LITHOSTRATIGRAPHY VERSUS CHRONOSTRATIGRAPHY IN FACIES CORRELATIONS OF QUATERNARY DELTAS: APPLICATION OF BEDDING CORRELATION

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ABSTRACT: Outcrop and high-resolution seismic studies show that prograding delta deposits consist of seaward-dipping, offlapping clinoform strata. Despite this, many studies of Quaternary deltas, particularly those based on correlation of sediment cores, commonly depict sharp to gently undulating facies boundaries, similar to those originally shown by Scruton in 1960. The Scruton model emphasizes "layer-cake" lithostratigraphy that correlates similar-appearing but highly diachronous environmental facies, bounded by solid lines that cut across time lines.

In contrast, facies architectural and sequence stratigraphic studies of ancient subsurface deltas have largely abandoned this lithostratigraphic approach. The alternate "chronostratigraphic" approach uses outcrop and seismic examples as training images that are used to derive conceptual models that drive the correlation of the internal facies architecture of subsurface strata. These outcrop and seismic examples suggest that there is no observable physical boundary between Scruton's diachronous facies units. The conceptual "norm" depicts prograding deltas as seaward-dipping clinoform strata. Dipping delta-front sandstone beds roughly parallel time lines and interfinger with muddy prodelta bottomsets. If individual beds cannot be resolved, then diachronous, transitional facies boundaries are routinely drawn in a way that indicates that boundaries of this type are gradational rather than sharp, specifically by using lightning-stroke-type "shazam" lines.

We use the method of bedding correlation (i.e., correlation of beds and bedsets) derived from geometries observed in outcrops and seismic analogs as a conceptual guide to recorrelate beds and facies for several recently published modern examples, where data are limited to a few, widely spaced cores. The new correlations, although imprecise because of long correlation distances, are potentially more accurate depictions of the bed-scale facies architecture, and may be more useful in applications that involve modeling bed-scale growth of deltas or that require prediction of 3-D fluid-flow behavior of deltaic reservoirs and aquifers.

INTRODUCTION

Outcrop facies architectural studies began with the study of fluvial deposits (e.g., Allen, 1983; Miall, 1985). More recent outcrop studies emphasize deep-marine depositional systems, because of the recent global emphasis on deep-water exploration (Pickering et al., 1995; Bouma and Stone, 2000). Two-dimensional facies architectural studies of deltaic sand bodies, in contrast, have received much less attention, and there have been no 3-D studies integrating outcrop and subsurface data of these systems, despite the importance of delta deposits for energy resources and in environmental sciences.

Typically, delta-front sandstone bodies have complex intra-parasequence geometries and shapes, characterized by seaward-dipping inclined sandstones interbedded with shales (e.g., Barrell, 1912; Busch, 1971; Berg, 1982; Frazier, 1974; Van Wagoner et al., 1990; Bhattacharya, 1991; Bhattacharya and Walker, 1992; Willis et al., 1999; Chidsey, 2001). Accurate determination of these complex geometries is the key to addressing the bed-scale evolutionary history of a delta. Also, the distribution, orientation, and overall facies architecture of shale interbeds are especially important in controlling reservoir and aquifer behavior in delta-front sand bodies (e.g., Willis and White, 2000).

In illustrating the internal facies architecture of a sedimentary body, solid lines are generally used to refer to physical surfaces (e.g., Van Wagoner et al., 1990; Bhattacharya, 1993; Posamentier and Allen, 1999), which include bounding surfaces and bed boundaries. Diachronous facies boundaries, which are not physical surfaces, are commonly depicted with a "shazam line" (e.g., Rich, 1951; Van Wagoner et al., 1990; Posamentier and Allen, 1999). Shazam lines are irregular lines, which imply gradational boundaries that represent facies intertonguing.

One of the most influential early cross-sectional depictions through the modern Mississippi delta (Scruton, 1960) attempted to illustrate the relationship between facies and time of deposition during progradation of a delta (Fig. 1). In this depiction (Fig 1A), facies boundaries are shown as solid black, broadly horizontal to gently undulating surfaces, implying that they represent the boundaries between horizontal beds or layers. This represents a lithostratigraphic interpretation that lacks any information about internal variations of lithology and bedding geometry. The Scruton model has largely been abandoned in studies of ancient deltas with the advent of facies architectural and sequence stratigraphic concepts (e.g., Van Wagoner et al., 1990; Bhattacharya, 1991; Bhattacharya, 1993; Posamentier and Allen, 1993; Tye et al., 1999; Ainsworth et al., 1999), but it continues to be applied in studies of many modern deltaic systems where interpretations are based on a few boreholes, and in cases where high-resolution geophysical images do not exist or there is no access to outcrops (e.g., Cumming and Al-Aasm, 1999; Woodroffe, 2000; Hori et al., 2001; Ta et al., 2002b; Jones et al., 2003; Staub and Gastaldo, 2003; Tanabe et al., 2003). The objective of this paper is to illustrate the differences in models built using bedding correlation (i.e., correlation of beds and bedsets boundaries) and facies architectural concepts, versus facies correlation models built using the more traditional lithostratigraphic approach. We begin with a brief review of outcrop and subsurface examples of bed-scale architecture and then show how these examples can be applied to recorrelation of core data presented in several recently published Quaternary examples.

