THREE-DIMENSIONAL RECONSTRUCTION OF MEANDER-BELT EVOLUTION, CRETACEOUS McMURRAY FORMATION, ALBERTA FORELAND BASIN, CANADA

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ABSTRACT: The three-dimensional reconstruction of meander-belt deposits from ancient strata provides insight into the formative processes of meander-bend evolution and paleogeographic interpretations. A significant challenge to such analyses is limited exposures in outcrop belts and widely spaced or sparse subsurface datasets. An unprecedented dataset consisting of 600 km² of 3-D seismic data and over 1000 well penetrations from the Cretaceous McMurray Formation in northeastern Alberta, Canada, provides a unique opportunity to characterize an ancient continental-scale river system. Paleochannels ranged from 475 to 1180 m wide and from 35 to 50 m deep, with meander-belt width-to-thickness ratios between 107:1 and 401:1. The data reveal evidence for intra-point-bar erosion and punctuated rotation, counter-point-bar development, and protracted channel cut-off and meander-loop abandonment. Observations enable interpretation of morphodynamic processes that are commonly observed in modern systems, yet rarely described from the rock record.

A 3-D geocellular model and reconstructed paleochannel migration patterns reveal the evolutionary history of seventeen individual meander-belt elements, including point bars, counter-point bars, and their associated abandoned channel fills, which have been mapped using core, FMI logs, and seismic data. Results of the study show that intra-point-bar erosion surfaces bound accretion packages characterized by unique accretion directions, internal stratigraphic architecture, and lithologic properties. We provide evidence for channel-belt-edge confinement and development of a counter-point bar, as well as the deposition of side bars and preservation of a mid-channel bar during meander-bend abandonment. Analysis of changes in meander-belt morphology over time reveal a decrease in channel-belt width/thickness ratio and sinuosity, which we compare with observations from the lower Mississippi River and attribute to the landward migration of the paleo-backwater limit due to transgression of the Cretaceous Boreal Sea into the Alberta foreland basin.

INTRODUCTION

Meander-bend evolution is generally well understood based on planform analyses of point bars, which are by far the most common and distinctive forms found in sinuous rivers. (e.g., Fisk 1944; Hickin and Nanson 1975; Jackson 1976). The evolution and classification of meander loops was introduced by Brice (1974), following earlier work on meandering-channel processes and floodplain mapping (Fisk 1944; Leopold and Wolman 1960; Langbein 1964; Carey 1969; Daniel 1971; Handy 1972). Brice (1974) classified meander loops into four categories based on symmetry and complexity, which provided a foundation for describing accretion processes such as expansion, rotation, and translation by mapping successive stages of channel migration (Hickin 1974; Jackson 1976; Lewin 1983; Knighton 1998). Significant contributions to the understanding of flow mechanics and geometric characterization of meander bends were also made in the 1960s and 1970s (e.g., Bagnold 1960; Leopold and Wolman 1960; Langbein 1964; Ackers and Charlton 1970; Brice 1974; Leeder and Bridges 1975). The recognition of flow separation around a meander bend and its relationship to meander-bend geometry (i.e., meander radius and flow width: Leeder and Bridges 1975), is an example of a fundamental linkage between sedimentary process, geomorphology, and deposition. In a particularly novel study, Jackson (1976) compared the hydraulic and geometric variables of a series of modern meander bends to the vertical sequence of sediments from the associated point bar and proposed a depositional model for point-bar sedimentation. Early efforts to link processes and resulting deposits, like those of Jackson (1976), provide a foundation for the interpretation of depositional processes from the rock record. However, beyond planform evolution, meander-bend classification, and grain-size trends, a relative paucity of comprehensive research has been presented on linkages between morphodynamic processes of meander-bend evolution observed in modern environments and the three-dimensional product in the rock record (e.g., Jordan and Pryor 1992; Smith et al. 2009; Toonen et al. 2012; Ielpi and Ghinassi 2014; Durkin et al. 2015).

Recent studies of modern and ancient meander-belt deposits have emphasized morphodynamic processes that are commonly understated in the analysis of stratigraphic products, such as intra-point-bar erosion and...
rotation, counter-point-bar development, and meander-bend abandonment (Fig. 1; Smith et al. 2009; Hubbard et al. 2011; Smith et al. 2011; Micheli and Larsen 2011; Toonen et al. 2012; Durkin et al. 2015; Ghinassi et al. 2016). Significant changes to meander-bend morphology can result from erosion along inner banks, often associated with substantial bar rotation. In the stratigraphic record, intra-point-bar erosion surfaces truncate previously deposited point-bar strata, across which the direction of accretion may shift up to 50° (Fig. 1; Durkin et al. 2015). The recognition of these stratigraphic surfaces reveals that point-bar surfaces are formed through a complex interplay of erosional and depositional processes. Simplistic facies models that emphasize cut-bank erosion, lateral accretion, and point-bar expansion, commonly overlook these additional processes, despite the potential for honed paleoenvironmental reconstruction. Another commonly overlooked feature of meander belt deposits are counter-point-bar deposits (or concave bank benches), which are characterized by concave scroll-bar patterns, immediately downstream of a convex point bar (Fig. 1; Lewin 1983; Nanson and Page 1983; Smith et al. 2009; Hubbard et al. 2011; Ghinassi et al. 2016). Counter-point bars develop in response to channel confinement or erosion-resistant cut-bank material, which promotes downstream translation of the concave bank (Smith et al. 2009; Smith et al. 2011; Ghinassi et al. 2016). The resulting deposits are typically fine-grained, compared to the upstream-adjacent point-bar deposits. Channel abandonment processes are commonly simplified into neck or chute cutoff, followed by channel avulsion (Fisk 1947; Lewis and Lewin 1983; Gagliano and Howard 1984; Smith et al. 1989; Erskine et al. 1992; Hooke 1995; Stouthamer and Berendsen 2000; Micheli and Larsen 2011); however, recent research has provided insight into abandonment processes and the ability to deduce paleochannel dynamics from abandoned-channel fills (e.g., Toonen et al. 2012).

In order to address these understated processes and interpret their depositional product in the rock record, a comprehensive understanding of flow structure in a meander bend is required. A significant amount of research has been presented on the geomorphology (e.g., Leopold and Wolman 1960; Allen 1965; Nanson and Hickin 1983; Whiting and Dietrich 1993a, 1993b) and fluid mechanics (e.g., Ikeda et al. 1981; Parker et al. 1982; Parker et al. 1983; Ferguson et al. 2003; Blanckaert 2010) of meandering rivers (Camporeale et al. 2007). Generally, flow structure in a river bend is a helix, where flow velocity is higher near the surface and flows toward the outer bank, where it is directed downward and along the bed toward the inner bank (Thomsen 1879; Leopold and Wolman 1960). In sharply curved bends, a recirculation eddy may form due to flow separation at the inner bank, restricting the helix to only the outer portion of the channel (Rozovskii 1957; Leopold et al. 1960; Leeder and Bridges 1975; Ferguson et al. 2003). Where channels impinge at high angles against the outer bank, flow separation also results in reverse eddy currents and scour-pool formation on the upstream side of the impingement point (Carey 1969; Burge and Smith 1999; Smith et al. 2011). The depositional products of these complex processes are reflected in the rock record, and understanding the morphodynamics of meander bends allows us to establish that linkage.

