PALEOHYDROLOGY AND 3D FACIES ARCHITECTURE OF ANCIENT POINT BARS, FERRON SANDSTONE, NOTOM DELTA, SOUTH-CENTRAL UTAH, U.S.A.

CHENLIANG WU, JANOK P. BHATTACHARYA, and MOHAMMAD S. ULLAH

1C&C Reservoirs Inc., 10333 Harwin Drive, Suite 270, Houston, Texas 77036, U.S.A.
2School of Geography and Earth Sciences (SGES), McMaster University, 1280 Main Street West, Hamilton, Ontario L8S 4L8, Canada
3Department of Earth and Atmospheric Sciences, University of Houston, 4800 Calhoun Road, Houston, Texas 77204-5007, U.S.A.
e-mail: wuchenliang1@gmail.com

ABSTRACT: Most outcrops of fluvial deposits consist of a series of cliff exposures, either natural or manmade (e.g., roadcuts). Predictions, and especially observation of plan-form geometry, such as might be made with numerical experiments or from studies of modern rivers, are challenging to test in most ancient outcrops. This study examines ancient exhumed channel belts from the Cretaceous Notom Delta of the Ferron Sandstone Member in south-central Utah. Extensive plan-view exposures with local vertical cliff exposures allowed documentation of channel plan-form, channel-belt dimension, bar migration patterns (translation versus expansion), and cross-sectional facies architecture. Channel-fill thickness and bedding structure, documented from the cliff exposures, were used in paleohydraulic reconstructions. Approximately 270 paleocurrent directions were integrated with grain-size measurements to reconstruct the 3D facies architecture. Paleocurrent measurements are consistent within specific facies architectural units (such as unit bars) and show systematic variation at the channel-belt scale that can be used to infer channel and bar migration patterns. In this example, the migration pattern of the single-thread channel bend was interpreted to change from expansion to translation with a corresponding bend sinuosity that increased from 1.0 to 1.44. Inclined large-scale foresets are interpreted to be indicative of unit bars. Empirical equations result in estimated average channel depths from 1.7 m to 3.6 m with corresponding widths of 23 m to 89 m respectively. These empirical estimates match the dimensions measured in the field. For example, channel widths of around 50 m were measured from abandoned channel fills. Bar thickness, measured from vertical outcrops, ranges from 5.4 m to 6.3 m, which yields a narrower estimate of channel width ranging from 47 to 59 m. Integration of sediment size, bedforms type, and channel depth were used to estimate the discharge of the river, which is on the order of < 400 m³/s. This suggests that the Ferron deltas were characterized by small, steep-gradient “dirty” rivers, which is consistent with the hyperpycnal nature of linked downstream deltaic systems.

INTRODUCTION

Point bars are common features of fluvial depositional systems, and the growth and sedimentary architecture of the resultant channel belt may be quite complex, depending on the evolution and flow patterns of the formative river (Schumm and Khan 1972; Hickin 1974; Jin and Schumm 1987; Smith 1998; Peakall et al. 2007; Duan and Julien 2010). Studies of river evolution and their consequent deposits have been focused on modern rivers (e.g., Sambrook-Smith et al. 2006; Hooke and Yorke 2011; Kasvi et al. 2012), ancient outcrops (e.g., Ghazi and Mountney 2009; Li et al. 2010), flume tests (Schumm and Khan 1972; Smith 1998; Peakall et al. 2007; Van Dijk et al. 2012), and mathematical modeling (Bridge 1977; Willis 1989; Willis 1993b; Sun et al. 2001a; Sun et al. 2001b; Willis and Tang 2010; Duan and Julien 2010). Early studies focused on descriptions of sedimentary structures and bedding architecture of point bars from trenches and cores of modern point bars (Frazier and Osani 1961; Boersma et al. 1968; Jackson 1976; Levey 1977), outcrops of ancient deposits (Puigdefabregas and Viet 1977; Nijman and Puigdefabregas 1977), or both (McGowen and Garner 1970).

Traditional outcrop facies models of fluvial systems emphasize the use of vertical profiles and bedding architecture that are used to predict plan-view architecture and lateral grain-size variability (e.g., Allen 1965; McGowen and Garner 1970; Miall 1985; Galloway and Hobday 1996; Bridge 2006). However, there are very few ancient outcrop examples in which plan-view geometry of channel-belt deposits can be observed directly (Hilton 2013; Ielpi and Ghinassi 2014). Recent 3D seismic examples provide plan-view images of the geomorphology of channels and channel belts, from which channel migration patterns can be inferred (e.g., Zeng and Heniz 2004; Wood 2007; Reijenstein et al. 2011) but these seismic examples typically lack data on facies, grain-size variation, paleocurrent variability, and detailed cross-sectional facies architecture.

More recently, Sambrook-Smith et al. (2006) and Bridge (2006) have shown the unit bar to be a fundamental element that builds larger-scale point bars and braid bars. This suggests that point bars and braid bars are not fundamental bar-scale units in fluvial systems, because they are essentially compound in nature. However, the concept of unit bars has not been well tested in studies of ancient fluvial systems. Moreover, despite the efforts of flume studies to try to unravel the controls of channel migration pattern (Peakall et al. 2007; Van Dijk et al. 2012; Van De Lageweg et al. 2013), very few ancient examples have been studied to test the hypotheses from these flume experiments.

