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TERMINAL DISTRIBUTARY CHANNELS AND DELTA FRONT ARCHITECTURE OF RIVER-DOMINATED DELTA SYSTEMS

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ABSTRACT: **Using modern and ancient examples we show that river-dominated deltas formed in shallow basins have multiple coeval terminal distributary channels at different scales. Sediment dispersion through multiple terminal distributary channels results in an overall lobate shape of the river-dominated delta that is opposite to the digitate Mississippi type, but similar with deltas described as wave-dominated. The examples of deltas that we present show typical coarsening-upward delta-front facies successions but do not contain deep distributary channels, as have been routinely interpreted in many ancient deltas. We show that shallow-water river-dominated delta-front deposits are typically capped by small terminal distributary channels, the cross-sectional area of which represents a small fraction of the main fluvial "trunk" channel.**

Recognizing terminal distributary channels is critical in interpretation of river-dominated deltas. Terminal distributary channels are the most distal channelized features and can be both subaerial and subaqueous. Their dimensions vary between tens of meters to kilometers in width, with common values of 100–400 m and depths of 1–3 m, and are rarely incised. The orientation of the terminal distributary channels for the same system has a large variation, with values between 123° (Volga Delta) and 248° (Lena Delta). Terminal distributary channels are intimately associated with mouth-bar deposits and are infilled by aggradation and lateral or upstream migration of the mouth bars. Deposits of terminal distributary channels have characteristic sedimentary structures of unidirectional effluent flow but also show evidence of reworking by waves and tides.

INTRODUCTION

Many ancient subsurface examples of river-dominated deltas deposited in shallow intracratonic seaways are depicted as thick, narrow, branching shoestring sandstones, interpreted as distributary-channel complexes, which lack fringing delta-front sandstones (Fig. 1; Busch 1959, 1971; Cleaves and Broussard 1980; Rasmussen et al. 1985; Bhattacharya and Walker 1992). In interpreting these examples, the passive-margin, shelf-edge Mississippi bird-foot delta has historically been used as a modern analogue which may be inappropriate given the peculiar environmental conditions of the Mississippi. More recent studies have reinterpreted many of these deeply incised "distributary channels" as incised valleys (Willis 1997; Bowen and Weimer 2003). A reevaluation of river-dominated deltas that have multiple distributaries is needed to reconcile these differences in interpretation.

In this paper we reconsider the scale and the presence of channelized deposits that commonly lie at the top of delta deposits, using modern river-dominated deltas as well as ancient examples. To address this problem, our focus is on the terminal distributary channels, which are the most distal channelized features of a distributive system. This study shows

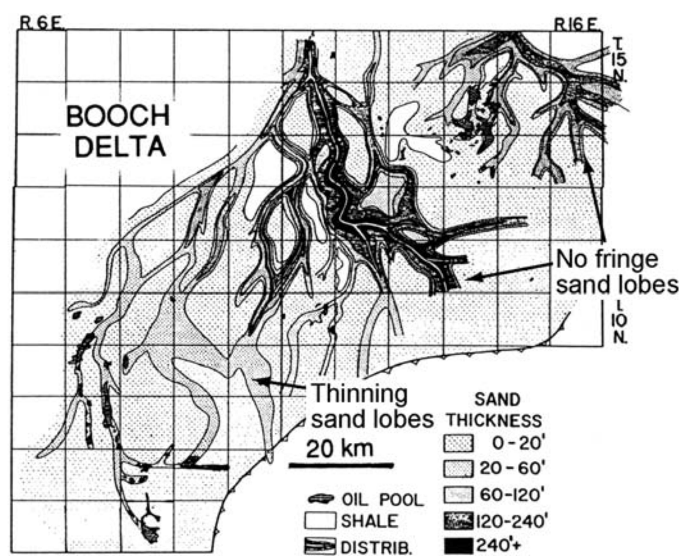

FIG. 1.— Pennsylvanian Booch delta (from Busch 1971). Extremely thick, elongate sand bodies interpreted as a river-dominated delta through analogy with the modern Mississippi Delta. Note that the fringe lobes are missing at the basinward end of the elongated features. Sand thickness is in feet (1 foot ≈ 0.304 m).

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that river-dominated deltas formed in shallow-water basins typically exhibit a lobate shape with multi-scale coeval terminal distributary channels.

Unfortunately, there are limited examples of small terminal distributary channels described in ancient deposits (Olariu et al. 2005) despite their presence in many modern deltas (Fig. 2). We suggest that the lack of recognition of these features is a result of a lack of criteria for identification and indicate the need for a revision of the existent facies models of delta front in river-dominated deltas especially those formed in shallow-water basins.

Formation of terminal distributary channels and their relationship with coeval mouth bars has been described for modern deltas by Axelsson (1967), Zenkovich (1967), Baydin (1970), van Heerden (1983), van Heerden and Roberts (1988), and DuMars (2002), but no attempt to describe a typical depositional succession or indicate facies architecture has been made. Distributary channels described in ancient delta-front deposits and reinterpreted by us as terminal distributary channels provide detailed data related to sedimentary facies architecture (Bhattacharya et al. 2001; Olariu 2002; e.g., Chidsey et al. 2004).

The delta front was described as a sheet of sand by Fisk et al. (1954), but recent studies (van Heerden and Roberts 1988; Tye et al. 1999; Rodriguez et al. 2000; Bhattacharya et al. 2001; DuMars 2002; Overeem et al. 2003; Olariu et al. 2005) show that both modern and ancient delta fronts have a complicated morphology, consisting of multiple terminal distributary channels, subaqueous levee deposits, and mouth bars. Few studies have been dedicated to delta-front deposits, despite the key importance of this delta sub-environment to understanding delta growth and facies architecture.

This paper:

1. presents a new paradigm for interpretation of ancient river-dominated delta-front deposits that have multiple terminal distributary channels at different scales, which is opposite to the Mississippi type, which has only a few large distributary channels;
2. documents the large variation in dimensions and orientation of terminal distributary channels (within the same system), and discusses formation and evolution of terminal distributary channels on the basis of modern examples; and,
3. sets the basis for recognition of terminal distributary channels in ancient delta-front deposits on the basis of sedimentary facies architecture.

SCALES OF CHANNELS

There is huge variability in the scale of channel-like features, from small elongate ephemeral scours to canyons, but there is also a complete continuum between these scales. In this section we discuss the relative size of the channels that are likely to be recognized in deltas and their position within delta systems.

Fluvial "Trunk" Channel

Valleys typically form in areas undergoing degradation and erosion. Such large areas define and form drainage basins, and the general pattern of rivers within these coalesce to form larger "trunk" rivers (Fig. 3). The "trunk" channel is defined as the largest channel of a fluvial-distributive system. "Trunk" rivers also commonly occupy valleys (e.g., the Mississippi Valley). A fluvial channel is maintained both because it is confined within an erosional valley or depositional levee and due to its downslope gradient, even where slopes are exceedingly low, such as 3×10^{-4} for typical meandering rivers to 2–4 $\times 10^{-5}$ for the lower Mississippi and Amazon (Olsen 1993). In the case of deltas, the "trunk" channel feeds the distributive system that starts at the apex. The apex represents the point downstream from where the general pattern of the flow forms distributary channels (Fig. 3).

Distributary Channels

Distributary channels are described from deep-sea fans (Damuth et al. 1983; Posamentier and Kolla 2003), alluvial fans (Prior and Bornhold 1990), and delta plains and form when the main channel reaches an area with low variability of lateral gradient (Fig. 3). Gradient values in a distributary system might be similar to the lower part of a "trunk" channel, but the gradient variation normal to the stream direction is similar to the downstream gradient, in contrast to tributary systems, where gradients normal to the stream direction are typically higher (Fig. 3). Because delta-plain gradients are small and sedimentation rates are high, the direction of distributary channels can be changed easily by aggradation or differential subsidence and compaction, such that the gradient will be steeper in other directions and might capture part of the flow, creating a new distributary channel (Fig. 3).

In many modern deltas, the discharge from the "trunk" channel is split into a few major distributaries (Fig. 2), each with different discharges. The main distributaries bifurcate farther downstream, and with each bifurcation the discharge and sediment load is split between newly formed channels. As a consequence of this successive splitting, the distributary channels become smaller in the downstream direction. Yalin (1992) indicates that with each bifurcation or avulsion the channel width and depth changes as $B_{k+1} \approx 0.7B_k$ and $h_{k+1} \approx 0.8h_k$ respectively, where B is channel width, h is channel depth, and k is channel order. For a large delta system (Volga Delta, Lena Delta), distributaries can rejoin, forming a delta pattern similar to braided or anastomosed rivers (Morisawa 1985). However, in a distributary system there should be more bifurcations than confluences overall, which generally results in an increasing number of smaller distributary channels downstream (Morisawa 1985).

Terminal Distributary Channels

Terminal distributary channels are formed within a delta at the very end of a distributive channel system. Terminal distributary channels start from the last subaerial bifurcation and extend to the last channelized expression on the subaqueous delta front. Terminal distributary channels represent the most active part of the distributive channel network and are intimately associated with mouth bars.

We use the term "terminal distributary channel" rather than "*n*"-order channel to describe these channels because it is typically impossible to count the numbers of channel splits in ancient systems given the scarce data relative to the detailed morphology of ancient deltas. Even in large modern delta systems with hundreds of bifurcations, it can be difficult to count the order of channels accurately, because some channels are only seasonally active.

Because the terminal distributary channels are formed through multiple successive splits from the "trunk" channel, they are shallow and narrow compared with the fluvial "trunk" channels of the same delta system (Fig. 2). The distributary system ultimately changes from the feeding "trunk" river channel to the smallest terminal distributary channels, in a reversed pattern of the drainage basin (Fig. 2).

EXAMPLES OF TERMINAL DISTRIBUTARY CHANNELS

Modern (Atchafalaya, Wax Lake, Volga, Lena) as well as ancient (Panther Tongue, Perrin, Ferron) examples of terminal distributary channels are presented in the following section to build a conceptual model about how terminal distributary channels evolve, and to describe their resulting delta-front facies architecture. We include reinterpretation of the previously published data, analysis of aerial images from modern deltas, and new outcrop measurements from several ancient deltas.

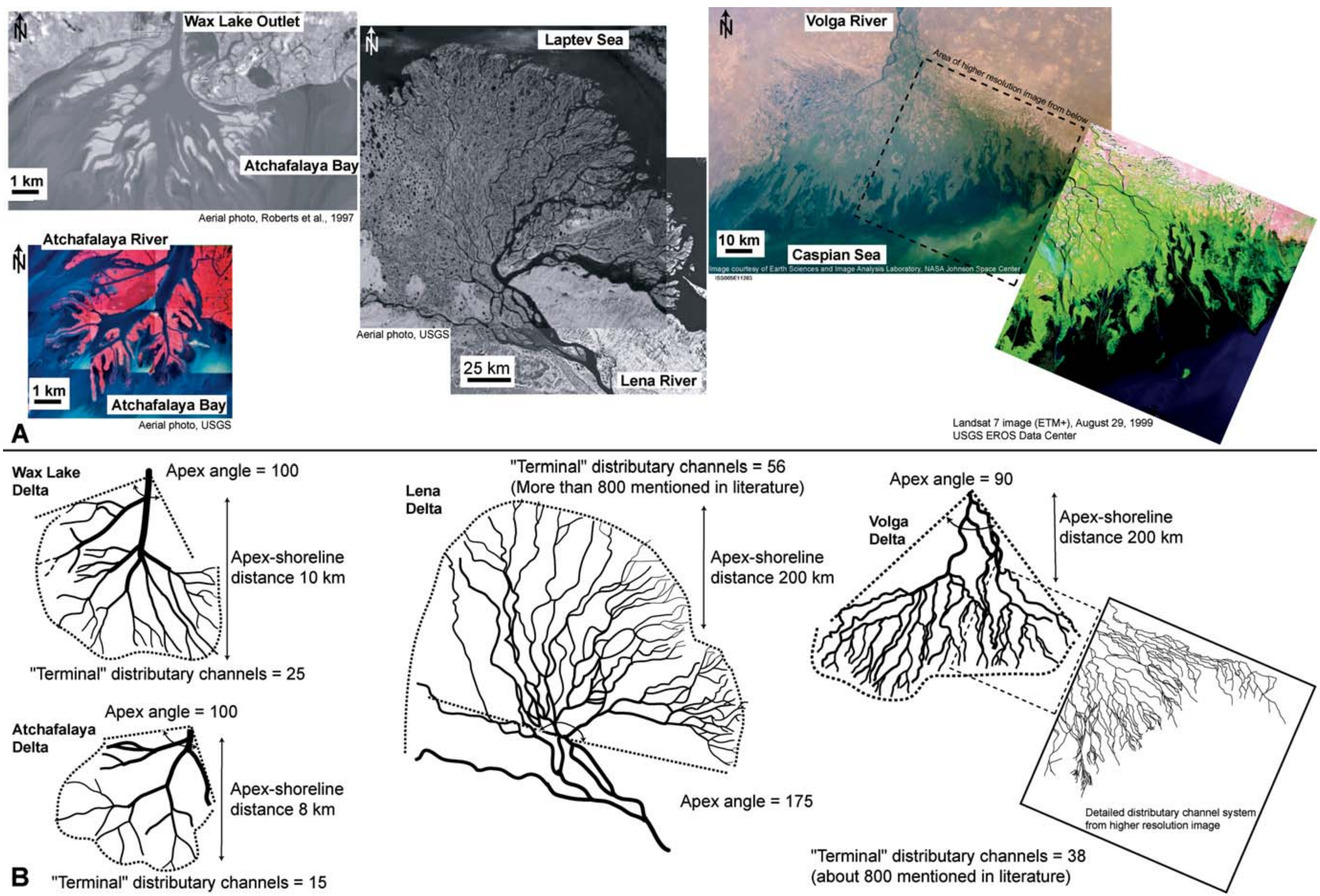

FIG. 2.—Modern delta examples with multiple terminal distributary channels. **A)** Aerial images of Wax Lake Delta, Atchafalaya Delta, Lena Delta, and Volga Delta. **B)** Distributary pattern for each aerial image with morphometric information related to distributary network.