On a larger scale, longitudinal changes in meander-belt morphology and processes have been a recent focus (e.g., Hudon and Kesel 2000; Li et al. 2006; Nittrous et al. 2012; Blum et al. 2013). For example, the backwater zone of a river system is the segment over which sea level influences flow.
characteristics. A series of studies on deep, low-gradient rivers demonstrated that the backwater zone can extend hundreds of kilometers upstream from the river mouth (Li et al. 2006; Nittrouer et al. 2012; Blum et al. 2013). Changes in meander-bend migration rate, channel-bend width/depth ratio, and sinuosity have been observed as rivers enter and flow through the backwater zone. However, few studies have attempted to recognize the impact of the backwater zone in the stratigraphic record (e.g., Parker et al. 2008).

In an effort to address some of the shortcomings listed above, we investigate deposits of the Cretaceous McMurray Formation in northeastern Alberta, Canada. We strive to better constrain meander-belt evolution, with particular emphasis on intra-point-bar erosion and rotation, counter-point-bar development, and channel abandonment processes. We utilize 3D seismic data integrated with high-density well penetrations to map the evolution of a series of geomorphic elements through paleochannel migration analysis. To document the internal stratigraphic architecture and lithologic characteristics of individual geomorphic elements (e.g., point bars), a high-resolution geocellular model is created for a portion of the study area. The robust subsurface data set featured in this study provides planform perspectives typically associated only with satellite imagery or air photos, which are calibrated by hundreds of cores. The remarkable data set enables the first recognition of numerous meander-belt elements in the rock record; the established facies models have the potential to be used for more sophisticated interpretations of limited datasets. The objective of this work is to reconstruct meander-belt evolution, linking widely understood morphodynamic processes (e.g., bar translation, rotation, and abandonment) to their resulting stratigraphic product. Such linkage is rarely interpreted from ancient successions because of a lack of complete 3D data. We also hypothesize that a record of backwater processes can be elucidated from the ancient meander-belt record by characterizing changes in meander-belt morphology through time.

GEOLOGIC SETTING

The Lower Cretaceous McMurray Formation in northeastern Alberta, Canada (Fig. 2) records a complex nonmarine to marginal-marine depositional history, influenced by an overall transgression of the Boreal Sea into the Alberta foreland basin (Mossop and Flach 1983; Ranger and Pemberton 1997; Hein and Cotterill 2006). Deposition of the formation took place on the sub-Cretaceous unconformity, the character of which provided a significant paleotopographic control on sediment distribution; local accommodation enhancement resulted from dissolution of the underlying Devonian Prairie Evaporite Formation, as well as differential erosion across the surface (Christopher 1974; McPhee and Wightman 1991; Ranger and Pemberton 1997; Broughton 2014). The overlying Wabiskaw Member of the Clearwater Formation is composed of marine transgressive deposits (Fig. 2B, C).

The McMurray Formation has been subdivided into three informal lithostratigraphic units: lower continental (fluvial, floodplain, lacustrine) deposits, middle estuarine to fluvial point-bar-dominated deposits, and upper marginal marine deposits (Fig. 2B; Carrigy 1959; Hein and Cotterill 2006). These units were deposited under the influence of a complex cut-and-fill history (Mossop and Flach 1983; Ranger and Pemberton 1997; Hein et al. 2000; Langenberg et al. 2002; Hein and Langenberg 2003; Hein and Cotterill 2006; Fustic et al. 2012; Boyd et al. 2012; Boyd et al. 2014; Jablonski and Dalrymple 2016), such that these lithostratigraphic units are highly diachronous (particularly the middle and upper members). The interval of interest for this study is the uppermost part of the middle McMurray unit, which comprises a wide incised channel belt that trends north-northwest (Hubbard et al. 2011; Musial et al. 2012). Based on 3D seismic data, scaling relationships, and detrital-zircon geochronology, Musial et al. (2012), Benyon et al. (2014), and Blum and Pecha (2014) suggest that the catchment for these fluvial sediments was potentially of continental scale, comparable to that of the modern Mississippi River (Fig. 2A). Evidence for tidal influence has been interpreted in the fluvial point-bar-dominated deposits in the study area (e.g., Hubbard et al. 2011; Labrecque et al. 2011; Musial et al. 2012). Recent bed-scale analyses of brackish-water trace fossils (cf. Gingras et al. 2016) and palynofloral assemblages (Dolby et al. 2013) have been debated in the context of a purely fluvial-depositional-setting interpretation (Blum 2017). This study emphasizes the less contentious meander-belt architecture revealed in high-quality lithologic and seismic data.

Study Area and Data Set

The deposits of interest are located ~70 km southeast of Fort McMurray, Alberta, Canada, within a 775 km² study area. Locally, the McMurray Formation occurs at a depth of 350 to 500 m below the surface, and is covered by ~600 km² of high-quality 3D seismic reflection data (Fig. 3A). The bandwidth of the data is 8 to 200 Hz, and the minimum vertical resolution is considered to be ~5 m. Seismic data are augmented by a dense grid of oil-well penetrations with a common suite of well logs including gamma ray, resistivity, and density/neutron. Approximately 80% of the wells have formation micro-resistivity imaging (FMI) data, and 20% of the wells are continuously cored over the McMurray Formation interval.

Seismic stratigraphic units were identified on the basis of consistency of seismic reflection character and interpreted to be part of a regional stratigraphic sequence. Two main stratigraphic units were identified, defined by the top of the McMurray Formation and the background stratigraphic framework below. The upper stratigraphic unit is defined by the top of the McMurray Formation (Fig. 3A). The western meander-belt edge is highly irregular and lacks obvious scroll patterns that are evident in the meander-belt deposits (Fig. 3A). The eastern edge of the meander-belt deposit is not captured in the study area. This relationship highlights the limitations of the traditional, lithostratigraphic subdivision of the McMurray Formation into lower, middle, and upper. In this study, what has been referred to as Middle McMurray meander-belt deposits, incise into Upper McMurray coarsening-upward packages; therefore, at this location, Middle McMurray deposits are younger than Upper McMurray units.

Although scroll-bar topography is not observed in the subsurface data, accretion patterns can be deduced from the lithologic contrast between dipping lateral-accretion layers (cf. Hubbard et al. 2011). The interbedded lithology is validated by cores, as well as gamma-ray and FMI logs (Fig. 2C). Although point-bar deposits are the most common depositional elements, counter-point-bar, side-bar, and abandoned-channel-fill (oxbow lake) deposits are common as well (Fig. 1; Smith et al. 2009). In this study, we refer to side bars as side-attached bars that form during meander-loop abandonment and filling (e.g., Fig. 1). Abandoned-channel fills range from 475 to 1180 m in width, with an average width of 730 m (Fig. 3B). The meander-belt position ranges from 34 to 50 m, and abandoned-channel fills are 5 to 40 m thick (Fig. 2C). FMI logs provide measurements of dip angle and azimuth of lateral-accretion surfaces and trough cross bedding (Fig. 5A). Trough-cross-bedded sandstones indicate an overall northward paleoflow direction, and lateral-accretion patterns (e.g., erosion
FIG. 2. — A) Paleogeographic reconstruction of the Early Cretaceous Western Canada Sedimentary Basin (WCSB), including the location of the ancient meander-belt deposit of this study. B) Stratigraphic setting of the McMurray Formation in the lower Mannville Group. C) Four typical gamma-ray logs through the interval of interest. Locations of wells are shown in Figure 3. Well A intersects a typical abandoned-channel-fill deposit ~ 25 m thick. Well B is a typical upward-fining counter-point-bar deposit ~ 45 m thick. Well C is a typical upward-fining point-bar deposit ~ 40 m thick. Well D intersects the sandstone-dominated channel deposit ~ 55 m thick. The interval imaged in the seismic stratal slice is highlighted.
at the upstream extent of bars) are consistent with this interpretation (cf. Hubbard et al. 2011; Fustic et al. 2012; Musial et al. 2012).

