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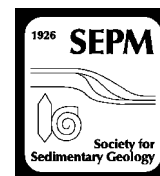
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UPSLOPE-MIGRATING BEDFORMS IN A PROGLACIAL SANDUR DELTA: CYCLIC STEPS FROM RIVER-DERIVED UNDERFLOWS?

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ABSTRACT: Backstepping cross-strata on steep foresets of a Gilbert-type proglacial fluviodeltaic system are ascribed to cyclic steps and other associated supercritical bedforms. They provide insight into how sandur river flows transition into the marine realm. These sedimentary structures are located on steep foresets (up to 17°) with corresponding top-lying, flat-based topsets in an upper Pleistocene delta on the North Shore of the Gulf of St. Lawrence, Québec, Canada. Packages of backstepping cross strata of sand and gravel, lying in the lower part of the delta front outcrop, are organized in 10–20 m spaced pseudo-foresets with a mean slope of 11–12° seawards. Backstepping strata include frequent internal erosion surfaces that onlap upslope on pseudo-foresets and are interpreted as cyclic steps. Narrow, deep, and asymmetrical scours and upslope-climbing cross beds are interpreted as chutes-and-pools and antidunes respectively. Very shallow (< 15 m) depositional paleo-bathymetry is inferred from the preservation of the delta brink. The well-organized stratal pattern in cyclic step to antidune deposits indicates relatively steady and uniform flow patterns. There is insufficient distance for a headscarp large enough to transform to the volume of observed accreted sands or for a flow transformation from a gravitational collapse to net-depositional cyclic steps. These deposits are sandier than the topsets beds and are thus not derived from them, but rather correspond to topset erosional surfaces. The development of cyclic steps from hyperpycnal flows was likely enhanced by tidal drawdown processes. The resulting sediment-laden supercritical flows plunged inertially and evolved into an underflow that generated the cyclic steps on the upper foresets. The cyclic steps have a high aspect ratio and represent an end member of coarse-grained sediment deposited on steep slopes, in contrast to low-gradient, low-aspect-ratio muddy deposits.

INTRODUCTION

Bedforms and resulting cross-strata originating from supercritical flow conditions have been identified from subaerial and subaqueous outwash systems (Russell and Arnott 2003; Duller et al. 2008; Lang and Winsemann 2013; Girard et al. 2015) to the deep sea (Cartigny et al. 2011; Talling 2014), including deltaic (Massari 1996; Hughes Clarke et al. 2012) and fluvial (Fielding 2006) systems. Recently, their significance and origin has been better understood owing to the higher resolution of geophysical imaging tools, *in situ* monitoring, and numerical or analogic models (Mulder and Alexander 2001; Sequeiros et al. 2009; Spinewine et al. 2009; Muto et al. 2012; Cartigny et al. 2014; Covault et al. 2014). Among structures related to supercritical flow conditions, those referred to as cyclic steps (Parker 1996) have received increasing attention during the last decade (e.g., Spinewine et al. 2009; Kostic et al. 2010; Cartigny et al. 2013; Postma et al. 2014). Large-scale (> hundreds of m) fine-grained (fine sand and silt) up-slope migrating sediment waves, interpreted or not as cyclic steps, are ubiquitous in deep-water channels and levees (Hughes Clarke et al. 1990; Migeon et al. 2000; Fildani et al. 2006; Lamb et al. 2008; Zhong et al. 2015). Smaller examples, described as crescentic bedforms, have been identified over delta slopes (Hill 2012; Hughes Clarke et al. 2012; Turmel et al. 2015) and in the axis of deep-water (Smith et al. 2005; Babonneau et al. 2013; Paull et al. 2013) and shallow-water (Hughes Clarke et al. 2012; 2014; Normandeu et al. 2014; 2015) submarine canyons. Coarse-grained

cyclic steps (sand and gravel) have been so far less well documented (Postma et al. 2014; Postma and Cartigny 2014; Ventra et al. 2015; Girard et al. 2015).

Although the identification of supercritical bedforms is crucial for the reconstruction of past depositional environments and in the understanding of formative flow dynamics, there is no full consensus on their genesis (e.g., Lee et al. 2007; Paull et al. 2010). The most commonly accepted view of their origin relate to turbidity currents associated with mass-wasting processes (Piper et al. 2002; Lamb et al. 2008; Talling 2014). In places where delta foresets accrete under tidally-influenced conditions, tide-supported gravity flows may occur (Wright and Friedrichs 2006; Ayranci et al. 2012). The potential link with river-derived hyperpycnal flows is less explored (Turmel et al. 2010; Ventra et al. 2015) but has been suggested to explain some particular occurrence of such features in fan-delta settings fed by bedload-dominated rivers (Prior and Bornhold 1989, 1990; Babonneau et al. 2013; Turmel et al. 2015). A better understanding of these structures requires the identification of the full spectrum of their occurrence in the variety of depositional settings.

Here, we illustrate a case study where supercritical flow conditions can be inferred from coarse-grained, undulating backstepping cross-strata associated with subordinate backsets. Such structures, which arguably resulted from upslope-migrating cyclic steps, characterize a fluvioglacial delta succession where there is no evidence for the occurrence of related mass-wasting processes. These structures typify channelized shallow (< 20 m) environments in the upper part of the deltaic foresets, immediately beneath the foreset–topset

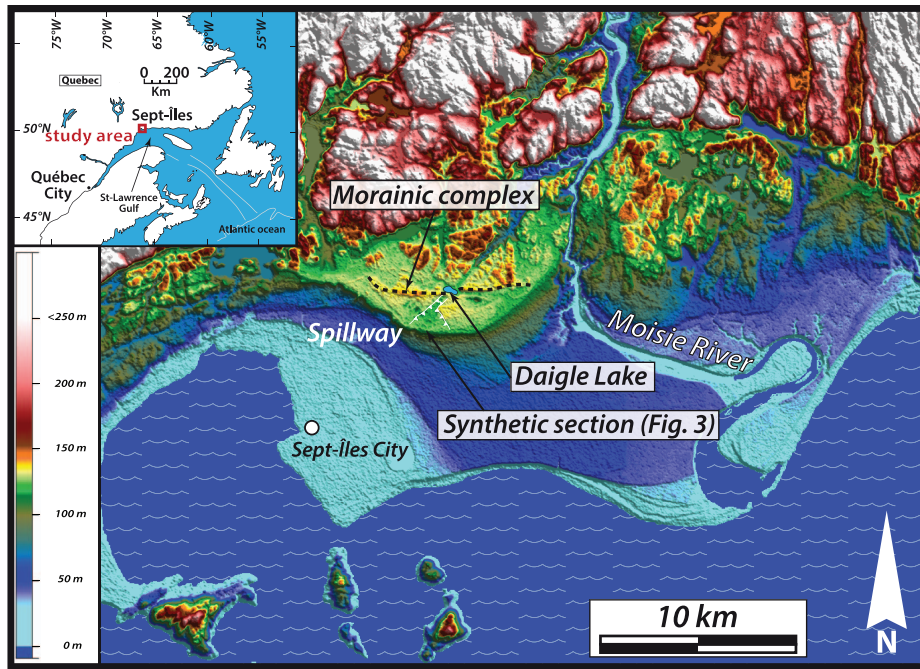


FIG. 1.—The Sept-Îles area on the North Shore of the Gulf of St. Lawrence, Quebec. Backstepping cross-strata were observed along foresets of a Gilbert delta exposed in a sand pit at the southern edge of a large, topographically well expressed subaqueous outwash fan. The red bar locates the synthetic profile of Figure 3.

contact. This contribution thus sheds new light on the potential link between cyclic-step-related bedforms and hyperpycnal underflows.

