and model (Willis and Tang, 2010) examples of skewed downstream point-bar configurations. Consequently, scroll bars are mainly deposited on the downstream, widening half of the point bar where flow velocities decrease. This suggests that width variations along the channel are pivotal to explain point-bar development and, ultimately, river-pattern evolution and construction of the sedimentary architecture of point bars.

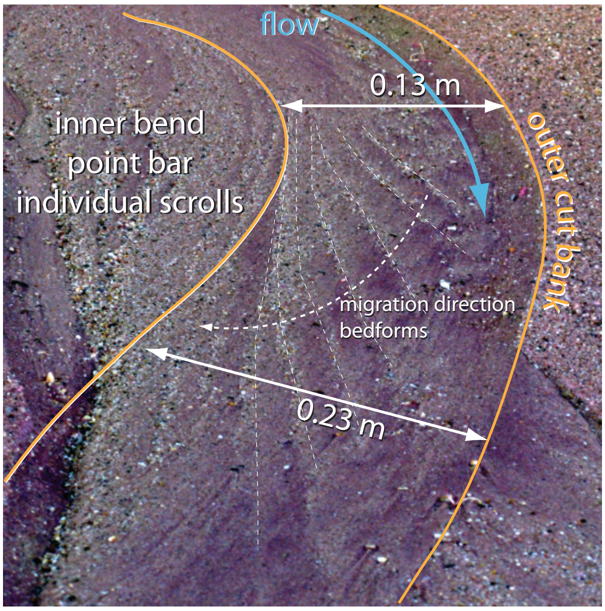

Figure 2: *Image of a flume experiment showing the migration of bedforms shoaling onto the point bar as a result of flow deceleration and helical flow in the widening bend.*

3.2. Effect of interventions on point-bar development

First, we studied bends that migrated naturally in control experiments (case 1). Sediment tracers confirm earlier findings (Pyrce and Ashmore, 2005) that sediment eroded from the outer bank upstream of the bend apex deposits on the point bar downstream of the same bend apex (case 3). In contrast, sediment eroded downstream of the bend apex deposited on the next, downstream point bar. Other bends were naturally static for some time in the experiment (case 2) for lack of upstream dynamics (Lanzoni and Seminara, 2006; Van Dijk et al., 2012).

Second, the mechanism of inner-bend bar pushing was tested by adding pulses of sediment just upstream of point bars in migrating bends (case 4). This sediment deposited on top of the existing scroll ridge. It neither formed a new ridge nor caused outer bank erosion, but flattened the existent ridge-and-swale topography. Also larger sediment pulses did not cause bar-push (Fig. 3A). In a naturally static bend (case 5, Fig. 3B) sediment pulses neither activated scroll-bar formation nor caused outer-bank retreat, which indicates that flood-caused sediment pulses alone are insufficient to form scroll bars and to cause outer-bend bank erosion.

Table 1: *Overview of measured and manipulated point-bar cases. The precondition gives the current development of the tested bend, migrating laterally or static on one position. The results identify the effect of the bar push or bank pull on the development of the point bar or bank retreat compared to the control experiments.*

Experiment	precondition	intervention	cases	results
control	migrating	-	1,3	multiple scrolls per flood
control	static	-	2	no scrolls, no bank retreat
bar push	migrating	5 sediment pulses	4	no increase in bank retreat
bar push	static	3 sediment pulses	5	no bank retreat
bank pull	migrating	outer bank fixed, 5 sediment pulses	6	point-bar accumulation
bank pull	migrating	4 manual bank shifts	7	new scroll bars form
cohesive sediment	migrating	add cohesive sediment	8	dynamic meander (Van Dijk et al., 2013)