River Deltas—Concepts, Models, and Examples
SEPM Special Publication No. 83, Copyright © 2005
SEPM (Society for Sedimentary Geology), ISBN 1-56576-113-8, p. 31–48.

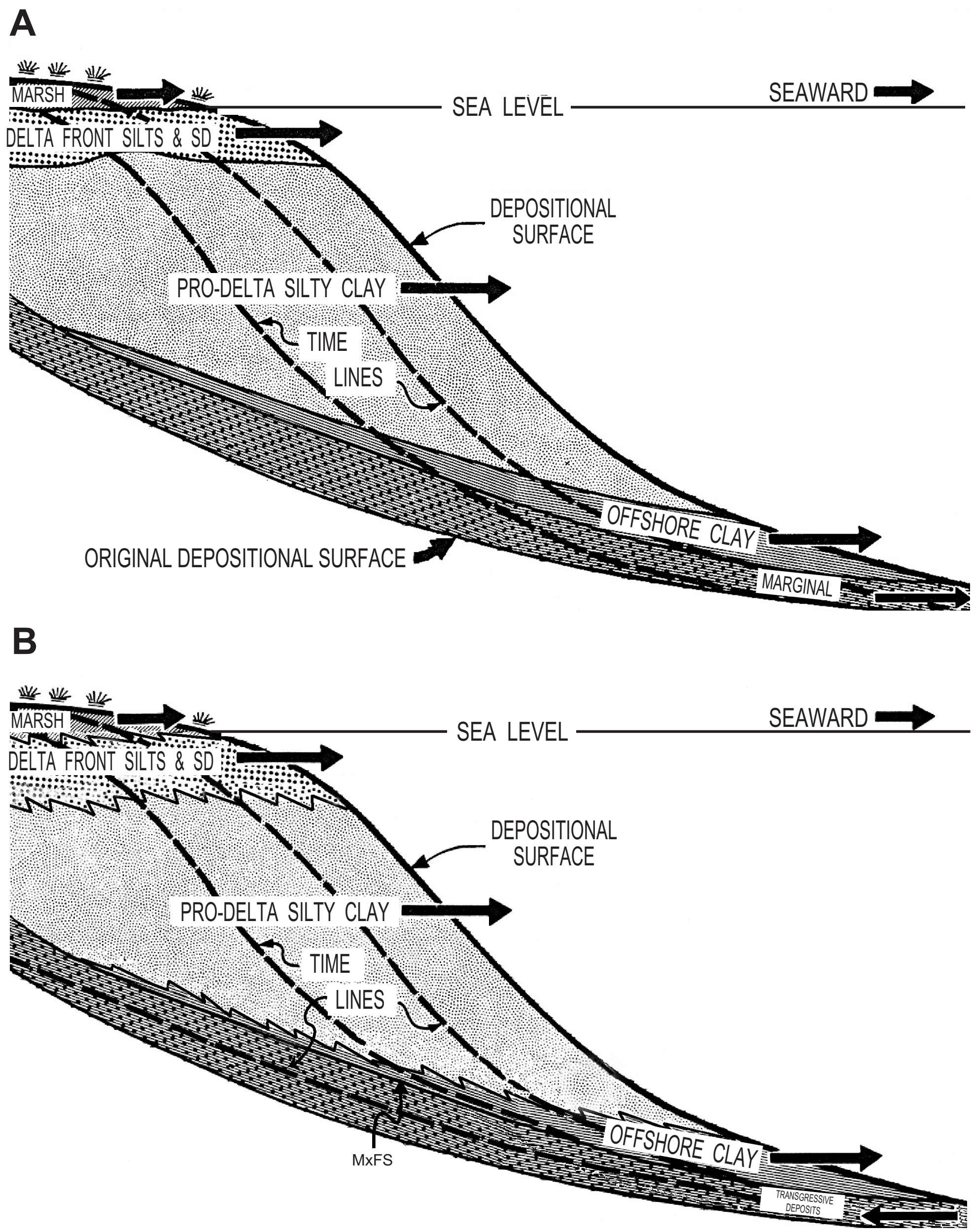

FIG. 1.—**A)** Seaward progradation of delta as illustrated by Scruton (1960). This is a lithostratigraphic demonstration of layer-cake and flat-bottomed facies zones (reprinted by permission of the American Association of Petroleum Geologists, whose permission is required for further use). **B)** Modified version of Scruton diagram. Figures not to scale. See text for discussion.

