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Depositional development of the Muskeg Lake crevasse splay in the Cumberland Marshes (Canada)

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ABSTRACT: Crevasse splays are common geomorphological features in alluvial and deltaic floodplains. Although crevasse splays can develop into full avulsions, thereby transforming large areas of floodbasins, little is known about their sedimentary and geomorphological development at the decadal scale and their avulsion potential. We used aerial photography and lithological cross-sections to reconstruct crevasse-splay formation in the largely unmanaged floodplain of the Saskatchewan River in the Cumberland Marshes (Saskatchewan, Canada). Based on surface geomorphology and subsurface deposits, various stages of crevasse-splay development were described which were linked to both external forcing and internal morphodynamics. Initial splay deposition, following a levee breach during a large flood, occurred as a broad but relatively thin sandy sheet in a down-basin direction in the receiving backswamp area. In a next phase, these primary crevasse-splay deposits blocked local down-basin flow, thereby forcing the crevasse-splay channel in a direction perpendicular to the parent channel and original floodbasin gradient. This created an asymmetrical splay sequence composition, which differs in appearance from more commonly observed dendritic crevasse splays. It is concluded that sedimentation patterns in the splay have been influenced by inherited effects of previously formed deposits. Feedbacks of the original floodbasin gradient and earlier stages of splay formation are suggested as prominent mechanisms in creating the current morphology, orientation, and architecture of its deposits. Copyright © 2015 John Wiley & Sons, Ltd.

KEYWORDS: crevasse splay; Cumberland Marshes; geomorphological feedbacks; floodbasin; avulsion

Introduction

Natural levees of low-gradient river systems commonly breach as a result of peak discharge or factors influencing levee strength or river stage (e.g. ice or log jamming). Directly following a levee breach, crevasse splays form in low areas of the adjacent floodplain. Although most crevasse splays become inactive in the years following the initial levee breach (e.g. Bristow *et al*., 1999; Cahoon *et al*., 2011), splays can continue to prograde into floodbasin areas for decades (Smith and Pérez-Arlucea, 1994). With time, redirected flow and sediment cause the splay to enlarge and mature, in combination with vegetation establishment. This usually results in the development of a typical configuration of crevasse-splay elements with a characteristic dendritic pattern (Smith *et al*., 1989; Farrell, 2001; Cahoon *et al*., 2011): (1) a stable main feeder channel, flanked by small levees and bifurcating distally into (2) minor and often unstable distributary channels which feed (3) sediment lobes that prograde into the backswamp.

Crevasse splays can represent the initial stages of full channel-belt avulsions (e.g. Makaske *et al*., 2002; Aslan *et al*., 2005) if sufficient discharge is redirected along a favourable gradient. As floodplain geomorphology and evolution are strongly controlled by sediment supply, the relocation of fluvial activity by avulsion causes significant changes in the alluvial landscape.

Sediment load is severely reduced in the parent channel downstream of the avulsion site and is relocated to other parts of the delta or floodplain. Such changes in sedimentation patterns can have major consequences for the ecologic and economic status of affected areas. For example, in the Mississippi River delta, avulsive redirection of sediment delivery has increased subsidence in sediment-starved portions of the floodplain (Blum and Roberts, 2009). Moreover, few new crevasse splays are formed in parts of the Mississippi delta due to flood protection measures. This has led to drowning marsh vegetation by impounding water (Day *et al*., 2000) and increased the exposure and vulnerability of low-lying urban areas to flooding during storm surges (Day *et al*., 2007).

Crevasse-splay deposits in floodbasin and palaeovalley fill sequences can be economically important as hydrocarbon reservoirs (Mjos *et al*., 1993) and for coal exploration (Jorgensen and Fielding, 1996; Davies-Vollum and Kraus, 2001). Previous research has mainly focussed on mapping, describing and dating sedimentary successions (e.g. Allen, 1965; Farrell, 2001; Stouthamer, 2001; Makaske *et al.*, 2002), and sedimentary patterns and fluvial morphology following regional avulsion events (e.g. Smith *et al.*, 1998; Pérez-Arlucea and Smith, 1999; Morozova and Smith, 2003). Although the formative causes and sedimentary products of crevasse splays are relatively well understood (O'Brien and Wells, 1986; Smith *et al.*, 1989; Farrell, 2001), intermediate stages of crevasse-splay formation have drawn less attention. Likely explanations for this are (1) that crevasse splays often are relatively minor features in the floodplain, (2) that larger crevasse splays and splay complexes which evolved into full avulsions led to erosion of previous proximal deposits formed during initial stages of splay formation by channel incision and migration, (3) that crevasse splays are geomorphological features that form and develop mainly during short episodes of peak discharges, which makes it difficult to monitor and study their development in the remote unmanaged floodplains where natural crevasse-splay formation still occurs.

This study presents a reconstruction of decadal-scale crevasse-splay development by integrating aerial photography, sedimentological and geomorphological data. The combination of different data types enables reconstruction and description of different stages in active splay formation and associated sedimentary products. Furthermore, mechanisms and morphodynamics leading to the characteristic geomorphology of crevasse splays in the Cumberland Marshes are discussed and summarized in a generalized scheme for crevasse-splay development to aid future study of similar features and to allow advanced interpretation from crevasse-splay deposits.

Regional Setting

The Cumberland Marshes are located in the western (upper) part of the Saskatchewan River delta, which straddles the border between Saskatchewan and Manitoba in south-central Canada and terminates in Cedar Lake (Figure 1). With ~10