GEOLOGICAL SETTING

The study area is located on the north shore of the Gulf of St. Lawrence (Québec, Canada) 10 km north of the city of Sept-Îles (Fig. 1). We describe a suite of sedimentary structures and facies, among them the backstepping cross-strata ascribed as being cyclic steps, characterizing a Gilbert-type fluvio-glacial fan delta (Fig. 2). This delta constitutes the downstream reach of a triangle-shaped spillway exiting a morainic ridge emplaced 3 km upstream (The Daigle Lake Morainic Complex, Fig. 1).

Lying at 135 m above sea level (the marine limit of the literature, Dredge 1983), this Gilbert delta marks the first emergence of the sedimentary system following the retreat of the Laurentide Ice Sheet margin and the deglaciation of the area ca. 12 ka cal BP. The deglaciation was initially marked by a succession of stillstands, the morainic ridge being the last (Shaw et al. 2002; Occhietti et al. 2011; Lajeunesse and St-Onge 2013). The study area exclusively experienced a glacio-isostatically forced regression since the emergence of the system. Despite high rates of sea-level fall (several cm/yr, Shaw et al. 2002; Peltier et al. 2015), no RSL fluctuations can be evidenced from the stratigraphic architecture. It suggests that the development of the proglacial delta formed in a short timespan: tens to a few hundreds of years considering other comparable case studies on fjord-head or sandur deltas that typically have progradation rates in the 10–50 m.yr⁻¹ range (e.g., Syvitski and Farrow 1983; Lønne and Nemeč 2004; Gilbert and Crookshanks 2009).

Observations were carried out in a pit excavation located at the edge of the sandur plain (Fig. 1). Faces up to 25 m high, however with poor lateral continuity, were available either perpendicular or parallel to the foreset bedding. Figure 3 is a synoptic compilation of the observed architectural elements.

BACKSTEPPING CROSS-STRATA IN A DELTA-FRONT DEPOSITIONAL SETTING

The delta architecture shows three superimposed depositional units, from the base to the top (Figs. 2, 3): (i) upper delta foresets, bearing the backstepping cross-strata; (ii) distal sandur to mouth deposits constituting the topsets; (iii) beach barrier and storm-berm deposits. The stratigraphic emplacement of the

backstepping cross-strata is detailed below; their description occurs in a further section.

Description of Depositional Units

Two facies assemblages are observed in the upper delta foresets. They consist of either fine- to medium-grained sand, including silty intervals, or of coarse-grained pebbly sand. The former are gently sloped (10°) and regularly stratified; the latter, which include the backstepping packages, are more intriguingly organized. The two facies assemblages occur in turn repeatedly. In both cases, master beds dip to the SW.

Fine- to medium-grained sand shows gently dipping, well-stratified beds, 5–30 cm thick. Some of the foreset beds include a well-defined break in slope. Upslope, a concave-up profile is observed in places (Fig. 3). Sand beds occasionally show finer-grained bioturbated drapes (Fig. 4A). In-phase climbing ripples, cross lamination, and foreset-parallel planar laminae prevail. Millimeter-thick horizons concentrating heavy minerals are observed in places.

The coarse-grained facies assemblage shows a variety of architectures (Figs. 2, 3, 4B): steep (up to 27°) foresets including fining-upward sequences, channel structures and related backstepping cross-strata and V-shaped scours. Steep foresets are regularly organized with bed-parallel lamination. Suites of steep foresets are in some cases truncated and unconformably overlain by finer-grained and gentler-dipping foresets (Figs. 3, 4B). A view perpendicular to the foreset slope revealed that the coarse-grained assemblage including the backstepping cross-strata specifically constitute the infill of channelized structures (Fig. 3, left). The channel form was up to 10 m deep and less than 20 m wide, and characterized by steep (> 60°) margins. Finally, numerous V-shaped, steep-flanked (45°) and meter-scale scours also occur in the coarse-grained pebbly sand (Figs. 2, 4B). Their infill is massive to faintly stratified. The V-shaped scours include upslope-dipping (up to 17°) backsets that fine upward from clast-supported pebbles and cobbles to sand. Backsets occasionally show a cyclic organization marked by repeated change in grain size (Fig. 4B).

The topset beds, ~6 m thick, constitute an erosion-based fining-upward unit. Topset beds wedge out southward beneath the erosion-based third unit (Figs. 2, 3). The overall bedding is essentially horizontal. The lower bounding surface shows in places superimposed channelized structures, up to 2.5 m deep and in excess of 15 m wide, cutting into foreset deposits. However, a basal transitional

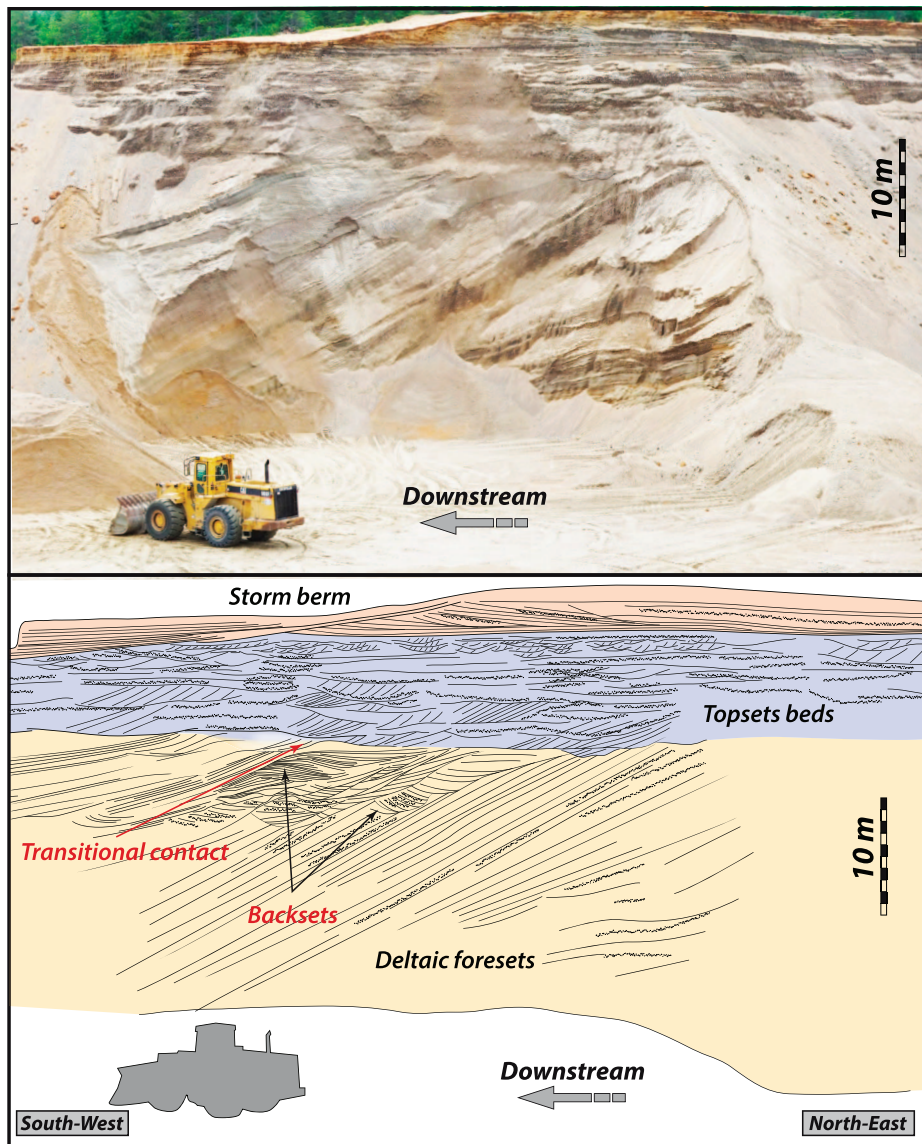


FIG. 2.—Depositional units in Gilbert-type delta. Note that delta foresets display both steep-sloped beds with backsets and fine-grained, gentler-sloped beds (to the left). Foresets are overlain by topsets, with either a transitional (red arrow) or sharp contact. The flat-based upper unit (storm berm) shows landward-dipping (toward the right) master beds.