METHODS

High-quality 3D seismic data are used to delineate and characterize depositional elements in meander-belt strata (Fig. 3). FMI logs characterize dipping surfaces, which constrain migration direction of bars and paleocurrent trends (Fig. 5A; Fustic 2007; Brekke 2015; Brekke et al. 2017). Conventional well-log suites (gamma-ray, resistivity and density) were utilized for lithologic characterization in boreholes where FMI data were not available.

Fisk (1944) mapped the paleochannel evolution of the lower Mississippi River meander belt using crosscutting relationships, accretion topography, and known migration rates; we apply an adapted approach to the subsurface deposits of this study (Fig. 6). We utilize relative ages (deduced through crosscutting relationships), accretion patterns, bed orientations, paleocurrent indicators, and abandoned-channel positions to reconstruct the paleochannel evolution of the meander belt imaged in 3D seismic data (Durkin et al. 2017). The series of reconstructed channel positions are typically highly constrained by the aforementioned data; however, in some instances alternative interpretations are plausible. The highest uncertainty lies in the correlation between bar deposits that are neither adjacent nor linked by bar-accretion patterns. These are typically early deposits, which consist of small discontinuous remnants not removed or reworked by later channel evolution. The margin of error for channel correlations between bars is likely within one or two accretion steps (50 m–150 m). A set of “rules” for the reconstruction of paleochannel locations employed in this study and for use in future studies are illustrated in Figure 6 and described below. The methods build on general fluvial geomorphology and sedimentology concepts (i.e., how meander-bends migrate and point bars are deposited), and are heavily influenced by comparisons with analogous deposits documented in the lower Mississippi River system (Fisk 1944; Holbrook et al. 2006).

Step 1) Identify meander-belt edges (if present) and define the meander-belt deposits to be reconstructed. Determine relative ages of elements using crosscutting relationships.

Step 2) Determine dip direction of accretion surfaces and paleocurrent directions for all elements. This can be done using dipmeter and/or FMI logs, or planform analyses (e.g., bar heads tend to be truncated whereas bar tails are more conformable).

Step 3) Locate the youngest bar or abandoned channel. In planform, reconstruct the position of the active channel at the time of abandonment across the area of interest. This is the final stage of evolution.

Step 4) Using accretion patterns from the youngest bars associated with the final stage (gray), reconstruct a channel location that is two channel widths worth of migration before the final stage. This is done by correlating accretion patterns between adjacent bars, and working...
backwards from the known channel position (i.e., abandoned channel) and following the orientation of the accretion pattern.

**Step 5** Continue working backwards in time from the final stage using a set migration magnitude in between successive stages (e.g., two channel widths in Step #4). The migration magnitude can be defined arbitrarily, and should be at an appropriate scale to answer the research question for the study. Abandoned-channel locations are high-quality “tie” points that the channel must occupy at some point during the evolutionary history. Working backwards, the uncertainty increases and there will be less constraint on channel location (less shaded gray area). It is recommended to consult river meander patterns from modern analog settings similar to those being reconstructed.

**Step 6** Follow normal physical processes of channel migration and honor all crosscutting relationships, accretion patterns, and locations of abandoned-channel fills. It is recommended to reconstruct only as far back as the relatively oldest bar preserved (Fig. 6: Step 6). Predictive equations (e.g., Knighton 1998) and summaries of published examples (e.g., Gibling 2006; Blum et al. 2013) for morphometric parameters such as meander wavelength, radius of curvature, meander-belt width, bankfull channel width, point bar thickness, width-to-depth ratios and sinuosity, can be consulted to assist in constraining interpretations.

A focused study area was characterized (Fig. 3B) to capture the stratigraphic architecture of depositional elements and their relationship with the regional stratigraphy. The meander-belt base, top, and the internal...
boundaries between and within depositional elements are emphasized, providing a comprehensive 3D stratigraphic framework for the meander-belt deposit. This framework was used as the basis for a geocellular model of the deposits, which was constructed in the software Petrel 2014. Each depositional element is constructed as a separate zone in the model, which captures the 3D representation of the geobody. Each zone is then internally layered based on bedding characteristics (e.g., dipping lateral-accretion surfaces in point-bar deposits). The stratigraphic architectural model is populated with lithologic properties from over 350 boreholes in the focused study area. Specifically, vShale (Shale Volume Ratio) is modeled, which is derived from core-calibrated gamma-ray logs and used as an inverse proxy for lithology in this clastic system (Fig. 5B: cf. Asquith and Krygowski 2004).

RESULTS AND ANALYSIS

Facies Analysis

Five main lithofacies (F1 to F5) comprise the deposits of interest (Table 1). Observations of grain size, bedding characteristics, sedimentary and biogenic structures, etc., were made from core logging and FMI analysis (Fig. 7), as well as corroborations with previous studies in the region (e.g., Labrecque et al. 2011; Hubbard et al. 2011; Musial et al. 2012). Facies 1 (F1) consists mainly of massive and trough cross-stratified upper-fine- to medium-grained sandstone (Fig. 7A). Surfaces of dipping foresets are evident, and their dip angle and azimuth are measured from FMI logs (Fig. 7F). F1 is commonly closely associated with F2, which consists of siltstone-clast breccia with an upper-fine- to medium-grained sandstone matrix (Fig. 7B). Siltstone clasts are often subangular to angular and sometimes exhibit weak imbrication. F2 is obvious in FMI logs due to the contrast in resistivity between the bitumen-saturated sandstone matrix and the subangular, low-resistivity siltstone clasts (Fig. 7G). Facies 3 (F3) is composed of upper-fine-grained sandstone with siltstone interbeds, and Facies 4 (F4) consists of siltstone with fine-grained sandstone interbeds (Fig. 7C, D). F3 and F4 are characterized by planar dipping beds, ranging from 2 to 15°, which appear as sinusoidal traces in FMI logs (Fig. 7H, I). Facies 5 (F5) consists primarily of siltstone, with rare fine-grained sandstone interbeds (Fig. 7E). Horizontal to subhorizontal laminations that are difficult to resolve in core samples are evident in FMI logs (Fig. 7J). Biogenic structures are common to rare in F3 to F5 and absent in F1 and F2.