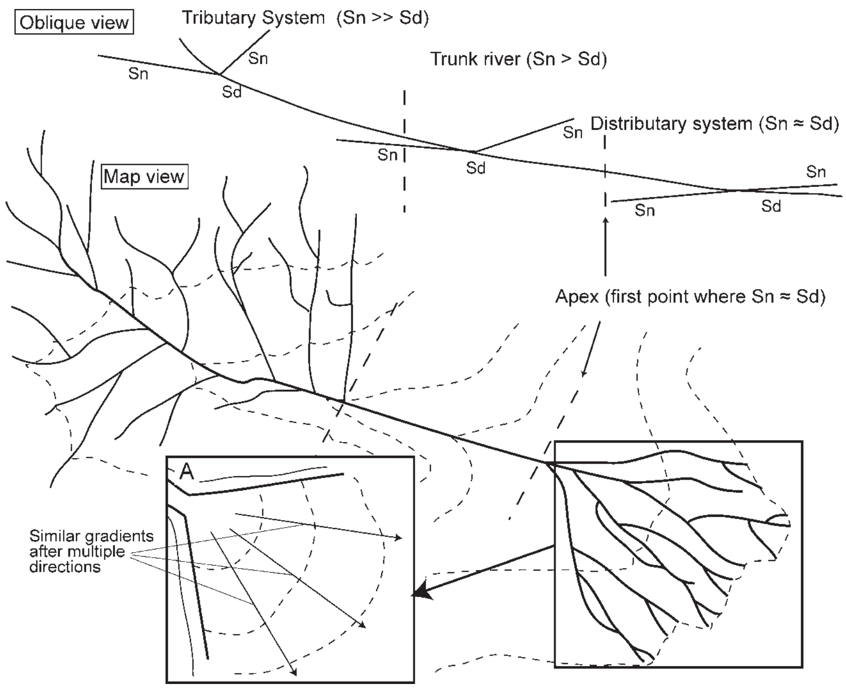

FIG. 3.—Sketch with formation of distributary systems due to unconfined, low-variable-gradient conditions. Sn, slope normal to the flow direction; Sd, slope down flow (main direction of the flow). Dashed lines represents contour lines. **A)** Topographic map of a distributive system indicates similar gradients (arrows) away from the main direction of the main "trunk" valley. When a confined flow (channel) reaches an open area, flow tends to spread but still forms channels because of subtle topographic differences.

Modern examples allow us to extract the distribution and dimensions of specific morphometric features and allow a process-based analysis of the formation of terminal distributary channels. The modern examples have been chosen from deltas that are river-dominated and have multiple distributary channels. Ancient examples were selected on the basis of the presence of small channelized features within delta-front deposits. The ancient examples provide insight about facies architecture and cross-sectional facies variability.

Modern Deltas

Atchafalaya Delta.—The modern Atchafalaya Delta, formed after 1950 (Roberts 1980; Tye and Coleman 1989), progrades into the 3-m-deep Atchafalaya Basin. The delta became subaerially exposed following an extreme flood in 1973 (Roberts 1980). Subsequent aerial images show major morphological changes within only a few years (Fig. 4). Growth of subaerially exposed mouth bars indicates significant upstream accretion as well as lateral migration of the mouth bars (Fig. 4). Downstream accretion is predominant, but upstream and lateral accretion are the dominant controls on the discharge and sedimentation through the associated terminal distributary channels. Cross sections through the delta, based on vibracores (van Heerden 1983; van Heerden and Roberts 1988) show a general coarsening-up pattern. In a dip section (Fig. 5A), landward-inclined beds are interpreted to form during upstream growth of bars. These upstream-inclined surfaces have a slope of 0.001 (1 m/km) versus 0.0005 (0.5 m/km) for the basinward-dipping surfaces. Successive aerial images, as well as successive bathymetric surveys of the terminal distributary channels (van Heerden 1983; van Heerden and Roberts 1988), indicate that the channels are infilled by aggradation, and lateral and upstream bar growth (Figs. 4, 5B, C). Terminal distributary channels are extremely shallow (Fig. 5C), less than 2 m deep, with width-to-depth ratios of a few hundred.

The cyclic pattern of formation of terminal distributary channels has been repeated, but neither advance nor incision of the deeper "trunk" channel has occurred. Four phases of delta-lobe evolution have been distinguished (van Heerden 1983; van Heerden and Roberts 1988; Roberts 1998): (1) formation of prodelta and distal bar (subaqueous platform); (2) formation of distributary-mouth bars and subaqueous levee formation; (3) formation of subaerial levees and channel elongation; and (4) upstream accretion and lobe fusion.

Wax Lake Delta.—The Wax Lake Delta is similar to the Atchafalaya Delta, in that the water is derived from a branch of the Atchafalaya River and also discharges into Atchafalaya Bay (Fig. 4A). The Wax Lake Delta was formed at the end of the Wax Lake outlet, dredged in 1942 by the U.S. Corps of Engineers (Roberts 1980). The delta has morphology similar to that of the Atchafalaya Delta, with multiple terminal distributary channels separated by mouth bars (Figs. 2, 6A). Cross sections based on vibracores do not allow reconstruction of bedding surfaces (Majersky et al. 1997), but thicker sand deposits occur in a landward direction (Fig. 6B) and suggest upstream accretion.

A morpho-hydrological study of the Wax Lake Delta related to channel flow velocities and suspended-sediment variability concluded that sediment flux and deposition is highest at the distributary thalweg where the mouth bar is formed (DuMars 2002). Our analysis of channel profiles indicates that channel cross-sectional areas decrease basinward following each channel split. The area decreases at different percentages with each split (Fig. 6C, D). Despite this decrease, no change has been observed on cross-sectional area or geometry of terminal distributary channels during the subaerial-to-subaqueous transition. Subaqueous channels extend basinward at least 3–4 km (Fig. 6C). The sum of all small terminal distributary channels represents a larger cross-sectional area than the initial channel requiring lower overall velocity associated with the discharge of terminal distributary channels. The overall loss of flow

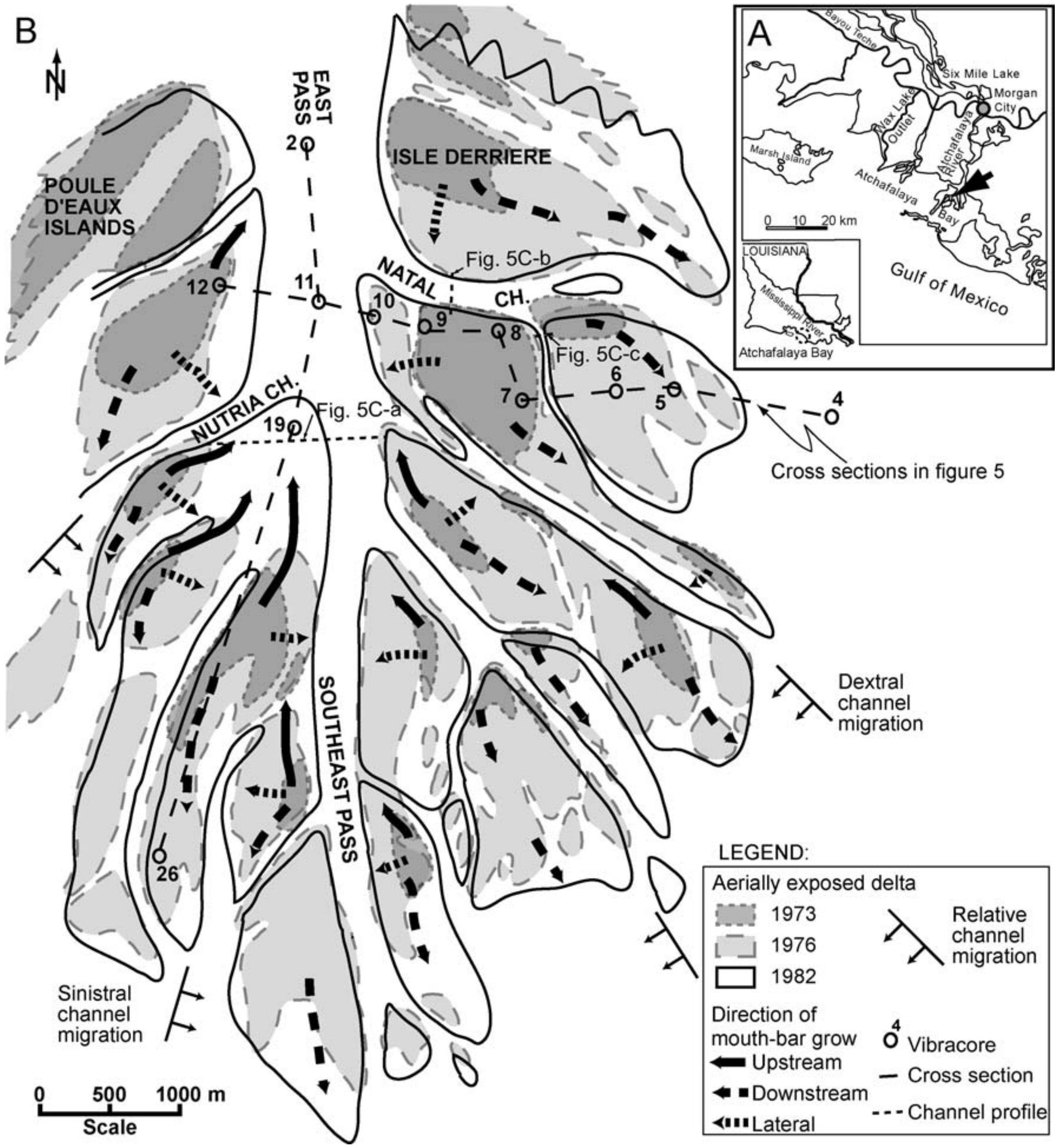

FIG. 4.—**A)** Atchafalaya Delta location (arrow). **B)** History of subaerial delta evolution and mouth-bar growth, based on maps from van Heerden (1983). The arrows emphasize the migration of the bars, the length represents the degree of growth. Downstream migration forms and extends the channels while the lateral and upstream migration infills and closes channels. The channels on the right part of the delta have a primarily sinistral migration, whereas channels on the left side of the delta lobe have a primarily dextral migration.

velocity results in high sedimentation in the terminal distributary channel area. As in the Atchafalaya Delta, terminal distributary channels on the Wax Lake Delta are extremely shallow (Fig. 6E) with width-to-depth ratios of a few hundred.

Volga Delta.—The modern Volga and Lena deltas allow the analysis of dimensions and distributions of terminal distributary channels in a continental-scale river-dominated delta. The Volga Delta built into the Caspian Sea (Fig. 7A), a closed basin with sea-level variations up to 15 cm/year. The present Volga Delta has about 800 terminal distributary channels (Kroonenberg et al. 1997; Alekseevskiy et al. 2000; Overeem et al. 2003) that coalesce upstream into a single "trunk" channel (Fig. 2). An increasing number of distributary channels were formed in the lower delta plain from 200 at the end of the 1800s to 1000 by 1980 during sea-level fall and delta progradation (Fig. 7B). This happened with coeval channel abandonment in upper parts of the delta (Alekseevskiy et al. 2000). Incision and increased discharge through the main distributary channels and a decrease in the number of distributary channels in the upper delta plain during sea-level fall (Alekseevskiy et al. 2000) can be attributed to slight slope changes, despite a relatively constant slope of 5 cm/km in delta-plain and offshore area (Kroonenberg et al. 1997; Overeem et al. 2003).