This study addresses the relationship between cross-sectional analysis of fluvial systems and their plan-view expression in unique outcrops in the
Cretaceous Ferron Notom Delta complex. The plan-view and cliff exposures enable characterization of the 3D facies architecture as well as vertical, lateral, and plan-view variability of bedforms, bar-forms, paleocurrents, sinuosity, and grain size in an ancient system. Recorded data are used to reconstruct the paleohydraulic evolution of a channel. Outcrop can be used to test empirical paleohydraulic equations and evaluate the predictive ability of previous models of fluvial point bars. This study also aims to examine an ancient point-bar deposit in 3D to determine whether point-bar deposits are formed from smaller-scale unit bars.

We address a number of more specific questions in interpretation of our outcrop, including 1) the role of the floodplain in allowing a channel to maintain a meandering planform (Peakall et al. 2007; Van Dijk et al. 2012), 2) the role of mid-channel and unit bars in channel abandonment (Peakall et al. 2007), 3) whether the migration pattern of a single-thread channel is characterized by consecutive stages of dominantly expansion followed by dominantly translation (Peakall et al. 2007), 4) whether grain-size distributions in a point-bar deposit show downstream fining, and fining towards the accretionary inner bank (Willis 1989; Willis and Tang 2010).

GEOL OGICAL SETTING

The Ferron Sandstone Member of the Mancos Shale comprises three fluvio-deltaic complexes, the Last Chance, Notom, and Vernal, which prograded into the Western Interior Seaway during the Late Cretaceous (Turonian) (Bhattacharya and Tye 2004). The Ferron Member overlies the Tununk Shale Member of the Mancos and is overlain by the Blue Gate Shale Member (Peterson and Ryder 1975). The Notom Delta complex is located in east-central Utah near Capital Reef National Park, USA (Fig. 1). The studied outcrop is part of the uppermost fluvial sequence of the Ferron Notom Delta, as detailed in several other publications (Fielding 2010; Li et al. 2010; Zhu et al. 2012; Li and Bhattacharya 2013).

STUDY AREA AND METHODOLOGY

The study area lies north of the Fremont River and southeast of Factory Butte, and contains extensive plan-view exposures of an ancient channel belt (Fig. 1, 2, 3). Seven measured sections incorporating observations of lithology, bed thickness, sedimentary and biogenic structures, and paleocurrents were recorded from adjacent vertical cliffs (locations shown in Fig. 3). Miall’s 1996 classification scheme with minor modifications was used to describe the facies. Four photomosaics of the cliff exposures were used to construct bedding diagrams for analysis of facies architecture (Fig. 3). The bounding-surface scheme of Miall (1988) was used to define a hierarchy of cross-set boundaries, bar surfaces, and channel boundaries in bedding diagrams.

Google Earth and lidar images of the field area were integrated with field mapping to define sandstone and mudstone lithosomes in plan view. Sandstones 1, 2, 3, and 4 (Fig. 2) form distinct ridges that are more than 100 m long and can also be traced in the field. Sandstones 5, 6, 7, and 8 (Fig. 2) were identified and interpreted based on sedimentary structures and their locations relative to the larger sandstone belt. Grain size, sorting, preserved cross-set thickness, the width of rib-and-furrow structures (Fig. 4A), and paleocurrent directions were recorded and tied to GPS coordinates. Paleocurrent directions (n = 265) were measured primarily from rib-and-furrows of trough cross beds exposed in plan view (Potter and Pettijohn 1963). Grain size, sorting, cross-set thickness, and cross-set width were measured from 1700 points on top of the outcrop. Data points are mapped in the Eris software package using Arcmap®. The trends of each parameter were interpolated based on mapped data points using spatial-analysis tools in Arcmap®. The semiquantitative sorting terms (very poorly, poorly, moderate, well, and very well) were converted to numerical values (1 to 5 respectively) for interpolation. Lithofacies at the top of each sandstone were also mapped.

Channel style is interpreted using the methods of Willis (1993a) and Li et al. (2010). Paleo-hydraulic parameters of the channel belt were calculated using the empirical equations of Ethridge and Schumm (1977), Lorenz et al. (1985), Bridge and Mackey (1993), Bridge and Tye (2000), Leclair and Bridge (2001), Bhattacharya and Tye (2004), and Pranter et al. (2007). A semiquantitative model of channel-bend migration was reconstructed based on the paleocurrent measurements, calculated paleohydraulic parameters, and identification and interpretation of discrete sandstones and associated facies architectures in plan view. Channel-bend length and downstream distance during different stages of migration were measured in the model and then used to calculate the sinuosity of the migrating channel bend.

LITHOFACIES DESCRIPTION

Facies 1 Coarse- to Fine-Grained Large-Scale Foreset-Dominated Sandstone (Sf)

Description.—Facies 1 (Sf) comprises large-scale steeply dipping foresets, greater than 3 m in height (Fig. 4B, C, Table 1), characterized by alternating very fine- and coarse-grained sandstone beds approximately 0.5 cm thick (Fig. 4D). Beds show both inverse and normal grading, and contacts are either obscure or sharp (Fig. 4D). In dip view (Fig. 4B), most foresets have concave-upward or straight inclined profiles, with some showing listric or sigmoidal profiles. The facies Sf also show a single set that extends more than 10 m laterally with set thickness over 0.5 m. Foresets are straight inclined at angle of repose in plan view. In strike view (Fig. 4C), set boundaries can be distinguished by an abrupt increase in grain size and the presence of granules at the base of the set. The upper part of facies Sf usually pass gradually into small-scale cross beds (facies St) (Fig. 4C). The foresets of facies Sf change upward into sets of cross beds (Fig. 4B, C). Individual foresets of facies Sf extend from several decimeters to meters in width.