The range of facies documented in the study area is consistent with a fluvial environment, including point-bar, counter-point bar, and abandoned-channel deposits (Miall 2010; Leeder 2011; Ghinassi et al. 2016). Cross-stratified sandstone of F1 was deposited by relatively high-energy, unidirectional, transitional upper–lower-flow-regime currents, at the base of the channel or lower point bar (Allen 1970; Labrecque et al. 2011). Sandstone and siltstone layers (F3, F4) represent inclined heterolithic features and attributed their deposition to lateral channel migration (e.g., Fisk 1944; Hickin and Nanson 1975; Jackson 1976). Interbedded sandstone and siltstone layers (F3, F4) represent inclined heterolithic stratification (HIS) that dips roughly perpendicular to paleoflow trends, supporting the lateral-accretion interpretation (Thomas et al. 1987). Previous studies of the McMurray Formation have identified point-bar deposits as the most common depositional element in both the subsurface and outcrop data sets (e.g., Mossop and Flach 1983; Strobl et al. 1997; Wightman and Pemberton 1997; Hein et al. 2000; Fustic 2007; Hubbard et al. 2011; Musial et al. 2012; Nardin et al. 2013). A total of five bar deposits are characterized by concave-to-convex accretion patterns (Bars 2, 5, 10, 11, and 15; Fig. 3B). In plan view, convex sandstone and siltstone of Facies 3 and 4 records sedimentation under fluctuating current energy, where Facies 3 is dominated by higher energy, compared to Facies 4. The inclined nature of the bedding and the perpendicular relationship to the dip direction of trough cross stratification suggest a lateral-accretion origin, likely on the mid- to upper-point-bar surface (Thomas et al. 1987; Labrecque et al. 2011; La Croix and Dashtgard 2015). Siltstone of F5 records sedimentation from suspension in a quiescent setting. Previous workers have attributed similar facies to channel abandonment (Labrecque et al. 2011; Musial et al. 2012). A series of observations are suggestive of marine influence on the deposits, including mudstone drapes, rare dinoflagellates, and an overall low-diversity and diminutive trace-fossil assemblage (Hubbard et al. 2011; Musial et al. 2012; Dolby et al. 2013). These observations are consistent with an environment influenced by suppressed, or fluctuating, salinity levels (Pemberton et al. 1982; Gingras et al. 1999; Hauck et al. 2009; Dashtgard et al. 2010; Musial et al. 2012; Dolby et al. 2013). Previous workers have speculated on the origin of fluvial stratigraphic architecture overprinted with evidence for marine processes in the McMurray Formation, considering a system with highly variable seasonal river discharge (e.g., Hubbard et al. 2011; Jablonski and Dalrymple 2016).
FIG. 6.—A set of “rules” for the reconstruction of paleochannel locations employed in this study and for use in future studies are illustrated as a series of steps, using a hypothetic meander-belt deposit. Step 1) Identify meander-belt edges and use cross cutting relationships to determine relative ages of elements. Step 2) Determine dip and paleocurrent directions. Step 3) Reconstruct position of channels at abandonment. Step 4) Reconstruct a channel two channel widths earlier than abandonment position. Correlate accretion patterns between adjacent bars, working backwards from the youngest known channel position. Step 5) Continue working backwards in the manner described in Step 4. Step 6) Continue working backwards until as far back as the relatively oldest bar preserved (Step 6: Bar 1).
accretion patterns transition to concave across inflection points (dashed lines in Fig. 3B). A sharp discordant boundary separates the concave portion of the bar deposit from older, adjacent deposits. These concave bar deposits are less common but similar in size and thickness to purely convex bar deposits. Vertical facies successions are unique to accretion pattern type. The area of the bar with a convex scroll pattern is associated with a typical upward-fining succession similar to that of convex bars (Well C; Fig. 2C). However, the downstream, concave-scroll-pattern portion of bar deposits is often associated with reduced proportions of F1/F3 and increased F4 and F5, defining an overall finer-grained upward-fining profile (Well B: Fig. 2C).

Bar deposits with convex-to-concave accretion patterns are typically associated with downstream accretion and/or translation; the convex portion is interpreted as a point bar and the concave portion is interpreted as a counter-point bar (cf. Smith et al. 2009). Downstream translation of a meander bend has been observed in modern floodplains, and the associated deposits are characterized by convex and concave accretion patterns (Brice 1974; Hickin 1979, 1986; Lewin 1983; Nanson and Page 1983; Ghinassi et al. 2016). In the McMurray Formation, previous studies have documented the significant proportion of point-bar strata that dip northward (paleo-basinward), and these trends have been attributed to down-dip translation of meander bends (Hubbard et al. 2011; Fustic et al. 2012). Counter-point bar (concave-bank-bench) deposits have been identified in studies of modern meander-belt floodplains (e.g., Hickin 1979; Lewis 1983; Nanson and Page 1983; Hickin 1986; Smith et al. 2009). Grain-size fining along the transition from point bar to counter-point bar is characteristic in the examples studied (e.g., Smith et al. 2009). The first example of an ancient counter-point bar deposit was documented in the McMurray Formation, and its characteristics are consistent with the counter-point-bar deposits of this study (e.g., Smith et al. 2009; Hubbard et al. 2011).

Abandoned-channel fills are characterized by a relatively homogeneous, moderate seismic-amplitude response that results from heterolithic to fine-grained fill (F4-F5; Well A; Figs. 2C, 3). They occur in sharply defined curvilinear-trending bodies with a sinuosity index of 2.3 to 3.8. Abandoned-channel fills are 475 to 1180 m wide (average of 720 m) and are up to 40 m thick. In cross section, abandoned-channel fills are typically asymmetric around bend apices, and they transition to more symmetric fills at inflection points between channel bends.

The channel elements are particularly informative since they record a mold of the active channel present at the time of abandonment. The siltstone-filled abandoned-channel fills are interpreted as meander-bend cut-offs that record the filling of an oxbow lake by suspension settling of fine-grained sediment (Nielsen 2008). Modern meander belts are typically characterized by several abandoned-channel fills that record previous channel locations (e.g., Fisk 1947; Piet 1992; Camporeale et al. 2008; Toonem et al. 2012).

An anomalous late-stage straight channel is unique in that it is characterized by low sinuosity and a dominantly sandstone fill (filled in stipple pattern; Fig. 3B). Crosscutting relationships demonstrate that this channel is the youngest depositional element in the study area. The late-stage straight, sandstone-filled channel is interpreted as the final channel location of the depositional system before the deposition of an overlying coarsening-upward package (Well D; Fig. 2C). Similar sand-dominated channel fills have been recognized in modern delta plains, at the basinward end of large meandering-river systems (e.g., Blum et al. 2013). Hubbard et al. (2011) observed a similar sandstone-dominated channel fill in the McMurray Formation, yet the origin remained enigmatic.

### Paleochannel Evolution

The paleochannel evolution of the meander-belt deposits was reconstructed from the detailed architectural-element analysis described above (Fig. 8). Twelve stages of evolution are identified, where Stage 1 is the oldest and Stage 12 is the youngest (Fig. 8). The magnitude of channel migration between stages was chosen to match the intervals from similarly scaled lower Mississippi River paleochannels mapped by Fisk (1944). Each stage interpretation is characterized by a sinuosity value and an active-channel-belt width (Fig. 8). Important evolution events are documented and described herein. (1) Increasing channel sinuosity from 1.68 at Stage 1 to 2.52 at Stage 5, which results from continued lateral migration of active bars 2, 3, and 4 (Figs. 3, 8). (2) Development of a counter-point bar downstream of Bar 2 from Stage 2 to Stage 3, which is coincident with the cut-off of Bar 1 (Fig. 8). (3) Neck cut-off of Bar 3 at Stage 6, resulting in a significant decrease in sinuosity from 2.52 at Stage 5 to 1.94 at Stage 6 (Fig. 8); (4) Bars 1, 5, 10, and 11 are characterized by some degree of reoccupation of previous bar locations, in an overall eastward direction (Fig. 8). (5) Continued overall decrease in sinuosity from 2.61 at Stage 10 to 1.11 at Stage 12 is caused by meander cut-offs and a relative dominance of downstream migration in active bars (Fig. 8).

### Meander-Bend Evolution

To consider the processes associated with the evolution of a single meander bend, we selected a subset area of the data set to perform a detailed analysis (Fig. 9). This area includes point bar a (PBa), point bar b (PBb), counter-point bar (CPB), side bar a (Sba), side bar b (Sbb), side bar c (Sbc), mid-channel bar (MCB), and abandoned channel (AC) (Figs. 8, 9). Meander-bend evolution is considered in a series of stages.

- Stage 1 is characterized by a low-sinuosity (sinuosity index = 1.19) channel that flowed northward (Fig. 10C). At this stage, the meander bend was of low amplitude and symmetrical, and the accretion pattern was consistent with lateral migration. From Stage 1 to Stage 2, the channel increased in sinuosity (sinuosity index = 1.78) and the meander-bend amplitude increased. Deposition of PBb was associated with expansion and downstream translation, as evident in the rotation of the accretion pattern and erosion at the upstream end of the bar (Fig. 10D). At this stage, the cut bank eroded previously deposited meander-belt strata (Fig. 10D). From Stage 2 to Stage 3, the channel increased in sinuosity (sinuosity index = 2.55) and the meander-bend amplitude increased while the wavelength decreased. Lateral accretion was dominant due to bend expansion and reduced downstream translation. Significant erosion of the upstream portion of PBb created accommodation for downstream migration of the preceding meander bend associated with the deposition of Pba (Fig. 10E).