The density of channels along the shoreline is up to 6 channels per km (Kroonenberg et al. 1997; Overeem et al. 2003). The terminal distributary channels average 1–3 m deep (Kroonenberg et al. 1997), like the Atchafalaya and Wax Lake examples, and are rarely wider than 10–

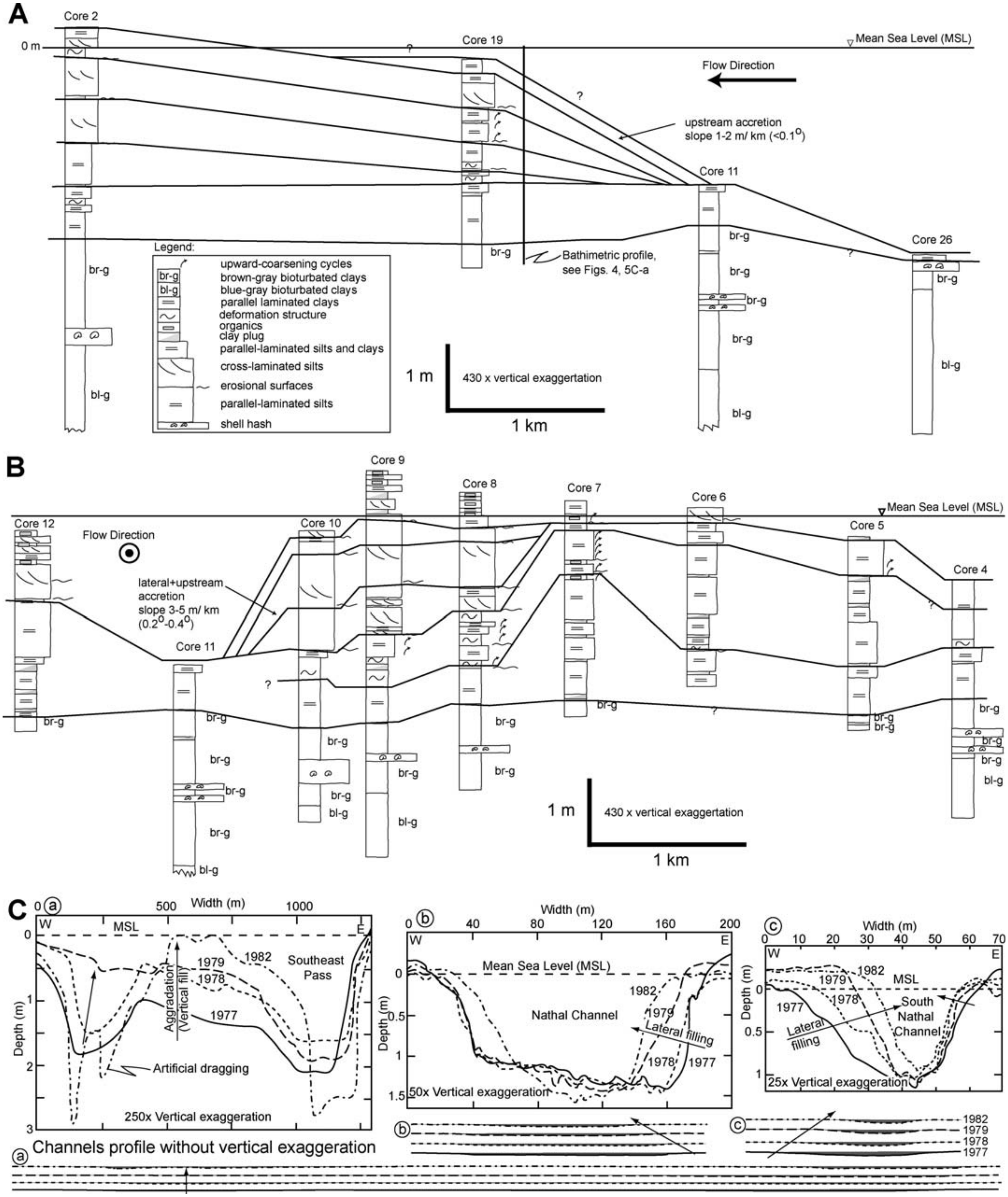

FIG. 5.—**A)** Dip-oriented cross section through eastern Atchafalaya Delta mouth-bar deposits (data from van Heerden 1983). **B)** Dip-oriented section through mouth-bar deposits (modified from van Heerden 1983). **C)** Variation of terminal distributary-channel profiles through time. The arrows on cross sectional profiles indicate accretion, or lateral infill as in exaggerated profiles. For locations of cross section and profile see Figure 4.

20 m (Overeem et al. 2003). The flow velocity and suspended-sediment concentration vary with position within the delta-front area, and this is reflected in sedimentation pattern and superficial recent sediment distribution in front of the delta (Fig. 7C). The sediment distribution indicates that sediments derived from terminal distributary channels form narrow ribbon patterns in front of the channels, but commonly these merge together (Fig. 7C).

A sedimentological study of the modern and recent delta front deposits, based on a large auger dataset (Overeem et al. 2003), indicates that terminal distributary channels have low to moderate sinuosity and contain the coarsest deposits in the system (fine sands 0.12–0.21 mm). The spatial variability of channel deposits in the subsurface is as high as in the modern delta, with ribbons tens of meters wide. Terminal distributary channels initially build subaqueous levees, a few kilometers long and tens of meters wide, with maximum topography of 1–2 m. Mouth-bar deposits are relatively thin (less than 1 m) with a coarsening-upward trend for regressive (forced regression) periods and a fining-upward trend for the transgressive period (Overeem et al. 2003).

Lena Delta.—The Lena Delta progrades into the Laptev Sea. The evolution of the delta was highly influenced by tectonic activity during the last 80,000 years (Are and Reimnitz 2000; Schwamborn et al. 2002). The Lena Delta has not been studied in detail, like the Atchafalaya and Caspian examples, but from analysis of the present morphology (Fig. 2) multiple terminal distributary channels can be observed. Most of the "trunk" channel ("Lena pipe") discharge is taken by the Trofimovskaya distributary toward the east (61%). This distributary also has most of the active network of terminal distributary channels (Fig. 2), and is associated with the most actively subsiding eastern part of the delta. Subsidence does not favor bifurcation directly but increases slope and thus increases discharge, which is reflected in a larger number of bifurcations. Terminal distributary channels are extremely shallow in the seaward part of the Trofimovskaya Channel (Fig. 8A), with water around 1 m deep for a few kilometers offshore (Are and Reimnitz 2000).

Changes in distributary-channel width were measured on a satellite image of the Lena Delta (Fig. 8B, C). The channel width decreases by splitting, but at different rates than was predicted by the equation, $B_k \approx 0.7B_{k+1}$ (Yalin 1992). The differences appear because the theoretical estimations were made for equilibrium channels, which distributary channels are not. The measurements of terminal distributary widths and inter-channel distances, along the delta shoreline (Fig. 8D) indicate that 200–400 m wide terminal distributary channels are the most frequent (Fig. 8E). Inter-channel distances of 200–500 m are the most frequent, with another high frequency at 800 m (Fig. 8E). The channel width and inter-channel distances may also be biased by the resolution of the satellite image, which cannot resolve channels less than about 100 m wide.

Ancient Deltas

Campanian Panther Tongue Delta.—Exposures of the Cretaceous Panther Tongue delta in Spring Canyon in central-northeast Utah, in the Book Cliffs, are oriented at different angles relative to paleoflow. Depositional strike and dip exposures of cliffs up to 30 m high through proximal delta-front deposits allow the 3-D facies architecture to be mapped (Fig. 9; Olariu et al. 2005). On strike-oriented cliff faces, terminal distributary channels were interpreted based on 3-D bedding diagrams, ground-penetrating-radar (GPR) profiles, and sedimentary sections (Olariu et al. 2005). The channelized features have low topography, with less than 4 m of relief, and are tens to hundreds of meters wide. Erosion of the channels into adjacent deposits is rare and typically appears only on one side of a given channel (Fig. 9A, B). The lateral migration and aggradation of the same terminal distributary channel compensates for differential topography. The lateral migration is on the order of hundreds of meters. During each lateral migration, the channels aggrade a few meters (Fig. 9C). The channels are infilled with fine to medium sandstone with structureless, trough-cross-laminated or parallel-laminated beds. Associated with terminal distributary channels are mouth-bar deposits, which are mostly formed from parallel-laminated and massive fine sandstones (Fig. 9D). Interbedded with the sandstone beds are silt to very fine sandstone beds with rippled or highly bioturbated tops. Ichnofacies (Olariu et al. 2005) represent the *Skolithos* or proximal *Cruziana* assemblages (Pemberton et al. 1992). Mouth-bar deposits infill the channels as they migrate laterally. On dip-oriented sections, beds are inclined in a basinward as well as a landward direction (Fig. 10B, C). The upstream-inclined beds are mostly structureless to parallel-laminated, fine- to medium-grained sandstones. These are interpreted to represent upstream growth of bars (Olariu et al. 2005), which infilled terminal distributary channels. From a limited number of dip-oriented exposures it is difficult to evaluate the direction of bar migration precisely, and it is probable that bars migrated laterally as well as in the upstream direction, as observed in the modern Atchafalaya Delta. The slope of upstream-inclined beds is around 12 degrees relative to the top of the outcrop, which, corrected for regional structural dip, corresponds to an angle between 2 and 7 degrees (Olariu et al. 2005). On an adjacent cliff face (Fig. 10B) we measured seaward dips of delta-front clinoforms between 1 and 8.2 degrees that is in general less than that of upstream-inclined surfaces (Fig. 10C) but steeper than the range of values of modern delta-front slopes (Coleman and Wright 1975).

Pennsylvanian Perrin Delta.—The Perrin Delta prograded into a Pennsylvanian cratonic basin, and is part of the Placid Formation of the Canyon Group, which consists of four thick limestones with interstratified clastic deposits (Brown et al. 1990). Delta deposits representing parts of the Perrin Delta crop out west of Wizard Wells, Texas (Fig. 11A). According to Brown et al. (1973), the Placid Formation consists of "high constructive" (i.e., river-dominated) elongate deltas, which are composed of highly contorted, superposed mouth-bar and distributary-channel sandstones. A photomosaic of the Wizard Wells outcrop oriented at a high angle to paleoflow (Fig. 11B, C) shows channelized features with low topographic expression. Growth faults and contorted beds present on the photomosaic (Fig. 11C, D) are syndepositional features associated with delta-front slides, similar to the Mississippi (Coleman et al. 1998). Channelized features are infilled mainly with trough cross-stratified fine sandstones with mudchips and plant fossils. Secondary, parallel-laminated or massive beds are also present (Fig. 11E). Parallel-laminated beds are interpreted as mouth-bar deposits and are finer than cross-stratified or massive beds. Classification of the channels as terminal distributary channels rather than fluvial channels is based on the presence of structureless sandstone deposits, fining up, turbidite-type beds indicating waning flows and wave ripples, which suggest a shallow-

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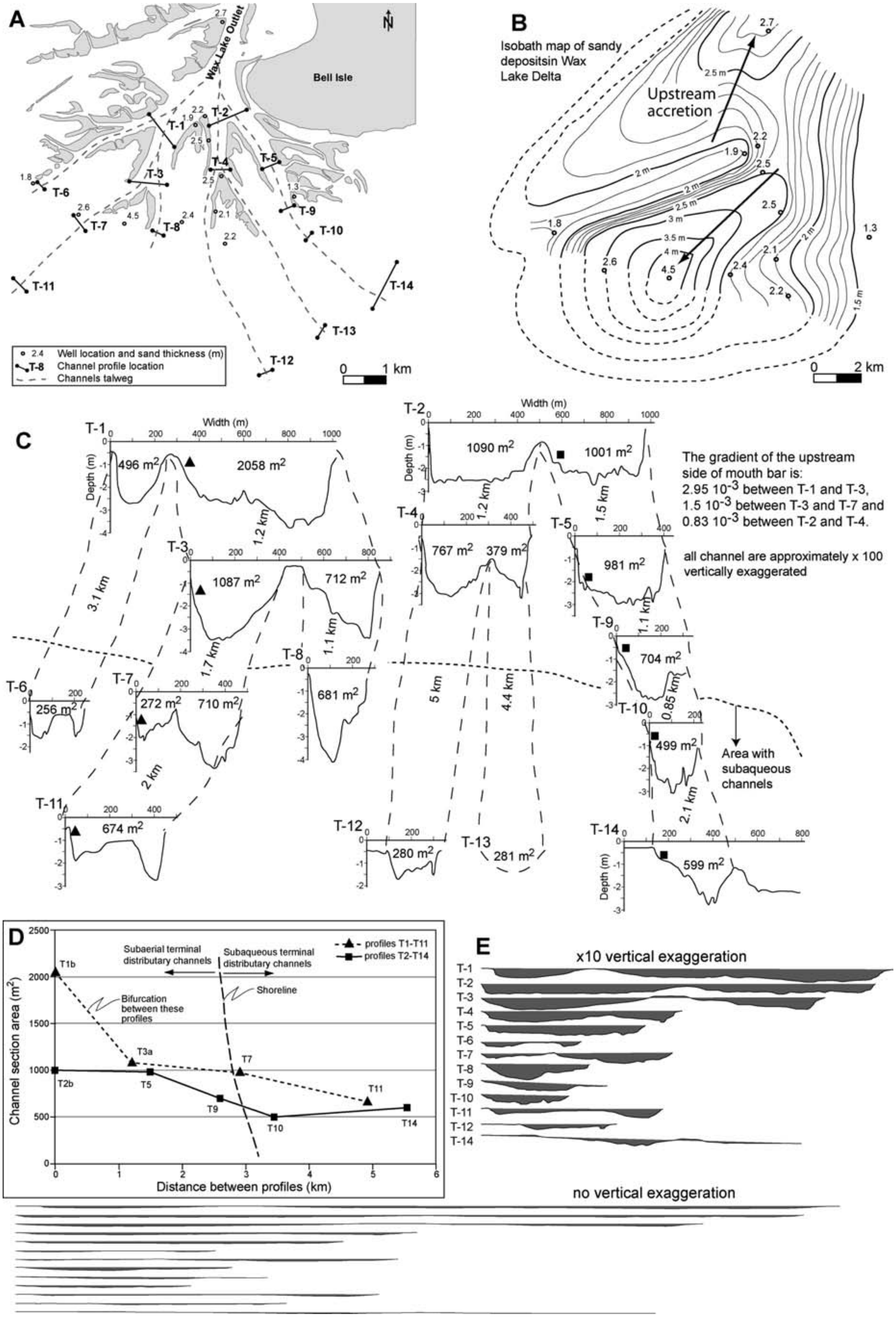
FIG. 6.—For Wax Lake Delta location see Figure 4A. **A)** Morphology of the Wax Lake Delta with location of channel transects (from DuMars 2002) and vibracores with sand thickness in meters (from Roberts 1998). **B)** Isopach of sandy deposits. Contour intervals are in meters. **C)** Terminal-distributary-channel sections, with characteristic profiles and area (modified after DuMars 2002). Triangle and square dots indicate profiles used for Part D. **D)** Variations in terminal-distributary-channel area downstream direction. For profile location see Parts A and C. **E)** Typical geometry of Wax Lake Delta terminal-distributary-channels cross sections, with 10 times vertical exaggeration and without vertical exaggeration.