Interpretation.—The large foresets are formed by avalanching of bedload sediments down the leesides of unit bars. Each individual foreset is interpreted to have formed by tongue-shaped avalanching sediments, which have limited lateral extent so that the foresets are not continuous in
strike section. The mechanism that formed these large-scale inclined strata is interpreted to be the migration or collapse of unit bars. Similar structures have been described by Sambrook Smith et al. (2006) and Parker et al. (2013) in modern fluvial systems and interpreted by Boersma et al. (1968) and Hartkamp-Bakker and Donselaar (1993) in ancient deposits. The original external bar forms were not preserved due to erosion (e.g., Parker et al. 2013). The presence of Sf facies is considered indicative of a unit bar. The transition from facies Sf to St suggests waning flow conditions.

Facies 2 Medium- to Fine-Grained Trough Cross-Bedded Sandstone (St)

Description.—Facies 2 (St) is dominantly medium-grained trough-cross-bedded sandstone. Cross-sets range in thickness from 3 cm to 20 cm (Fig. 4E), an order of magnitude thinner than Facies 1 (Sf). Small-scale and medium-scale trough cross-sets can be distinguished from each other. The former have set thicknesses ranging from 4 cm to 9 cm whereas set thickness of the latter ranges from 14 cm to 20 cm. Coarse gravel-size mudstone intraclasts, petrified wood logs, and pebbles are present at the base of the facies (Fig. 4F). At some locations, facies 2 (St) overlies facies 1 (Sf) with either a gradual change in structures and grain size or a sharp contact.

Interpretation.—Trough cross bedding was formed by migration of sinuous-crested dunes (Ashley 1990) by unidirectional flow. The presence of mudstone intraclasts, petrified wood logs, and pebbles indicate the thalweg of a channel.

Facies 3 Medium- to Fine-Grained, Planar Tabular Cross-Bedded Sandstone (Sp)

Description.—Facies 3 (Sp) comprises fine- to medium-grained, tabular sets of cross-bedded sandstone, forming compound cross-bedded units typically less than 3 meters thick (Fig. 5A, B). Individual cross-set thickness ranges from 3 cm to 9 cm. Each coset contains 3 to 12 cross sets in an overall fining-upward trend. The set boundaries dip upstream at
about 10'. Mudstone and carbonaceous clasts can be found in the lower part of the facies. Facies Sp is capped by facies Sr/Sl and overlies facies Fm.

**Interpretation.**—The planar cross-bedded sandstones are interpreted to have formed by migration of straight-crested 2D dunes (Ashley 1990). The overall thickness of facies Sp suggests a shallower flow depth compared to the thicker facies Sf (Miall 1996). Upstream-dipping set boundaries are interpreted to reflect either upstream accretion or deposition of mid-channel bars.

**Facies 4 Ripple Cross-Laminated or Upper-Flow-Regime Plane-Bed Sandstone (Sr/Sl)**

**Description.**—Facies 4 consists of very fine-grained sandstone with ripple cross lamination (Sr) (Fig. 5C) or upper-flow-regime plane bed (Sl) (Fig. 5D, F). This facies is found mainly in the form of co-sets of alternating rippled to planar sets within an overall muddy succession. This succession is truncated by adjacent sandy facies Sf, St, and Sp showing erosional contacts. Upper-flow-regime plane beds are usually found above facies Sr. Set and coset thickness are about 3 cm and 10 cm respectively. Facies 4 is laterally continuous and can be traced for about 50 m in individual exposures. Facies Sr is also found on top of facies Sp or St with a gradual contact. Areas where the top of facies 4 is exposed show a cemented dark-reddish-colored ironstone with *Beaconites* trace fossils (Fig. 5E). This red coloration is especially evident at the southern margin of the studied outcrop. The ironstone present on top of facies 4 is largely overlain by mudstone that is 1 to 2 meters in thickness.

**Interpretation.**—Facies Sr was formed by migration of ripples (Ashley 1990), and facies Sl was formed by low-amplitude bed waves (Best and Bridge 1992; Bridge and Best 1997). Facies Sr and Sl may represent upper parts of channel fills, because of the fine grain size and the location at the top of the sandy facies. They are also interpreted as overbank deposits when multiple depositional cycles are present within overall muddy successions, which are truncated by sandy facies (Miall 1996). The trace fossil *Beaconites* suggests fresh-water deposition without marine influence.

**Facies 5 Massive and Parallel-Laminated Mudstone (Fm)**

**Description.**—Facies 5 is characterized by massive mudstone with interbedded layers of siltstone or parallel-laminated mudstone with variable silt content (Fig. 5F). Abundant fossilized plant fragments (e.g., stems and leaves) and rare amber are found in this facies. The more extensive occurrences of the facies are usually 1 to 3 meters thick and are either erosional overlain by sandstone (Sf, St, and Sp) or overlie sandstone (Sr/Sl and St) with a sharp contact. The mudstone in the latter case shows an elongate channel shape in plan view (marked A in Fig. 2). Smaller occurrences are usually 0.2 to 1 meters thick and alternate with cosets of facies Sr/Sl, forming an overall muddy succession 1 to 6 meters in thickness. The contacts between facies Fm and Sr/Sl in the muddy successions are abrupt.

**Interpretation.**—The thick occurrences of facies Fm, where they are found below the sandy facies, are interpreted as floodplain lake fill, due to the presence of plant fossils and the massive to laminated nature of the...
Lithology
Coarse- to fine-grained sandstone.
Sedimentary structure
3-m-high large-scale foresets with dip direction perpendicular to paleocurrent direction.