BACKGROUND

The earliest cross-sectional depiction of deltaic facies architecture recognized a tripartite division (Gilbert, 1885). Barrell (1912), extending Gilbert's ideas, coined the terms topset, foreset, and bottomset as the basic threefold division of a delta (Fig. 2A). Rich (1951) introduced the terms undaform, clinoform, and fondoform, to refer to the topographic units (landforms) produced above wave base, below wave base, and on the flatter deep basin floor of a standing body of water, respectively (Fig. 2B). However, the term clinoform is now used to refer to the sloping surface of a depositional system irrespective of environment of deposition. Rich (1951) was one of the first to use shazam lines to depict the interfingering of sandy undaform deposits with muddier prodelta clinoform deposits (Fig. 2B). Scruton (1960) presented a dip-oriented cross section (Fig. 1A) summarizing delta-building processes. His depiction of time lines was intended to clarify how a delta progrades, giving rise to different types of facies. However, the depiction of diachronous facies boundaries as solid lines, especially when compared to the depiction of Rich (1951), gives the impression that the diachronic facies units are separated from each other by sharp physical surfaces. As we shall show in various outcrop and high-resolution seismic examples, interfingering of delta-front sands and prodelta muds, without the

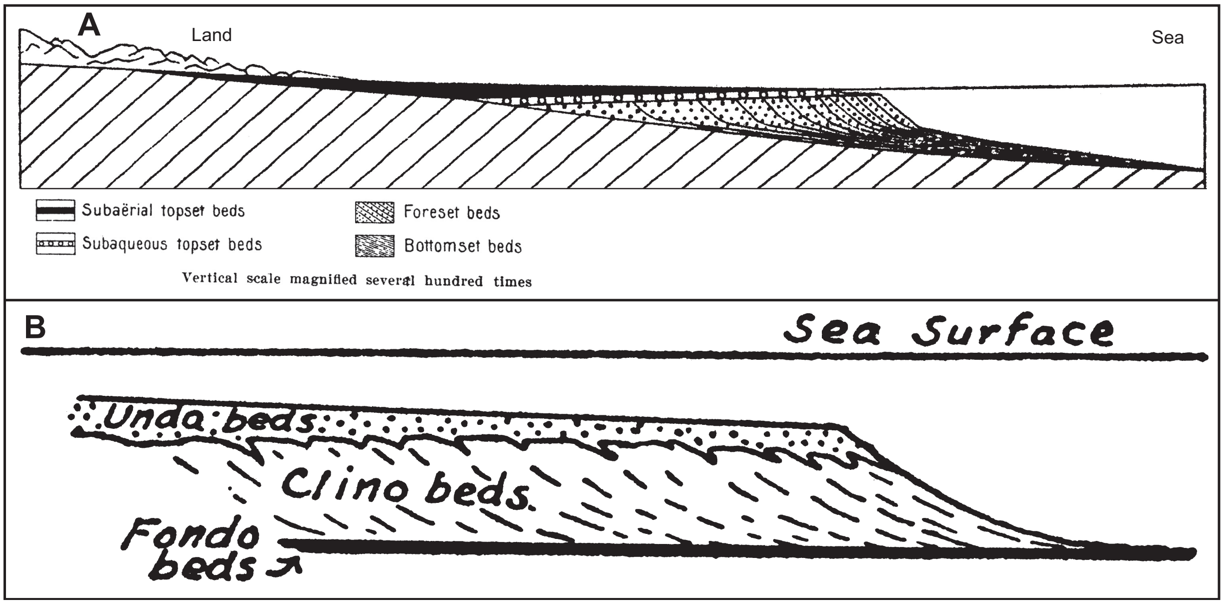

FIG. 2.—**A)** Internal geometry of a "mature" delta as illustrated by Barrell (1912). **B)** Rich's (1951) example of facies interfingering (drawn as shazam line) between undaform strata and clinoform strata. See text for discussion. (Reprinted by permission of the Geological Society of America).

development of such sharp surfaces, is the norm rather than the exception.

Scruton recognized two phases of delta development: a constructional phase, during which the delta progrades seaward, and a destructional phase, during which marine transgression reworks the delta top. With the advent of sequence stratigraphy these phases are now better understood, as illustrated in a modified version of the Scruton diagram (Fig. 1B). In the redrawn version, facies boundaries are shown using shazam lines. Scruton's "marginal" facies can be recognized as transgressive deposits, which should be underlain by a transgressive surface and may be overlain by a maximum flooding surface (MxFS), after the development of which the delta starts to prograde. Consequently, this transgressive deposit should migrate landward (not seaward), and the deltaic time lines should not penetrate into these deposits (compare Fig. 1B with Fig. 1A). It may also be logical to draw the boundary between delta front and the prodelta somewhat lower in the clinoform set, where the dip of the clinoform starts to decrease rapidly.

A more generalized intra-parasequence architecture of a prograding delta, in both dip and strike sections, during a slow sea-level rise is presented in Figure 3. The direction of shoreline trajectory (Helland-Hansen and Gjelberg, 1994) indicates that it is a normal progradation, as opposed to a forced regression, which may create a sharp to erosional surface between prodelta and delta-front deposits (e.g., Plint, 1988). During earlier transgression, the top part of older deltaic deposits can be reworked by marine processes with the development of a transgressive surface of erosion overlain by transgressive lag deposits. After sea level reaches its maximum position, giving rise to a maximum flooding surface (MxFS), a new delta starts to build seaward such that seaward-dipping master bedding planes (bedset boundaries) downlap (in dip view) and sidelap (in strike view) onto the MxFS. The term "clinoform" (which roughly follows time lines) is widely used to refer to these seaward-dipping beds (Rich, 1951). The clinoform is the single most important feature characterizing the internal geometry of deltas (e.g., Bhattacharya and Walker, 1992). At the finer scale, small-scale facies dislocations typically occur across bedding surfaces (more specifically, intra-parasequence bounding discontinuities) and shazam lines are drawn to separate lithofacies. In facies architectural (e.g., Miall, 1985) and seismic and sequence stratigraphic (e.g., Vail et al., 1977) studies it is generally assumed that beds approximate time lines. The strike section shows distinctive bidirectional clinoforms (Fig. 3B). Steeply dipping (and coarser) sediments along the depositional axis pass laterally into muddy bottomsets of prodelta and interlobe, bay-fill sediments. Unfortunately, there are very few outcrop examples that demonstrate the facies architecture of delta lobes along depositional strike.