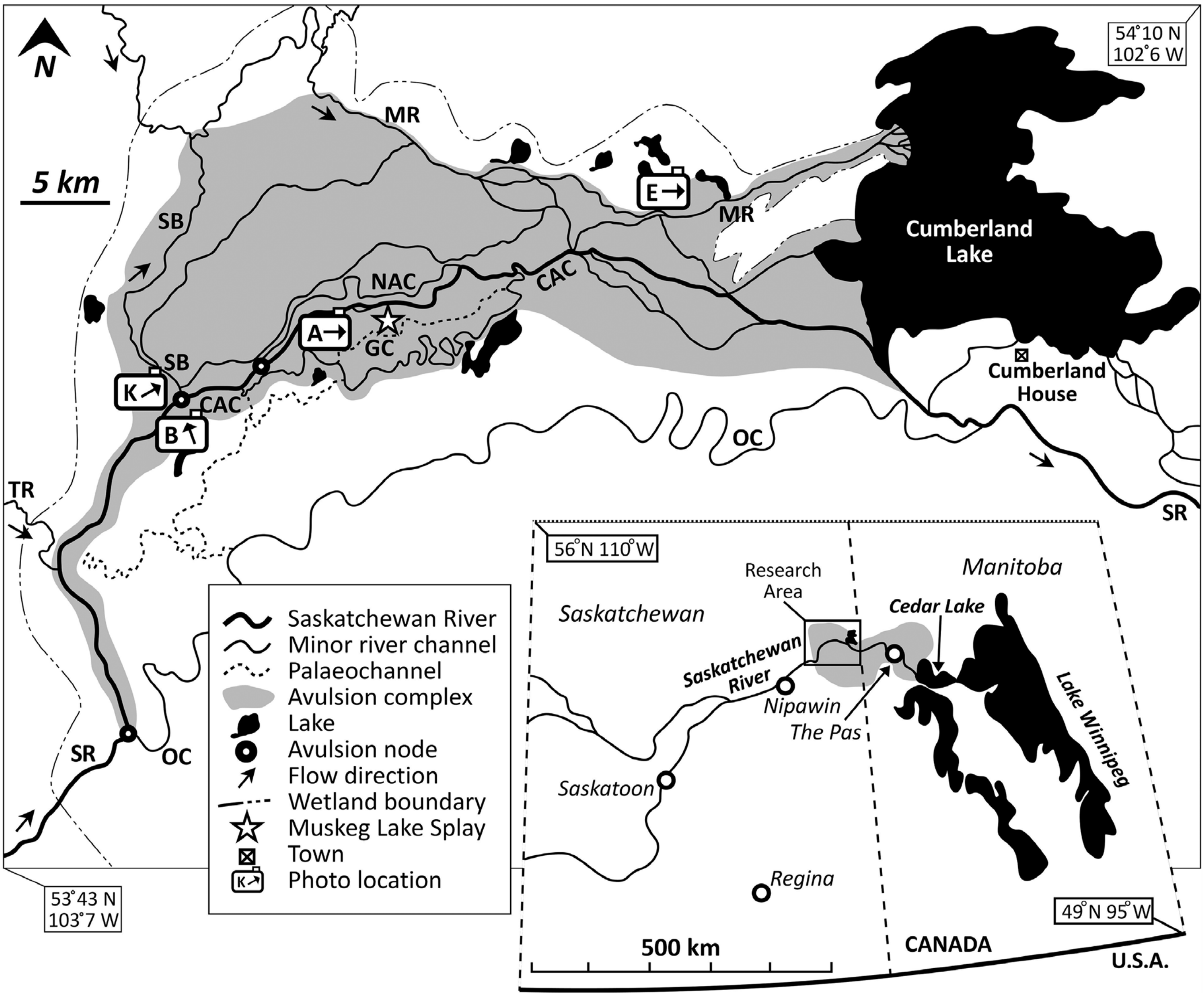

Figure 1. The 1870s avulsion belt of the Saskatchewan River (SR) in the Cumberland Marshes, based on historical accounts (Voligny, 1916), mapping (PFRA, 1953), and aerial photography. The North Angling Channel (NAC) existed prior to the 1870s avulsion, probably as an extension of the Torch River (TR) channel belt (Pérez-Arlucea and Smith, 1999). The Centre Angling Channel (CAC) formed by a gradual diversion of flow from the Steamboat (SB) channel and NAC. The Muskeg Lake splay (indicated with a star) was initiated around 1953. The upstream part of the 1870s avulsion belt has changed little since 1982 (Smith and Pérez-Arlucea, 2004). GC, Gun Creek; MR, Mossy River; OC, Old Channel. The inset shows the location and extent of the Saskatchewan River delta (after Morozova and Smith, 2000). Photographs of the local landscape are shown in Figure 2; the photograph camera symbols on the map indicate the location and the arrow inside the symbol indicates the direction of view.

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000 km^2, it is the largest inland delta in North America. The delta is dominated by the eastward-flowing Saskatchewan River whose drainage basin extends westward to the Rocky Mountains. Discharge is highly seasonal and, in the area of this study, averages about 450 m^3 s^{-1}. Peak discharges usually occur in the spring or summer months. Maximum recorded discharge at the federal gauge in Nipawin, ~90 km upstream of the current delta apex (Figure 1), is 4870 m^3 s^{-1}, in June, 1953. From November to March, the Saskatchewan River is covered with ice.

Deposition of alluvial sediment initiated around 8500 calendar years before present (cal yr BP), following the retreat of the Laurentide ice sheet (Morozova and Smith, 1999). The most recent major avulsion occurred in the 1870s (Smith *et al.*, 1998), when the Old Channel was diverted northward into the adjoining floodplain to form a ~500 km^2 complex of small marshes and ponds separated by interconnected and variously-sized channels (Figure 1). This created a highly dynamic fluvial environment with frequent crevassing and partial avulsions (Smith *et al.*, 1989; Morozova and Smith, 1999, 2000, 2003; Pérez-Arlucea and Smith, 1999; Slingerland and Smith, 2004).

Muskeg Lake, formerly a marshy lake but currently an intermittently exposed backswamp area (Figures 2A, 2D, and 2J), is situated between the alluvial ridges of the currently active Centre Angling Channel (CAC) and the abandoned Gun Creek to the south (GC; Figures 1, 2A and 2D). Sometime after 1911, probably in the 1920s, the CAC was formed by gradual avulsion of the North Angling Channel (NAC; PFRA, 1953). At that time, discharge through the NAC was already reduced as a result of an upstream avulsion that created the Steamboat (SB) channel (Figures 1 and 2B). The new flow path gradually captured more discharge to eventually become the presently dominant CAC of the Saskatchewan River (Smith *et al.*, 1998; Figure 1). As the CAC enlarged, levees were breached repeatedly, forming a series of crevasse-splay complexes in the flanking backswamp areas. The current average gradient of the Saskatchewan River in the Cumberland Marshes, based on water surface elevations during mean discharge from the 1870s avulsion point to Cumberland Lake (Smith and Pérez-Arlucea, 2008), is ~9.4 × 10^{-5}. The gradient of the CAC at the investigated crevasse splay is ~4.6 × 10^{-5}.

The Muskeg Lake splay (MLS; Figures 1, 2A and 2I) is part of a crevasse-splay complex located in the backswamp between the CAC and the elevated ridge of the GC palaeochannel to the south. The splay complex was initiated in the 1940s and early 1950s and consists of six large crevasse splays that have gradually filled in the former backswamp area (Muskeg Lake: ~7.5 km^2). The MLS is the most eastern and youngest splay in the complex and occupies a former lake area of ~750 m × 500 m (Figures 2A and 2J).

Methods

Aerial photographs from 1953, 1977 and 2003 (ISC, 2007; Figure 3) were used to study splay growth and to reconstruct splay geomorphology of the MLS. The aerial photographs are black/white panchromatic images with original scales ranging from 1:5000 (1977 and 2003) to 1:60 000 (1953). The photographs were cropped to show the same area, which led to a relatively low resolution of the depicted 1953 image.

The photographs indicate the geomorphological development of the splay at three time slices mainly by change in reflectance patterns which are directly related to vegetation type and density. Dirschl (1972) described vegetation, general species assemblages, succession stages, and relations of specific biotopes to the local geomorphology in the Cumberland Marshes. This relationship, which determines nutrient availability and local water levels relative to the surface, was used to interpret the geomorphological development of the crevasse splay over the past five decades. The reflectance levels and clusters of dense vegetation on the 2003 photograph were compared with a 2008 colour photograph of the splay, taken from a small airplane during fieldwork. Vegetation types were described in the field, related to local geomorphological features and surface elevation, and compared with Dirschl's (1972) classification. The field logging of general vegetation types served as a ground-truth for observed patterns and zoning in vegetation visible on the aerial photographs. Comparison of the 2003 and 2008 photographs indicates nearly identical patterns, so it was assumed that the currently observed vegetation differs little from the situation in 2003. Pioneer vegetation (dominated by ratroot, bulrush and arrowhead; Figures 2D and 2J) was found on freshly deposited splay lobes and in shallowing parts of the former Muskeg Lake and correlates with relatively high reflectance on the aerial photographs (vegetation zone 3; Figure 3D). Dense shrub vegetation (dominated by alder and willow with a horsetail undergrowth: Figure 2F) occurs on higher fens and levees and correlates with low reflectance (dark colour; vegetation zone 1; Figure 3D). Transitional zones between these two dominant vegetation types are associated with intermediate reflectance levels. In this intermediate vegetation zone (zone 2 in Figure 3D) reeds, sedges, and horsetail occur frequently (Figure 2G). Willow shrubs occur rather dispersed and are of limited size.

Field observations of geomorphological elements corresponded well with zones of different reflection (vegetation) on the 2003 aerial photograph; importantly, dense shrub growth and trees occurred exclusively on levees and relatively high fens. Based on currently existing patterns in vegetation, it was assumed that the three photographs provide a reliable basis for interpreting geomorphic development of the splay. As no ground-truth exists for the 1953 and 1977 aerial photographs, the information from these specific time slots is used in this paper mainly to supplement geomorphological interpretations following from sedimentary information. Information from aerial photographs nonetheless provides important clues to the pacing of changes in the local landscape and crevasse-splay geomorphology. Such information is difficult to interpret from sedimentary products alone, which are the final end-members of crevasse-splay processes and dynamics from splay growth initiation to termination.