Internal features
Alternating very fine- and coarse-grained sandstone foresets approximately 0.5 cm thick. Some beds show inverse or normal grading. Granules present at set boundaries.

Contacts
Erosional lower boundary with facies Fm and gradational upper boundary with facies St.

Geometry
Arcuate or lobate-shaped in plan view.

Macroforms
Lateral accretion.

Environmental interpretation
Compound point bar or unit bar.

Lithology
Medium- to fine-grained sandstone.
Sedimentary structure
Small- to medium-scale tough cross beds, with set thickness of 3–9 cm and 14-20 cm, respectively.

Internal features
Coarse gravel-size mudstone intraclasts, petrified wood logs, and pebbles at the base of the facies.

Contacts
Erosional lower boundary with facies Fm or gradual lower boundary with facies Sf.

Geometry
Arcuate or sheet-like in plan view.

Macroforms
Channel-fill or bedform deposits.

Environmental interpretation
Channel-fill or mid-channel bar.

Facies
St
Sp
Sr/Sl
Fm

Description.—Cross section A is oriented east–west and includes exposures of the southern margin of sandstones 2 and 3 (Figs. 3, 6). Cross section A contains lithofacies Sf and St with Sr/Sl and Fm at the upper west margin of the cross section. Five orders of bounding surface were observed. The first-order surface bounds sets of Sf and St. The second-order surfaces separate cosets in facies Sf and St. The boundary between sandstones 2 and 3 is recognized as a third-order surface. This surface is marked by an abrupt increase in grain size with granule- and pebble-size mud clasts above it. The fourth-order surface is the upper surface of sandstone 3. The base of the channel is a fifth-order surface. From bottom to top, the sedimentary structures change from large-scale foresets to small- to medium-scale cross bedding (Fig. 4B). The upper part of the Sf facies shows a general fining-upward trend, whereas the lower part shows a coarsening-upward trend with interbedded sandstone or siltstone of facies Sr/Sl and mud drapes at the base (lower part of sections 6 and 7 in Fig. 6). The facies Sf has a sharp erosional contact with the underlying Fm facies and Sr/Sl facies to the east of the cross section. This Fm and Sr/Sl facies thin to the ESE (to the right of the section). The overall thicknesses of sandstones 2 and 3 are about 5 m to 6 m. Paleocurrents measured from rib-and-furrow structures of facies St at the upper part of the cross section point dominantly to the NNE 30°, indicating that paleoflow was into the section. The dip directions of the large-scale foresets are nearly towards the ESE 120°.

Interpretation.—The paleocurrent data from the dip direction of facies Sf are nearly perpendicular to each other, and the sandstones are thus interpreted to be laterally accreting macroforms (Miall 1996). Large-scale foresets are usually formed near the thalweg of a river (Lunt and Bridge 2004; Parker et al. 2013). The succession of facies Fm and Sr/Sl facies to the right of the cross section is interpreted as overbank deposits (Galloway and Hobday 1996). Thus, the sharp contact between facies Sf and the overbank facies is interpreted to be the cut bank of the paleo-river. The crosscutting relations between first-order and second-order bounding surfaces in facies Sf indicate that unit bars were amalgamated at the time of the formation of sandstones 2 and 3. Therefore, sandstones 2 and 3 are interpreted as compound bar deposits (Bridge 2006; Bridge and Lunt 2006; Parker et al. 2013) formed at the inner bank of
the paleo-channel. These compound bars are also point bars in terms of the macroform-scale feature of lateral accretion and their position in the channel belt (Allen 1965; Galloway and Hobday 1996; Ghinassi et al. 2014). The unusual mud and fine-grained deposits at the bottom of the facies Sf may reflect frequent fluctuation of flow level, which allowed mud deposition during low flow level. Alternatively, these could represent the toes, or the basal expression of a counter point bar (Smith et al. 2009).

**Cross Section B**

**Description.**—Cross section B changes from a predominantly north–south to an east–west orientation (Fig. 3). Sandstone 2 extends below sandstone 3 to the SE (Figs. 2, 3) so that the section contains exposures of both sandstones 2 and 3 (Fig. 7). The section contains lithofacies Sf and St. First-order bounding surfaces in facies Sf are generally horizontal to slightly undulating. A U-shaped surface at the middle part of the section, in facies Sf, forms a second-order bounding surface, which crosscuts the underlying sandstone beds. The third-order bounding surface (Miall 1988), which separates sandstones 2 and 3, can be distinguished by the facies change from Sf to St (Fig. 4E) and an abrupt grain-size decrease from medium- to fine-grained sandstone. The fourth-order surface marks the top of sandstone 3. The base of sandstone 2, or the fifth-order surface, is not exposed in this section. From bottom to top in section B, the sedimentary structures change from large-scale foresets (Sf) to small- and medium-scale cross bedding (St). Paleocurrent directions are generally to the NNE 30°. Most beds of the large-scale foresets are nearly parallel to the set boundaries and the paleocurrent directions.

**Interpretation.**—Cross section B shows a strike view of the laterally accreting compound bars described in cross section A–A′. The U-shaped surface in the Sf facies is interpreted as a scour and fill.