DELTAIC BEDDING ARCHITECTURE: OUTCROP, SUBSURFACE, AND MODELED

The best data sets to study bed-scale clinoformal architecture of deltas are outcrop (e.g., Gardner, 1995; Willis et al., 1999; Chidsey, 2001; Soria et al., 2003; Barton, in press; Plink-Björklund and Steel, this volume), high-resolution seismic (e.g., Tesson et al., 1993; Hart and Long, 1996; Harris et al., 1996; Roberts and Sydow, 2003; Anderson and Fillon, 2004; Anderson, this volume), and ground penetrating radar (GPR) (e.g., Eilertsen et al., 2002; Lee et al., 2004; Smith et al., this volume) data. Outcrop data have the additional advantage that lithofacies and bedding geometry can be observed directly, whereas in seismic data lithology must be inferred unless well or core data are available. In continuous and well exposed outcrops, individual beds can be traced until they end by lapout or truncation. In this section we show a few representative examples that will set the basis for recorrelation of modern examples.

An outcrop example from the Cretaceous Ferron Sandstone Member, in central Utah, shows the bed-scale facies architecture of fluvially dominated prograding delta deposits (Fig. 4; Chidsey, 2001). The prograding delta front forms an upward-coarsening

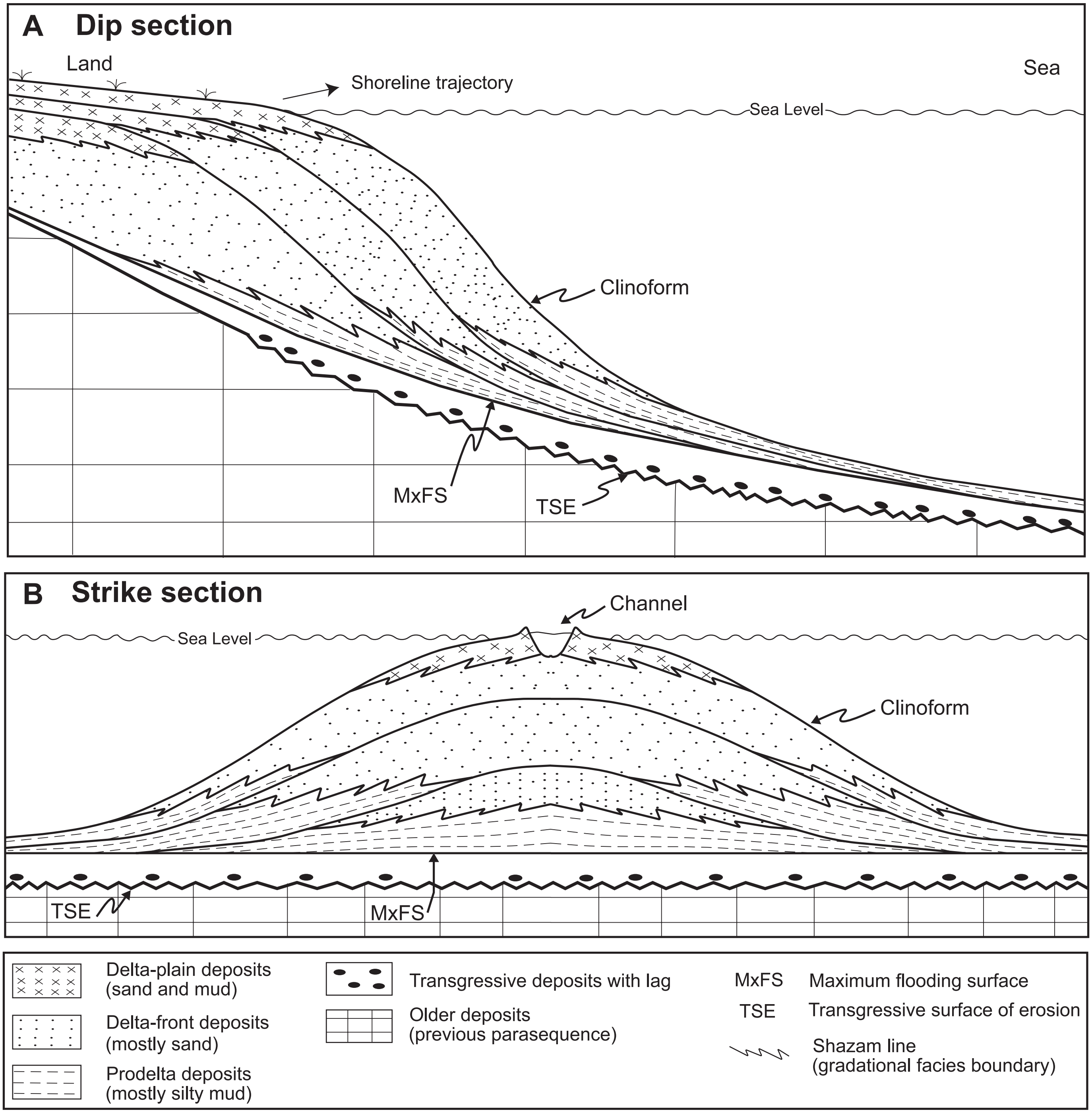

FIG. 3.—Generalized intra-parasequence bedding geometry and facies architecture of a prograding delta during a slow sea-level rise. **A)** Dip section shows the seaward-dipping bedset boundaries (clinoforms), which follow time lines and are bidirectional in **B)** strike section. Note the facies dislocations across bedset boundaries. Figures not to scale. See text for discussion.

sediment body, 25 meters thick, that shows delta-front sandstones (i.e., foresets) interfingering with muddy, prodelta bottomset beds. Delta-front clinoform strata dip seaward at an average of 10°, and shale out over a lateral distance of about 1.5 km down depositional dip. Proximal delta-front sandstone facies (Fig. 4) show low-angle to trough cross-stratification with rare hummocky cross-stratification. Medial delta-front facies consist of fine-grained sandstones, showing dominantly horizontal bedding with some ripple, trough, and low-angle cross-stratification. Fine-grained to very fine-grained sandstones with horizontal lamination and ripple cross-lamination characterize the sandy portion of the distal heterolithics facies. Reworked delta-top facies are very fine-grained to fine-grained sandstones that show horizontal bedding with trough and low-angle cross-stratifica-