The sedimentary build-up of the MLS was investigated by drilling three main sections across the proximal, middle and distal parts of the splay (Figure 3C). Using an Edelman hand auger and gouge, 34 boreholes were obtained from the surface to the regionally occurring pre-splay clay substratum. Individual boreholes were typically spaced 5–25 m apart and positioned on the basis of local geomorphology. Relative surface elevations were recorded with a theodolite and total station. Borehole data was logged at 10-cm intervals for sediment texture (using the standard USDA texture classification), colour, plant remains, calcium carbonate ($CaCO_3$) content (tested with hydrochloric acid), and oxidation/reduction (following the methodology for sediment classification in the field by Berendsen and Stouthamer, 2001). Organic layers were sampled at 5 cm intervals using a 5 cc sampling device to measure variations in organic content by determining the loss-on-ignition (Heiri *et al.*, 2001; Van Asselen *et al.*, 2010). Borehole data was primarily used to identify architectural elements of the splay; e.g. levees, sheet deposits, and infilled channel features. Deposits and the configuration of larger geogenetic elements (e.g. continuous strata with a comparable lithology) were correlated with different stages of splay formation and geomorphology as indicated by the patterns in reflectance on aerial photographs. The age of pre-splay

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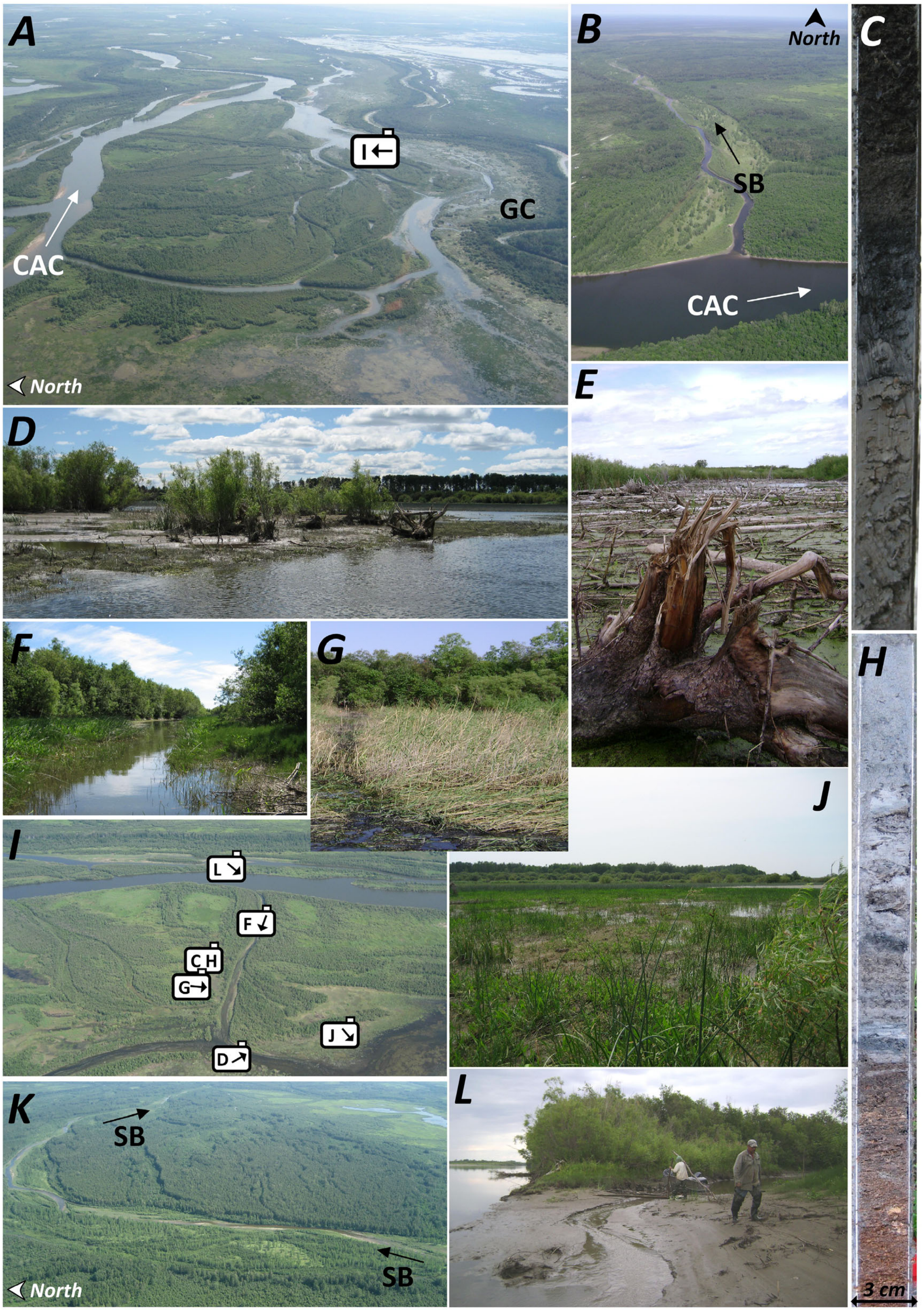

Figure 2. (A) The Muskeg Lake splay (MLS)-crevasse complex, looking towards the east with the Centre Angling Channel (CAC) to the north (left) and the Gun Creek (GC) palaeochannel ridge to the south (right). (B) The almost completely abandoned Steamboat (SB) channel at the CAC avulsion point. (C) The transition of stiff clays into overlying peat, dated to 2664 ± 101 cal yr BP, underlying the MLS (Figure 4). (D) Recently deposited crevasse-splay lobe in Muskeg Lake at the southern end of the Muskeg Lake Splay: the largely bare soil is sparsely occupied by establishing pioneer vegetation. Trees in the background indicate the location of the GC palaeochannel ridge. (E) Log jams in river channels in the Cumberland Marshes. (F) The main crevasse channel of the MLS, with recent in-channel banks (covered with bulrush), and flanked by levees with shrub vegetation (corresponding with low reflectance on aerial photographs; Figure 3). (G) Sharp transition of fen vegetation (high reflectance in Figure 3) dominated by reeds and sedges to the slightly higher western crevasse-channel levee in the background with alder and willow stands (low reflectance). (H) The transition of peat into clayey overbank deposits, dated to ~702 ± 29 cal yr BP (Figure 4). (I) Northward aerial view of MLS showing CAC (top) and the shore of the largely infilled Muskeg Lake (bottom). (J) Terrestrialization of Muskeg Lake with establishing pioneer vegetation. (K) The abandoned SB channel near the CAC-avulsion point, looking in an eastward down-gradient direction, with extensive (inactive) crevasse complexes; currently occupied by dense shrub vegetation, indicating relative dry conditions on relatively high elevations. (L) Largely infilled entrance of the MLS crevasse channel, at the bifurcation with the CAC. Photograph camera symbols on images A and I indicate the location and direction of view on other photographs (outside the MLS area, locations of photographs are shown in Figure 1). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