**Cross Section C**

**Description.**—Cross section C (Fig. 8) is predominantly SSW–NNE oriented and includes sandstone 6 and mudstone A at the southern margin of the outcrop belt. Sandstone 6 thickens from 1 to 3 meters and merges with sandstone 2 to the northeast (Fig. 3). First- and second-order bounding surfaces in facies Sp dip at an angle of about 10° to the SSW. The third-order surface is not present in this section. The fourth-order surface bounds sandstone 6 and mudstone A. The fifth-order bounding surface marks the erosional base of the sandstone facies (Sp and St). From SSW to NNE, the sedimentary structures change from medium-scale St to Sp and back again. Sandstone 6 has an erosional contact with the underlying Fm facies. Mudstone and carbonaceous clasts are present at the base of sandstone 6. A thin layer of facies Sr is present on top of the Sp facies. The sandy facies are also overlain by Fm facies except at the two ends of the section where facies St dominates. Paleocurrent measurements show flow was generally NNE and roughly parallel to the orientation of the bedding diagram.
Interpretation.—The lower Fm facies is interpreted to be floodplain lake deposits due to the presence of fossilized plant fragments and amber, whereas the upper Fm facies is interpreted to be a mud plug based on its elongate shape in plan view, which formed after channel abandonment. Sandstone 6 is interpreted to be a channel fill because of its elongated shape and the presence of a basal lag (mudstone and carbonaceous clasts). The upstream-dipping first- and second-order surfaces suggest that the channel fill is also an upstream-accretion macroform. The contrast in sandstone thickness between the channel fill and point bars shown in cross sections A and B suggests that the channel fill present in cross section C mark the crossover area of a channel bend (Bridge and Mackey 1993; Willis and Tang 2010; Ghinassi et al. 2014).

Cross Section D

Description.—Cross section D (Fig. 9) is oriented north–south and exposes the southwest margin of sandstone 5 (Fig. 2), which contains facies Sf and Sp. First- and second-order surfaces in facies Sp and Sf dip in opposite directions to the south and north, respectively. The third-order surface separates facies Sp and St. The fourth-order surface marks the top of sandstone 5. The base of the sandstone is not exposed in this section. From south to north, the facies change from Sp to Sf. Paleocurrent direction is around NE 45°.

Interpretation.—This section exposes an upstream portion of the mid-channel bar shown in cross section C. The paleocurrent direction and the dip of the Sp cross bedding indicate upstream accretion, and suggests a diffuence zone at the back of a mid-channel bar. This mid-channel bar is interpreted to be a compound bar, since it was formed by amalgamated unit bars and dunes, which yield the Sf and St facies respectively. The original unit bar forms were not preserved due to erosion, but are indicated by the large-scale foresets. The unit bars showed both downstream and lateral accretion.

Composite Cross Section

Description.—A composite cross section, shown in Figure 10, integrated six measured sections logged along the southern margin of the outcrop (Figs. 3, 10). Facies Sp, St, and Sf dominate the southwestern, middle, and northeastern parts of the section respectively with gradational transitions between each. The relief of the erosional contact between the different sandstone facies and underlying mudstone facies increases towards the northeast. At measured section 3, a 20-centimeter-thick very fine-grained unit with interbedded silt layers and mud drapes (Fig. 5F, facies Sr/Sl in section 3 of Fig. 10) marks the contact separating facies St of sandstones 2 and 3. This contact, which is the third-order surface identified in cross sections A and B, dips to the northeast. The paleocurrent directions show a systematic change from ENE to NNE along the section.

Interpretation.—Paleocurrent measurements and orientation of the section indicates that the section is mostly parallel to paleoflow (Willis 1993b; Ghinassi et al. 2014). Thus, the facies changes, sediment thickness increase, and deepening of the erosional base of sandstone facies are the results of localized hydraulic conditions along the channel (Willis and Tang 2010). The overall geometry of the sandy facies and the presence of lateral accretion in sandstones 2 and 3 also indicate that the sandy facies were deposited through the migration of a single-thread channel (Galloway and Hobday 1996; Willis 1993b). Therefore, the thinner southwest part of the channel deposits are interpreted as the crossover area of a channel bend, whereas the thalweg cut deeper toward the downstream bend apex and formed a thicker deposit at the northeastern part of the section (Bridge and Mackey 1993; Willis and Tang 2010).
PLAN-VIEW FACIES DISTRIBUTION

Description.—Facies St has the most extensive plan-view distribution (Fig. 11), consisting about 90% of the exposed outcrop. The southern margin of the outcrop shows facies Sf, St, Sl, and Fm. The southwesternmost part of the outcrop is the lobate-shaped sandstone 5 of facies St and Sf with both upstream-accretion and lateral-accretion bedding styles (Fig. 9). Sandstone 5 is capped by facies Fm (mudstone A in Fig. 2) to the northeast. The mudstone has an elongate shape, is about 50 m in width, and is more than 100 m in preserved length. To the northeast of facies Fm, lobate-shaped sandstone 7 can be distinguished (Figs. 11, 12A, B, C, D). This particular sandstone is composed of a single set of large-scale foresets (Facies Sf) with beds dipping at the angle of repose. The southeastern part of sandstone 7 is covered by facies St (Fig. 12B). The sets of facies St change downward into foresets of facies Sf. A similar transition is also present in Figure 4C or cross section A. Therefore, the foresets of facies Sf and facies St dip at NE 45° and SE 135° respectively, which are perpendicular to each other. Sandstone 8 is a very fine-grained sandstone sheet underlying sandstone 7. It is around 30 meters long and 10 to 20 meters wide, and is composed of facies Sr/Sl

Fig. 8.—Photo mosaic (upper), bedding diagram (middle), and facies architecture (lower) of cross section C. The bedding diagram and facies architecture diagram are vertically exaggerated.

Fig. 9.—Photo mosaic (upper), bedding diagram (middle), and facies architecture (lower) of cross section D.
The cut bank identified in cross section A marks the margin of the sandstones of the channel belt (Fig. 12E).