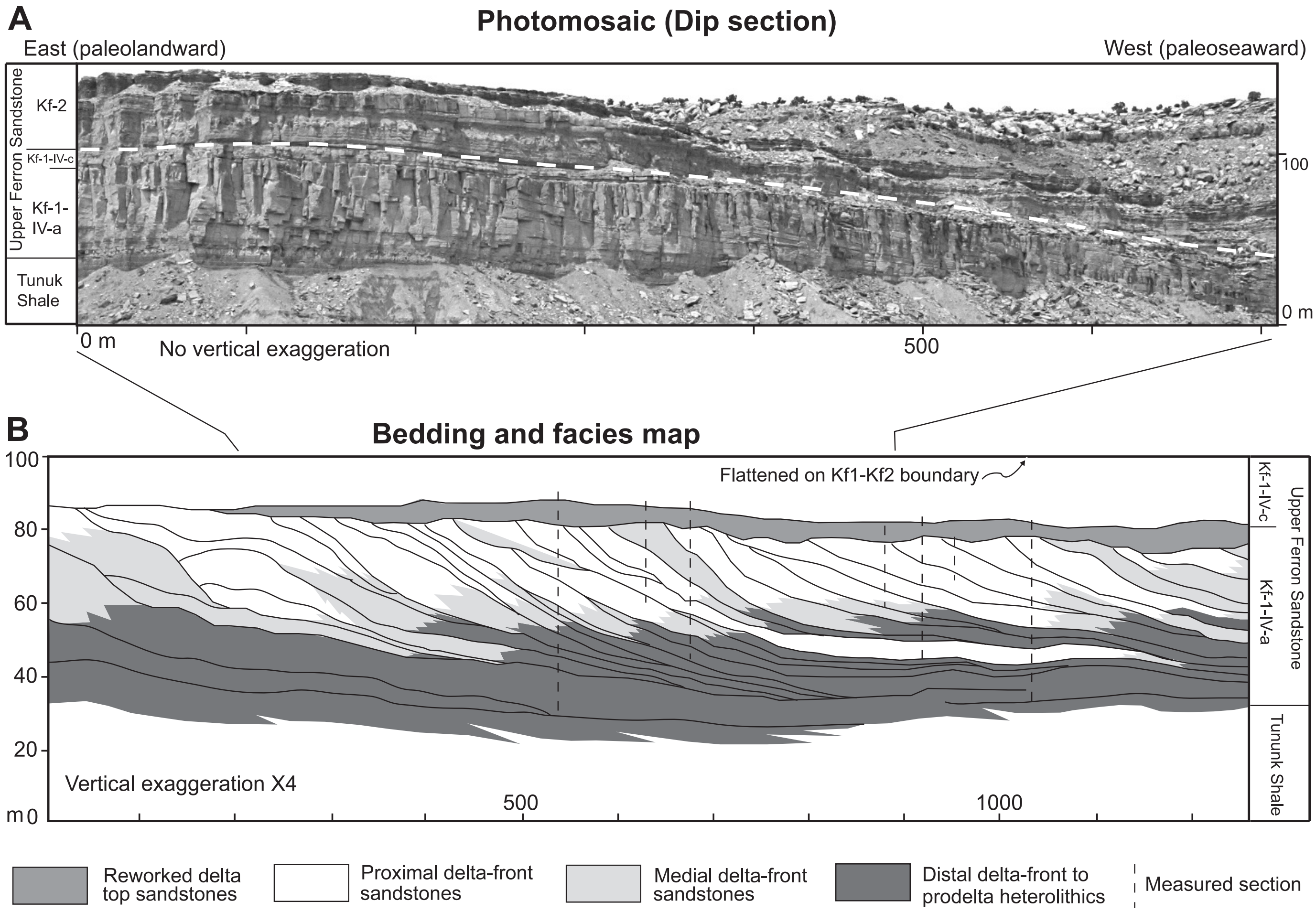

FIG. 4.—**A)** Photomosaic with **B)** bedding and facies map of a cliff face (along depositional dip), Ivie Creek amphitheater, Emery County, Utah. The diagrams show prominent seaward-dipping clinoforms (average 10° dip) of a river-dominated delta of the Cretaceous Ferron Sandstone. Note both the landward and seaward shift of facies across clinoform boundaries (modified from Chidsey, 2001).

tion. No sharp facies boundary between the bottomsets and foresets can be observed. Bed-set packages show both landward and seaward minor shifts of facies across their boundaries. This example (Fig. 4) shows the internal complexities of beds and facies in a deltaic parasequence that is markedly different from the facies architecture implied by the Scruton (1960) diagram (Fig. 1A).

The second outcrop example is taken from the Upper Cretaceous (Cenomanian) Frewens sandstone, in central Wyoming. Cliff exposures show an upward-coarsening prograding succession, 30 m thick, of sandstone foresets and muddy prodelta bottomsets (Fig. 5). An abundance of double-mud drapes, classic linsen and flaser bedding, and tidal bundles have been used to interpret this as a strongly tide-influenced deltaic deposit (Willis et al., 1999; Willis, this volume). Internally, the sediment body consists of a series of offlapping and inclined bedsets (Fig. 5). In dip section (Fig. 5B), the bedsets form a series of wedge-shaped sandstone–mudstone couplets that thin and become muddier down the clinoforms, which represent deeper and more distal facies. Dislocations of facies occur across the bedding contacts, which approximate time lines. The sandy beds overlie a 10-m-thick platform of thin-bedded, distal delta-front, rippled sandstones and prodelta mudstones. The prodelta facies form the flatter-lying bottomset beds. In strike section (Fig. 5C), clinoforms show characteristic bidirectional dip. The muddy bottomset deposits interfinger with the sandy foreset facies in both dip and strike sections. The boundary between the mapped facies also forms a "shazam" type boundary, rather than a sharp facies boundary, identical to that shown in Figures 1B and 3.

A third smaller-scale outcrop example of Pennsylvanian strata in the Taos Trough, New Mexico, shows a 12-m-thick coarsening-upward vertical facies succession (Fig. 6). The succession is interpreted as a river-dominated, prograding distributary-mouth-bar deposit, in which prodelta mudstones grade upward into coarse-grained pebbly sandstone foresets, interpreted as proximal delta-front beds. A dip-oriented cliff section indicates basinward migration of offlapping, wedge-shaped, and steeply dipping (13°) foreset beds (Fig. 6A, B). Individual beds are sharp-based, mainly structureless to normally graded conglomeratic sandstones overlain by mudstones (Fig. 6C). The foreset beds are interpreted to be frontal splays, formed by sediment gravity flows moving down the front of a steeply dipping, prograding distributary-mouth bar. The beds represent geologically instantaneous events, and the bed boundaries thus approximate time