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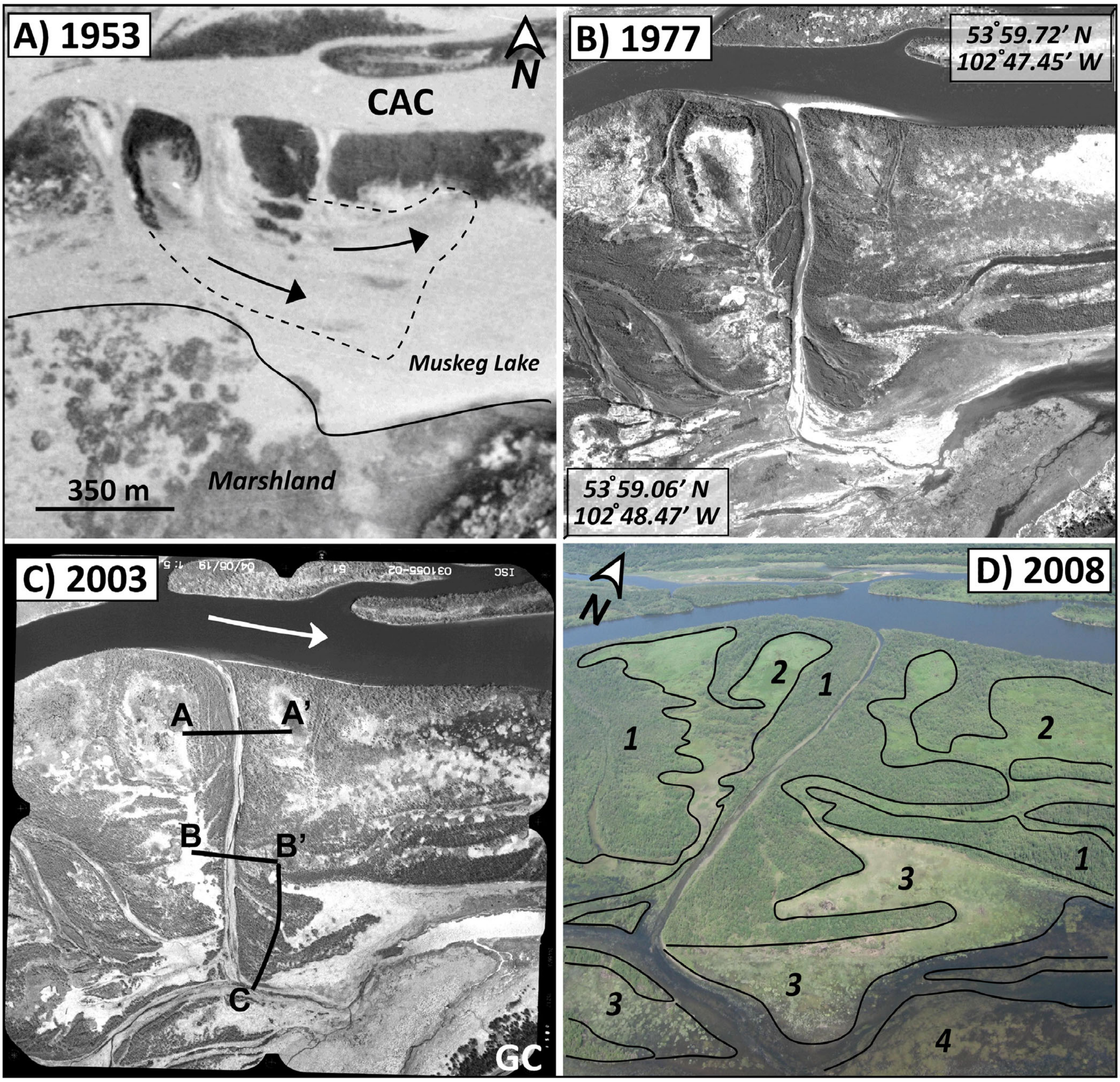

Figure 3. Aerial photographs of the Muskeg Lake splay. The dashed line in the 1953 frame indicates the extent of initial splay deposition, based on visible bar features and sheet deposits (slightly lower reflectance than Muskeg Lake). The dominant flow direction through Muskeg Lake is indicated by the arrows. The location of the lithological cross-sections (Figure 4) and the Gun Creek (GC) palaeochannel are shown in the 2003 frame. The 2008 photograph was taken from a small airplane and has the generally occurring vegetation zones indicated: (1) dense willow and alder shrubs with horsetail undergrowth; (2) dispersed willow shrubs with a dominant occurrence of reeds, sedges and horsetail; (3) pioneer vegetation such as bulrush ratroot, and arrowhead; (4) aquatic plants in shallow water (mainly pondweed, arrowhead, and buckbean). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

peat accumulations was determined by accelerator mass spectrometry (AMS) radiocarbon dating on terrestrial macrofossils (van de Graaff laboratory, Utrecht University). Three radiocarbon dates were calibrated to calendar ages using Oxcal 4.1 (Bronk Ramsey, 2009) and the INTCAL09 calibration curve (Reimer *et al.*, 2009).

Results

Sedimentology

The local substratum consists of stiff clay with a thickness of at least 1 m. The colour ranges from blue-grey to light-grey, without any clear spatial pattern. Local pockets with increased silt content (up to 50%) also appear to be randomly distributed, although the top 10 to 30 cm is typically enriched in silt. Organics such as small wood and reed fragments are commonly encountered and are also more common in the top ~20 cm of the substratum. The top metre contains numerous small (<1 mm) $CaCO_3$ concretions indicating soil formation (Van Asselen *et al.*, 2010). Internal layering or other visible sedimentary structures are absent.

The upper 10 cm of the stiff clay grades into an overlying peat layer whose thickness ranges between 40 and 190 cm (Figures 2C and 4). Peat accumulation has been smallest in the southeast portion of the splay where only detrital peat was encountered. Where thicker peat has accumulated, three

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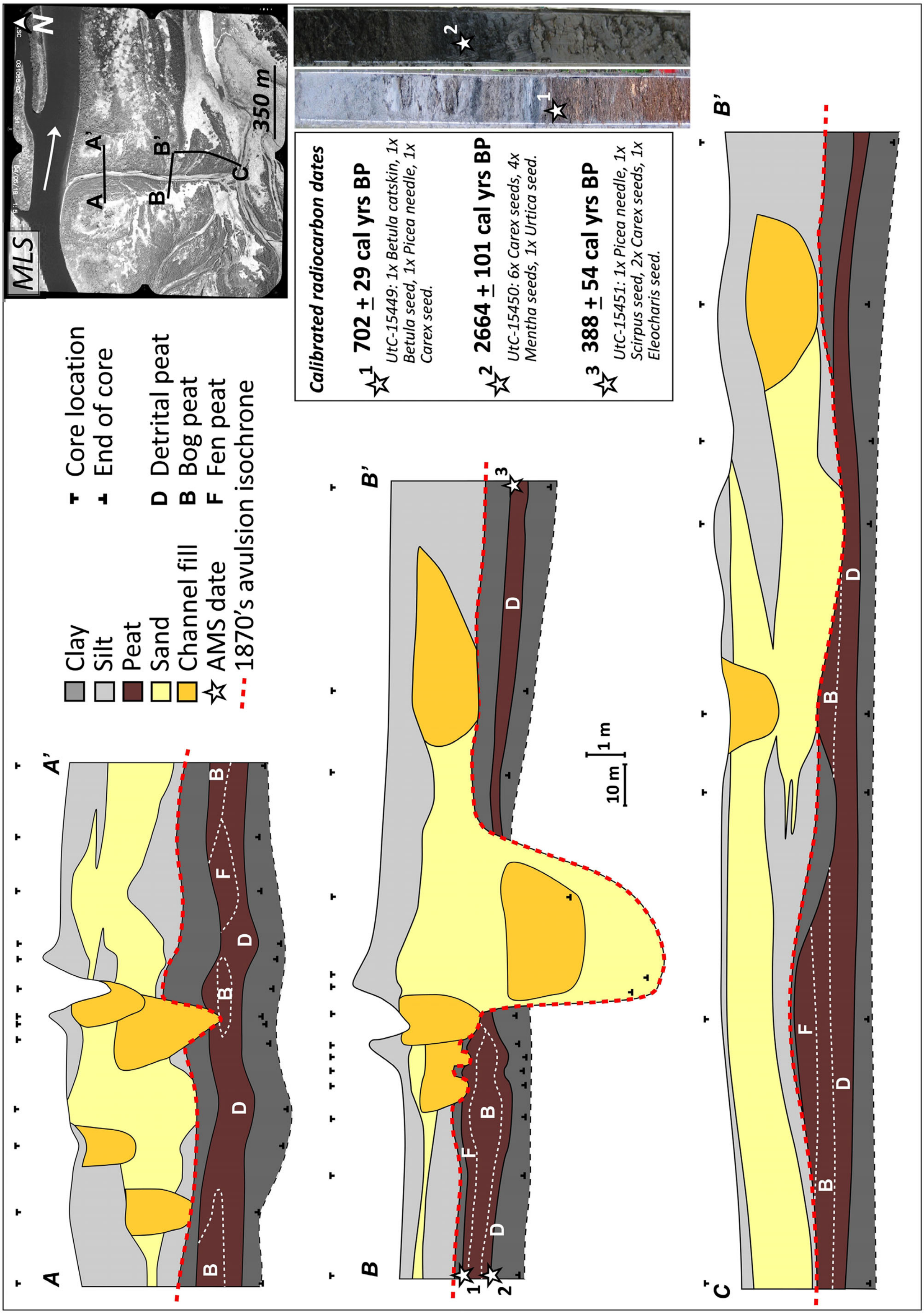