From south to north, over the entire outcrop, the paleocurrent distribution shows a systematic change from ENE to NNW (Fig. 13). The paleocurrent directions are consistent in each of the mapped sandstones and across the entire outcrop.

The width and preserved thickness of cross sets show very distinct patterns (Fig. 14A, B). The thickest cross sets are distributed mainly in sandstone 3 and the southern part of sandstone 4 near the margin of the outcrop belt. The widest preserved cross-set furrow widths are around the middle of sandstones 1 to 4, and the distribution of width shows an abrupt decrease near the east and southeast of the channel belt. Grain size and sorting (Fig. 14C, D) show similar patterns: grain size fines to the north and west with a decrease in the degree of sorting. Therefore, coarse grains were deposited mostly along the eastern margin of the outcrop belt, which also shows the lowest degree of sorting. A map of grain-size distribution shows a north–south-oriented, anomalously coarse-grained area between sandstones 3 and 4. This same area is also characterized by poor sorting and relatively narrow cross-bed furrow width.

**Interpretation.**—The dominance of facies St indicates that dunes were the main type of bedform at the top of the channel belt, especially in sandstones 1 to 4. However, these high percentages of facies St are not replicated in the sections (Fig. 6, 7). This suggests that facies Sf was formed in greater flow depths (Bridge et al. 1986; Bridge et al. 1995; Bridge et al. 1998). After the deposition of the large-scale foresets (Sf), the channel floor was elevated, which decreased the flow depth and formed dunes. The deposition of trough cross-bedded sandstone may also be associated with waning flow conditions (Parker et al. 2013).

The elongate shape of mudstone A suggests that it was formed as a mud plug after abandonment of a channel. Sandstone 5 is interpreted to be a mid-channel bar that may have actively plugged the channel by both upstream and lateral accretion (Fig. 9). Sandstone 7 is interpreted as a well-preserved unit bar. The lee side of the unit bar avalanched into the channel, forming steeply inclined strata (Bridge 2006; Ashworth et al. 2011).

The variations of thickness and furrow width of facies St reflect localized paleohydrologic conditions. Since dune height is proportional to flow depth (Leclair and Bridge 2001; Leclair 2002), the thickest cross-sets were formed where flow reached maximum depth. This also suggests that the thalweg of the channel was at the southern and eastern margin of the outcrop belt with flow depth progressively decreasing westward. This interpretation is consistent with the grain-size distribution, since grain-size distribution is strongly associated with flow depth and relative position in a channel bend (Willis 1989; Willis and Tang 2010). The interpretation of channel location can also be confirmed by the location of the cut bank in cross section A (Fig. 12E). The coarse-grained area between sandstones 3 and 4 may mark a cross-bar channel.

**PALEOHYDROLOGY**

**Overview of Empirical Equations**

Empirical equations for calculating paleohydrological parameters, such as channel width and channel depth, can be used to estimate channel dimensions, when limited data are available (Lorenz et al. 1985; Bridge and Mackey 1993; Bridge and Tye 2000; Bhattacharya and Tye 2004). Early studies developed empirical relations to calculate channel-belt width or channel width from sandstone thickness (Ethridge and Schumm...
Although these approaches can provide a rough estimation of width, there are several problems that may render inaccurate estimations (Bridge and Mackey 1993). Channel sinuosity, geometry, discharge, and sediment supply are not taken into account, and preserved sandstone thicknesses in any given location may not represent the maximum thickness at the channel-bend apex. Statistical approaches that use regression analysis to relate channel depth to channel belt width (Fielding and Crane 1987; Bridge and Mackey 1993) were used to overcome these problems and incorporate modern and ancient data from the published literature to provide more reliable estimates, with errors that are statistically acceptable (Bridge and Mackey 1993).

**Dimension of the Channel**

Two methods were used in this study to calculate and compare paleohydraulic parameters. Method 1 determined the paleohydraulic parameters based on 360 measurements of cross-set thickness, and method 2 calculated the parameters from average sandstone thickness (Tables 2, 3). In method 1 the measurements of cross-set thickness were collected over point bars 2, 3, and 4 at randomly selected points.

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**Fig. 11.**—Plan-view facies distribution. Sandstones are marked by black dashed lines and labeled 1 to 8. The white dashed line at the lower right corner of the figure marks the exhumed sandstone, which underlies the studied channel belt. The studied channel belt is truncating the lower sandstone belt.

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**Fig. 12.**—A) Sandstone 7 is lobate-shaped in plan view (marked by dashed line) with a single set of beds dipping toward SE. Location of Part B is marked by a black dot southeast of sandstone 7. B) Facies St on top of the east part of sandstones 7. The dip directions of cross-bed foresets and bed sets are perpendicular, which suggests a lateral-accretion macroform. C) Facies Sf in sandstone 7 are dipping at the angle of repose. D) Cross-sectional view of sandstones 7 and 8. E) Cut bank of the channel bend.
Sandstone 1 was not measured for cross-bed thickness because the relief of cliff exposures was insufficient. Mean flow depth, $d$, is calculated based on equations from Bridge and Tye (2000), Leclair and Bridge (2001), and Leclair (2002):

$$d = h_{m} - 6.10 \times 10^{-1} \beta$$

$$h_{m} = 5.3 \beta + 0.001 \beta^{2}$$

$$\beta \approx s_{m}/1.8$$

where $d$ is the mean flow depth, $h_{m}$ is the mean dune height, $\beta$ is the mean value of the exponential tail of the probability density function for topographic height relative to a datum, and $s_{m}$ is the mean cross-set thickness.