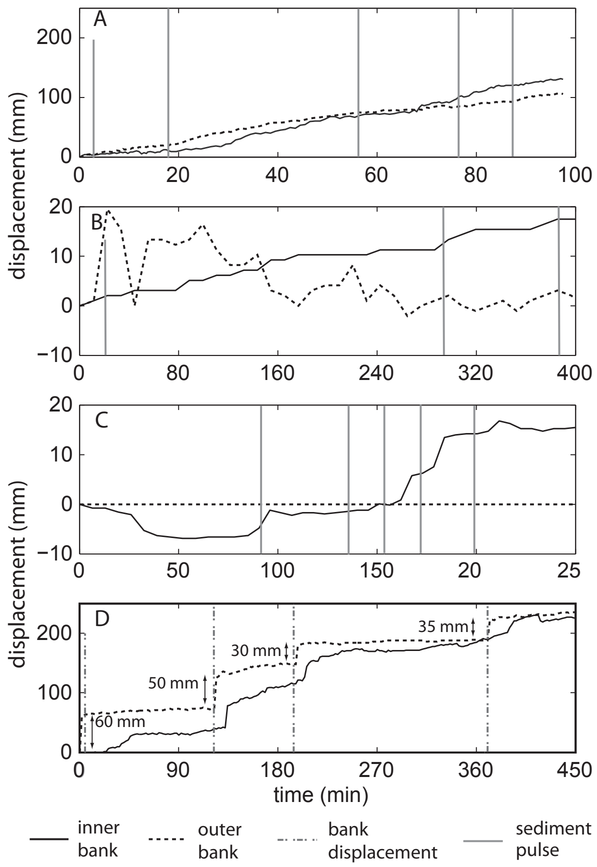

Figure 3: *Time series of inner- and outer-bank displacement in response to interventions. Figures a-b provide evidence against the bar-push hypothesis and d shows evidence for the bank-pull hypothesis. a) Well-coupled migration of inner- and outer bank despite five sediment pulses to feed the inner bank bar (case 4). c) Static bend remains static despite sediment pulses (case 5). d) Sediment pulses cause point-bar sedimentation when outer bank of initially migrating bend is fixed (case 6). e) Manually forced bank retreat induces inner-bank sedimentation migrating downstream through the widened channel reach (case 7).*

Third, we fixed the outer-bend bank of a migrating bend and applied upstream sediment pulses, which represents a river with highly cohesive banks (case 6, Fig. 3C). This caused in-channel sedimentation and a decrease of channel width and depth, overbank flow and eventually a chute cutoff across the point bar. This result suggested that in natural rivers with highly cohesive banks continuous deposition of sediment flattens the characteristic ridge-and-swale topography.

Fourth, to test if scroll ridges are the result of outer-bend bank pull, we repeatedly widened the channel by removal of outer-bank material of about a tenth to a fifth of the channel width. In all cases this resulted in slightly delayed and significant growth of the point bar by inner-bend accretion (case 7, Fig. 3D). Flow-velocity measurements confirmed that the forced retreat of the outer bank and resulting channel widening caused a decrease of flow velocity, in particular close to the inner bank. This eventually led to the deposition of a sediment volume along the point bar which was similar to the volume that was manually removed from the outer bank. Clearly, the outer-bend displacement determined the available lateral accommodation space and inner-bend deposition ceased when the channel approximated its initial width. The width reduction resulted from the formation of a single scroll but due to a shallower channel the scroll ridge was lower compared to the control experiment with a natural bank-retreat rate.

Fifth, we added slightly cohesive silt-sized silica flour to the sediment feed to study the formation of fining-upward lateral-accretion packages and their relation to meander bend migration (case 8). The silt was mainly deposited on the floodplain at outer bends and in low-lying swales between successive scroll ridges (Fig. DR1). Silt deposition was highly unsteady and required low flow velocities. Typically, outer bank erosion caused channel widening which resulted in lower flow velocities and ultimately in silt deposition on the existent scroll ridge. These inclined layers of fines reduced erodibility (Van Dijk et al., 2013). Moreover, the dimensions and distribution of these fine-sediment layers determine the hydraulic properties of meander deposits as they are potential fluid-flow barriers, which can compartmentalize reservoirs. The synthetic sediment peels based on stacked DEMs with silt concentration as attribute (Fig. 4A) and real sediment peels made during cutting of the deposit at the end of the run (Fig. 4B) of the point-bar deposit clearly show laterally inclined surfaces, but only some of these have a fine silt drape. The thickest silt deposits are found in the low-lying swales and gradually thin along the lateral-accretion surfaces in downstream direction. These inclined silt drapes are mostly restricted to the upper 75% of the point-bar deposit. The outer point-bar deposits, corresponding to later times of deposition (Fig. 4A), received more silt than the inner point bar. This is caused by point-bar expansion, gradient reduction and consequent flow velocity decrease, which result in increasing silt deposition.