A
Wax Lake Outlet
Bell Isle
T-1
T-2
T-3
T-4
T-5
T-6
T-7
T-8
T-9
T-10
T-11
T-12
T-13
T-14
Well location and sand thickness (m)
Channel profile location
Channels talweg
0 1 km
B
Isobath map of sandy depositsin Wax Lake Delta
Upstream accretion
0 2 km
C
Width (m)
Depth (m)
496 m2
2058 m2
1090 m2
1001 m2
767 m2
379 m2
981 m2
1087 m2
712 m2
704 m2
499 m2
256 m2
272 m2
710 m2
681 m2
674 m2
280 m2
281 m2
599 m2
3.1 km
1.2 km
1.5 km
1.7 km
1.1 km
5 km
4.4 km
0.85 km
2 km
2.1 km
The gradient of the upstream side of mouth bar is: 2.95 10-3 between T-1 and T-3, 1.5 10-3 between T-3 and T-7 and 0.83 10-3 between T-2 and T-4.
all channel are approximately x 100 vertically exaggerated
Area with subaqueous channels
D
Subaerial terminal distributary channels
Subaqueous terminal distributary channels
profiles T1-T11
profiles T2-T14
Bifurcation between these profiles
Shoreline
Channel section area (m2)
Distance between profiles (km)
E
x10 vertical exaggeration
no vertical exaggeration

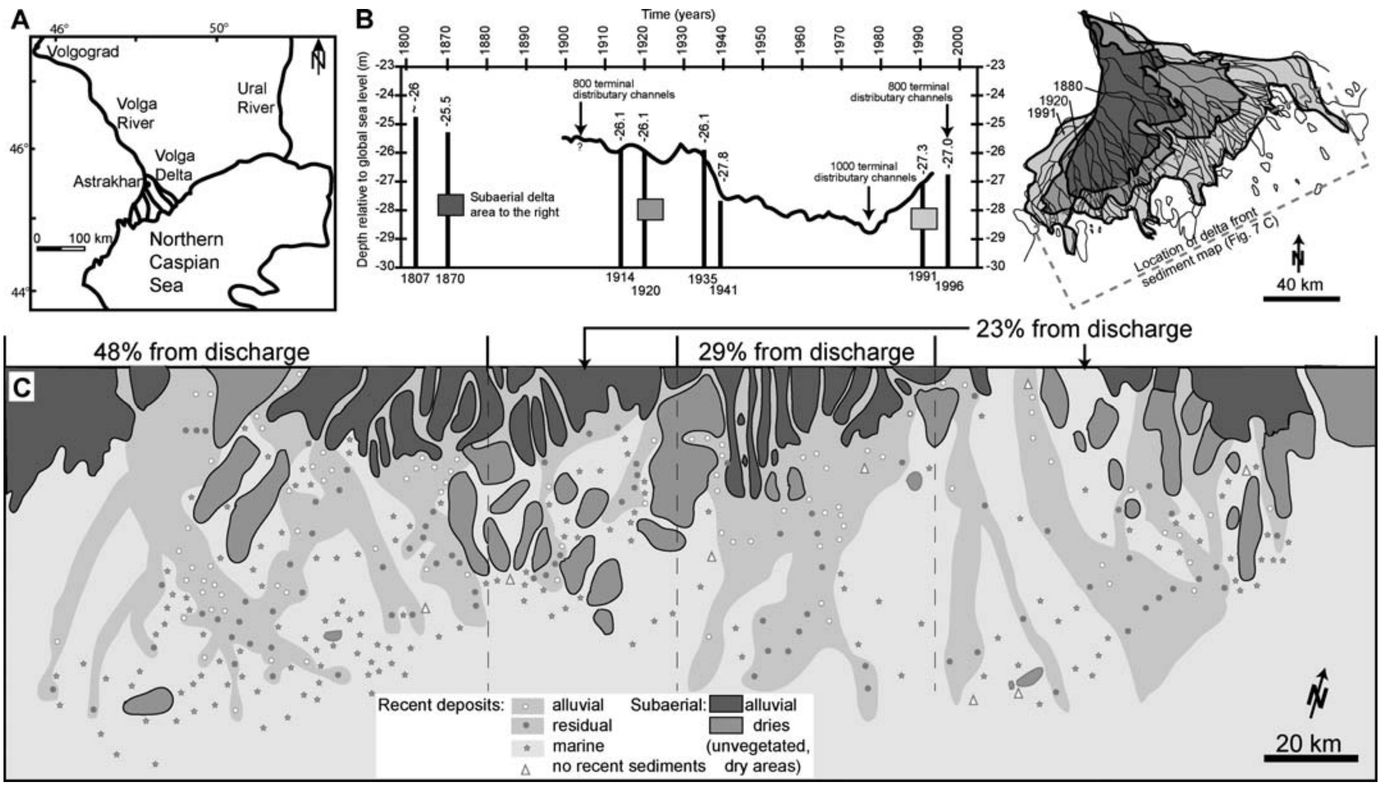


FIG. 7.— Modern Volga Delta. **A)** Location. **B)** Modern sea-level changes (modified after Alekseevskiy et al. 2000), with indication of relative number of terminal distributary channels; on the right map, each shade represents the relative extent of the delta at different stages. **C)** Map of recent sediments in the delta-front area (modified from Belevich 1969). The unvegetated dry areas have been exposed since the 1930 sea-level fall. Top of the figure shows percent of total discharge in different areas; the second and the fourth areas have together 23% of discharge.

water setting. Erosional cut banks of the channels are present only on one side, and mouth-bar migration infills the channel on the other side. These observations are similar to the terminal distributary channels seen in both the Panther Tongue and the modern examples described earlier.

Turonian Ferron Delta.—Large continuous outcrops of the Turonian Ferron Delta from east-central Utah have been extensively studied as outcrop analogs for river-dominated and wave-dominated delta reservoirs (Barton 1994; Gardner 1995; Corbeanu et al. 2001; Chidsey et al. 2004).

Based on outcrop observations, the Ferron Sandstone has been separated into seven major stratigraphic cycles (Ryer 1981) with different stacking patterns. Subsequent studies (Barton 1994) distinguished upward-coarsening facies successions separated by minor flooding surfaces, and were interpreted as delta-front deposits. The first three seaward-stepping progradational deltaic parasequences are interpreted as river dominated (Barton 1994). Given the relatively low number of bifurcations and limited number of distributary channels or channel belts mapped by different authors within the Ferron Delta, Bhattacharya and Tye (2004) suggested that all the parasequences have a strong wave influence. The first parasequence is indeed composed of multiple stacked and laterally extensive mouth-bar deposits (Barton 1994; Gardner et al. 2004; van den Berg and Garrison 2004) indicating a strong river influence, but these studies do not indicate the geometry of terminal distributary channels associated with the mouth bars. Barton (1994) described the mouth-bar deposits as consisting of bar-front, bar-flank, and bar-crest subdivisions. Bar-front deposits have characteristics of delta turbidite deposits, including convoluted strata, massive and thin graded beds exhibiting sharp bases and incomplete Bouma sequences, variable bioturbation, common ripple lamination, and hummocky cross stratification. Draped mudstone is laminated and contains plant debris and bioturbation. Bar flanks represent the area between the bar front and the bar crest, where the influence of waves is stronger; the characteristic sedimentary structures are massive to planar lamination, wavy lamination, and HCS. Bar-crest facies consist of amalgamated, unidirectional, high-angle cross-strata with poorly sorted material containing clay clasts and organic matter. Bar-crest facies consist of numerous reactivation surfaces and scour-and-fill structures. These deposits have a lenticular geometry that thickens over short distances into lenticular coarse-grained channel fills with distinct erosional bases. We suggest that the bar-crest facies, interpreted by Barton (1994) as the product of shallow channelized flows, represent terminal distributary channel facies.

Eocene Battfjellet Deltas.—Extensive outcrops of the Eocene Battfjellet Deltas in Spitsbergen show large, complete clinoforms on the paleoshelf edge (Steel et al. 2000; Plink-Björklund et al. 2001; Mellere et al. 2002). Facies described from the deltas include laminated and massive sandstones with erosional bases and rip-up clasts and coal debris that indicate scours and channels (Plink-Björklund et al. 2001; Mellere et al. 2002). Also current ripples and planar lamination intercalated with shales were interpreted as mouth bars (Mellere et al. 2002). The Battfjellet deposits were interpreted as shelf-edge deltas containing abundant hyperpycnal-flow deposits dispersed into the basin through multiple terminal distributary channels (Mellere et al. 2002). The terminal distributary channels which were connected to the distributary system are named by Mellere et al. (2002) as slope channels, because the delta front is prograding over the continental margin slope. The terminal distributary channels are up to 5 m deep, and 50–200 m wide and can be

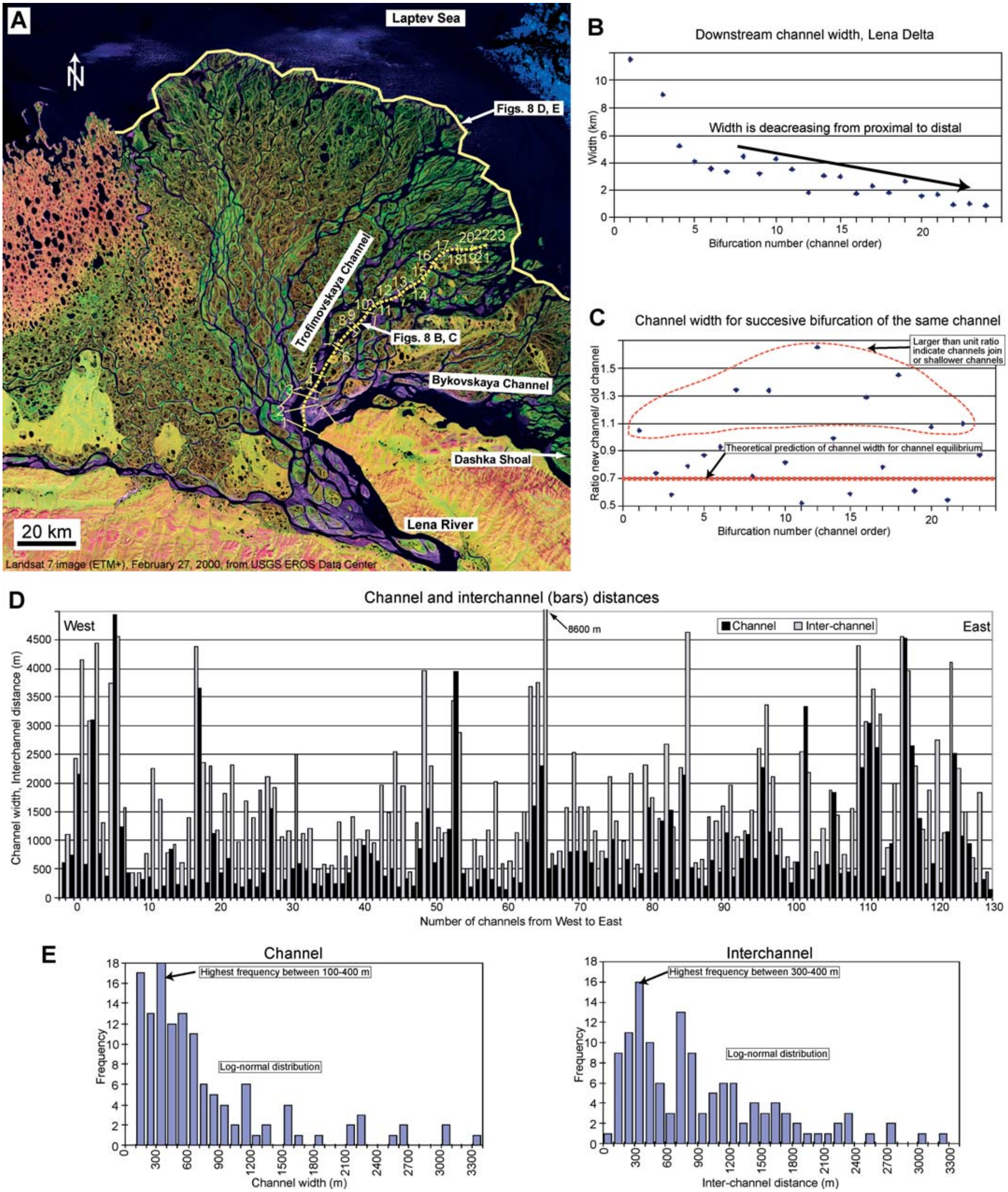


FIG. 8.—Variations in distributary channels in the Lena Delta. **A)** Measurement locations. **B)** Variation of the Trofimovskaya channel width after each bifurcation. **C)** Width ratio between new and old channels for each bifurcation. Values larger than 1 appear due to channel confluences or areas with shallower channels. Also all values seem to be overestimated, because measurements follow the largest branch. **D)** Plot of subaerial mouth-bar width and the adjacent distributary channel along the shoreline; see Part A for transect location. **E)** Frequency distribution for terminal-distributary-channel widths and distances between distributary channels.