contact is in places evidenced laterally (Fig. 2). Planar, trough, and sigmoidal cross-stratified pebbly sand prevails. Clast-supported, frequently imbricated, well-rounded gravels include subordinate ball-shaped clasts. Uniform paleocurrents toward the SW are evidenced by laminae dips and pebble imbrication.

The third unit is located on the outer edge of the topsets. It forms a subdued flat-topped ridge, reaching up to 2.5 m high. Its cross section is asymmetrical. Seaward, a sloped (5°), concave-up erosional surface is observed (Figs. 2, 3). Landward, a more extensive, gently dipping (ca. 1°), planar surface develops over a distance of 150 m. Internally, sloped master beds (ca. 4°) evidencing a

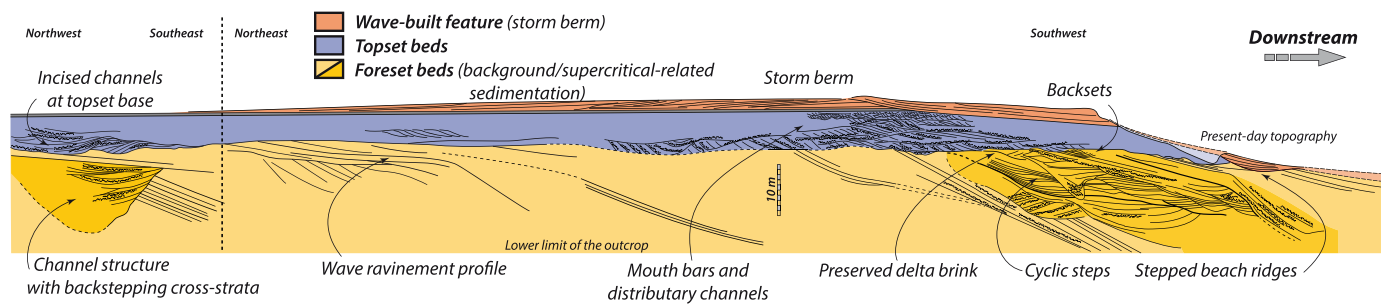


FIG. 3.—Synoptic profile of the Sept-Îles Gilbert-type, proglacial, deltaic system. Backstepping cross-strata are identified as channel fills (deep yellow) embedded within the foreset beds. Paleoflow is to the right.

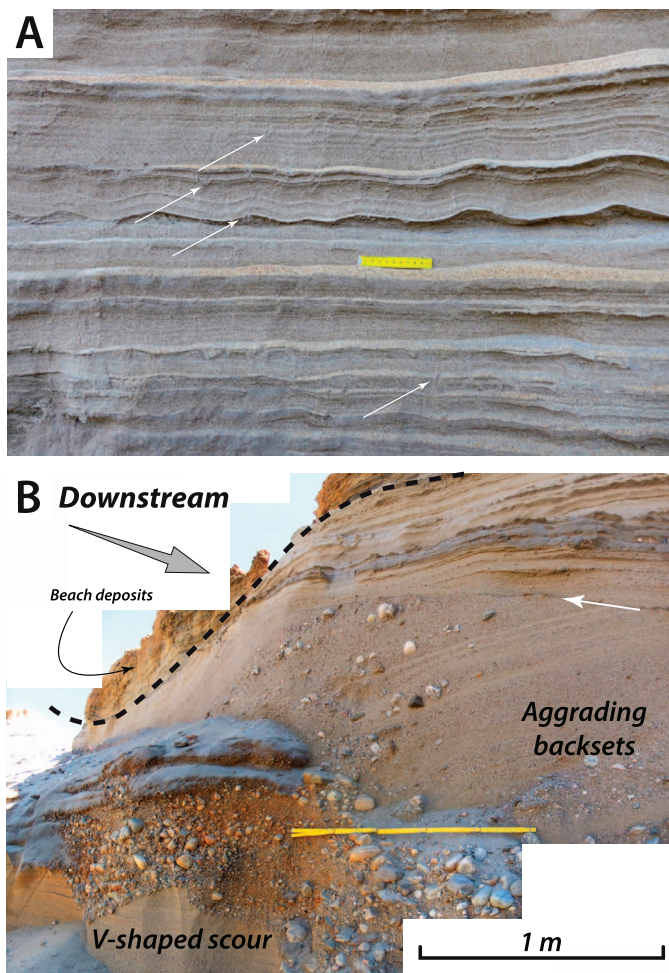


FIG. 4.—A) Fine-grained rippled sand and silt drapes with abundant bioturbation (white arrows) tied to background sedimentation stages. The yellow scale is 10 cm long. B) V-shaped scour with backsets sharply truncated (white arrow) by fine-grained foresets. Note alternating coarse and fine facies constituting the backsets. Regressive beach deposits are at the top of the succession. The yellow rule is 1 meter long.

landward progradation have downlap relationships over the basal contact (Figs. 2, 3). Pebbles to pebbly coarse sand with bed-parallel laminae, occasional pebble imbrication, and smaller-scale planar cross-strata prevail. Both indicate north- to northwestward-oriented currents. Beds of open-framework gravels characterize the upper part of the succession. Landward, the third unit thins progressively, down to less than one meter in thickness. At the base, a distinctive finely laminated mud bed, 10–30 cm thick, includes organic debris and rare pebble-size limestones.

Detailed Description of Backstepping Cross-Strata

Backstepping cross-strata were observable on a single continuous vertical face, 12 m high and 70 m long, which intersected the deltaic upper foreset deposits (Fig. 5). It was however poorly accessible due to slope instabilities.

At the foreset scale, an undulating bedding with 11–12° mean dips is observed. Internal erosion surfaces form either deep and narrow scours or steep-sloped amalgamation surfaces, in the middle and lower part of the exposure, respectively. Amalgamation surfaces, here referred to as “pseudo-foresets,” correspond to seaward-oriented, concave-up truncation surfaces (Fig. 6A). They have a 10–20 m spacing and dip at higher angle (< 25°) than the overall mean foreset slope. Deposits observed in the lower, middle, and upper parts show distinctive bedding patterns.