Figure 4. Lithological cross-sections of the Muskeg Lake splay. The location and orientation of the coring transects are shown in the top-right inset. Accelerator mass spectrometry (AMS) radiocarbon dates are shown in calendar years before present (cal yr BP) and the dated plant macrofossils are listed. This figure is available in colour online at wileyonlinelibrary.com/journal/espl

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phases were identified. From base to top, these are: (i) black detrital peat dominated by wood particles and oxidized plant remains, and (ii) red-coloured *Sphagnum*-dominated bog peat, which usually grades into (iii) brown fen peat dominated by sedges and reeds (described in more detail in Smith and Perez-Arlucea, 2004; Van Asselen *et al.*, 2010). Organic content of these peat types is respectively 50–60%, ~90%, and ~80%. Compaction by later sediment loading has reduced peat thickness by 30–40% (Van Asselen *et al.*, 2010).

The transition from peat into overlying clay deposits is rather sharp, generally within 3 cm (Figure 2H), and occasionally also slightly erosive with millimetre-thick intercalating light-grey clays, locally eroded peat, and intervals of dark-coloured organic clays. The clay overlying the peat layer is much less cohesive and densely packed than the substratum clay, although both are of similar texture. This 20 to 70 cm thick clay stratum, which is thickest in the eastern part of the splay area where also relatively little peat has accumulated, coarsens upward into clay loam. In the central part of the splay subsurface, the clay layer is missing, probably due to later erosion by splay channels (see later).

The upper facies were divided into three main strata: (i) a lower stratum of coarsening-upward silty deposits, (ii) an upper stratum of fining-upward silts, extending to the present surface, and (iii) sands deposited in sheets and channel features, at most locations separating the lower and upper silt strata (Figure 4). Intercalating sands are absent in the eastern part of the study area, where the upper and lower silt layers were indistinguishable.

The thickness of the lower silt layer is highly variable. Maximum thickness occurs in the western part of the splay where it reaches approximately 1 m. The transition to underlying silty clays is non-erosive and marked by a rapid upward increase in grain size and the frequent occurrence of 5 mm laminae ranging from loam to loamy sand with occasional plant remains. Admixed sand in these small sets is relatively fine-grained (75–150 μm).

The sandy deposits were divided into sheets and channel features, based on sand body geometries and sedimentological characteristics (Figure 4). Relatively narrow and deep channel features lie erosively against underlying fines and organics, while sandy sheets have non-erosive lower contacts. Moreover, channel sands are slightly coarser than sandy sheets (105–150 versus 75–105 μm) and more heterogeneous than the uniform and well-sorted sheets. Sands in the channel features tend to fine upwards but contain admixtures of fines, organics and shell fragments. Moreover, sorting of the sand fraction is poor, and occasionally strongly laminated intervals are encountered, especially in the deepest incised sections. Channel features are mainly located in the proximal part of the splay, there representing at least half the volume of deposited sands. Towards the distal part of the splay (southern lobes and east of the proximal part), most sand is deposited in sheets (~90% of the deposited sand volume in transect C–B′; Figure 4).

The upper silt layer has a maximum thickness of ~150 cm. The thickness is strongly related to the thickness of underlying sandy sheet or channel deposits; where these are thin or absent, for example in the northwest portion of MLS, silt deposits are usually thicker. Moreover, the silt drape is generally thicker in the eastern part of the splay, which corresponds to overall higher surface elevations (Figure 4). At these higher elevations, brown-coloured poorly-developed organic soils with oxidized iron stains were observed in the top ~50 cm. These silt-dominated deposits fine upwards, grading from sandy loam at the basal contact with the sand towards silty clay at the surface. In contrast to the lower silt-dominated interval, laminated profiles are largely absent and only found in levees of the main crevasse-splay channel.

Palaeogeographic development

The MLS area

Based on the nesting and distribution of sedimentary architectural elements, three pre-crevasse phases of deposition are distinguished: (1) an early stage of floodbasin deposition; (2) peat accumulation; (3) a second stage of floodbasin deposition (Figure 4). The early stage of floodbasin deposition is marked by the stiff clay substrate. The minor lateral variation in the elevation of the tops of these clays and the regional occurrence at similar depths of this stratum (Van Asselen *et al.*, 2010) indicates sedimentation in a large low-energetic (lacustrine) floodbasin (Morozova and Smith, 2000). Deposition of this clay substratum was succeeded by peat accumulation (Figure 2C), which initiated around 2664 ± 101 cal yr BP (basal peat sample 2; Figure 4) and corresponds to a regional initiation of peat growth (Van Asselen *et al.*, 2010). The transition from detrital peat into bog peat indicates terrestrialization of the former lake, which allowed plants to encroach on the remaining lake and bogs.

The accumulation of bog peat (*Sphagnum spp.* dominated) indicates oligotrophic waters in a closed drainage basin (Dirschl, 1972). The upper portion of the peat layer is marked by the occurrence of mesotrophic peats (labelled as fen peats in Figure 4), which suggests an increased influx of nutrients, presumably from a fluvial source. Increasing fluvial deposition probably also resulted in the termination of peat growth, as indicated by the transition from mesotrophic peat into overlying floodbasin deposits (Figure 2H). The transition is dated between 702 ± 29 and 388 ± 54 cal yr BP (Figure 4), which precludes the 1870s avulsion as the cause of the increased influx of sediment. Again this date for peat growth termination is regionally consistent (Van Asselen *et al.*, 2010), and is probably related to reactivation of the nearby GC palaeochannel around 640 ± 40 cal yr BP (Morozova and Smith, 2000). Directly overlying the clayey overbank deposits of the GC palaeochannel are the silty deposits formed after the 1870s avulsion. These are inferred as overbank deposits that formed the distal part of the CAC levee prior to crevasse-splay formation.

Muskeg Lake splay (MLS)

Due to gradually increasing discharge redirected from the abandoning SB channel to the CAC (Figure 1), multiple breaches of the south bank occurred between the 1920s and 1953 (Figure 3A). The MLS was probably initiated during the high-flow years of 1952 to 1953.

The 1953 aerial photograph shows three closely spaced levee breaches of which the middle one has developed into the present MLS (Figure 3A). Flow diversion through the levee was initially perpendicular to the CAC (following the gradient of the local levee), but bent sharply towards the east when entering Muskeg Lake. This initial flow followed the original west–east (W–E) oriented topographical gradient of the Muskeg Lake basin, indicated on the photograph by the presence of slightly darker eastward elongated bar-like features east of the levee breach (preserved as low ridges; visible on later photographs) and unaffected marshland in the distal part of Muskeg Lake. Sedimentation during this initial phase of crevasse-splay formation mainly occurred by sand-sheet deposition (Figure 4). The fine sands were deposited non-erosively on the underlying silty deposits – locally minor erosion may have occurred where the sand sheet is directly overlying peat layers. All transects clearly show that initial deposition mainly occurred in the eastern part of the splay. The presently active part of the splay has shifted to the west, where younger crevasse-channel deposits are located closer to the surface and display locally dissected

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sheet deposits (C–B′: Figure 4). Moreover, thicker sand-sheet deposits to the east in the proximal part of the splay indicate a dominant eastward flow in the early stage of splay formation, as was inferred from the aerial photograph. Both from the photograph and the sedimentary structures, evidence for the existence of well-defined splay channels during this phase is absent, suggesting that sands were initially deposited by unchannelized flow, as similarly observed by others (Farrell, 2001; North and Davidson, 2012).