- At Stage 3, the meander-bend cut bank reached the paleo-meander-belt edge and began to erode the more resistant regional deposits (Fig. 10E). The likely increase in resistance to erosion of the cut bank promoted downstream translation and the development of a counter-point bar (concave bank bench) from Stage 3 to Stage 4 (Fig. 10F). Recirculation eddies formed along the concave bank and resulted in fine-grained sedimentation (e.g., Smith et al. 2011). As recognized in previous studies of counter-point-bar deposits, a significant shift in facies from sandstone-dominated to siltstone-dominated successions is recognized from upstream to downstream, respectively (Fig. 10B; e.g., Lewin 1983; Smith et al. 2009). In plan view, the facies transition is consistent with the inflection point between convex and concave scroll patterns (Fig. 10F). The increase in channel sinuosity (sinuosity index = 3.24) is associated with expansion of the upstream and downstream meander bends.

In the accretion packages deposited from Stage 3 to Stage 4, a significant discordance between accretion trajectories is evident within Pbb (Figs. 11A, B). In seismic cross section, a discordant surface truncates previously deposited point-bar strata and is onlapped by subsequent units (Fig. 11B). Eight such discordances between accretion packages are identified in Pbb and are associated with the changes in the accretion direction (Fig. 11B). The discordant truncation surfaces are interpreted as intra-point-bar erosion surfaces that reshape the point bar and result in accretion in a different direction. Similar features have been recognized in outcropping point-bar deposits of the Horseshoe Canyon Formation, south-
<table>
<thead>
<tr>
<th>Lithofacies</th>
<th>Grain Size/Sorting</th>
<th>Sedimentary Structures</th>
<th>Biogenic Structures</th>
<th>FMI Character</th>
<th>Upper/Lower Contacts</th>
<th>Process Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>F1: Massive and cross-</strong></td>
<td><strong>stratified sandstone</strong></td>
<td><strong>fL to mL; well-sorted</strong></td>
<td><strong>Absent</strong></td>
<td><strong>High-amplitude sinuosoidal surfaces; bands of high and low resistivity; dipping at 20–40°</strong></td>
<td><strong>Sharp, erosional base; sharp and gradational upper</strong></td>
<td><strong>Moderate to high-energy unidirectional current flow; traction dominated</strong></td>
</tr>
</tbody>
</table>
| **F2: Siltstone- clast**  | **breccia**         | **fL to mL sand: silt clasts  
< 1 cm to > 30 cm blocks; subangular to angular**                             | **Absent**                  | **High-resistivity sandstone, low-resistivity siltstone clasts; high-amplitude erosional surfaces at base** | **Sharp base; gradation upper contact, typically from F2 to F1** | **Traction dominated; unidirectional current flow; erosion of previously deposited silt beds, short transport distance** |
| **F3: Sandstone with**   | **siltstone interbeds** | **fL to fU sand; silt to clay; sand well sorted**                                        | **Planar lamination; cross stratification; ripple cross- laminae; wavy and discontinuous silt laminations and beds** | **Cylindricals, and Planolites, rare  
Gyrolithes, Rosselia, and Skolithos** | **Gradational lower; sharp and gradational upper** | **Moderate- to low-energy unidirectional current flow; fluctuations in discharge** |
| **F4: Siltstone with**   | **sandstone interbeds** | **vfU to fU sand; clay to silt; moderately to well-  
sorted sand**                                                                     | **Abundant Cylindricals,  
Planolites, Gyrolithes, and Paleophycus** | **Centimeter-scale alterations of high and low resistivity; dipping at 6–15°** | **Gradational and sharp** | **Low-energy unidirectional current flow; fluctuations in discharge** |
| **F5: Siltstone**        | **Clay to silt**    | **Planar lamination, rare  
discontinuous sandstone interlamination; massive silt fissile** | **Chondrates, Planolites, and Paleophycus**   | **Regular thin alterations of high and low resistivity** | **Sharp or gradational at base; sharp upper** | **Low-energy deposition from suspension** |
RECONSTRUCTION OF MEANDER-BELT EVOLUTION

The Durkin et al. (2015) outcrop study lacked a planform perspective to confirm the presence of discordances between accretion-package scroll patterns; however, examples of intra-point-bar erosion documented in this study of the McMurray Formation reveal the planform expression and provide evidence for the cause of major shifts in meander-bend evolution (Fig. 11). Reconstruction of paleochannel history suggests that major shifts in accretion direction are related to significant morphologic changes upstream, specifically meander-bend cut-off. For example, from Stage 2 to Stage 3 of channel development, the neck cut-off of Bar 1 is coincident with a change in the accretion pattern of bars 2 and 3 from lateral expansion to downstream translation (Fig. 8). The neck cut-off of Bar 6 (Stage 5) also impacts the geometry of Bar 2, and occurs just before the cut-off of Bar 3 (Fig. 8). At Stage 4 the meander bend began the initial stages of channel filling and abandonment. The abandoned-channel fill is characterized by a variable width and depth around the meander bend (Fig. 12A). At the meander-bend apex, the channel fill is ~ 25 m thick (Fig. 12B, C). Along the channel limbs, the channel is broader, shallower, and more symmetrical. Locally, the mudstone-dominated portion of the abandoned-channel fill is as thin as 5 m, whereas the adjacent and genetically related point-bar deposits are up to 45 m thick (Fig. 13B). Below the abandoned-channel deposit, the MCB depositional element is a sandstone-dominated elongate bar deposit up to 20 m thick that follows the trend of the abandoned channel (Fig. 9). SBB, SBb, and SBC are bar deposits adjacent to the abandoned channel fill that are characterized by sandstone-dominated to heterolithic deposits (Figs. 4A, 8).

The abandoned-channel depositional element is interpreted as an abandoned meander loop formed through chute cut-off (e.g., Toonen et al. 2012). The example presented here is characterized by a complex internal stratigraphic architecture and the presence of previously understated depositional elements that are related to the abandonment process (Fig. 13). Stage 4 was characterized by an ~ 45-m-deep active channel that migrated to the north, eroded the PBb deposit, and deposited PBa (Fig. 13C). As the meander loop became more sinuous (Stage 4B) and the cut bank eroded into regional deposits to the west, the channel became broader and began to vertically aggrade at the meander-bend inflection point (Fig. 13D). We propose that the highly sinuous nature of the meander bend and the erosion-resistant cut bank inhibited further lateral migration and accommodation creation through cut-bank erosion (Smith et al. 2009; Smith et al. 2011). This resulted in deposition of side bars as the channel limbs attempted to migrate north and then south, while the meander bend largely remained stagnant (Stage 4C, 5; Fig. 13E, F). At Stage 5b, a lack of cut-bank erosion and accommodation creation resulted in formation of a mid-channel bar (Fig. 13G). This deposition is coincident with channel broadening and a dual thalweg geometry around the mid-channel bar (Fig. 12D). Finally, chute-cut-off of the meander bend initiated fine-grained suspension sedimentation and filling of the channel at Stage 6 (Fig. 13H).