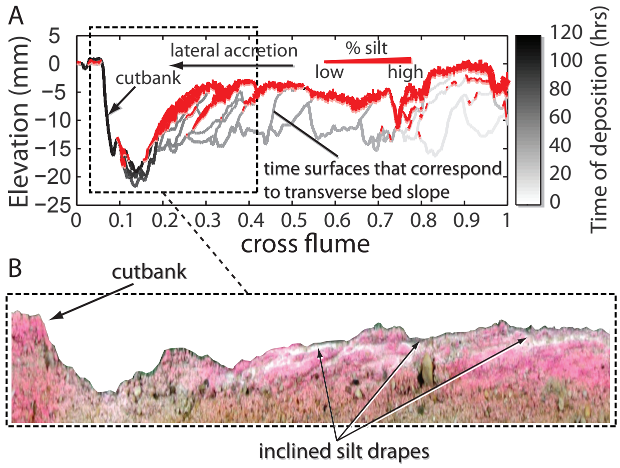

Figure 4: *Cross-sections of point-bar deposits from experiment (case 8). a) Synthetic slice through experimental point-bar deposit, showing cohesive sediment layers and time of deposition. b) Sediment peel from same location as shown in (a).*

The dip slope of these experimental finer-grained lateral-accretion surfaces is well predicted from basic morphological and sedimentological parameters and a transverse-bed slope predictor (Eq. 1 in DR1, Van Dijk et al., 2012). Application of this transverse-bed slope predictor to the modern coarse-grained meandering river Rhine (Erkens et al., 2009), Germany, and the ancient fine-grained McMurray Formation (Mossop and Flach, 1983; Crerar and Arnott, 2007), Canada, (Table 2) shows that also the dip angle of the lateral-accretion surfaces of natural point-bar deposits is well predicted. The required morphological and sedimentological parameters can generally be reconstructed from seismic observations (channel dimensions and curvature) and cores (grain size). The scale-independence of the predictor implies that for a wide range of meandering river systems a robust prediction of the dip slope and the number of individual fining-upward lateral-accretion deposits within a point bar can be made. This is an essential first step to improve the prediction of dimensions and spatial distribution of the flow-limiting finer-grained deposits for stratigraphic models.

Table 2: *Application of transverse bed slope predictor to the modern coarse-grained River Rhine, Upper Rhine Garben, Germany, and to the fine-grained Cretaceous McMurray FM, Canada. For both systems we assumed valley slope of 10^{-5}, a Chezy coefficient of 25 $m^{0.5}/s$, a κ of 0.4 and a g of 9.81 m/s^2*

Parameter	Rhine	McMurray
h_{mean}	8 m	25 m
sediment	gravel to sand	sand-silt-mud
Typical grain-size	0.5 mm	0.125 mm
$tan(\partial z/\partial n)$	0.37 R/h	0.11 R/h
Typical R/h	125	40
Predicted dip	1–2^o	13$_o$
Observed dip	4–7^o	8–12^o

4. Conclusions

Our study demonstrates that the formation of the characteristic ridge-and-swale topography of point bars is a consequence of channel widening induced by outer bank erosion (bank-pull) mechanism rather than a bar expansion following deposition (bar-push) mechanism. The findings point to the importance of incorporating river bank erosion processes in numerical models (Simon and Collinson, 2002; Parker et al., 2011) as inner-bank bench or scroll-bar formation is a direct consequence of flow expansion due to the widening of the channel. Incorporating dynamic models of cut-bank erosion rather than just static models of deposition along the inner bank of river bends is therefore expected to improve simulations of the planimetric evolution of meandering rivers on geological time scales. Moreover, the widening causes deposition of finer-grained layers within point-bar deposits indicating that the bank pull model is also pivotal to characterize the sedimentary architecture of point-bar deposits. Our experiments show that finer-grained flow-limiting layers develop along the transversely sloping bed at a dip angle that is well predictable. Application to natural modern and ancient meandering systems shows that the analytic transverse-bed slope predictor correctly estimates slope and number of lateral-accretion deposits within natural point-bar deposits. These findings suggest that the non-permeable fine-sediment layers within point-bar deposits such as found in the McMurray Formation can be predicted, and that the ridge-and-swale topography at the surface and in seismic observations is a good indicator for these potential flow barriers within point-bar deposits.