The lower part of the section exposes the backstepping cross-strata (Fig. 5). It consists of sand or pebbly sand including rare drapes of fine sand. Individual strata are conformably superimposed or bounded by low-angle subordinate erosional surfaces. They successively onlap landward onto pseudo-foresets. They have a hummocky pattern including some second-order, convex-up bed surfaces (Fig. 6B) and are truncated seaward by the seaward-next pseudo-foreset. Internal mean dip of the strata in between two successive pseudo-foresets is either horizontal or seaward dipping. Only strata related to convex-up geometry have weak landward dips. At the sub-bedform scale, laminated to diffusely layered sand prevails. Faintly to well-laminated sand especially characterizes convex-up geometries. Normal grading occurs in a few massive sand beds. Gravels, floating into a laminated to diffusely layered sand matrix, are concentrated in beds abutting against the pseudo-foresets. More abundant gravels in the lower part of the succession, which also contains some decimeter-scale sand intraclasts (Fig. 5), provide evidence for an overall fining-upward trend. Liquefaction structures are present. Small-scale flame structures in fine-grained intervals are affected by a conspicuous top-to-the-south shear deformation (Fig. 6C). Convolute bedding is also present.

A narrow, deep, and asymmetrical scour and its infill were observed in the middle of the exposure (Fig. 5). Downstepping extensional fractures affecting both the infilling and the underlying truncated sands are observed on its landward flank. Massive and chaotic to faintly laminated pebbles grade upward into pebbly sand with undulating beds and diffuse laminae, which are similar in nature to those of the lower part of the exposure. They form distinctive upslope-dipping backsets onlapping the landward flank and essentially conformably overlying the opposite, seaward flank of the scour (Fig. 5).

In the upper part of the exposure, above a sharp truncation surface, stratified sands are better organized (Figs. 5, 6D). They show regular seaward-dipping, 25–40 cm thick, master beds including tangential climbing cross-strata with upslope dips, ca. 1 m in wavelength (Fig. 6D). They consist of laminated granular sands with scattered gravels.

INTERPRETATIONS

Depositional Architecture and Constraints on Paleo-Water Depths

The flat-topped ridge comprising the third, topmost unit is interpreted as a wave-built feature. Planar cross-strata and northward-dipping master beds are washover deposits (Orford et al. 1991). The latter constitute a typical storm berm, similar to those observed in sandur settings (Hine and Boothroyd 1978). The steep seaward-dipping erosional surface corresponds to the beach-face of the highest-stage beach ridges. The clastics prograded landward into a finer-grained back-barrier showing laminated muds deposited in slackwater conditions at the distal toe of the sandur (Hine and Boothroyd 1978). Lonestones are interpreted as ice-rafted debris. The horizontal, landward development of the washover complex over the topset beds conforms to the idea of rapid construction and abandonment of the entire system in a short timespan. The glacio-isostatic uplift did not prevent the retrograding behavior of the barrier.

The stratigraphic contact between the storm berm and the underlying topsets approximates the mean high tide at the time of the delta progradation. The lower bounding surface of the topsets was formed close to the mean low tide, considering a present-day tidal range of ca. 3.5 m. The occasional preservation of transitional contacts between topset and foreset beds shows in addition that the correlative delta brink was positioned at the same level (Figs. 2, 3). Thus, the position of the topset–foreset contact mostly reflects a regular erosion depth by mouth channels. In this view, cross-stratified pebbly sands of the topsets correspond to the infill of constantly shifting channels within the intertidal toe of a prograding sandur (Syvitski and Farrow 1983). The deepest of these channels (Fig. 3) highlights particularly severe downcutting related to spring-tide episodes (Smith et al. 1990) and/or to flood conditions on the delta plain. Planar and trough cross-strata essentially record normal flow conditions. Sigmoidal cross-strata may specifically relate to high rates of sedimentary aggradation at flow transitions between dunes and upper-stage plane beds

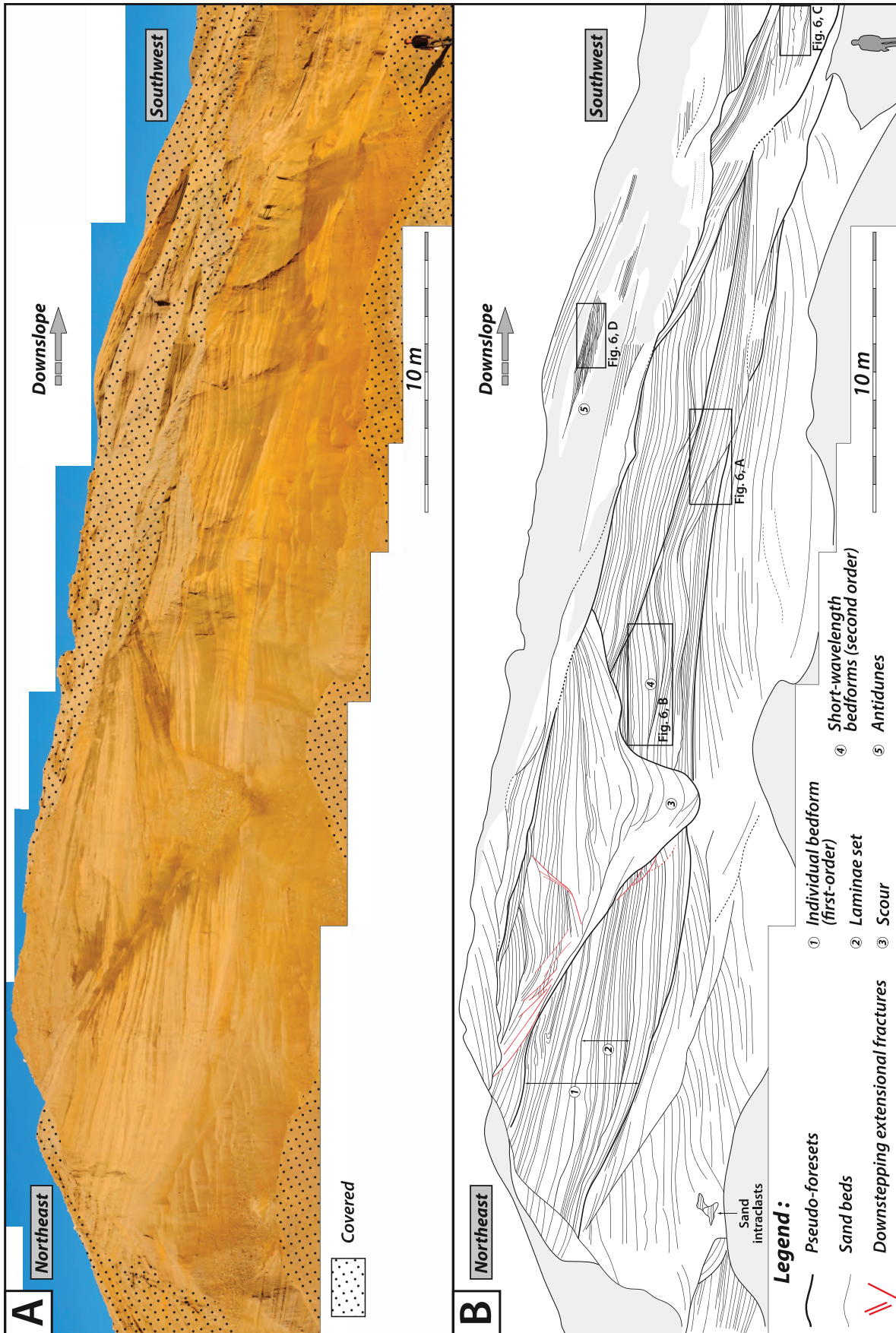


FIG. 5.—Photomosaic and line drawing of backstepping cross-strata interpreted as cyclic steps. The flow was to the right. Geologist (approx. 1.70 m) in the lower right corner for scale. Bold lines highlight pseudo-foresets (amalgamation surfaces) while thinner lines evidence conformable to paraconformable bed contacts. Frames locate photographs of Figure 6.