By 1977, the splay had changed significantly in outline and morphology (Figure 3). Splay deposition transformed the former marshy and lacustrine environment of Muskeg Lake into vegetated levees and adjacent fens (Figure 2G). Deposition concentrated around newly formed distributary channels. Although one main channel currently remains (Figures 2F and 2I), relict channel forms (both in the proximal and distal parts of the splay; Figure 5) indicate a multi-branched system during previous stages of splay formation. Reduced width of the CAC levee breach gap, now partly reoccupied by vegetation, indicates that the initially wider crevasse-channel entrance narrowed considerably by deposition – referred to as crevasse ‘healing’ (Figures 2L and 3). Rapid sedimentation at high-angle bifurcations is commonly observed in river systems (similar to plug bar formation in abandoned channels; Toonen *et al.*, 2012), as a result of locally reduced energetic conditions and transport capacity (Constantine *et al.*, 2010). In the first ~25 years of crevasse-splay formation, levees flanking the main crevasse channel were formed. These levees align in the same direction as the gradient along the main levees of the CAC: perpendicular to the topographical gradient of the larger floodbasin (N–S instead of W–E; Figure 2I). Again, most sedimentation occurred in the eastern part of the splay, indicated by an increased area of shrubby fen vegetation (growing on relatively high and dry locations) and the asymmetry of levees – the eastern levee of the crevasse channel is higher and wider than the western levee (Figures 3 and 4). The splay deposits confirm the observations from the aerial photograph (B–B′: Figure 4): at least a metre of silt has accumulated over the sand sheet in the east and in the proximal part of the splay. Abandoned channel deposits occur in all cross-sections and are typically laminated, caused by varying energetic conditions in an infilling channel depression (Toonen *et al.*, 2012). In the central part of the MLS, a large sand body contains channel-fill deposits. This sand body is probably related to a scour hole formed during the levee breach that has locally removed pre-crevasse deposits (transect B–B′; Figure 4) and created the accommodation space for the later infill.

The 2003 (and present) situation differs only slightly from 1977, suggesting that splay development had largely terminated by then. Apart from some new features in the distal part of the splay, including (1) development of a new fen by deposition of a new sand sheet (indicated by newly settled shrub vegetation, Figure 3C; B′–C profile, Figure 4) at the southeastern lobe, (2) further infilling of the lake basin (Figure 2D), and (3) minor deposition on levees and existing fens, the 1977 morphology has remained largely unchanged (Figure 3). Based on these observations, it is concluded that main splay formation took place in a short period; most activity is recorded in the first ~25 years.

Based on the current characteristics, the MLS can be classified as a stage I splay according to the classification system of Smith *et al.* (1989), indicating it has a basic and rather unmatured channel network, a short active life span, and has not eroded underlying strata on a large scale. This is confirmed by the wedge-shaped sand sheet that directly overlies wetland deposits and the existence of unstable distributary channels.

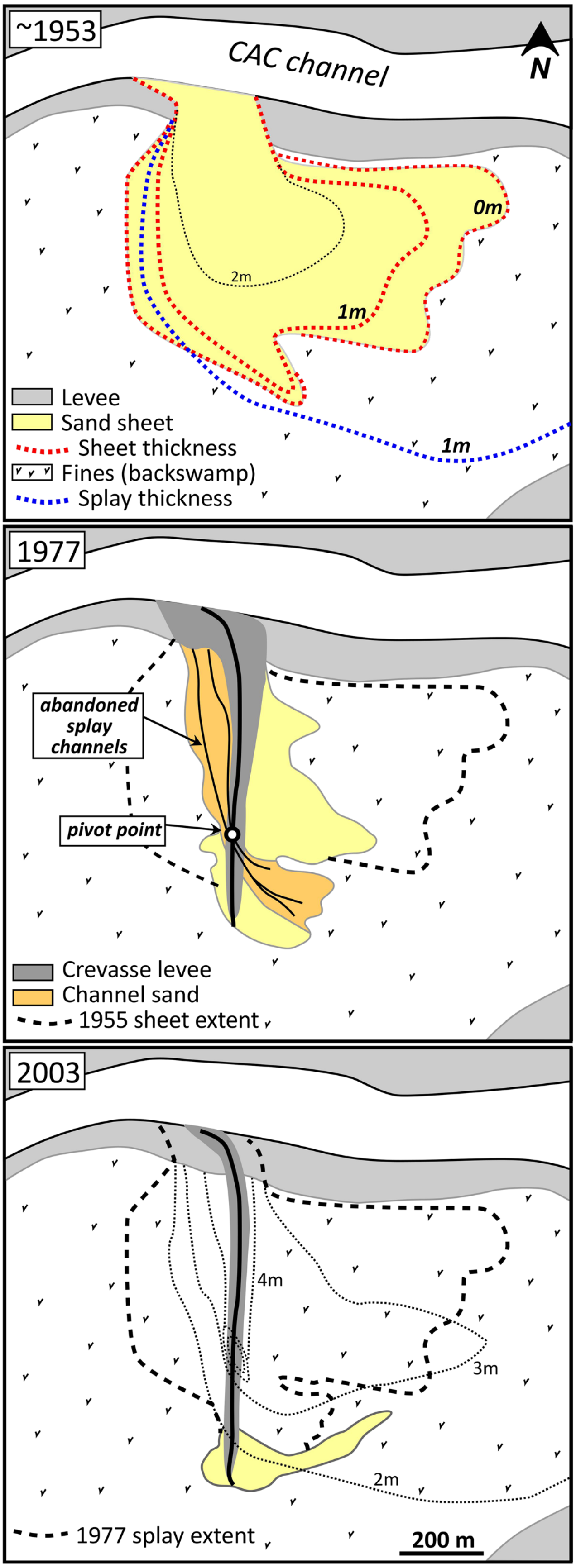

Figure 5. Schematic representation of the Muskeg Lake splay (MLS) with the different stages of splay formation (area corresponding with the aerial photographs; Figure 3). Each frame shows the location and type of deposition, formation of main geomorphological elements of that specific phase, the cumulative thickness of crevasse-splay deposits (1977 and 2003 are assumed to be similar due to limited splay activity), and splay extent during the previous phase (mostly buried). This figure is available in colour online at wileyonlinelibrary.com/journal/espl

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Crevasse-splay Development: Stages, Sedimentary Products, and Controls

The combination of aerial photograph interpretation, local geomorphology, and sediment characteristics allows identification of distinctive phases in crevasse-splay development. This phasing is useful for discussing progressive formation of crevasse-splay deposits that may have been influenced by previous stages of crevasse-splay deposition, which are controlled by both internal and external factors, and subsequently have led to a typical configuration of sediments, distributary channel, and patterns in vegetation (Figure 6).

Levee breach and initial splay formation

In most described cases of crevasse-splay formation, the initial phase acts on an event scale, as the initial processes are strongly linked with the trigger that caused a levee to breach, generally flood events. During a relatively short period, local river banks and floodbasin substrate are initially subject to