**Facies Mapping**

To better characterize 3D meander-belt stratigraphic architecture and sediment distribution patterns, a geological model was constructed in a focused study area (Figs. 3, 9) and populated with lithologic properties. The geological model is similar to geocellular models that have been constructed and used for reservoir engineering and production simulation (e.g., Enge et al. 2007; Pranter et al. 2007; Su et al. 2013; Deschamps et al. 2013). The geological model covers an area of approximately 130 km² and consists of 5 m by 5 m cells populated with vShale values (derived from gamma-radiation borehole logs), which are used as a proxy for lithology. 3D seismic mapping combined with detailed well-log analysis was used to delineate a series of zones that constitute the framework of the geocellular model (Fig. 14A). Accretion packages are constructed as individual zones, which allows for each zone to be layered separately so that internal stratigraphic architecture can be represented (Pranter et al. 2007; Sech et al. 2009; Graham et al. 2015). Other depositional elements, including side bar, mid-channel bar, and the abandoned channel, are also modeled as discrete zones (Fig. 14A, B). A series of facies maps show the distribution of the vShale property for every 5 ms below the top McMurray Formation surface, to a depth of 30 ms (Fig. 14C, I).

The observed lithologic trends are consistent with those observed in numerous studies of ancient and modern meander belts (Jackson 1976; Jordan and Pryor 1992; Willis and Tang 2010; Labrecque et al. 2011; Musial et al. 2012; Nardin et al. 2013; Deschamps et al. 2013); however, the results from this study reveal unprecedented three-dimensional perspectives. Four main trends are observed (Fig. 14B): (1) an overall variable increase in vShale from the base of the meander belt to the top; (2) an increase in vShale from older to younger deposits across an entire bar; (3) an increase in vShale from upstream to downstream, and from point bar to counter-point bar; (4) an increase in vShale in individual accretion packages in both the upstream-to-downstream direction, and from older to younger deposits (e.g., Fig. 14E, G).

The decrease in vShale from the top of the meander belt to the base is consistent with an overall upward-finining in point-bar and counter-point-bar deposits as a result of across-channel grain-size sorting and lateral-

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**Table 2.—Characteristics of meander-belt depositional elements.**

<table>
<thead>
<tr>
<th>Depositional Element</th>
<th>Width (km)</th>
<th>Length (km)</th>
<th>Thickness Average (m)</th>
<th>Thickness Range (m)</th>
</tr>
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<tbody>
<tr>
<td>Bar 1</td>
<td>4.48</td>
<td>2.76</td>
<td>44.3</td>
<td>43–48</td>
</tr>
<tr>
<td>Bar 2 + 5</td>
<td>7.05</td>
<td>8.51</td>
<td>46.3</td>
<td>43.48</td>
</tr>
<tr>
<td>Bar 3</td>
<td>2.32</td>
<td>9.51</td>
<td>43.2</td>
<td>40–46</td>
</tr>
<tr>
<td>Bar 4*</td>
<td>3.09</td>
<td>7.63</td>
<td>43.8</td>
<td>41–46</td>
</tr>
<tr>
<td>Bar 6</td>
<td>4.95</td>
<td>3.51</td>
<td>42.4</td>
<td>40–46</td>
</tr>
<tr>
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<td>Bar 8</td>
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<td>Bar 9</td>
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<td>8.61</td>
<td>44.2</td>
<td>42–47</td>
</tr>
<tr>
<td>Bar 10</td>
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<td>9.26</td>
<td>44</td>
<td>40–48</td>
</tr>
<tr>
<td>Bar 11</td>
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<td>5.41</td>
<td>46.3</td>
<td>43–50</td>
</tr>
<tr>
<td>Bar 12</td>
<td>2.13</td>
<td>5.4</td>
<td>40.4</td>
<td>35–45</td>
</tr>
<tr>
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<td>1.23</td>
<td>No Data</td>
<td>No Data</td>
</tr>
<tr>
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<td>8.27</td>
<td>43.8</td>
<td>39–50</td>
</tr>
<tr>
<td>Bar 15</td>
<td>2.6</td>
<td>6.31</td>
<td>45.7</td>
<td>44–48</td>
</tr>
<tr>
<td>Bar 16*</td>
<td>3.03</td>
<td>6.95</td>
<td>42.8</td>
<td>41–45</td>
</tr>
<tr>
<td>Bar 17*</td>
<td>6.7</td>
<td>4.61</td>
<td>47.8</td>
<td>46–50</td>
</tr>
<tr>
<td>Average</td>
<td>3.88</td>
<td>6.73</td>
<td>44.1</td>
<td>N/A</td>
</tr>
</tbody>
</table>

* minimum; incomplete bar remnant or extends beyond seismic data

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**Fig. 7.—** Core and FMI examples of lithofacies F1–F5 from Table 1. Cores are 75 cm long; sandstones are saturated with bitumen and appear black. FMI logs are 200 cm long and 360° around a borehole. Sinusoid picks for accretion surfaces (red), bedding (green), trough cross-stratification (blue), scour surfaces (yellow), and erosional surfaces (black) are shown. The facies in this area have been extensively documented in previous studies (Labrecque et al. 2011; Hubbard et al. 2011; Musial et al. 2012), and for brevity we refer to their descriptions for further detail.
accretion processes (e.g., Allen 1970; Jackson 1976; Smith et al. 2009; Willis and Tang 2010; Labrecque et al. 2011). The abandoned channel fill also exhibits this same trend, where the uppermost part of the fill is predominantly fine-grained (Figs. 7E, 14C, D), and the mid-channel-bar and basal-channel deposits are sandstone prone (Fig. 7A, 14E, F).

The bar-scale trends of increased fine-grained deposition through time may be explained by channel-sinuosity and flow-separation processes (Leeder and Bridges 1975). During the initial stages of point-bar migration, the active channel is characterized by low sinuosity (Stages 1 to 3: Fig. 8) with little to no interpreted flow separation from the inner bank (Leeder and Bridges 1975). As sinuosity increases, channel gradient decreases and flow separation becomes more pronounced, resulting in fine-grained deposition in slack-water zones along the inner bank (Leeder and Bridges 1975; Willis and Tang 2010). This pattern is widely observed in the stratigraphic record (e.g., Thomas et al. 1987; Pemberton and Wightman 1997; Durkin et al. 2015; Ghinassi et al. 2016).

Of note, siltstone-clast breccia may be represented by high vShale values (e.g., Fig. 5D) depending on clast content, which may explain the presence of high vShale values in the basal point-bar deposits of maps G and H. Siltstone-clast-breccia deposits are associated with high energy and erosion.

Fig. 8—Stages of paleochannel evolution for the meander-belt deposits of the McMurray Formation. Stage 1 is the oldest, and Stage 12 is the final stage, and represents the seismic-amplitude stratal slice from Figure 3A. Sinuosity (Sin.), active channel-belt width (CBW), and channel-belt width/thickness ratio (CBW/T) values are indicated for each stage.
of previously deposited point-bar strata and/or cut banks, and are often concentrated in the channel-base to lower-point-bar environments (e.g., Labrecque et al. 2011; Sisulak and Dashtgard 2012; Durkin et al. 2015; Brekke et al. 2017).

On the accretion-package scale, a trend from sandstone-dominated (Fig. 7A) to IHS-dominated (Fig. 7C, D) deposits is evident, from older to younger strata and in the downstream direction along elements (Fig. 14B). Each accretion package is bounded by an intra-point bar erosion surface that often coincides with a shift in accretion direction. High-energy events and significant channel adjustments often result in coarse-grained deposition directly above intra-point-bar erosion surfaces (Durkin et al. 2015). Continued migration and more modest flood events deposit relatively fine-grained point-bar strata in the new accretion direction (Durkin et al. 2015). The downstream increase in fine-grained deposition is caused by flow separation from the inner bank and recirculation eddies that promote suspension settling of fine sediment (Leeder and Bridges 1975; Lewin 1983; Ferguson et al. 2003; Willis and Tang 2010; Smith et al. 2011). Downstream fining along a point bar has been widely described from the rock record (e.g., Leeder and Bridges 1975; Lewin 1983; Wood 1989; Smith et al. 2009; Hubbard et al. 2011; Labrecque et al. 2011; Musial et al. 2012; Deschamps et al. 2013; Ghinassi et al. 2016).