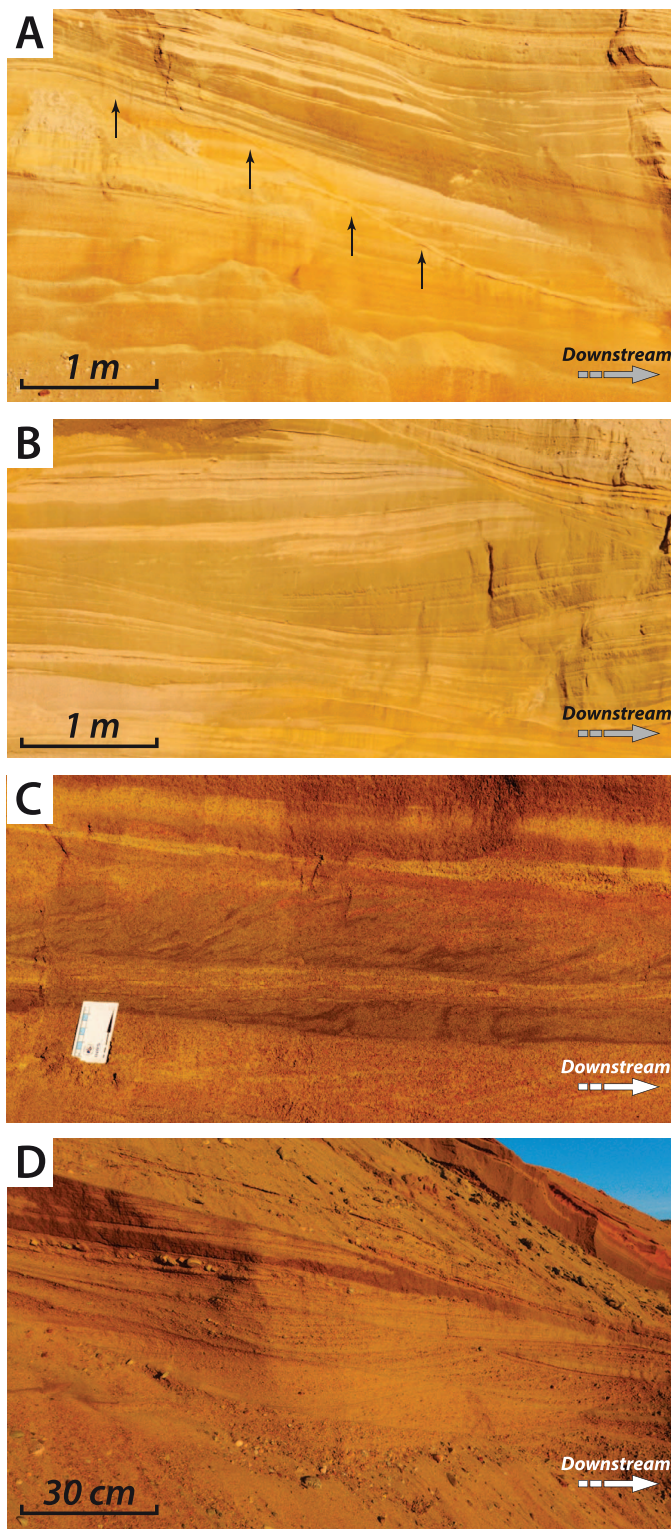


FIG. 6.—Depositional facies in cyclic-step deposits. The paleoflow is to the right. **A**) A downslope-dipping pseudo-foreset (black arrows), sharply truncating underlying strata and on which backstepping strata onlap. **B**) Second-order climbing cross strata (antidune deposits). **C**) Flame structures showing a top-to-the-south shear. **D**) Pebbly sandy antidune cross-strata in the upper foresets.

(humpback dunes, e.g., Fielding 2006). The development of the storm berm over the topsets records a fluvio-glacial sediment cutoff, at least at the local scale.

According to their stratigraphic positions (Fig. 3), the backstepping cross-strata were formed in a delta-front setting. The most landward and topographically highest of them are truncated by the lower bounding surface of the topsets pointing to the depth of the delta brink (Figs. 2, 3). Basinward, the lowest of the observed backstepping cross-strata was emplaced at a depth of > 15 m. Similarly, upslope-dipping, undulating beds (Figs. 2, 5, 6D) were emplaced at a depth in the 0–5 m range. The uncertainty about these estimates is in the order of the tidal range. The occurrence of a conformable relationship between topset and foreset deposits (Fig. 2) implies that this contact is not an unconformity, but only a diastem. No greater depth can be inferred from the overall depositional setting.

A Cyclic-Step Interpretation for the Backstepping Cross-Strata

Patterns of stratification in backstepping cross-strata resulted from the progressive aggradation of depositional bedforms. A southward sense of flow as indicated by the mean dips of foreset geometries and the overall geomorphic setting indicates that stoss sides were essentially preserved while erosion prevailed along lee sides. Bedform amplitudes are in the 1–3 m range. Wavelengths are reflected by the horizontal spacing of the pseudo-foresets (10–20 m). Individual bedforms (first-order) and superimposed convex-up geometries (second-order) have climbed upslope, and the dip of the pseudo-foresets corresponds to the angle of climb of the aggrading bedforms.

Coarse-grained backstepping strata are interpreted as the result of net-depositional Froude-supercritical flows. In such conditions, laminae geometries correspond to the morphologies of the formative bedforms. Quasi-permanent bedforms that migrate upstream in an orderly train as shown by regularly spaced pseudo-foresets point to either cyclic-step or stable antidune flow conditions (Cartigny et al. 2011, 2014; Postma et al. 2014). Occurrences of second-order, shorter-wavelength bedforms superimposed onto first-order larger-wavelength bedforms indicate that second-order and first-order bedforms correspond to antidunes and cyclic steps, respectively (Spinewine et al. 2009; Cartigny et al. 2014). Scour-dominated cross-stratal patterns in exposures not parallel to the paleoflow suggest curvilinear bedform crests, reminiscent of crescentic, upslope-migrating bedforms highlighted in a number of delta slopes or turbiditic canyons (e.g., Smith et al. 2005, 2007; Hughes Clarke et al. 2014; Normandeau et al. 2014; Turmel et al. 2015).

Erosion associated with successive hydraulic jumps (Parker 1996; Kostic et al. 2010; Cartigny et al. 2014) resulted in the steep erosional surfaces that were referred to in the above description as pseudo-foresets. The hydraulic jumps were positioned on the lee sides and not in the troughs of the bedforms, permitting onlapping contacts of the depositional structures onto the jump-related pseudo-foresets.