	Crevasse stage	General characteristics	Sedimentary products	Geomorphologic controls and feedbacks
Weeks	Initial levee breach	*Local levee erosion *Flow diversion into backswamp	*Formation of ripup clasts (Farrell, 2001). *Onset of deposition of fines in low-energetic conditions	*Orientation of dike or natural levee breach and regional gradient influence splay planform
Years	Crevasse splay formation	*Unconfined flow in basin *Shallowing of lake *Terrestralisation in proximal part of backswamp	*Deposition of well-sorted fine sands *Formation of sedimentary sheets; thickest in proximal part of crevasse splay *Deposition of fines continues in distal part of backswamp	*Receiving basin characteristics (depth, width, gradient) influence splay extent and planform. *Deep and low-gradient basins promote fast proximal deposition *Shallow and high-gradient basins promote protruding splays *Splay asymmetry increases with the angle of levee breach orientation with main gradient
		*Channelised flow *Erosion of substratum and previous splay deposits *Initially multiple small channels *Later single main feeder channel *Splay channel levees form *Deposition concentrates around main feeder channel *Increased deposition in distal part of crevasse splay *Proximal fens largely unaltered with maturing vegetation	*Deposition focussed around main splay channels *Increasing coarseness of sandy deposits and poor sorting *Laminated levee, infilled channel, and scour hole deposits *Limited deposition on existing fens	*Initial local basin gradient is obstructed by sandy sheets *Down-floodbasin-gradient-oriented splays develop a typical dendritic pattern *Perpendicularly-oriented splays develop an asymmetrical pattern with a gradually increasing angle between main crevasse channel and initial basin gradient; up to 90 degrees as a result of blockage by previous splay deposits *Local factors, such as differential compaction of the substrate, may influence splay morphology and development.
Decades	Splay termination	*Shallowing of feeder channel *Re-establishing main levees and plugging of crevasse channel entrance ('healing') *Decreased deposition in distal part of the backswamp	*Deposition limited to infilling depressions *Fine sands deposited inside the splay channel and at the bifurcation point *Silt and clay drapes form on in-channel banks *Decreasing rate of deposition of fines in distal part and possibly fining.	*Receiving basin size, orientation, relative gradient, and drainage type (open or closed basin) influence the duration and scale of discharge and sediment diversion and thus potential of crevasse splay to develop into a (partial) avulsion *Basins with a large storage capacity and open basins favor prolonged splay growth and establishment of large crevasse feeder channels. *Closed-drainage basins cause ponding and promote crevasse splay healing *Crevasse splays are likely to fossilise when the full basin width becomes occupied by progressive splay growth *Terminating splays suffocate by in-channel deposition, mainly at the bifurcation with the parent channel *Reorientation of splay growth in the direction of a favourable gradient is needed to continue progradation and may result in the formation of large crevasse splay complexes and (partial) avulsions
Century	or (Partial) avulsion	*Discharge through crevasse flow path increases *Excavation of main feeder channel in substratum and pre-existing splay deposits *Integration of basin outflow point in flow network *A full avulsion occurs when the majority of discharge becomes redirected	*Sedimentation focussed around the main crevasse feeder channel *Channel belt development with typical architectural elements (e.g., Smith et al., 1989; Perez-Arlucea & Smith, 1999; Stouthamer, 2001)	

Figure 6. Overview of crevasse-splay development with a characterization of different stages. For each stage main geomorphologic changes, associated sedimentary products, and controlling factors are summarized.

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strong erosion. Levee sediments are eroded by high-velocity flow through the breach. The 1953 aerial photograph indicates that these breaches were much wider than the width of the main feeder channel of the crevasse splay that is established during a later phase. Apart from erosion at the breach, local erosion of the floodbasin substrate and occasionally the formation of rip-up clasts are also commonly observed (e.g. Jacobsen and Oberg, 1993; Farrell, 2001; this study – Figure 4). Erosion during the initial levee breach is nearly always restricted to the area directly surrounding the breach, as flow velocity decreases sharply into the backswamp, where the initial phase of splay formation is marked by deposition of fines in unchannelized flow.

Splay progradation

Relatively coarse sediments (fining in more distal locations) are deposited in downstream and laterally distal positions of the first chute through the levee breach. Eroded (sandy) sediments are deposited in a wide lobe which thins and fines into the backswamp. Together with sediment introduced from the parent river channel, these sediments can lead to large-scale shallowing and terrestrialization of aquatic environments in the floodbasin. The MLS demonstrates that no channelized flow occurred in this initial phase. Fens formed during this initial phase of deposition became occupied by typical shrubby fen vegetation. The vegetation has gradually matured but stable patterns in vegetation indicate that no major changes occurred after this initial phase.

The initial splay lobe, dominated by sandy sheet deposits, plays a significant role in the orientation of later splay channels and deposits by modifying the initial local eastward floodbasin gradient, and resulted in the asymmetrical outline of the splay, with an orientation perpendicular to the parent channel (CAC) and overall floodplain basin gradient. The location of abandoned distributary channels indicates a progressive increase in the angle of the main splay channel relative to the parent CAC channel (Figure 5). The channel orientation perpendicular to the regional gradient is caused by both the eastward migration of the splay mouth (where discharge is diverted from the parent river channel into the crevasse-splay channel) and, more importantly, by westward migration of the main splay channel in the distal part of the splay (Figure 5). The latter results from obstructive effects of older splay deposits which redirected the discharge. The sand, deposited in a sheet in a down-gradient direction, obstructs the initial flow path in a manner similar to mouth bars during delta progradation (Edmonds and Slingerland, 2007). The eastward migration of the splay mouth is probably caused by outer-bend scour at the downstream part of the crevasse channel entrance by discharge that is diverted into the crevasse mouth during normal to bankfull discharge. Continuation of the migrating trend of the crevasse channel seems unlikely, as it would eventually counter the pre-existing topographic gradient. Moreover, crevasse-splay channel migration is probably also gradually reduced by maturing vegetation that increasingly strengthens the levees and stabilizes the main crevasse channel. The inferred pivoting point (Figure 5) of the shifting crevasse channel is a large scour hole (B–B′; Figure 4). Channelized flow eroding the erosion-resistant peat layer at the same location during different stages of splay formation uncovered the less resistant underlying fluvial deposits (Figure 4). Further incision then concentrated at that location, resulting in the formation of a local deep scour hole (cf. Smith and Pérez-Arlucea, 2004).

Channel morphology changed simultaneously with the shift in orientation. The flow through the crevasse became concentrated into fewer stabilizing feeder channels, presumably with an increased stream power, resulting in channel incision and levee formation. Further channel stabilization presumably also contributed to the formation of well-developed levees. It cannot be established, however, if channel enlargement continued gradually as the splay increased in size, although this has been hypothesized (e.g. Mjos *et al.*, 1993), and is likely to occur in the transformation of crevasse-splay channels into partial avulsions.

The gradient-blocking effect of proximal sheet deposits further promoted deposition in the more distal parts of the splay (Figure 5), leading to large-scale terrestrialization in the floodbasin. This process continues to the present day, although at a gradually decreasing rate, and allows new fens with pioneer vegetation to establish. As new distal lobes were formed, the channel protruded even further into the backswamp (Figures 2D and 2J), trying to circumvent these new obstructions. This repetitive process is currently not spatially confined, but inevitably cannot continue when the far end of the receiving basin has been reached and no further progradation perpendicular to the main channel is possible. At that point it is likely that progradation is either interrupted and the splay becomes inactive, or splay growth begins to follow the general gradient of the larger basin.

Splay termination or development into an (partial) avulsion

Based on current deposition in the MLS main feeder channel (Figure 2L), the decreasing width of the CAC levee breach, and only minor morphological changes since 1977, the MLS is likely to terminate soon. Observations of active crevassing indicate that a relatively short time of splay activity is common, ranging from several years to few decades (e.g. Smith and Pérez-Arlucea, 1994; Bristow *et al.*, 1999; Cahoon *et al.*, 2011; this paper). This study demonstrates that splay growth may indeed quickly decelerate and even terminate after the initial favourable gradient between levee and basin is reduced. This is supported by other studies of crevasse-splay deposits (Törnqvist *et al.*, 1993; Gouw, 2008).

Progradation in the direction of the general gradient of the floodbasin is a possible next phase of splay formation. Older splays in the splay complex upstream of the MLS currently follow the general floodbasin (and CAC) gradient after initial perpendicular growth (Figure 2A). Such reorientation is also observed in floodbasin deposits (Bristow *et al.*, 1999; Stouthamer, 2001; North and Davidson, 2012) and can, depending on the basin size (see later), support crevasse-splay activity for a longer period (up to several centuries; Berendsen, 1982). An analogue of such progradation, albeit on a larger scale of (partial) avulsion, is provided by the progradation of the SB channel of the 1870s avulsion belt (Figure 1; Smith *et al.*, 1998). The SB channel initially prograded northwestward into the floodbasin perpendicular to the regional eastward basin gradient, but redirected down-gradient after approaching the far end of the basin (Figures 1, 2B and 2K). In the SB channel, this phase was followed by reactivation of the proximal part of the diverted stream (Figure 1; Pérez-Arlucea and Smith, 1999), marked by multiple minor channels branching off the main channel down the regional slope toward Cumberland Lake (Figure 1).