Equation 1 is used to provide a relatively narrow range of channel-depth prediction, and it applies to all types of river dunes (Bridge and Tye 2000). Cross-set thickness is calculated from Equation 2, which is the regression equation based on compiled published data, and it is the regression expression of all the data included (Leclair and Bridge 2001).

Channel width and channel-belt width are calculated from Bridge and Mackey (1993):

![Fig. 13.—Plan-view paleocurrent distribution.](image)

![Fig. 14.—Predicted features over the channel belt based on interpolation. Ridges of sandstones 1 to 4 and locations of sandstone 5 to 8 and mudstone A are marked by dashed lines. A) Distribution pattern of the rib width. B) Distribution pattern of the preserved cross-bed thickness. C) Distribution pattern of sorting. D) Distribution pattern of grain size.](image)
Paleohydraulic parameters estimated from Method 1.

\[
W_c = 8.88 d_m^{1.52}
\]

\[
cbw = 59.9 d_m^{0.585}
\]

where \( W_c \) is the channel width, \( cbw \) is the channel belt width, and \( d_m \) is the mean channel depth.

The results show large variations in both parameters (Table 2). Method 2 used the thickness of a sandstone, typically a macroform (e.g., a lateral-accretion unit), as the channel maximum depth. Mean channel depth and channel width were calculated using

\[
D = 0.585 D^* / 0.9\]

\[
W = 1.5 W^* \]

where \( D \) is mean channel depth, \( D^* \) is maximum channel depth, \( W \) is channel width, and \( W^* \) is the width of the inclined surface of a point bar.

The sandstone thickness is assumed to be equal to \( D^* \). The coefficient 0.585 in Equation 6 was determined by experiment (Schumm and Khan 1977). However, in the field, the width of a point bar at its bend apex is generally unavailable because exposures are usually oblique to the channel axis. Method 2 resulted in a narrow range of the mean channel depth. A short-lived cross-bar channel lay between point bar 3 and 4 during this stage. The sinuosity of the bend reached its maximum of 1.44 in stage 4. At this point, the channel was obstructed by mid-channel and unit bars and was abandoned (Fig. 15E–F). The blockage of the channel by the mid-channel bar was possibly also responsible for initiating a chute channel at the upstream bend, which delivered sediments to the entrance of the bend. Similar cases of channel abandonment associated with bar formation in channels have been documented both in modern fluvial studies (Bridge and Lunt 2006; Bridge et al. 1986; Ashworth et al. 2011; Sambrook Smith et al. 2006) and flume studies (Peakall et al. 2007). During the four stages of migration, a point-bar complex was formed at the inner bank of the channel bend with component alternate bar, compound bars, and unit bars.

**DISCUSSION**

**Facies Architecture of the Channel Belt**

The point-bar facies architecture described in this study differs from the classical models for point bars formed by meandering rivers (Allen 1963; McGowen and Garner 1970; Galloway and Hobday 1996) in several respects: 1) there is a low abundance of heterolithic strata, 2) facies show relatively limited vertical variations, and 3) there is a low proportion of facies Sr/Sl, which either lie near the base of channel deposits or are associated with floodplain and levee deposits. The channel-belt facies architecture in this study shows some similarities with braided-river deposits (Bridge and Lunt 2006; Sambrook Smith et al. 2006; Parker et al. 2013) and low-sinuosity rivers (Bridge et al. 1986; Bridge et al. 1995; Bridge et al. 1998); such as 1) abundance of large-scale inclined strata, 2) abundant sandy unit bars, and 3) complex channel-abandonment fills with both active (sand bars) and passive (mud) fill.

The plan-view grain-size distribution follows the point-bar models of Willis (1989) and Willis and Tang (2010). The calculated flow depth using techniques from Leclair and Bridge (2001) and Leclair (2002) is considered accurate because it is consistent with the grain-size pattern, which is related to flow depth (Willis and Tang 2010). Therefore, the result of this study shows that the preserved cross-set thickness is sensitive to the change of flow depth, which supports the use of cross-set thickness for estimating the flow depth of ancient rivers (Leclair and Bridge 2000; Leclair 2002). The cross-bed furrow width, on the other hand, does not seem to be directly related to flow depth, although the furrow width decreased abruptly near the thalweg. One possible explanation for this is...
that the flow structure changed dramatically near the thalweg in response to the inner-bank morphology. In general, the patterns in the plan-view maps showed that the fundamental properties of the deposits are very good indicators of ancient hydraulic conditions.

**Migration of the Channel Bend**

Since the channel bend in this study shares similarities with both braided and meandering rivers in terms of facies architecture and migration pattern respectively, it is important to answer the question: what does the migration pattern imply, what is the river type, and what parts of the fluvial deposits were ultimately preserved in the rock record? Hickin (1974) suggested that the critical value of the ratio of the radius of channel curvature to channel width ($r_m/w$) controls the channel migration pattern. The numerical model of Duan and Julien (2010) suggests that the channel migration pattern of lateral accretion followed by downstream translation is the result of changing fluid momentum along the channel. Flume tests generated channels with a similar migration pattern (Peakall et al. 2007; Van De Lageweg et al. 2013; and Van Dijk et al. 2012).