Massive to graded beds similar to top-cut-out turbidites and faintly laminated to diffusely layered sands relate to repeated hydraulic-jump processes (Russell and Arnott 2003; Postma et al. 2009; Lang and Winsemann 2013). Such bed-scale features correspond to sedimentary structures typically described in cyclic steps with stratified flow patterns including a supercritical basal layer (Postma et al. 2014; Postma and Cartigny 2014). A hydraulic jump permits deposition of massive to pebbly sand as well as sand intraclasts (Russell and Knudsen 1999; Carling 2013) in the troughs of the bedforms. Soft-sediment deformation such as sheared flame structures resulted from pressure fluctuations under the unsteady flow (Postma et al. 2009, 2014). Variable near-bed flow conditions occurred along successive lee (mainly erosional) and stoss (depositional, reaccelerating from subcritical to supercritical) sides of the first-order cyclic-step bedforms (Kostic et al. 2010; Cartigny et al. 2014) conferring to the overall flow a transcritical state. Flow reacceleration up to renewed supercritical conditions approaching the following downslope bedform crest resulted locally in the formation of second-order antidunes (Figs. 5, 6B). As cyclic steps are known to scale to flow thickness (Spinewine et al.

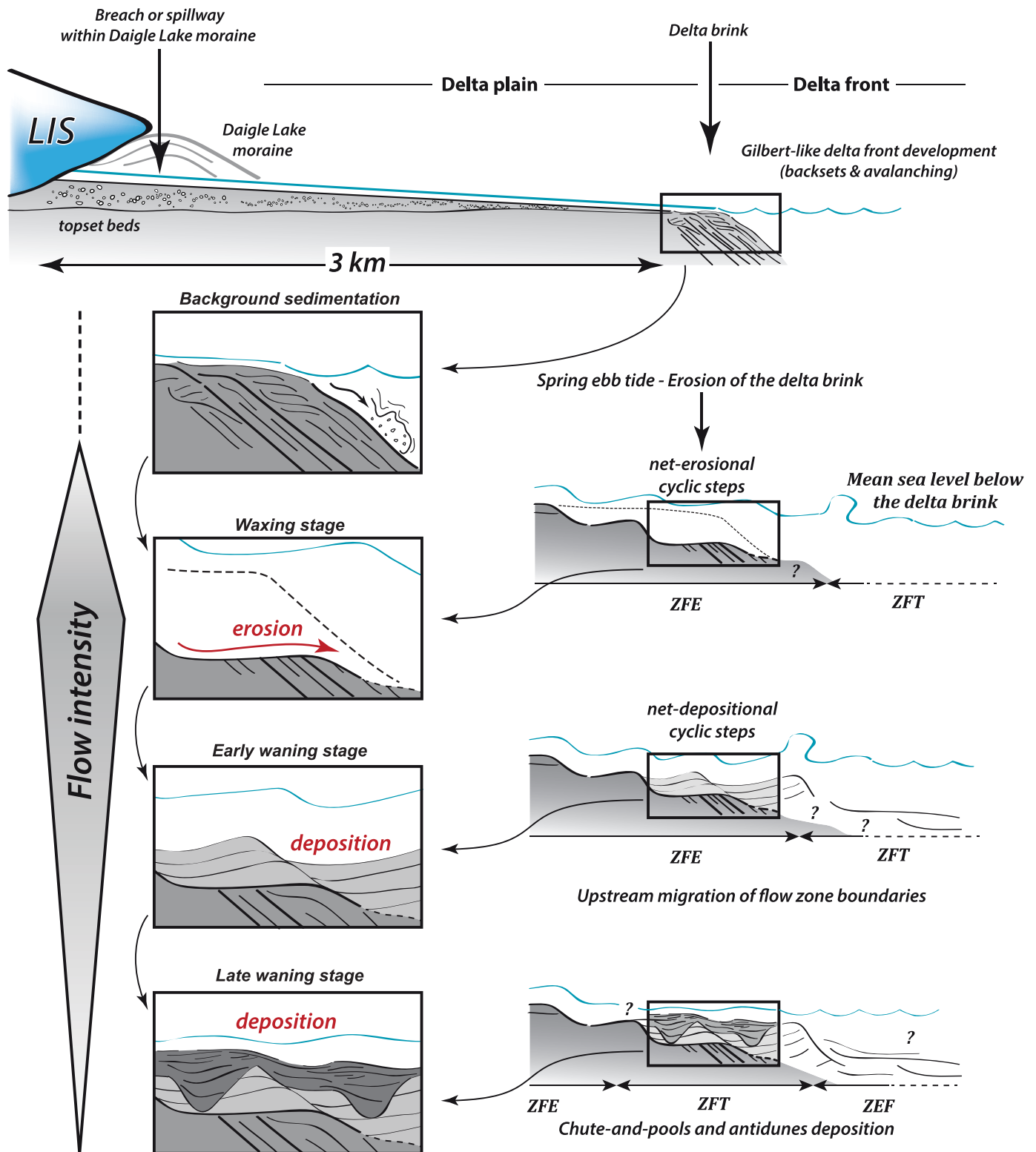


FIG. 7.—Depositional model for river-derived cyclic steps in a delta-front setting beyond the margin of the Laurentide Ice Sheet. ZFE, Zone of Flow Establishment; ZFT, Zone of flow Transition; ZEF, Zone of Established Flow (Russell and Arnott 2003).

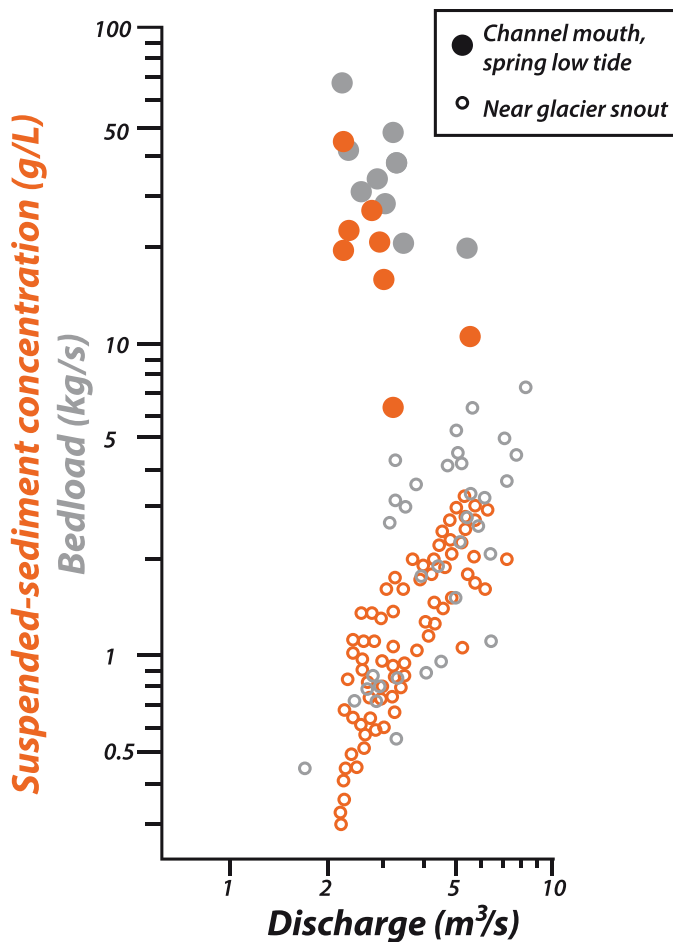


FIG. 8.—Increase in sediment yield in a proglacial river due to tidal drawdown processes. Modified from Smith et al. (1990).

2009; Kostic 2011), bedform wavelengths in the 10–20 m range suggest that the thickness of the transcritical flow was on the order of 1–2 m. This is also in agreement with second-order antidune wavelengths (< 6 m) that suggest a one-meter-thick flow (Normark et al. 1980; Prior and Bornhold 1990; Spine-wine et al. 2009).