Acknowledgments

MGK and WMvD were supported by the Netherlands Organization for Scientific Research (NWO grant ALW-VIDI-864.08.007 to MGK). WIvdL was supported by ExxonMobil Upstream Research (grant EM01734 to MGK and George Postma). We acknowledge Darren Box for discussion, Roy Teske for help with laboratory work and Henk Markies, Marcel van Maarseveen and Thony van der Gon-Netscher for technical support. We acknowledge two anonymous reviewers and reviewer Brian Willis for comments that helped improve the paper, and editor R. Cox for helpful guidance. The authors contributed in the following proportions to conception and design, data collection, analysis and conclusions, and manuscript preparation: WIvdL (30%, 25%, 25%, 35%), WMvD (30%, 25%, 25%, 35%), AWB (10%, 40%, 20%, 10%), JR (0%, 10%, 10%, 0%) and MGK (30%, 0%, 20%, 20%).

Footnotes

GSA Data Repository item 2014120, extended version of the experimental method section, Figure DR1 (from image to silt cover map), is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

References

Bierkens, M. F. P., and Weerts, H. J. T. (1994). Block hydraulic conductivity of cross-bedded fluvial sediments. *Water Resources Research*, 30:2665–2678, doi:10.1029/94WR01049.

Crerar, E. E., Arnott, R. W. C. (2007). Facies distribution and stratigraphic architecture of the Lower Cretaceous McMurray Formation, Lewis Property, northeastern Alberta. *Bulletin of Canadian Petroleum Geology*, 55:99–124, doi:10.2113/gscpgbull.55.2.99.

Dietrich, W. E., Smith, J. D. (1983). Influence of the point bar on flow through curved channels. *Water Resources Research*, 19:1173–1192, doi:10.1029/WR019i005p01173.

Erkens, G., Dambeck, R., Volleberg, K., Bouman, M., Bos, J., Cohen, K., Wallinga, J., and Hoek, W. (2009). Fluvial terrace formation in the northern Upper Rhine Graben during the last 20000 years as a result of allogenic controls and autogenic evolution. *Geomorphology*, 103:476–495, doi:10.1016/j.geomorph.2008.07.021.

Frascati, A., Lanzoni, S. (2013). A mathematical model for meandering rivers with varying width. *Journal of Geophysical Research*, 118:1641–1657, doi:10.1002/jgrf.20084.

Gibling, M. R., Rust, B. R. (1993). Alluvial ridge-and-swale topography: A case study from the Morien Group of Atlantic Canada *in* Marzo, M. and Puigdefabregas, C. (eds.) *Alluvial Sedimentation, Volume Special Publication*, 17:133–150.

Huggenberger, P. and Aigner, T. (1999). Introduction to the special issue on aquifer-sedimentology: Problems, perspectives and modern approaches. *Sedimentary Geology*, 129:179–186, doi:10.1016/S0037-0738(99)00101-3.

Jackson, R. G. (1976). Depositional model of point bars in the Lower Wabash River. *Journal of Sedimentary Petrology*, 46:579–594, doi:10.1306/212F6FF5-2B24-11D7-8648000102C1865D.

Labrecque, P. A., Jensen, J. L., Hubbard, S. M., and Nielsen, H. (2011). Sedimentology and stratigraphic architecture of a point bar deposit, Lower Cretaceous McMurray Formation, Alberta, Canada. *Bulletin of Canadian Petroleum Geology*, 59:147–171, doi:10.2113/gscpgbull.59.2.147.