Moreover, flume tests (Schumm 1977; Jin and Schumm 1987; Peakall et al. 2007) also examined slope and bank erosion as a control on formation of meandering rivers. Schumm and Khan (1972) concluded that slope is critical in developing different plan-view river forms, whereas Jin and Schumm (1987), Peakall et al. (2007), Tal and Paola (2010), and Van Dijk et al. (2012) addressed the importance of cohesive materials, such as clay, in both floodplain and suspended flows in formation of high-sinuosity channels. The necessity of cohesive materials in channel migration is also supported in this study as the whole channel belt overlies muddy lake deposits or overbank and levee deposits. It can be inferred from Figures 6 and 11 that the muddy facies diminish east of the channel belt and the thalweg of the channel eroded into underlying sandy facies. The decrease of fine-grained cohesive materials may make the outer bank too unstable and erodible to maintain a meandering plan form. Although the field-wide distribution of cotemporaneous fine-grained facies cannot be assessed, the transition from the underlying lake and overbank deposits to the sandy facies of the underlying channel belt (Figs. 6, 11) marked a significant change of the boundary lithology for channel-bend migration, which is a key variable in determining channel style (Van Dijk

**Fig. 15.—** Semiquantitative model for the channel-bend migration. A to D represent the four stages of point-bar formation, and E and F represent the stage of channel abandonment.
et al. 2012). However, the trigger of the transition from expansion to translation still needs further investigation.

Although the migration pattern of the channel bend in this study suggests a single-thread channel, the overall fluvial style of the whole system cannot be determined solely based on an outcrop that is formed by a single bend of a channel. Nonetheless, it is still helpful to infer possible overall fluvial style, which can be tested by examining channel patterns over the larger area of the exposure, which will be the focus of our future studies. The most prominent facies Sf in this study are mostly found in modern low-sinuosity and braided systems. The Calamus river (Nebraska) is an analog of a low-sinuosity river (Bridge et al. 1986; Bridge et al. 1995; Bridge et al. 1998). The Calamus River bar deposits show large-scale inclined strata at the lower part of the active channel belt with overlying small- to medium-scale cross bedding (Bridge et al. 1986; Bridge et al. 1995; Bridge et al. 1998) that are similar to those found in this study. Large-scale inclined strata are also present in braided systems, such as the South Saskatchewan River (Sambrook Smith et al. 2006; Parker et al. 2013). The large-scale inclined strata likely formed by sandy unit bars and may be indicative of low-sinuosity or braided systems.

The slope magnitudes of the Notom Delta are on the order of 0.001 (0.06°) (Bhattacharya et al. in review). These are two orders of magnitude higher than the Mississippi (0.00005, 0.002°). Meandering is favored by low slopes and low to moderate discharge. Braiding is favored by high slopes and high discharge. The Ferron is a high-slope but relatively low-discharge system, but rivers were likely dirty (i.e., they had high sediment discharge). Li et al. (2011) applied similar techniques to study the paleohydrology of incised-valley systems in the Ferron Sandstone, which lie directly below the channel belts in this study (Table 3). Comparing the sandstone thickness, average channel depths, and average channel widths of this study to those from the regional data, the local channel dimension of the studied channel belt is about half of the average river dimension in the underlying trunk valley. Considering this scale contrast, the local channel is interpreted to be a distributary channel of the Notom Delta system. The channels under investigation are unlikely to have been tributary channels, because tributary channels are usually incised and should lie within an incised valley or at the valley margin. Tidal influence is minimal, since no marine trace fossils or typical inclined heterolithic strata were found (Musial et al. 2012; Hubbard et al. 2011). We therefore interpret these channels as alluvial-plain or upper-delta-plain distributary channels.

**IMPLICATIONS**

This large-scale cross-bedded sandstone (facies Sf) is thought to be indicative of unit bars. Unit bars are now recognized to be ubiquitous features in modern fluvial systems, and ancient counterparts should be very common in outcrop and subsurface data, but have been under-recognized. We suggest that large-scale cross sets (facies Sf) may be a good criterion for identifying ancient unit bars. Ullah at al. (2013) have also identified large-scale foresets within confluence scour in braided systems in incised valleys in the Ferron sandstone. Although the empirical equations resulted in a large range of estimation of paleo-hydrological parameters, the calculated ranges have the same magnitude as those measured in the field. We therefore suggest that the empirical equations are useful in paleohydraulic estimations of ancient river systems.

**CONCLUSIONS**

The combination of plan-view and cliff exposures of ancient fluvial deposits in the Ferron Sandstone provides an outcrop example to assess how well vertical sections can be used to infer plan-view patterns, as well as using paleocurrents and grain-size distributions to estimate plan-form distribution of paleoflow fields and grain-size variability, which can be useful for modeling heterogeneity in analog reservoirs. The point bars analyzed in this study share similarities with point bars formed by both meandering and braided modern rivers in terms of sedimentary structures, facies architecture, and mechanics of formation. The key conclusions are:

- Point bars in this study were formed mainly by amalgamated unit bars and dunes during expansion and translation of a single-thread low-sinuosity channel. The newly introduced lithofacies Sf comprises large-scale, steeply inclined sandy strata and is interpreted to be indicative of unit-bar deposits, which are commonly in modern low-sinuosity and braided rivers.
- Channel abandonment was likely initiated with the formation of unit bars and mid-channel bars that blocked the upstream part of the channel bend.
- The paleohydraulic parameters calculated from empirical equations match the plan-view measurements, such as channel width; but the range of estimates calculated from these equations are wide, especially for channel width and channel-belt width.
- Gain size and grain sorting are controlled by flow depth, with the coarsest and most poorly sorted grains deposited near the thalweg. Preserved cross-set thickness is also sensitive to flow depth and can be used to estimate paleo-channel depth. Cross-bed furrow width is evenly distributed except near the thalweg, where it shows an abrupt decrease.

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