Backstepping cross-strata originating from cyclic steps are truncated and overlain by the narrow and deep scour in the middle part of the exposure (Fig. 5). Its geometry and its infill including backsets suggest a chute-and-pool structure (Russell and Arnott 2003; Russell et al. 2009; Cartigny et al. 2014). Downstepping faults along its landward flank suggest minor gravitational slides in the lee side of the chute-and-pool structure. The subsequent fluidization of larger sand collapses may explain some of the structureless sand layers contributing to the basal scour infill (Fig. 5, see also Turmel et al. 2012; Cartigny et al. 2014, their fig. 15). Well-laminated upslope-climbing tangential cross strata in the upper part of the exposure (Figs. 5, 6D) are ascribed to deposition under supercritical flow conditions characterized by the development of stable antidune bedforms (Cartigny et al. 2011).

The facies sequence including, from the base to the top, cyclic-steps, chute-and-pools, and antidune deposits follows an episode of initial erosion generating the host channel (net-erosional supercritical flows? see Fildani et al. 2013). This corresponds to a depositional context implying temporally and/or spatially decelerating flows. In the proglacial deltaic setting, such a scenario may relate to waning flow conditions, progressive in-channel aggradation driving overflows and expanding flow conditions, or flow interactions with diurnal tides (Smith et al. 1990).

Flood-stage, Background, and Intermediate Flow Conditions

As interpreted above, foresets with backstepping cross-strata relate to Froude-supercritical flow conditions. In contrast, well-stratified, fine- to medium-grained foreset deposits characterized by ripples, bioturbation, and concentrations of heavy minerals represent background sedimentation and intervening remobilizations along the upper foresets. A combination of marine processes such as waves, tides, and storms resulted in slopes gentler than those of typical Gilbert deltas (Gerber et al. 2008; Fernandez et al. 2011). Muds are virtually absent, indicating that they were exported farther offshore. Unconformable contacts truncating steep foresets (Fig. 3) may represent wave-ravinement surfaces developed after tributary-channel abandonment or migration, or during intervening periods between events of deposition by supercritical bedforms.

Coarse-grained backsets in V-shaped scours depart from structures of background sedimentation stages. Such backsets are frequently recognized in the upper foreset of high-energy Gilbert-type deltas (e.g., Massari 1996). Muto et al. (2012) argued that backsets reflect the development of fluvial cyclic steps on the delta plain and a hydraulic jump in mouth environments. Subcritical flow conditions thus developed downslope along the foresets, and the pseudo-cyclicality observed in backset cross-strata (Fig. 4B) is the consequence of repeated upstream migrations of the fluvial bedform crests and associated hydraulic-jump location. Here, coarse-grained backsets are regarded as the result of intermediate-discharge regimes. A very similar lithology (i.e., coarse-grained pebbly sand) composes the cyclic steps and backsets in V-shaped scours. It is in support of the idea that cyclic steps and backset cross-strata in this case study relate to a common hydraulic regime, the one producing backsets being only less energetic than the one related to cyclic steps (e.g., Gerber et al. 2008).

DISCUSSION

Cyclic Steps from Supercritical River-Derived Outflows?

In delta-front settings, supercritical high-density turbidity currents and related upstream migrating bedforms are usually interpreted as initiated by the collapse of oversteepened mouth bars (Hughes Clarke et al. 2012, 2014). This inception process is preferred to other processes tied to river-derived underflows (e.g., hyperpycnite deposits: Plink-Björklund and Steel 2004; Ponce and Carmona 2011) since the latter are generally considered to have too low sediment-carrying potential for generating relatively thick coarse-grained deposits (Talling 2014). In our case study, however, we argue that the mass-wasting hypothesis for generation of cyclic steps is unlikely, thus favoring the river-derived origin.

Indeed, the well-organized stratal pattern in cyclic-step to antidune deposits (Fig. 5) indicates relatively steady and uniform flow patterns. Also, there is no place either for an headscarp large enough to transform in the volume of observed accreted sands (e.g., Prior et al. 1981) or for a flow transformation that would have instantaneously evolved from a gravitational collapse to net-depositional cyclic steps (e.g., Ponce and Carmona 2011) because the cyclic steps are preserved up to the uppermost level of the foresets immediately beneath topsets beds. In addition, the bulk of the cyclic step related deposits contains far fewer coarse particles and is sandier than the topsets beds, the latter thus not being the source of the former.

In as much as cross-strata formed by cyclic steps were specifically emplaced within channels incised through the upper delta front, it can be inferred that supercritical flows were inherited from, or at least tied to, flow conditions characterizing the proglacial delta plain (e.g., Duller et al. 2008). This interpretation would conform to the observation of backsets in V-shaped scours, which can be understood as an indication of cyclic-step flow conditions on the delta plain (Muto et al. 2012). The lack of any patent record of supercritical flow conditions within the delta plain—with the possible exception of humpback dunes—suggests that related bedforms may have been net-erosional. Bedforms may also have formed and been reworked during subsequent background sedimentation stages. However, flow constriction transforming subcritical flows

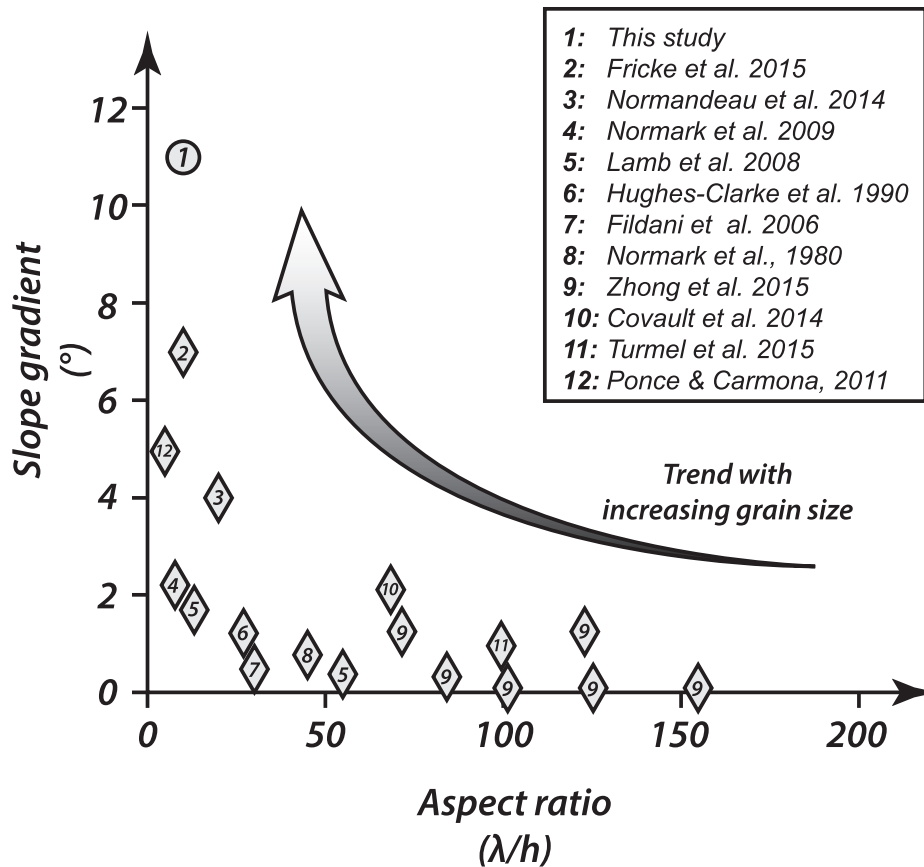


FIG. 9.—Relationships between a dimensionless aspect ratio (wavelength/height) and the depositional slope for some of the cyclic steps documented in the literature. The Sept-Iles case study (circle) is representative of a coarse-grained, steep-slope end member.

from the delta plain into supercritical flows in delta-front channels cannot be excluded.