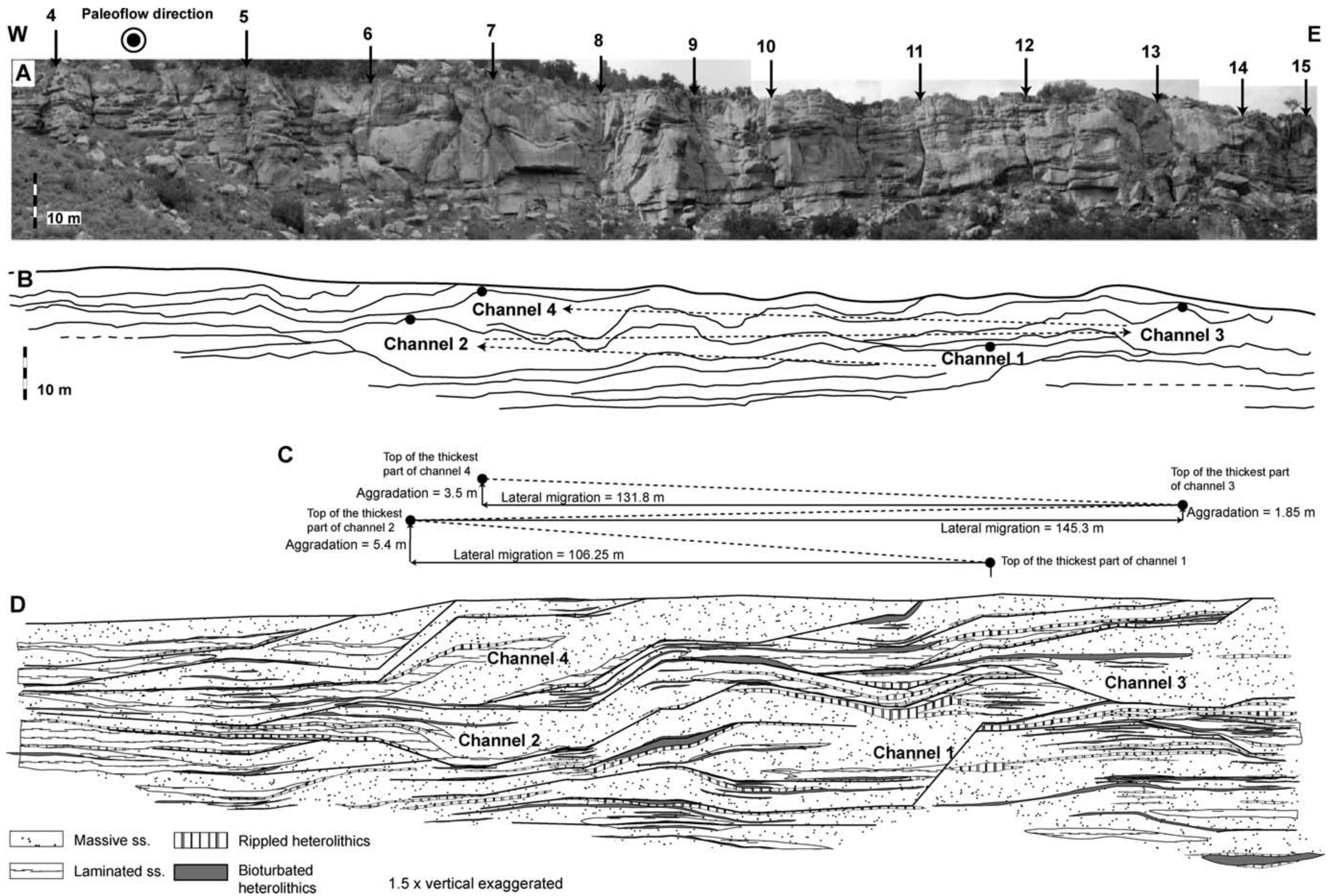


FIG. 9.—**A)** Strike-oriented photomosaic of the Cretaceous Panther Tongue sandstone, Utah. For location see Figure 10A; numbers along the top of the photomosaic indicate the location of the measured sections. **B)** Bedding diagram showing terminal distributary channels. **C)** Terminal-distributary-channel evolution, vertical aggradation and lateral migration for the same terminal distributary channels. Interpretation was considered between points where channel was stable for a longer time (reflected in thicker deposits and erosional margins). **D)** Mapped facies of terminal distributary channels and mouth bars (modified after Olariu et al. 2005).

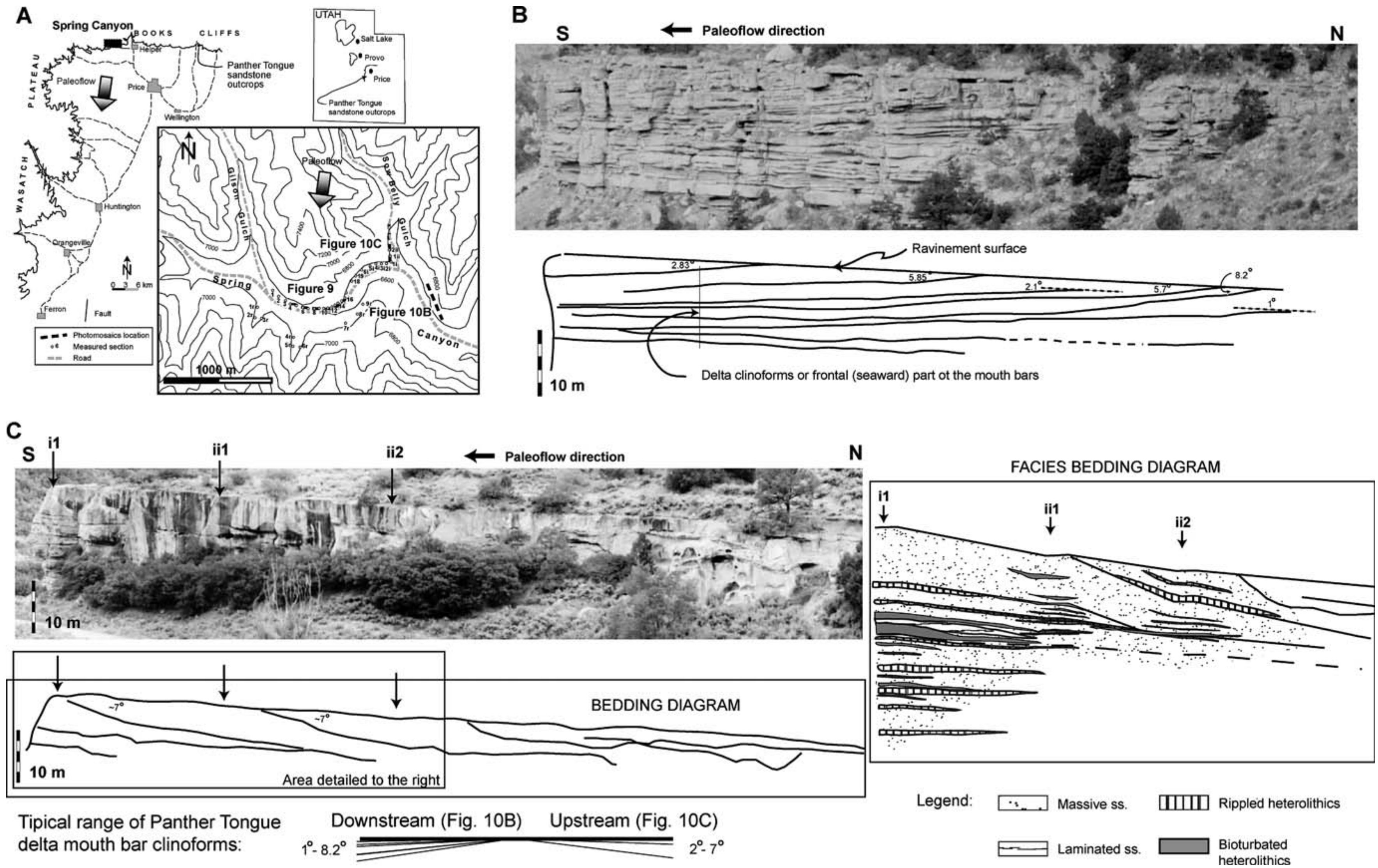


FIG. 10.—**A)** Location map of Panther Tongue outcrops. **B)** Dip-oriented photomosaic and bedding diagram showing seaward-dipping clinoforms. Clinoforms have angles between 1 and 9 degrees relative to the ravinement surface (paleohorizontal). **C)** Dip-oriented photomosaic, bedding diagram, and mapped facies of upstream aggradation of mouth-bar deposits. Numbers along the top of the photomosaic indicate the location of the measured sections.

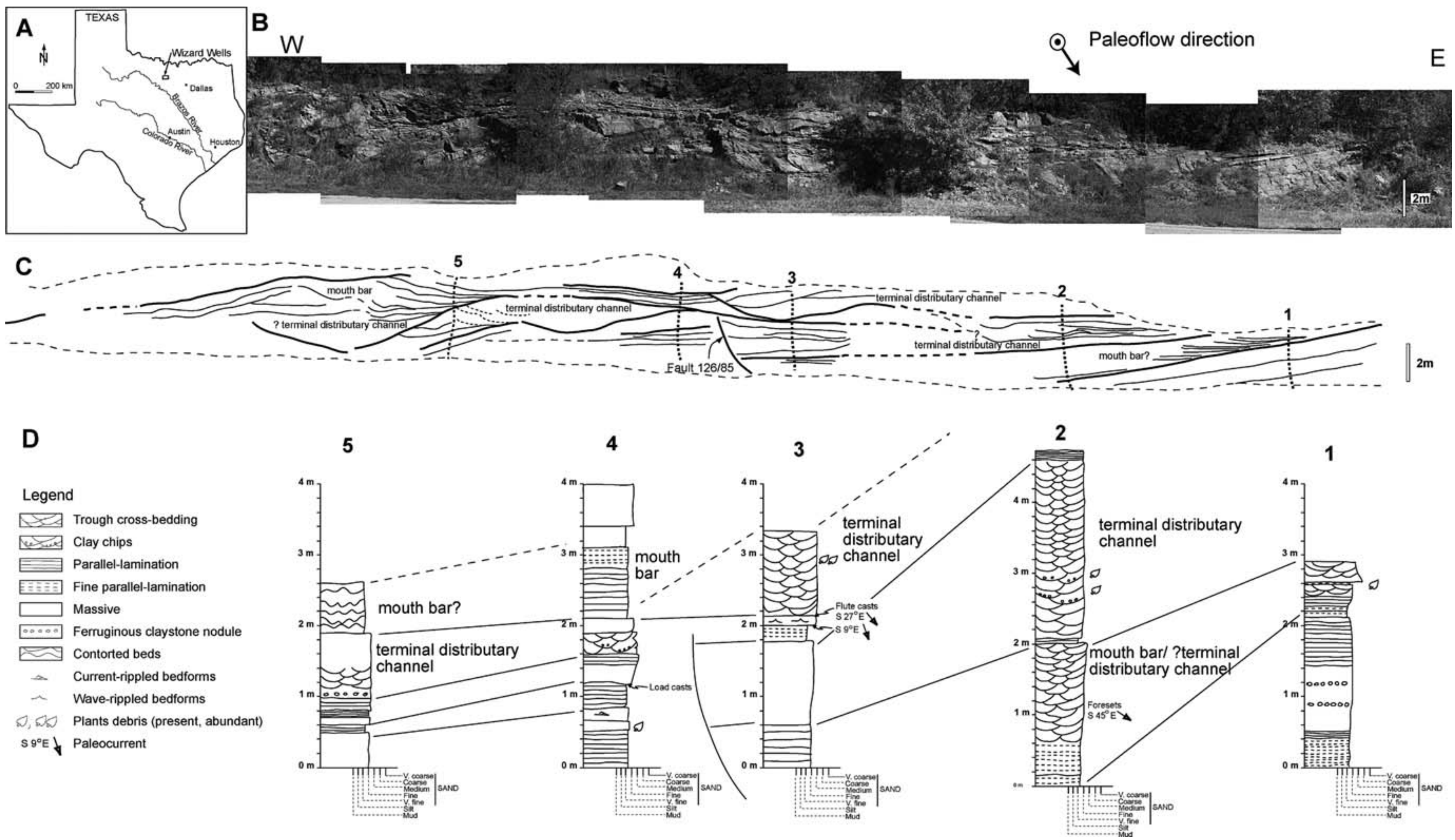


FIG. 11.—Outcrop example of terminal distributary channels in the Pennsylvanian Placid Shale Formation, Texas, U.S.A. **A)** Location map. **B)** Photomosaic oriented oblique to the paleoflow. **C)** Bedding diagram with location of measured sections. **D)** Measured sections and interpretations with distinction of mouth-bar and terminal-distributary-channel facies.