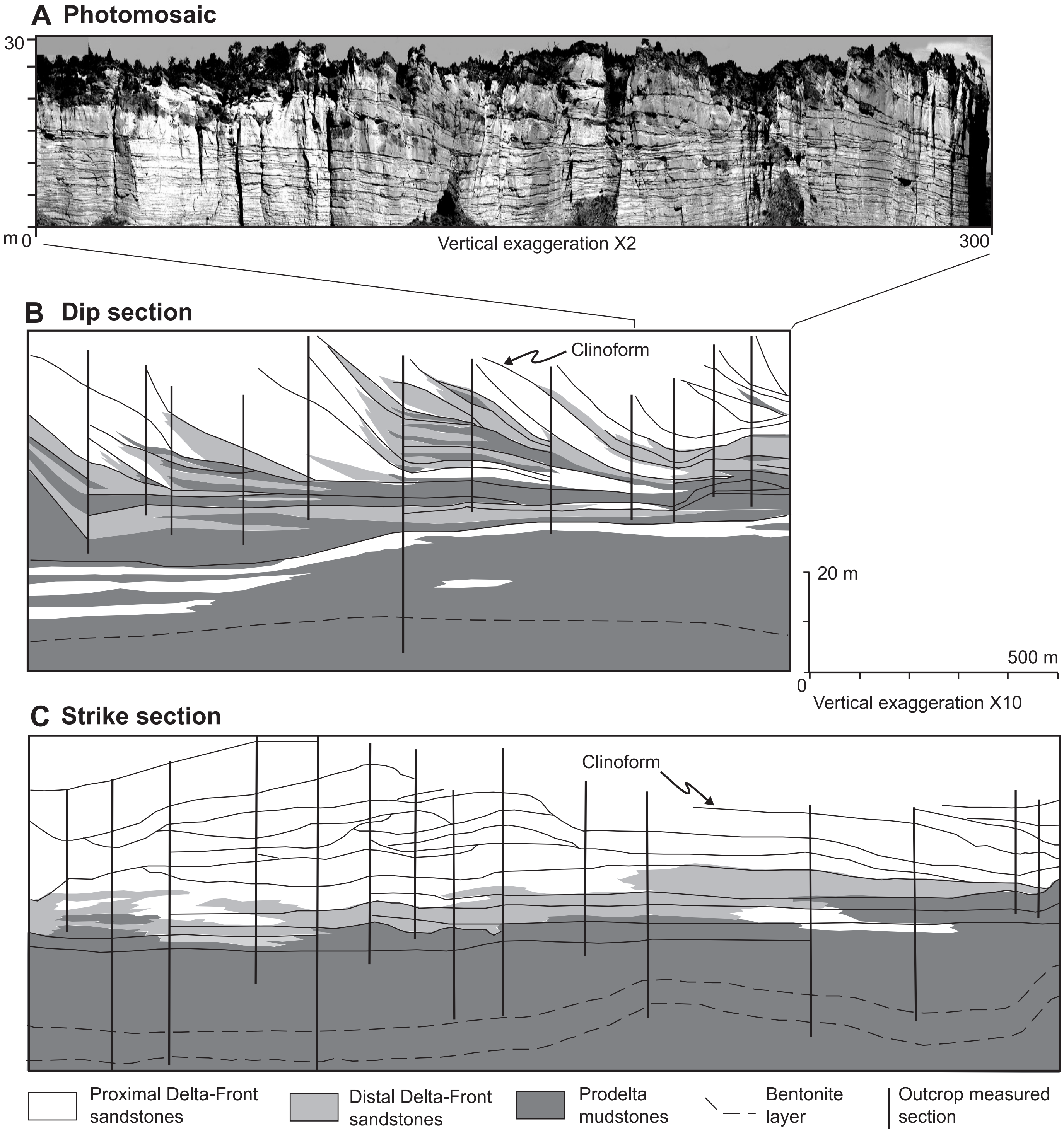

FIG. 5.—Outcrop example of complex internal architecture in the Cenomanian (Upper Cretaceous) tide-influenced river delta of Frewens allomember, Frontier Formation, central Wyoming. **A, B)** Dip view of the prograding delta shows the seaward-dipping clinoforms, whereas in **C)** strike view these clinoforms show bidirectional downlap, forming a classical lens-shaped geometry. In both cases, muddy bottomset facies interfinger with the sandy foreset facies forming a shazam-type facies boundary. Note that clinoform dip varies from 5 to 15° (modified from Willis et al., 1999).

lines. Like the tide-influenced Frewens example, the individual sandy foreset beds interfinger with the muddy prodelta bottomsets, forming a complex intertonguing between the delta-front and prodelta facies. This intertonguing contact provides a small-scale example of a “shazam” line in a highly river-dominated setting.