This in-channel configuration confined high-energy flows, which were thus poorly affected by dispersive energy loss in the mouth environment (in contrast of the model of Bates 1953). Such channels are scaled to the upstream distributary channels of the delta plain, in terms of both size and hydraulic regime. A genetic link is then argued between a primary sediment-laden supercritical flow on the delta plain that plunges down and evolves into an underflow that generates the cyclic steps on the upper foresets, a configuration suggested by Spinevine et al. (2009) and Muto et al. (2012). Owing to sufficient density and velocity, buoyancy and friction effects were overcome by the sediment-laden river-derived outflow, which transformed into an underflow (Mutti et al. 2003; Piper and Normark 2009; Turmel et al. 2015).

Flood conditions similar to those that are here inferred are illustrated today at some Icelandic sandur mouths. Here, a riverine flow is frequently observed entering the seawater with surface waves at tens to hundreds of meters off the shoreline in full continuity with those of the river. Then they rapidly narrow seaward, disappearing abruptly (see fig. 3 in Mulder et al. 2003 and fig. 14B in Hine and Boothroyd 1978).

The Role of Tides on Development of Cyclic Steps

The relative scarcity of cyclic-step cross-strata in the bulk of delta-front deposits suggests that only exceptional, low-frequency flow conditions have generated cyclic steps. We suspect that they most likely necessitated the conjunction of flood conditions (outburst, freshet) on the delta plain and their amplification by ebb-tide processes. In particular, tidal drawdown processes can explain the inception of channel downcutting at the delta brink (Smith et al. 1990). Channels were likely enlarged and rapidly overdeepened, partly owing to supercritical flow conditions derived from the delta plain. The channels thus

connected the delta plain and the upper foresets by establishing a new depositional profile (Fig. 7) characterized by largely lower slopes (11–12°) than that of the background Gilbert-type delta (Gerber et al. 2008; Turmel et al. 2015).

Also, tidal drawdown potentially allows both the suspended-sediment concentration (SSC) and the bedload of the proglacial river outflow to increase by one to two orders of magnitude (up to 50 g.L⁻¹ according to Smith et al. 1990) (Fig. 8). The sustained river-derived flow can thus plunge down along the delta foresets (Mulder et al. 2003), considering in addition that the estuarine water body of the St. Lawrence was at that time largely diluted by massive meltwater inputs.

Cyclic-step bedforms can be regarded as deposits characterizing a tide-influenced zone of flow establishment (ZFE) of a submerged plane-wall jet with jump (Fig. 7). Here, depositional processes relate to the conduit flow conditions (Russell and Arnott 2003) that characterize the portion of the chute channel located upstream of a main hydraulic jump lying farther downslope (e.g., Mutti et al. 2003). A complex facies suite of subcritical, turbiditic facies is expected to have been deposited farther downslope in the zone of established flow (ZEF) beyond the main hydraulic jump, depending on the residual sediment concentration, pattern of the river flow and the tidal hydrograph, and the gradient distribution along the foresets and in the channel. Afterwards, during the waning stage at low tide, the zone of transition flow is thought to have progressively migrated upstream as evidenced by the occurrences of chutes-and-pools and finally antidunes above the cyclic-step bedforms (Fig. 7; see also Lang and Winsemann 2013).

The Role of Slope on Development of Cyclic Steps

The aspect ratio (wavelength/crest height) of the cyclic steps was close to 10 (Fig. 9), a small ratio in comparison with that of cyclic steps developed in other coarse-grained sand in particular (e.g., Postma et al. 2014) and all other finer-

grained cyclic steps (e.g., Zhong et al. 2015). The restricted crest spacing may relate to the steep mean slope of the depositional surface (11°), considering that the wavelength of cyclic steps depends in part on the distance that the flow needs to become critical again after the hydraulic jump (Postma and Cartigny 2014).

We plotted the aspect ratio of a panel of cyclic steps found in the literature against the slope along which they develop (Fig. 9). A well-defined decreasing pattern is observed, suggesting that the higher the slope, the lower the aspect ratio. For the steeper slopes, transcritical flows cannot occur, being replaced by permanently supercritical flows (downstream-pulling of the flow by gravity: Kostic 2011; Zhong et al. 2015). In our case study, the slope of the channel incising the delta brink most likely approached the steepest setting in which cyclic steps can develop. In this view, the initial erosion of the delta brink by tidal drawdown, which reduced the initial delta-front slope, may have been a necessary condition in order to promote the development of transcritical flows, the formation of cyclic steps, and the deposition of backstepping cross-strata.

Further, considering that cyclic steps with the lower aspect ratio are generally developed in coarser material (sand and gravel), it seems that development and stability of cyclic steps over steep slopes is associated with coarse material. We thus document a case study where the relationship between the aspect ratio and the slope represents an end member in the field of the supercritical bedforms, at the opposite of long-wavelength, finer-grained cyclic steps deposited over largely less steep channel thalwegs (Zhong et al. 2015).

Implications for Supercritical River-Derived Outflows

Bedload-dominated, sustained, river-derived flows can be reasonably inferred, at least occasionally, from the overall ice-marginal depositional setting (Marren 2005; Duller et al. 2008). Such conditions may be encountered in a variety of high-energy settings, including glacial outwash and mountainous drainage basins, especially those affected by recurrent rainstorm events and/or if they drain into tide-influenced basins with a significant tidal range (Fielding 2006; Tinterri 2007; Babonneau et al. 2013; Ventra et al. 2015). In this perspective, the cyclic steps and inferred flow conditions documented here may offer a solution for the understanding of the specific circumstances permitting the deposition of thick-bedded, sand-dominated turbiditic successions ascribed to river-derived underflows (Plink-Björklund and Steel 2004; Girard et al. 2012), which are definitely not supported by inferences from modern depositional conditions (Talling 2014).

CONCLUSIONS

In this study we document coarse-grained (sand and gravel), short-wavelength (10–20 m) cross-strata related to supercritical flow conditions developed in a shallow, fluvio-glacial delta front. Both the sedimentary architecture, displaying truncation surfaces against which backstepping strata progressively onlap (pseudo-foresets), and bed-scale depositional facies tied to hydraulic jump processes, attest to cross-strata originating from cyclic steps. The emplacement of cyclic-steps-related cross-strata on upper foresets immediately below the basal topset contact strongly suggests that cyclic steps originate from river-derived, bottom-following underflows (hyperpycnal flows) in a delta-front setting (upper foresets). We suspect that the development of such backstepping cross-strata from hyperpycnal flows was enhanced by tidal drawdown processes. The latter favored the incision of the delta brink and permitted an increase in sediment yield relative to the river outflow, finally driving an inertia-driven underflow and the inception processes for net-depositional cyclic steps.

Our case study differs from most of the other subaqueous published examples by the low aspect ratio (~ 10) of the bedforms. With kilometer-scale cyclic steps of the deep sea, they represent the two end members of cyclic-steps related cross-stratification recognized in subaqueous slope settings.

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