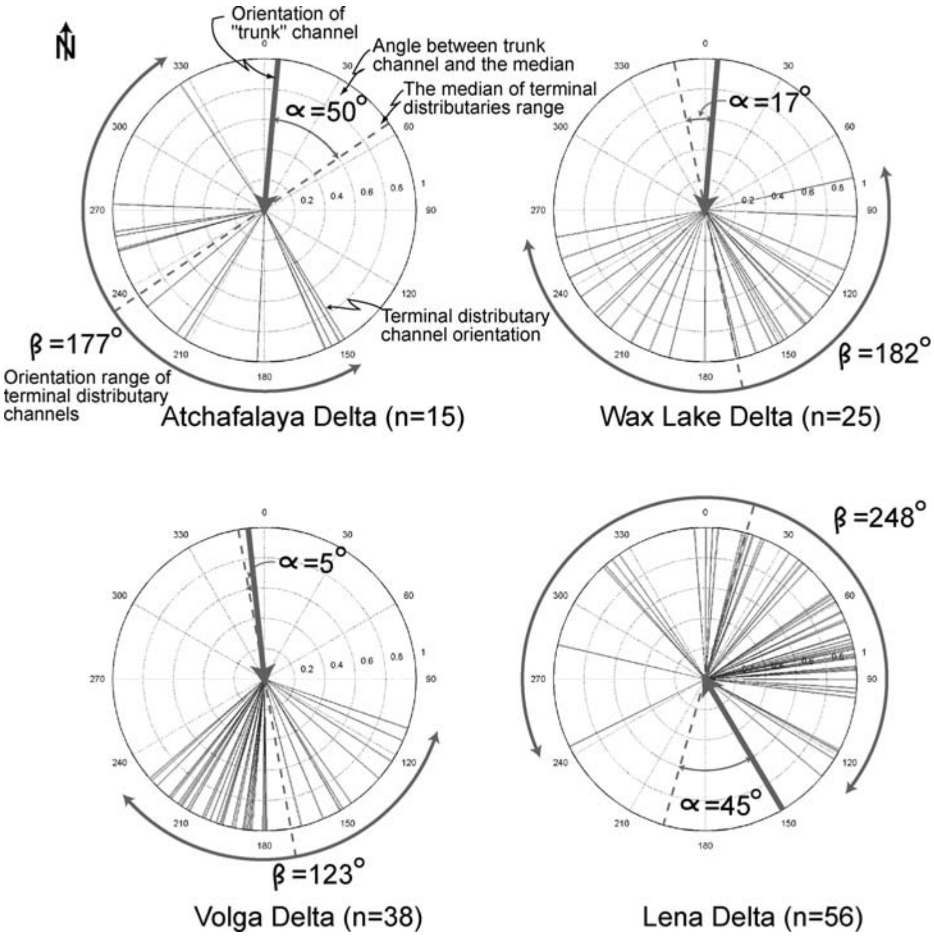


FIG. 12.—Orientation of terminal distributary channels in modern deltas; overall range of terminal distributary channel orientations (β) and the angle between median orientation of terminal distributary channels and the "trunk" channel (α). Zero is north for all the deltas. See Figure 2 for entire distributary pattern.

as narrow as 40 m on the distal slope (Mellere et al. 2002), but their distribution was not mapped in detail. The water depth for the active channels was about 50 m, which is considerably deeper than the previous examples.

SUMMARY OF EXAMPLES OF TERMINAL DISTRIBUTARYCHANNELS

Dimensions of Terminal Distributary Channels

The delta examples presented have shallow and narrow terminal distributary channels, and represent a small fraction of the "trunk" channel as the channel cross section decreases downstream due to multiple bifurcations (Fig. 8). Widths of terminal distributary channels vary between tens of meters to more than one kilometer, but the common width observed was in the range of 100–400 m (Figs. 4, 6, 8). The depths of terminal distributary channels range between 1 and 3 m, with width-to-depth ratios of about 100. No dimensional changes were observed in the transition from subaerial to subaqueous terminal distributary channels (Fig. 6). Within modern shallow-water deltas there are typically tens to hundreds of active terminal distributary channels, and the channel density reached up to 6, 4, and 3 channels/km for the Volga, Lena, and Atchafalaya deltas, respectively.

Orientation of Terminal Distributary Channels Relative to the "Trunk" Channel

The number of distributary channels increases from the delta apex to the shoreline (Fig. 2), and the number of active terminal distributary channels increases as the deltas progrades. With increase of terminal distributary channel the angle range relative to the "trunk" channel axis increases (Fig. 2). The orientations of terminal distributary channels range between 123° for the Volga Delta and 248° for the Lena Delta (Fig. 12). The median orientation of terminal distributary channels might be at a high angle relative to the main "trunk" channel: 50° in case of the Atchafalaya Delta (Fig. 12). Preferred channel orientation might be due to local tectonic factors such as higher subsidence. In the case of a high angle between the "trunk" channel and the median of the orientation of the terminal distributary channels (Fig. 12), this might be the result of basin topography and/or regional geological structures.

Formation and Evolution of Terminal Distributary Channels

Formation of terminal distributary channels is related to channel-mouth processes. Mouth-bar deposits form as the flow condition at the channel mouth changes from confined to unconfined and velocity decreases (Albertson et al. 1950; Bates 1953; Wright 1977). The initial mouth bar forms close to the channel axis and bifurcates the channel flow (Figs. 4, 5, 6). Based on the modern examples presented, several stages of evolution of terminal distributary channels have been differentiated and are closely related to mouth-bar evolution (Fig. 13). In phase one, new terminal distributary channels are formed by extension of subaqueous channel levees, widening of the channel, and bifurcation of the flows because of mouth-bar formation (Fig. 13). In phase two, the growth and migration of a mouth bar (lateral and upstream accretion) forms terminal distributary channels at different scales. In phase three, preferential mouth-bar accretion and filling of terminal distributary channels reduces the flow velocity and sediment discharge through that channel, which

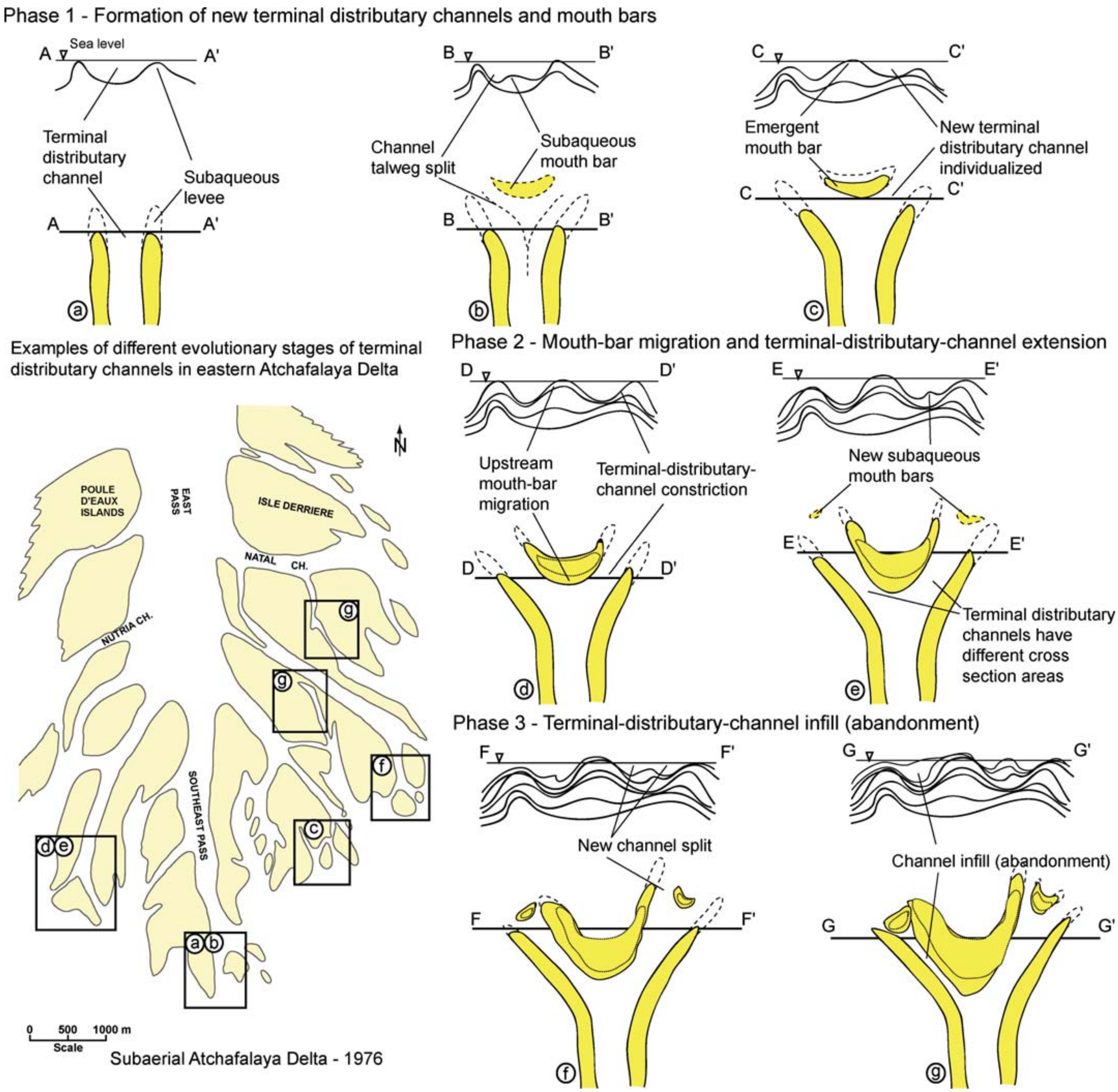


FIG. 13.—Conceptional formation and evolution of a terminal distributary channel mouth bar system (based on Axelsson 1967; Baydin 1970; van Heerden 1983; and examples presented). Three main phases of evolution have been distinguished: (1) formation of new terminal distributary channels and mouth bars; (2) migration of mouth bars and extension of terminal distributary channels; and (3) abandonment of terminal distributary channels. Dotted lines represent subaqueous features.

eventually is abandoned. Some of the terminal distributary channels bifurcate again and form another generation (order) of terminal distributary channels (Fig. 13).

These evolutionary phases become faster or slower in different areas of the delta as a consequence of gradient changes through time because of deposition or allocyclic factors. With each new cycle of mouth-bar formation, the terminal distributary channels become shallower and frictional processes of the river effluent (Wright 1977) increase as the system tries to carry bedload (sediment in traction and saltation) farther into the basin. Because mouth bars grow laterally, cross sections of terminal distributary channels become smaller and grain size decreases as flow capacity decreases after a critical stage is reached. Concomitantly with flow decrease in one terminal distributary channel, the flow is diverted toward another active terminal distributary channel or a new one is formed. This process might have a short recurrence time, even a few years, as was observed in the case of the Atchafalaya Delta (Fig. 4).

TABLE 1.—*Characteristic facies for terminal distributary channels and mouth bars in ancient deposits.*

FACIES	LOCATION		
	CAMPANIAN PANTHER TONGUE (Olariu et al. 2005)	PENNSYLVANIAN PERRIN DELTA (this study)	TURONIAN FERRON DELTA (Barton 1994)
TERMINAL DISTRIBUTARY CHANNELS	Fine to medium sandstone; massive, trough cross-stratified and parallel-laminated; variable bioturbation intensity with high bioturbation at the top of the beds; drag casts.	Trough cross-stratified fine sandstone, secondary parallel-laminated or massive; mud chips and plant fossils are common, load casts and drag casts are common.	Convoluted strata, massive and thin graded beds, sharp bases, variable bioturbation. Common ripple lamination and hummocky cross stratification. Laminated mudstone with plant debris and bioturbation.
MOUTH BAR	Fine sandstone parallel-laminated and massive; very fine sandstone to silt; highly bioturbated silty tops.	Parallel-laminated or massive very fine sandstone, low bioturbation.	Amalgamated, high-angle cross strata, clay clasts, and organic matter.

The cyclicity of formation and evolution of mouth bars and terminal distributary channels is controlled by: (1) the ratio of bedload to suspended load, (2) the amplitude of variation of seasonal river discharge, and (3) the accommodation (depth of the basin) relative to river sediment load. The cycle of lobe evolution is shorter for rivers with high bedload, high amplitude of discharge variation, and low accommodation (e.g., shallow water).

Sedimentary Facies of Terminal Distributary Channels

In the previous examples (Figs. 9, 10, 11) upward-thickening and -coarsening delta-front deposits have terminal-distributary-channel facies interbedded with mouth-bar deposits. In general, mouth bars have different sedimentary structures compared to terminal distributary channels (Table 1). Terminal distributary channels have the coarsest grain sizes, with common trough cross-beds and rip-up mud chip rip-ups. The ancient outcrop examples indicate that sedimentary structures from terminal-distributary-channel facies partially overlap the mouth bar, but the geometry of beds is different. More tabular beds with graded grain-size variation are observed for mouth bars, whereas terminal distributary channels have variable low topography, might have erosional boundaries, and are bounded by planar beds with low topographic expression (Figs. 9, 11). Channel incision into previous mouth-bar or delta-front deposits is very modest within the modern and ancient deltas presented. Erosion of terminal distributary channels was commonly observed only on a single side (Figs. 4, 5, 9, 11), and is probably produced by lateral channel migration. Trough cross-beds are formed by confined flow on the back side of the bar in terminal distributary channels. Because terminal distributary channels are decreasing in size basinward, it is expected that terminal-distributary-channel facies should be more common in the proximal delta front, with mouth-bar facies occurrence increasing in the distal delta front.

DISCUSSION

The presence of terminal distributary channels has implications for the facies architecture of river-dominated deltas and interpretation of ancient delta deposits.