**DISCUSSION**

**Meander-Bend Morphodynamics**

At the meander-bend scale, evidence for fine- and intermediate-scale processes is recognized and the relationship to the resulting stratigraphic product allows enhanced paleoenvironmental interpretations. Recent studies of modern and ancient meandering-river deposits have focused on morphodynamic processes to account for deposits that were previously understated (Smith et al. 2009; Smith et al. 2011; Toonen et al. 2012; Ghinassi et al. 2013; Ielpi and Ghinassi 2014; Ghinassi and Ielpi 2015; Durkin et al. 2015). We address the prevalence and formation of counter-point-bar deposits and interpretations of intra-point-bar erosion surfaces. Accretion patterns that are oblique to the bend apex of the surrounding abandoned channel, such as those from the convex-to-concave bars of this study (e.g., Fig. 3B), were dominated by meander-bend translation in the downstream or down-dip direction (cf. Fustic et al. 2012; Ghinassi et al. 2016). Downstream translation is often controlled by lateral confinement of the channel, which inhibits further lateral accretion and expansion. Smith et al. (2009) proposed that confinement was a requirement for counter-point-bar development, and the results of this study are a positive test of this hypothesis. From the examples presented in this study, two types of confinement are recognized: channel-belt-edge and intra-meander-belt. Channel-belt-edge confinement results from interaction of the active channel cut bank with older, erosion-resistant deposits of the regional marine parasequences at the meander-belt boundary to the west (Fig. 3B). The regional deposits inhibit further lateral migration of meander bends and promote downstream translation along the channel-belt edge; in some cases a counterpoint bar (concave bank bench) was deposited (e.g., Fig. 10). Intra-meander-belt confinement results from interaction between the active channel and an older, erosion-resistant meander-belt element, such as an abandoned-channel fill or a counter-point-bar deposit (cf. Smith et al. 2009). The heterolithic or siltstone-dominated nature of the meander-belt element acts as a resistant substrate, which inhibits further lateral expansion of the cut bank and results in downstream translation (Ghinassi et al. 2016). In this study, both counter-point bars and downstream-translated point bars result from this process (e.g., Bars 11, 12; Fig. 3B). The presence of several intra-meander-belt-confined bars may indicate the maturity of the meander belt, where mature belts contain more abandoned-channel oxbow-lake fills and counter-point-bar deposits that can restrict bar expansion and induce translation (cf. Smith et al. 2009).

Intra-point-bar erosion surfaces bound lateral-accretion packages, across which the direction of accretion has rotated (cf. Durkin et al. 2015). Evidence for punctuated rotation is common in many modern meander belts, but absent in others. Also, within the same meander belt it is
common to observe bars that are dominated by punctuated rotation, while others are characterized by gradual rotation or simple consistent expansion. The results of this study do not offer an explanation for why some meander belts or bars are characterized by intra-point-bar erosion and punctuated rotation; however, the examples presented here are linked to changes in upstream channel geometry, which may explain their erratic preservation. For example, the neck cut-off of Bar 1 resulted in a shift in the accretion direction of bars 2 and 3 (Figs. 3B, 7). Therefore, the change in gradient and flow hydraulics associated with the upstream meander-bend cut-off may impact the accretion direction of the adjacent downstream point bar (e.g., Camporeale et al. 2008). Many other controls on meandering dynamics can also result in punctuated bar rotation, which may explain the presence or absence of erosion surfaces in other meander belts; these controls include migration rates, meander-bend geometry (radius of curvature), high-magnitude changes in stage or discharge, and changing erodibility of the cut bank (Ackers and Charlton 1970; Hickin and Nanson 1975; Brizga and Finlayson 1990; Diaz-Molina 1993; Jones and Harper 1998; Durkin et al. 2015).

Meander-Belt Morphodynamics

At the meander-belt scale, it is difficult to draw conclusions about the impact of climate, sediment supply, or tectonics on fluvial meander-belt evolution; however, the impact of base level and resulting backwater influences can be inferred. The backwater segment of a river is defined as the zone over which the effects of the receiving basin influence flow (Fig. 15A; Chow 1959; Paola and Mohrig 1996; Li et al. 2006; Nittouer et al. 2012; Blum et al. 2013). The backwater limit is defined as the upstream point at which the channel-bed elevation is at or below sea level (Li et al. 2006; Blum et al. 2013). The backwater length (Lb) is defined as $L_b = HS^{-1}$,
where $H$ is the bankfull channel depth and $S$ is the channel slope (Fig. 15A; Paola and Mohrig 1996). In the lower Mississippi River, downstream changes in cross-sectional area of flow, water velocity, and sediment transport are attributed to backwater effects (Nittrouer et al. 2012). These changes are correlated to variations in meander migration rates, channel-belt width, and sinuosity (Nittrouer et al. 2012; Blum et al. 2013).

In a process-response approach to the influence of backwater limits, we first consider the changes in flow velocity and sediment transport recognized along a river system. During low-flow conditions, the cross-sectional area of flow increases downstream into the backwater zone, due to an increase in flow depth. This leads to a downstream decrease in flow velocity and therefore a reduction in sediment transport, and overall net deposition (Nittrouer et al. 2012). In the lower Mississippi River, the backwater limit is between 600 and 750 km upstream of the mouth, and the zone of decreased sediment transport occurs between 600 and 150 km upstream of the mouth (Fig. 15; Nittrouer et al. 2012). At high flow conditions, the trend is reversed and the cross-sectional area of flow decreases downstream, due to a decrease in channel width and marginal stage increases. This results in an increase in flow velocity and sediment transport between the mouth and 300 km upstream. Ultimately, the result is net channel-bed aggradation over a significant segment of the backwater zone (from 150 to 600 km upstream) and net channel-bed erosion over the downstream 150 km (Nittrouer et al. 2012).

Zones of net aggradation and net erosion coincide with significant morphologic changes in channel planform and kinematics (Fig. 15). For example, on the lower Mississippi River, elevated meander-bend migration rate correlates to where the river enters the backwater zone (800–400 km upstream of the mouth; Fig. 15B). This segment is also characterized by a high channel-belt width/thickness ratio (Fig. 15B). Downstream of this segment, meander-bend migration rates and channel-belt width/thickness ratios decrease significantly. These observations agree with theoretical models that indicate that channel-bed deposition forces cut-bank erosion and lateral migration (Ikeda 1989; Nelson and Smith 1989; Hasegawa 1989). Other rivers exhibit similar morphologic changes through the backwater zone, including the Teshio River, Japan (Ikeda 1989) and the Rhine River, Netherlands (Fernandes et al. 2016). Parker et al. (2008) also investigated the river response to rising sea level on the Fly River in Papua New Guinea. Blum et al. (2013) proposed that the relationship between spatially divergent sediment flux and channel-belt morphology should be recognizable in the rock record.

Comparisons of the McMurray Formation meander-belt deposits and the lower Mississippi River have been made previously (Musial et al. 2012; Hubbard and Dashtgard 2015; Blum 2017). Musial et al. (2012) calculated the mean discharge of the McMurray Formation to be approximately 15,000 m$^3$ s$^{-1}$ at bankfull discharge, which they compared to the discharge of the Mississippi River (18,000 m$^3$ s$^{-1}$, SAGE database). Calculated meander-bend migration rates from McMurray Formation point-bar deposits are also consistent with the lower Mississippi River; 30 to 65 m/year and an average of 45.2 m/year, respectively (Hudson and Kesel 2000; Musial et al. 2012). The meander-belt width/thickness ratio of the entire meander-belt deposit studied herein is $> 400$ (Table 3); similar width/thickness ratios for the lower Mississippi River fall between 500 and 900 km upstream from the river mouth.