Internal and external factors controlling crevasse splay development

In the MLS, some important morphodynamics seem driven by deposition in the downslope part of the splay and the geometry of the receiving basin. Crevasse-splay initiation and development can be influenced significantly by both internal (site-specific) and external factors such as compaction, characteristics of the parent channel (e.g. sinuosity, gradient, discharge and sediment load), characteristics of the bifurcation, geometry and gradient of the receiving basin, and human interference. In other crevasse splays, similar patterns by geomorphological feedbacks may therefore not be as straightforwardly interpreted as our example.

Van Asselen *et al*. (2010) indicate that sediment loading, thickness of peat layers, and peat types are important factors controlling local subsidence. This may significantly influence local splay development, as accelerated subsidence due to peat compaction creates additional local accommodation space and consequently may fix the splay in its initial position. Variable peat thicknesses and types may cause differentiation in subsidence due to compaction and thereby affect splay development. However, limited peat thickness (Figure 4) and rather uniform loading by the overlying deposits ensure that MLS development and geomorphological feedbacks are mainly driven by sedimentation and not by substrate compaction.

The MLS, with its initial formation perpendicular to the main basin gradient and asymmetrical morphology, may be regarded as typical for splays of aggrading low-gradient rivers with relatively low channel sinuosity. Similar morphodynamics and splay development have also been observed on low-gradient alluvial megafans (e.g. the Pantanal; Makaske *et al*., 2012). Other splays described in literature often yield a typical dendritic pattern (examples in Bridge, 2003; Cahoon *et al*., 2011). Although they differ in appearance, such splays developed in a similar way as described in this paper; with an initial bar or sheet deposit that modifies the initial gradient, obstructs the initial flow path and causes a redirection of flow and sediment. However, such splays are generally oriented in the direction of the main basin gradient, so similar crevasse-splay morphodynamics have resulted in a more symmetric pattern. This is common in highly sinuous river channels with local levees facing the down-valley gradient direction in downstream curves of meander bends and in delta environments where sedimentation rapidly modifies pre-existing favourable gradients (e.g. Mississippi; Jacobsen and Oberg, 1997). So based on the fluvial setting, similar morphodynamics may result in different crevasse-splay morphologies.

Characteristics of the main active channel, the receiving basin, and the bifurcation between the main river channel and crevasse channel can influence splay development during any stage of formation. Crevasse-channel depth, width, and angle with the parent channel may importantly influence the distribution of water and sediment over the different flow paths in a style similar to morphodynamics described for large river channel bifurcates (Kleinhans *et al*., 2008; Kleinhans *et al*., 2011). The initial (and later dynamic) configuration of the levee breach and flow diversion controls the downstream crevasse-splay formation (e.g. Makaske *et al*., 2012), which in turn influences further splay evolution and potential for full-scale avulsion. For example, a change in the distribution of water and sediment at the splitting point may cause erosion or deposition in the crevasse-splay channel and subsequently promote further splay growth or termination. This is likely a dynamic situation that can actively influence splay development and can reverse previous trends of splay growth or abandonment, as neither migration of the main splay channel nor the sediment load and discharge of the parent channel are stable over time. Recent large floods with extensive overbank deposition, such as the 2005 flood (2870 $m^3 s^{-1}$), however, had little effect on MLS dynamics, as the current local geomorphology is largely unchanged from the 2003 aerial photograph (Figure 3C), and splay termination and crevasse-channel infilling have progressed steadily.

Initial splay morphology largely depends on the gradients (locally at the entrance point of the splay and the overall basin gradient) and volume of the receiving basin, which also controls downstream flow velocities. Low-gradient and relatively deep basins result in rapidly declining flow velocities and thus trigger deposition (except for wash load) in the proximal part of the levee breach. The MLS is a good example of this, with extensive proximal sand sheet deposition in former Muskeg Lake. If flow velocities decrease more slowly, sandy sheets will extend further downstream into the receiving basin. As a result, only minor proximal sand sheets will probably develop, and the blocking mechanism as a feedback effect is reduced. The larger basin geometry is especially important for later stages of splay formation and controls (amongst other factors such as floods and sediment supply) the period of progressive splay growth and its potential to evolve into a larger splay complex or even an avulsion. Receiving basin width, length, depth, and down-gradient length determine the volume that can be infilled by crevasse-splay deposition (e.g. Bristow *et al*., 1999; Stouthamer, 2001). Basin width, as described for the MLS example, limits initial splay growth perpendicular to the parent channel, and many splays appear to terminate when the full width of the basin is occupied. The same applies for basin length when splay growth proceeds in a general down-floodplain direction (Pérez-Arlucea and Smith, 1999; Makaske *et al*., 2007). Logically, larger basins promote larger and more mature crevasse splays with better developed feeder channels (Mjos *et al*., 1993). Berendsen (1982) suggests that a downstream outlet of the basin is also important for splay growth and potential to develop into an avulsion. Closed basins promote ponding, deposition in the local basin, and infilling of crevasse-splay channels as sediment is not effectively conveyed downstream. The basin gradient and direction of maximum gradient in the wider region are also important for splay formation and potential to result in an avulsion (Törnqvist and Bridge, 2002). Larger gradient advantages or gradients oblique to the parent channel (typical for radial alluvial plains, delta and alluvial fan environments, or rivers with high rates of deposition within the main channel; Stouthamer and Berendsen, 2000) favour prolonged crevasse-splay formation and even avulsion, as continued splay growth does not immediately reduce the local gradient advantage. In contrast, closed basins in confined valleys or floodplains have limited potential to develop full avulsions that transform the regional landscape significantly as the duration and extent of splay growth is restricted by minor backswamp areas. In such basins, initial splay deposition is sufficient to annul the minor gradient advantage, causing splays to terminate soon after initiation.

Future research should focus on testing and validating internal morphodynamics of crevasse-splay development in different environmental settings. Although the available data types and temporal resolution do not allow for a full process-based analysis of continuous crevasse-splay development, the observations presented here strongly suggest an important role of internal responses to the previous stage of crevasse-splay formation which lead to typical crevasse-splay appearance and morphology. Testing such dynamics, for example using numerical models and laboratory experiments, can aid further process-based studies. Once internal crevasse-splay morphodynamics and the role of its causal factors and controls are sufficiently understood, a clearer relationship to avulsion events can be established. By understanding the factors that determine whether crevasse splays develop into full avulsions or become abandoned, it may become possible to explain successful avulsion sites of the past, why other avulsions have failed, and possibly to target potential future avulsion sites.

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Summary and Conclusions

Following the 1870s avulsion of the Saskatchewan River and the formation of the east-flowing CAC, overbank deposition of silts occurred in the Muskeg Lake receiving basin, a backswamp wetland area adjacent to and lying south of the parent CAC. In the 1950s, levees of the CAC breached at multiple locations, leading to the formation of a series of crevasse splays.

In the MLS, discharge through the levee breach initially followed the eastward topographical gradient of the Muskeg Lake basin, and fine sand was deposited in a broad sheet mainly southeast of the levee breach. In later stages of splay development, sedimentation gradually extended to more distal locations of the backswamp. As progradation continued, distributary channels gathered into one dominant channel with an increasingly north–south orientation, perpendicular to the main flow direction of the CAC and the initial topographical gradient of the Muskeg Lake basin.

Crevasse-splay development, as observed in the Cumberland Marshes and as described in other studies, can be roughly categorized in three phases: (i) levee breach and crevasse-splay initiation; (ii) active sedimentation in backswamp areas by splay progradation; (iii) the final stage in which a crevasse splay becomes inactive or evolves into a (partial) river avulsion (Figure 6). Early stages of sedimentation created a morphology that influenced later geomorphological development, including the orientation of the main splay channel and the current configuration of sedimentary deposits (Figure 6).

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