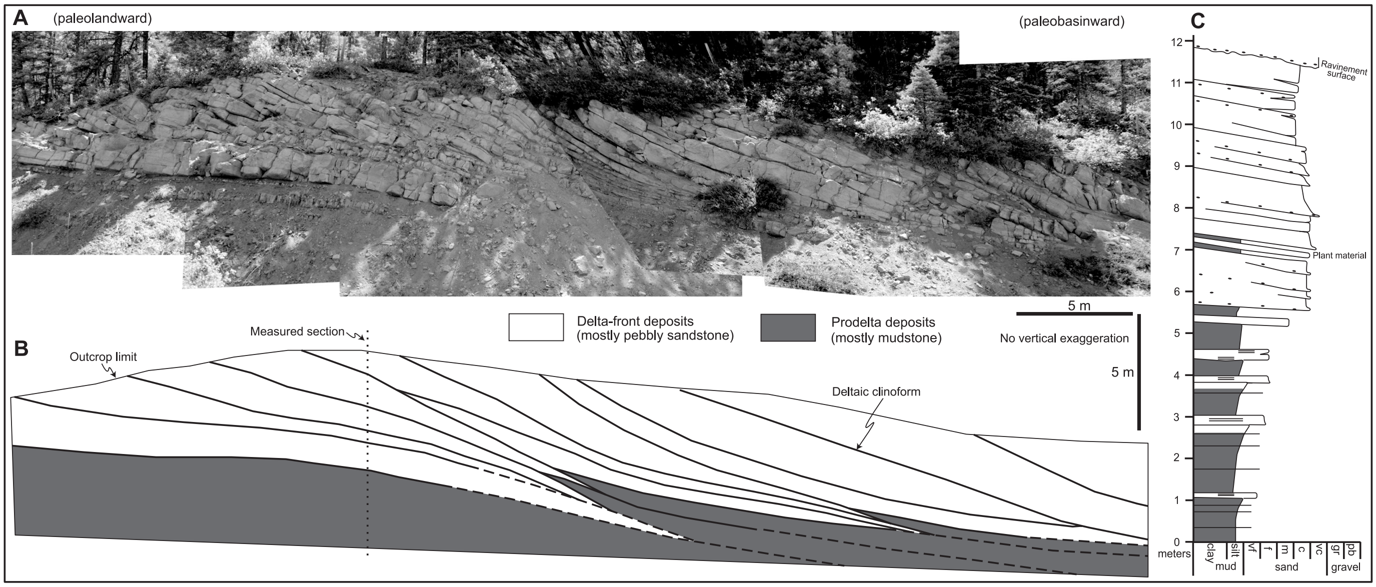

FIG. 6.—Details of shazam-type facies interfingering at the clinoform base of a small-scale outcrop example of Pennsylvanian delta, Taos Trough, New Mexico. **A)** Outcrop photomosaic. **B)** Line drawings of beddings with facies interpretation. Note that clinoforms are steeply dipping (average 13°). **C)** Lithologic column of this coarse-grained delta (position of the measured section is shown in Part B).

The clinoformal architecture is also seen in typical wave-dominated deltaic shoreface successions, although clinoform dips are typically much less (0.01–0.5°) than those from the more river- and tide-dominated deltaic examples presented above. Hampson (2000) has shown similar facies dislocation and intertonguing along clinoforms in wave-dominated, coarsening-upward, progradational delta-front and shoreface successions in the Cretaceous Book Cliff strata of Utah (Fig. 7). The upward-coarsening parasequence passes upward from bioturbated offshore mudstones to hummocky cross-stratified and flat-laminated lower-shoreface sandstones, and finally to cross-bedded and flat-laminated upper-shoreface sandstones. More recently (Hampson et al., this volume), these shoreface deposits have been interpreted in a more regional context as updrift components of large, asymmetric, wave-influenced deltas (Bhattacharya and Giosan, 2003).