Lanzoni, S. and Seminara, G. (2006). On the nature of meander instability. *Journal of Geophysical Research*, 111:F04006, doi:10.1029/2005JF000416.

Miall, A. D. (1985). Architectural-Element Analysis: A New Method of Facies Analysis Applied to Fluvial Deposits. *Earth-Science Reviews*, 22:261–308.

Mossop, G., and Flach, P. D. (1983). Deep channel sedimentation in the Lower Cretaceous McMurray Formation, Athabasca oil sands, Alberta. *Sedimentology*, 30:493–509, doi:10.1111/j.1365-3091.1983.tb00688.x.

Nanson, G. C. (1980). Point bar and floodplain formation of the meandering Beatton River, northeastern British Columbia, Canada. *Sedimentology*, 27(1):3–29, doi:10.1111/j.1365-3091.1980.tb01155.x.

Nanson, G. C. and Hickin, E. J. (1983). Channel migration and incision on the beatton river. *Journal of Hydraulic Engineering*, 109:327–337, doi:10.1061/(ASCE)0733-9429(1983)109:3(327).

Parker, G., Shimizu, Y., Wilkerson, G. V., Eke, E. C., Abad, J. D., Lauer, J. W., Paola, C., Dietrich, W. E., and Voller, V. R. (2011). A new framework for modeling the migration of meandering rivers. *Earth Surface Processes and Landforms*, 36(1):70–86, doi:10.1002/esp.2113.

Pyrce, R. S., and Ashmore, P. E. (2005). Bedload path length and point bar development in gravel-bed river models. *Sedimentology*, 52:839–857, doi:10.1111/j.1365-3091.2005.00714.x.

Rauber, M., Stauffer, F., Huggenberger, P., and Dracos, T. (1998). A numerical three-dimensional conditioned/ unconditioned stochastic facies type model applied to a remediation well system. *Water Resources Research*, 34:2225–2233, doi:10.1029/98WR01378.

Simon, A. and Collinson, A. J. C. (2002). Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. *Earth Surface Processes and Landforms*, 27(5):527–546, doi:10.1002/esp.325.

Struiksma, N., Olesen, K. W., Flokstra, C., and De Vriend, H. J. (1985). Bed deformation in curved alluvial channels. *Journal of Hydraulic Research*, 23(1):57–79, doi:10.1080/00221688509499377.

Sundborg, A. (1956). The River Klaralven âĂŞ a case study of fluvial processes. *Geografiska Annaler*, 38A:127–316.

Van de Lageweg, W. I., Van Dijk, W. M., and Kleinhans, M. G. (2013). Channel belt architecture formed by an experimental meandering river. *Sedimentology*, 60:840–859, doi:10.1111/j.1365-3091.2012.01365.x.

Van Dijk, W. M., Van de Lageweg, W. I., and Kleinhans, M. G. (2012). Experimental meandering river with chute cutoffs. *Journal of Geophysical Research*, 117:F03023, doi:10.1029/2011JF002314.

Van Dijk, W. M., Van de Lageweg, W. I., and Kleinhans, M. G. (2013). Formation of a cohesive floodplain in a dynamic experimental meandering river. *Earth Surface Processes and Landforms*, 38:1550–1565, doi:10.1002/esp.3400.

Wagner, B. J., and Gorelick, S. M. (1989). Reliable aquifer remediation in the presence of spatially variable hydraulic conductivity: From data to design. *Water Resources Research*, 25:2211–2225, doi:10.1029/WR025i010p02211.

Willis, B. J. and Tang, H. (2010). Three-dimensional connectivity of point-bar deposits. *Journal of Sedimentary Research*, 80:440–454, doi:10.2110/jsr.2010.046.

Zinger, J. A., Rhoads, B. L., and Best, J. L. (2011). Extreme sediment pulses generated by bend cutoffs along a large meandering river. *Nature Geoscience*, 4:675 – 678, doi:10.1038/NGEO1260.

Zolezzi, G., Luchi, R., and Tubino, M. (2012). Modeling morphodynamic processes in meandering rivers with spatial width variations. *Reviews of Geophysics*, 50:RG4005, doi:10.1029/2012RG000392.