**Implications for Interpretations of the McMurray Formation**

Previous work on the meander-belt deposits of the McMurray Formation featured in this study have recognized a marine influence on sedimentation, due to the presence of a brackish-water trace-fossil assemblage, marine palynomorphs, and sedimentary structures attributed to tidal modulation (Hubbard et al. 2011; Labrecque et al. 2011; Musial et al. 2012; Dolby et al. 2013). However, many of the stratigraphic-architecture features documented in this study are explained by fluvial processes, and meander-belt metrics are not consistent with close proximity to a shoreline. Recent advances in the understanding of the relationship between flow dynamics and geomorphic expression of meander-belt deposits along the fluvial-to-marine transition zone from the lower Mississippi River (Nittrouer et al. 2012; Blum et al. 2013) and the Rhine River (Fernandes et al. 2016) inspire re-evaluation of the paleoenvironment of McMurray Formation meander-belt deposits. Since the downstream deposits of the depositional system in the McMurray Formation have been eroded by glacial processes (Hayes et al. 1994; Fenton and Nielsen 1994), analyses of meander-belt characteristics provide a means to estimate important paleogeographic features, including shoreline positions. It is important to note, however, that key parameters, such as the tidal range of the Boreal Sea at the mouth of the paleoriver, are not known, which should be kept in mind as comparisons with the lower Mississippi River are considered.

From the paleochannel-evolution analysis of the McMurray Formation meander-belt deposits in this study, the average sinuosity of reconstructed channel locations is 2.08, the average active channel-belt width is 13.1 km, and the range of channel-belt width/thickness ratios is 1071:1 to 401:1 (Fig. 8; Table 3). Throughout the evolution, the overall channel morphology is consistent, except for Stages 11 and 12. Stages 11 to 12 are characterized by a relatively high-sinuosity channel, with common meander bend cut-offs (i.e., oxbow lakes; Fig. 8). The active channel-belt width is relatively consistent between 10.9 and 18 km, and the channel-belt width/thickness ratios are high, between 243:1 and 401:1. However, Stages 11 and 12 are characterized by a significant decrease in sinuosity (1.44 and 1.11; Fig. 8) and channel-belt width/thickness (151:1 and 107:1; Fig. 8). The final channel location (Stage 12) is preserved as a nearly straight, deep (~ 55 m), sandstone-dominated channel fill that has previously been described as enigmatic (Fig. 2C; Hubbard et al. 2011). We propose that the change in channel morphology and final-stage channel filling could be related to the landward migration of the paleo-backwater zone during overall transgression of the Boreal Sea. The transgression of the Boreal Sea, and resulting deposition of the marine Wabiskaw Member of the Clearwater Formation, is well documented (Carrigy 1971; Keith et al. 1988; Wightman et al. 1991; Hein and Cotterill 2006).

The temporal changes in channel morphology through time are similar in character to the present-day spatial morphologic variability of the modern lower Mississippi River from the backwater limit to the Gulf of Mexico. We consider that Stages 1 to 10 of McMurray Formation evolution occurred in the upper reaches of the backwater limit where meander-bend migration rate, sinuosity, and channel-belt width/thickness ratio is high (Fig. 15F). This interpretation is problematic however, in that it does not explain the presence of trace fossils attributed to saline-water intrusion into the meander-belt deposits studied (cf. Pemberton et al. 1982; Hubbard et al. 2011; Gingras et al. 2016). In the Mississippi River example, meander-belt deposits comparable to those studied are hundreds of kilometers upstream of the limit of saline water intrusion into the meander-belt deposits studied (cf. Pemberton et al. 1982; Hubbard et al. 2011; Gingras et al. 2016). In the Mississippi River example, meander-belt deposits comparable to those studied are hundreds of kilometers upstream of the limit of saline water intrusion into the meander-belt deposits studied (cf. Pemberton et al. 1982; Hubbard et al. 2011; Gingras et al. 2016).
CONCLUSIONS

The linkage of morphodynamic processes to products in the rock record is a key to enhanced stratigraphic and paleoenvironmental interpretations. In the case of the Cretaceous McMurray Formation, a high-quality, three-dimensional seismic volume combined with hundreds of well bores provides one of the best-constrained meander belts in the world. A complete reconstruction of paleochannel evolution is proposed, which has not been previously attempted on ancient deposits. We provide a set of “rules” for paleochannel reconstruction employed in this study and for use in future studies, and highlight the improved paleoenvironmental interpretations that result from this analysis. We provide recognition criteria for counter-point-bar development, and direct evidence that confinement of the channel-belt-edge resulted in downstream translation. We document one of the first examples of intra-point-bar erosion and rotation in the subsurface, with an emphasis on the planform discordance of accretion packages. The stratigraphic product is directly related to morphological changes in upstream channel evolution as demonstrated through the paleochannel reconstruction analysis. We document the formation of side bars as a result of meander-bend limb migration, and within-channel deposition in the form of a mid-channel bar. This mid-channel bar formed in response to the lack of accommodation during protracted meander-bend abandonment. The identification and interpretation of these previously understated depositional elements has significant implications for reservoir prediction and delineation.

A total of 12 stages of channel evolution are interpreted for the Cretaceous McMurray Formation in the study area. The mapped paleochannel locations provide information on active-channel-belt width and sinuosity over time. We recognize a significant decrease in channel...
FIG. 15.—Backwater-zone characteristics of a fluvial system (modified from Li et al. 2006). A) Generic fluvial profile and location of zones related to the backwater length. B) Graph of meander-bend migration rate and channel-belt width/thickness ratio compared to normalize distance upstream represented as a percentage of the backwater length (modified from Blum et al. 2013; Bentley et al. 2016). C) Graph of channel-belt width/channel width compared to backwater length (modified from Fernandes et al. 2016). D) Graph of sinuosity and channel-belt width/thickness over stage (time) from the McMurray Formation (Fig. 8). E) Channel-belt width/channel width over stage (time) for stages with an associated abandoned channel (Fig. 8). F) Fisk (1944) map of the lower Mississippi River south of Greenville, Mississippi. G) Fisk (1944) map of the lower Mississippi River from south of Baton Rouge, Louisiana. Both maps are at the same scale. Note the differences in channel-belt width and meander migration history over the same time period. Locations of maps are noted relative to the backwater length in Part B.
sinuosity and active channel-belt thickness ratio over the last two stages of evolution, and posit that it is a result of the landward-migrating paleo-backwater reach, developed in response to transgression of the Boreal Sea into the Western Interior Seaway during the Aptian. This is, to our best knowledge, one of the few known interpretations of a migrating paleo-backwater zone in the stratigraphic record.

ACKNOWLEDGMENTS

The authors would like to thank ConocoPhillips for allowing this data to be published. Funding for this project was provided by the University of Calgary as well as a Natural Sciences and Engineering Research Council (NSERC) Discovery Grant to SMH. Discussions with Dale Leckie, Fran Hein, Ian Gates, Darren Sjogren, and John Holbrook helped shape the ideas presented. This manuscript was improved by JSR Associate Editor Janok Bhattacharya and reviewers A. Ielpi and B. Willis, and Technical Editor John Southard, whose efforts are greatly appreciated. We would also like to thank Schlumberger (Petrél 2014) for software access.

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TABLE 3.—Statistics quantified from 3-D seismic data and paleochannel reconstruction.


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Received 3 February 2017; accepted 12 July 2017.