Architecture of River-Dominated Delta Facies

The modern Mississippi Delta is typically presented as the classic river-dominated delta (Galloway 1975; Coleman and Wright 1975). Other river-dominated deltas with different morphology, which are seldom used as modern analogs, include the modern Volga, Lena, and Atchafalaya Bay deltas. All these deltas are river-dominated, because they prograde into basins with low tides and low wave energy. These aforementioned deltas have tens to hundreds of small terminal distributary channels (Figs. 2, 4, 6, 7, 8) and do not have large "finger like" sand bodies (Fisk 1961) but rather small mouth bars merged together within an overall lobate shape (Figs. 4, 6B, 9, 10, 11).

The previous Mississippi delta lobes have been mapped as lobate and interpreted to have multiple terminal distributary channels, despite the fact that these terminal channels were not mapped in detail (Frazier 1967). In the Pleistocene Lagniappe Delta, a network of small distributary channels that build a succession of overlapped lobes has been inferred (Roberts et al. 2004). The distinction between elongate (deep water) versus lobate (shoal water) river-dominated deltas was made by Fisher et al. (1969). The difference is interpreted to relate to accommodation. The Mississippi is a shelf-edge delta, prograding into deep water, and the recurrence time for bifurcation and lobe switching of terminal distributary channels is long (hundreds to thousands years), mainly because of compaction, allowing channels to extend and to accumulate relatively coarse sediments as elongate sand bodies. Other shelf-edge deltas that form mouth bars and delta distributaries disperse the sediments through multiple small terminal distributary channels which extend to the slope as a function of the steep gradient (Steel et al. 2000; Plink-Björklund et al. 2001; Mellere et al. 2002). The presence of multiple terminal distributary channels on the Eocene Battfjellet deltas in Spitsbergen (Steel et al. 2000; Plink-Björklund et al. 2001; Mellere et al. 2002) compared to the modern Mississippi Delta might be related to the higher percentage of bedload and more frequent hyperpycnal flows in the case of Spitsbergen deltas.

Shoal-water deltas typically are lobate and have more outlets than deep-water deltas, relative to their discharges. This reflects a much shorter recurrence interval of bifurcation and avulsion, typically less than 100 years. In the case of the Atchafalaya and Wax Lake deltas, each has more than ten terminal distributary channels (Fig. 2) formed in less than a century. Classification of river-dominated deltas needs to include deltas with multiple terminal distributary channels with patterns similar to the modern shallow-water deltas presented (Fig. 2) or older Mississippi Delta lobes. The sand-body distribution of river-dominated deltas can also have a lobate shape, similar to wave-dominated deltas, as presented by Coleman and Wright (1975). The lobate sand body of a delta is built by coalescence of multiple terminal distributary channels and mouth bars (Figs. 7, 9, 11) and has a facies architecture different from that of the elongate or digitate deltas, which are more commonly described for subsurface river-dominated deltas (Fig. 14). The two types of deposits do not necessarily have significant differences in the succession of vertical facies, but the architecture is different, with significant difference in facies thickness. Lobate river deltas have high lateral variability with multiple terminal distributary channels interbedded with mouth bars, whereas in digitate deltas the channel is stable and generates stacked mouth-bar deposits. Elongate deltas typically produce thicker deposits than lobate river deltas, because in the latter the sediments are spread out into the basin (Fig. 14).

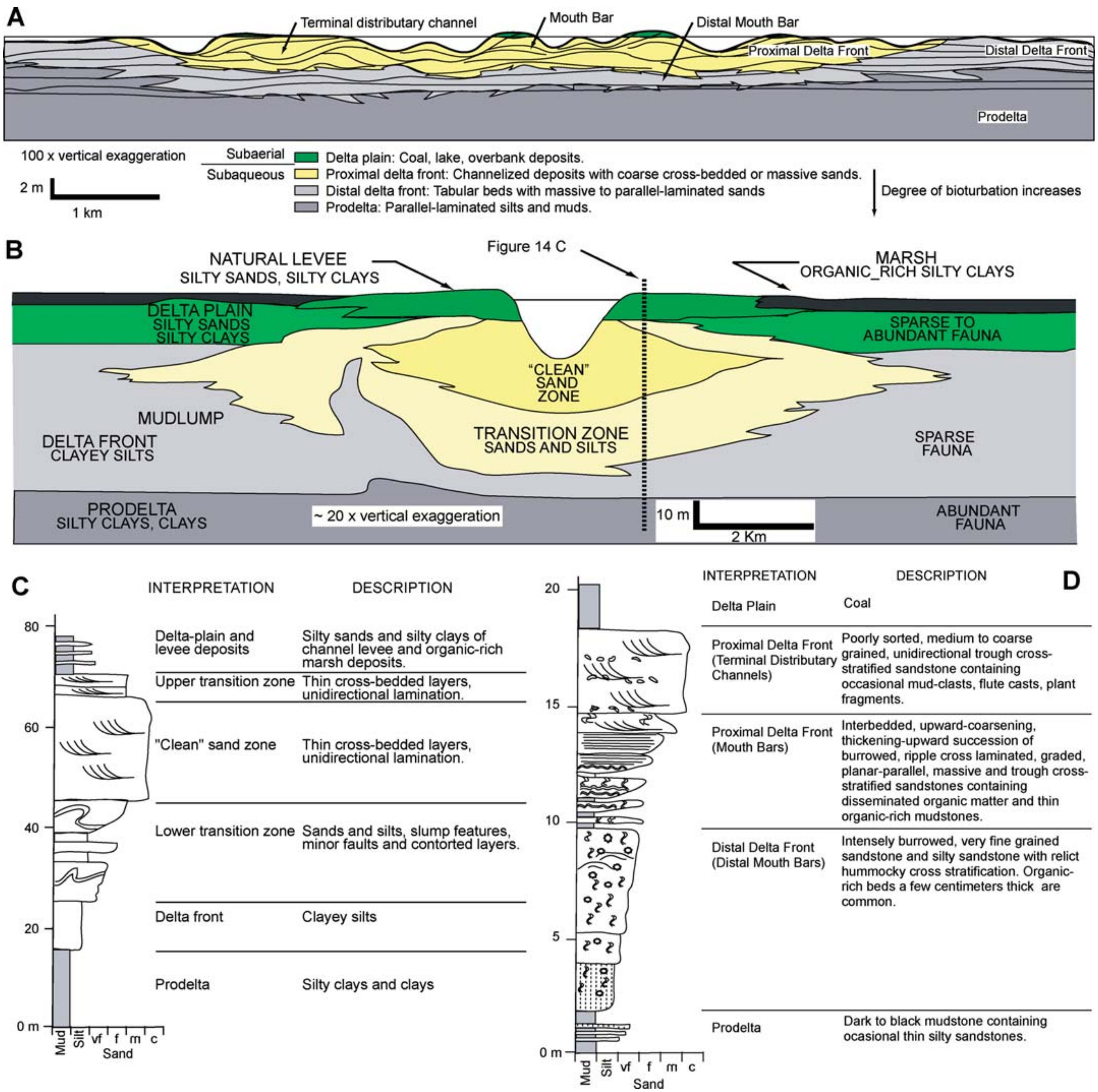


FIG. 14.— Comparison between digitate and lobate river-dominated deltas. **A)** Strike cross section through lobate river-dominated delta compiled from modern examples (Wax Lake Delta, Atchafalaya) for horizontal scale, and from ancient examples (Panther Tongue, Perrin Delta) for internal architecture. **B)** Bar-finger deposits of a digitate delta (Fisk 1961); note that the active channel is about 20% of sandbody thickness. **C)** Vertical section through digitate delta; for location see Part B. **D)** Vertical section of a lobate river-dominated delta (modified after Barton 1994). Note the thickness differences between digitate (C) and lobate (D) vertical sections.

Implications of Presence of Multiple Terminal Distributary Channels on Delta-Front Deposits

Numbers of Distributaries in Different Delta Types.—In river-dominated deltas, channel bifurcation and avulsion are common because sediment deposited at the river mouth is not removed by basin processes and the growth rates of mouth bars are high. Strongly wave-modified deltas tend to have only a few distributary channels, for the simple reason that waves remove material supplied to the coastline, thus inhibiting progradation and channel bifurcation (Bhattacharya and Giosan 2003; Bhattacharya and Tye 2004). In tidal deltas, tides maintain a reduced number of distributaries by increasing sediment dispersion because of amplification of the river current, especially during ebb tides.

However, in a delta, low-order, delta-plain distributary channels can be stable for long periods (i.e., enough time for initially straight channels to become highly sinuous) and have high preservation potential due to high sedimentation rates associated with large accommodation. The cause of the presence of multiple relatively stable large distributaries might be that the channel gradient is similar among distributaries, and their relatively long path to the basin requires a long time to change the channel gradient in order to capture a more significant part of discharge than other distributaries. In contrast, evolution of terminal distributary channels is more dynamic and is controlled by mouth-bar growth and migration. Mouth bars usually fill the terminal distributary channels by narrowing the channel section from a single side (Figs. 4, 5, 9, 11).

Because processes of formation of terminal distributary channels and mouth bars are not well understood, most numerical modeling programs, which mainly use process-based equations, have a simplistic approach for changes in sediment source. Most programs use stochastic methods (Syvitski and Daughney 1992; Slingerland et al. 1994) or lateral migration of a single channel (Tetzlaff and Harbaugh 1989) to describe the change of sediment source within a delta, which commonly is expressed as bifurcation or avulsion of distributary channels. The model proposed in this paper indicates that numerical models of dispersive systems also need to incorporate coeval multiple-scale terminal distributary channels.

Sand-Body Geometry.—The number of terminal distributary channels controls the distribution of sediment in the delta-front area and, as a consequence, sand-body geometry, as well as the overall shape of the shoreline. In the case of multiple terminal distributary channels, the distribution of sediments into the basin is rather more linear and forms an "apron" of sand deposits.

Sand-body geometries associated with modern deltas were described by Coleman and Wright (1975), but the number of terminal distributary channels associated with different sand-body morphologies was not indicated. If we associate the number of terminal distributary channels with typical sand bodies from modern deltas (Fig. 15), it is clear that elongate, Mississippi-type sand bodies are rather unusual for river-dominated deltas, but are more common for tide-dominated systems or even for highly asymmetrical wave-influenced systems. This reflects reworking of mouth-bar deposits by ocean processes, and the possibility of relatively stable channels for a long time. A low number of bifurcations can be found in wave-dominated systems with only one or two stable distributaries, followed by tide-dominated deltas with a few to tens of terminal distributary channels (Fig. 15). Actually the most tide-influenced deltas have many tidal channels but only one or two active distributary-mouth outlets, which might be stable for thousands of years (Tanabe et al. 2003). River-dominated systems may have multiple (hundreds of) terminal distributary channels and a lobate shape (Figs. 2, 15) similar to that described by Fisher et al. (1969) as shoal-water river-dominated deltas. The lobate shape of the sand bodies is formed because of successive bifurcation, avulsion, and increasing angle of dispersion. The orientation of terminal distributary channels may show a large variation within the same system. From the apex angle, which can be up to 180 degrees in the case of the Lena Delta (Fig. 2), it can be deduced that distributary channels in the same systems can be oriented at angles of more that 180 degrees (Fig. 12).

When the distributary system (i.e., delta) is not able to adjust to the increased friction, the main channel avulses and a new distributive system (sub-delta) is formed. This is a fundamentally autogenic process that drives avulsion in distributive depositional systems and causes lobe switching. In reality, compaction and tectonics interfere with autogenic processes in the distributive system. The position of the high-discharge channel within the system can change suddenly or can be stable for a longer time than can be predicted only from river-mouth processes (e.g., Mekong). Tidal reworking has allowed the distributary channels of the Mekong to be stable for over 1000 years (Tanabe et al. 2003).

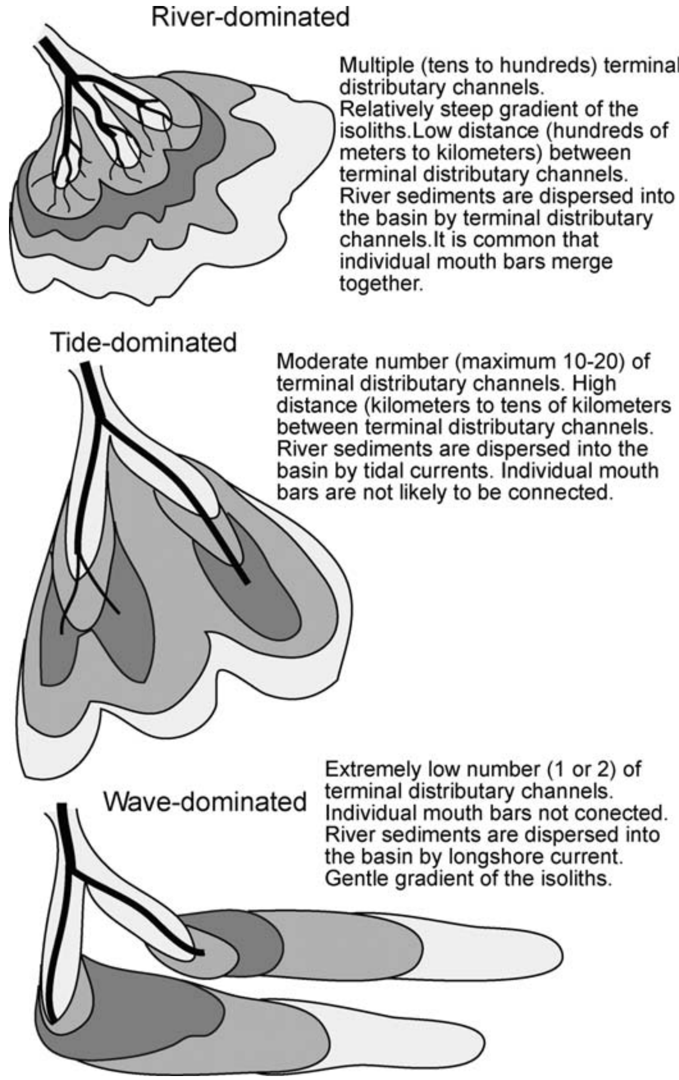


FIG. 15.—The shape of sand bodies for the main energy factors encountered in delta systems and expected number of terminal distributary channels. The shading/color pattern represents the relative thickness of deposits; thicker deposits are darker.

Mississippi Delta as an Analog.—Use of the Mississippi Delta as a modern analog to interpret ancient delta deposits (Fall River, Booch) might be erroneous. Because of the analogy with the Mississippi Delta, sand bodies with elongated patterns were interpreted as river-dominated deltas (Fig. 1). Most of the deposits interpreted as deltaic (Fall River, Booch) have recently been reinterpreted as incised valleys (Willis 1997).

The main argument against interpretation of elongate sand bodies as delta distributaries is that a single delta deposit has a lobate shape with decreasing grain size away from the source, and it is not an isolated sand body without its fringing lobe. The elongate shape of the sandstone can be explained by migration of successive lobes basinward, but this model is difficult to accept without environmental conditions similar to the Mississippi, or without strong structural control (e.g., Bhattacharya and Willis 2001). In fact, the Mississippi is an exception rather than a common analog for most ancient deltas because it drains a continent, discharges into a basin with a narrow shelf, and recently has been largely held in place by the U.S. Army Corps of Engineers.

Implications for Interpretation of Ancient Deposits

Recognizing Ancient Terminal Distributary Channels within River-Dominated Delta Fronts.—The delta front is the most dynamic deltaic setting. Processes acting on the delta front, which produce and define the architecture of deposits, are distinct from processes in adjacent deltaic areas; therefore, the resulting deposits have distinct characteristics compared with coeval delta-plain or prodelta deposits. Mouth bars and terminal distributary channels are the main component of river-dominated delta fronts, and describing the formation and evolution of these is critical for understanding (1) the dominant processes (i.e., fluvial vs. wave vs. tides) of sediment partitioning and (2) heterogeneities associated with delta growth.

However, identification of terminal distributary channels in ancient delta deposits is not trivial because of (1) the relatively low topographic expression of these features and (2) the different types of sedimentary structures (i.e., fluvial and marine), which create complex facies interfingering (Figs. 9, 10, 11; Table 1).

Sedimentary Facies Distinction of Terminal Distributary Channels.—Mouth-bar deposits are inseparable from terminal-distributary-channel deposits because the mouth bars infill the channels. There are also examples of passive, mud-filled distributary channels caused by flow decrease and channel abandonment in the Atchafalaya Delta (van Heerden and Roberts 1988).

Terminal-distributary-channel deposits are influenced by marine basin processes, such as waves and tides. Commonly, the influence of basin factors appears upstream of the last bifurcation. We still call these channels terminal distributary channels because, in ancient deposits, the influence of basin factors indicates that the channel is relatively close to the shoreline (the end of a delta distributive system). Thus, in ancient systems, terminal distributary channels can be distinguished based on the presence of sedimentary structures associated with basinal processes (waves, tides). Van den Berg and Garrison (2004) separated proximal and distal distributary channels in outcrops of the Cretaceous Ferron Delta on the basis of relative position, approximately 10 km, to the paleoshoreline. This approach might be useful where detailed paleogeographic reconstructions are available, but it is still desirable to rely on the presence of sedimentary structures such as symmetric wave ripples, HCS, and flaser bedding, rather than to a given distance from the shoreline, which might be highly variable for any given delta. Tidal signatures might be confusing in macrotidal environments, where tides can occur upstream as far as the apex of the delta. The presence of wave-formed sedimentary structures are the most useful to distinguish the subaqueous parts of terminal distributary channels.

Characteristic features of terminal-distributary-channel deposits are an assemblage of (1) continuous channelized flows with trough cross-beds, mudchips, and continent-derived organic matter, (2) flow-waning structures with graded (turbidite type) beds, structureless sandstone beds, and mud-capped sandstone beds, (3) sedimentary structures associated with waves (symmetric ripples, HCS) and tides (e.g., flaser bedding; Table 1). High-energy marine ichnofossil assemblages of *Skolithos* or proximal *Cruziana* also may be associated with terminal-distributary-channel deposits. The ichnofacies distribution appears to be cyclic, with highly bioturbated beds associated with periods of low discharge (Olariu et al. 2005).

Recognition and Preservation of Small-Scale Terminal Distributary Channels: Implications for Distinguishing Wave-Dominated and River-Dominated Deltas.—In subsurface settings, terminal distributary channels, while potentially important in controlling complex facies architecture, are typically too small to map or resolve within a mapped delta lobe. Despite mapping of large-scale valley and "trunk" rivers in the Dunvegan

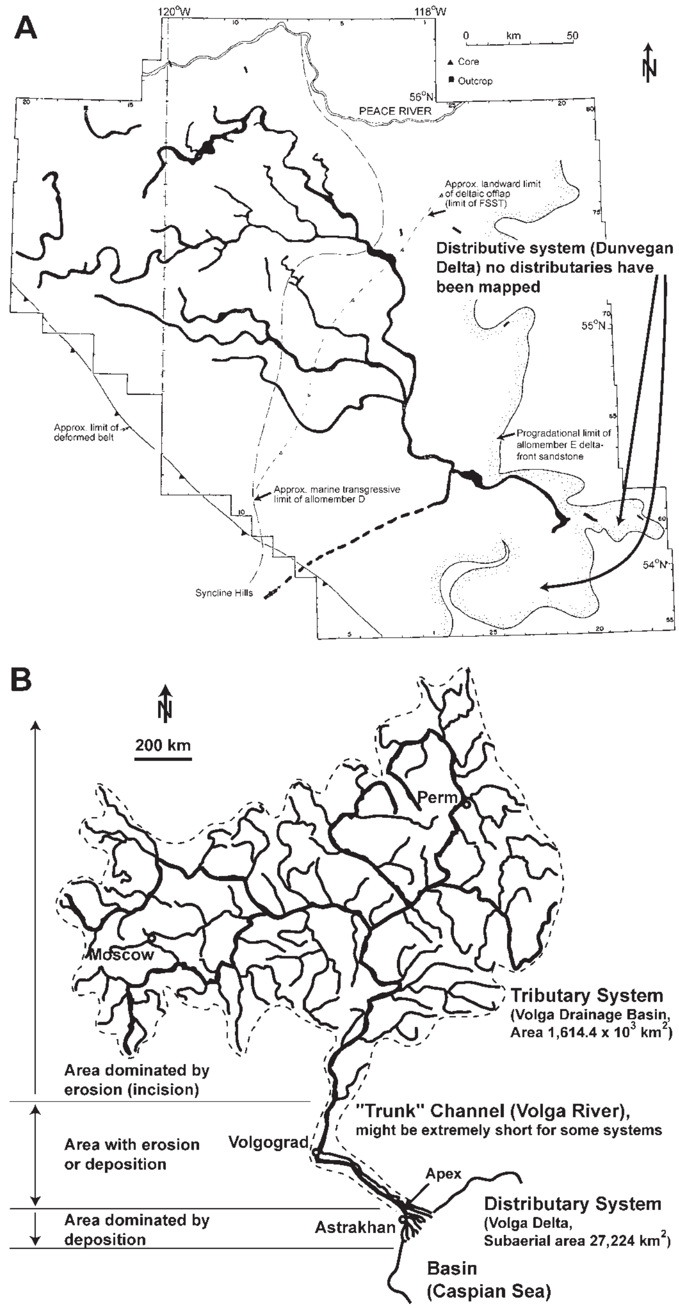


FIG. 16.— **A)** Example of a tributary–distributary system, Volga basin. The tributary pattern is an order of magnitude larger (tens to hundreds of times) than the distributary pattern; the main "trunk" valley connects the two patterns. (modified after Payne et al. 1975). **B)** The main fluvial system in Dunvegan River lacks details of distributary pattern because distributary channels are too small to image (from Plint and Wadsworth 2003).

Formation (Fig. 16A; Plint and Wadsworth 2003) or the Ferron Sandstone (e.g., Chidsey et al. 2004), these typically are shown as stopping tens of kilometers landward of the shoreline. Based on thousands of well logs, outcrop, and core data, river-dominated and wave-dominated delta types have been interpreted and mapped within different lobes of the Dunvegan Formation in the Western Canadian Sedimentary Basin (Bhattacharya 1991, 1994; Bhattacharya and Walker 1991; Plint 2000; Plint and Wadsworth 2003). Plint (2000) indicated that the successive deltas prograded hundreds of kilometers into a shallow-water basin. The resolution of the data for the Dunvegan Formation (Bhattacharya and Walker 1991; Bhattacharya 1994; Plint 2000; Plint and Wadsworth 2003), however, does not allow mapping of terminal distributary channels in the subsurface, and only the deeper "trunk" rivers can be mapped (Fig. 16A). These cannot be mapped farther seaward than approximately 40–50 km from shoreline. Comparison of the Dunvegan with the modern Volga drainage basin and delta network (Fig. 16B) shows that the incised-valley network covers a large area (hundreds of times larger than the delta) and has deeply incised valleys, whereas the delta-distributary part of the same system covers a smaller area and is composed of channels too small to resolve (Figs. 2, 9). In shallow-water basins, such as the Cretaceous Western Interior Seaway, rivers with relatively high discharge like the Dunvegan form deltas that have multiple small terminal distributary channels hundreds of meters wide and a few meters deep. The presence of multiple terminal distributary channels forms sand bodies or shorelines similar to wave-dominated environments. The paleogeographic conditions suggest formation of multiple distributary channels, and probably the same lobe was successively river-dominated followed by a period of wave reworking and lobe switching.

Misidentification of Distributary Channels and Incised Channels Because of Sea-Level Fall.—Ancient delta deposits are commonly associated with a coarsening-up facies succession with channelized deposits at the top (Fig. 14; Elliott 1978; Bhattacharya and Walker 1992; Reading and Collinson 1996). When channelized deposits are not present at the top of a deltaic succession, it is sometime assumed that these were ravined during subsequent transgression (Bhattacharya and Willis 2001; Burger et al. 2002). In the modern examples presented, no significant incision has been observed; the scenario with "incised" distributary channels at the top of a delta happens only in the case of sea-level fall or a sudden increase in discharge. In the case of stillstand periods or sea-level rise, while the delta progrades into the basin, a network of shallower terminal distributary channels is developed and no major incision occurs (Fig. 14). In the case of the Atchafalaya and Wax Lake deltas (Figs. 4, 6) there was no progradation of the major distributary, but rather progradation was associated with formation of smaller terminal distributary channels. As a consequence of non-incision of distributary channels into their own delta-front deposits during sea-level stillstand or rise, the top limit of delta-front deposits in a vertical succession is represented by the base of incision of large distributary channels, which do not represent delta-front deposits, or by subaerial exposure. The major distributaries might incise in the case of a major avulsion, like that between major Mississippi lobes (i.e., St. Bernard, Teche, Lafourche), but in these cases they incise within deposits of a previous lobe and not within their own deposits. The large incisions that form valleys filled with stacked fluvial channel deposits, usually described as distributary-channel deposits, more likely represent a subsequent fluvial incision due to sea-level fall or a major avulsion.

CONCLUSIONS

(1) River-dominated deltas have multiple terminal distributary channels, and there is no such thing as one scale of distributary channel. In shallow basins, river-dominated deltas might have hundreds of small terminal distributary channels. Terminal distributary channels are: (i) shallow and narrow channelized features relative to the main distributary channel and are intimately associated with mouth bars; (ii) have a large variability of orientation relative to the trunk channel; (iii) have low topographic expression; (iv) are rarely incised through previous deposits; and (v) sedimentary structures of terminal distributary channel represent a combination of fluvial and basinal processes (Table 1).

(2) Formation and evolution of mouth bars and terminal distributary channels are part of an autocyclic process. Mouth bars are initiated by bedload deposition and are formed from the coarsest deposits carried by the river. The mouth bar might migrate (grow) downstream, upstream, or laterally. Upstream and lateral migration of the bar controls evolution of terminal distributary channels.

(3) Terminal distributary channels are contained within delta-front deposits. Fluvial-distributary channels incise previous delta deposits only in the case of sea-level fall or huge increase in discharge. Barring such an allocyclic control, the channel avulses laterally and starts building another delta lobe. This is a fundamentally autogenic avulsion process, unrelated to the growth of alluvial ridges or other upstream mechanisms.

(4) The number of terminal distributary channels increases for deltas with high sediment discharge formed in basins with low accommodation. The result of increasing the number of terminal distributary channels is that sand bodies have a lobate shape because of decreasing distance among channels and fusion of proximal mouth-bar deposits. All deltas have multiple terminal distributary channels if development of these is not inhibited by high basin energy such as waves or tides. For ancient fluvial delta deposits modern analogs need to be chosen mainly from deltas with multiple terminal distributary channels if the paleogeography suggests high-discharge rivers which infill shallow basins.

(5) In shallow-water basins river-dominated deltas have tens to hundreds of terminal distributary channels that are coeval. The multitude of small channels that tend to distribute sediments radially form an overall lobate sand-body geometry opposite to Mississippi elongate sand bodies but similar in shape to wave-dominated deltas.

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