Two examples of high-resolution seismic cross sections through two Quaternary deltas (Figs. 8, 9) also emphasize the inclined geometry of delta-front sediments. Like the outcrop examples, these seismic cross sections (Figs. 8, 9) clearly show steeper foreset strata passing seaward into muddier bottomsets. This seismic stratal geometry is found in countless examples of delta systems (e.g., Brown and Fisher, 1977; Berg, 1982; Bhattacharya and Walker, 1992; Roberts and Sydow, 2003; Hiscott, 2003; Anderson and Fillon, 2004; Anderson, this volume). It is critical to recall that seismic reflections respond to changes in lithologic properties. These seismic examples illustrate clearly

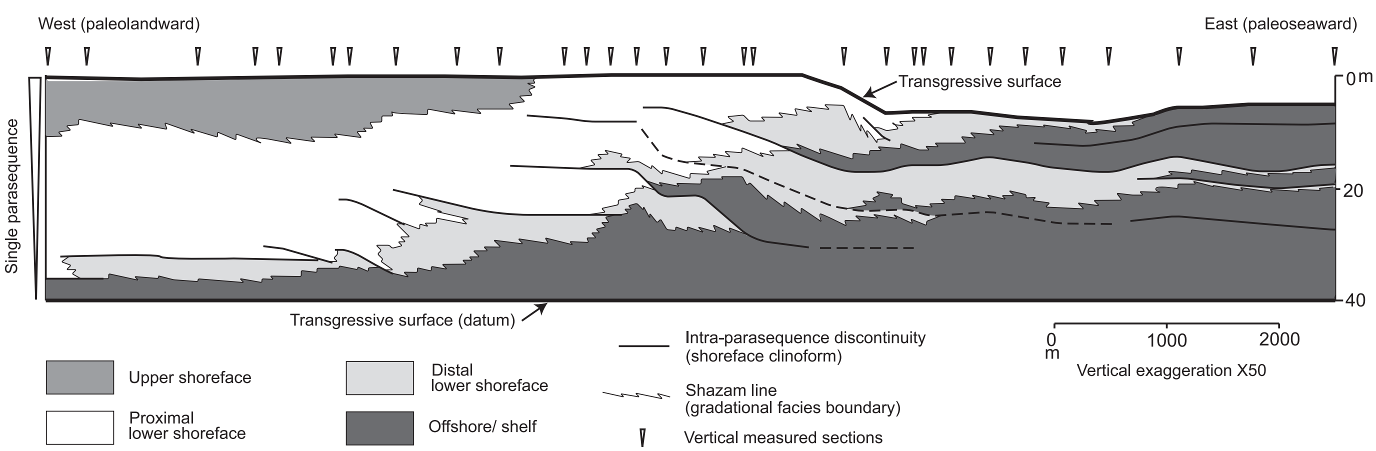

FIG. 7.—Outcrop example of intra-parasequence facies architecture in the Campanian (Upper Cretaceous) shoreface to deltaic strata of Kenilworth Member, Blackhawk Formation, Book Cliffs, Utah. The diagram emphasizes how the development of intra-parasequence discontinuities (shoreface clinoforms) affects the internal facies organization of a single prograding parasequence. Clinoform dip rages from 0.02 to 0.95° (modified after Hampson, 2000).

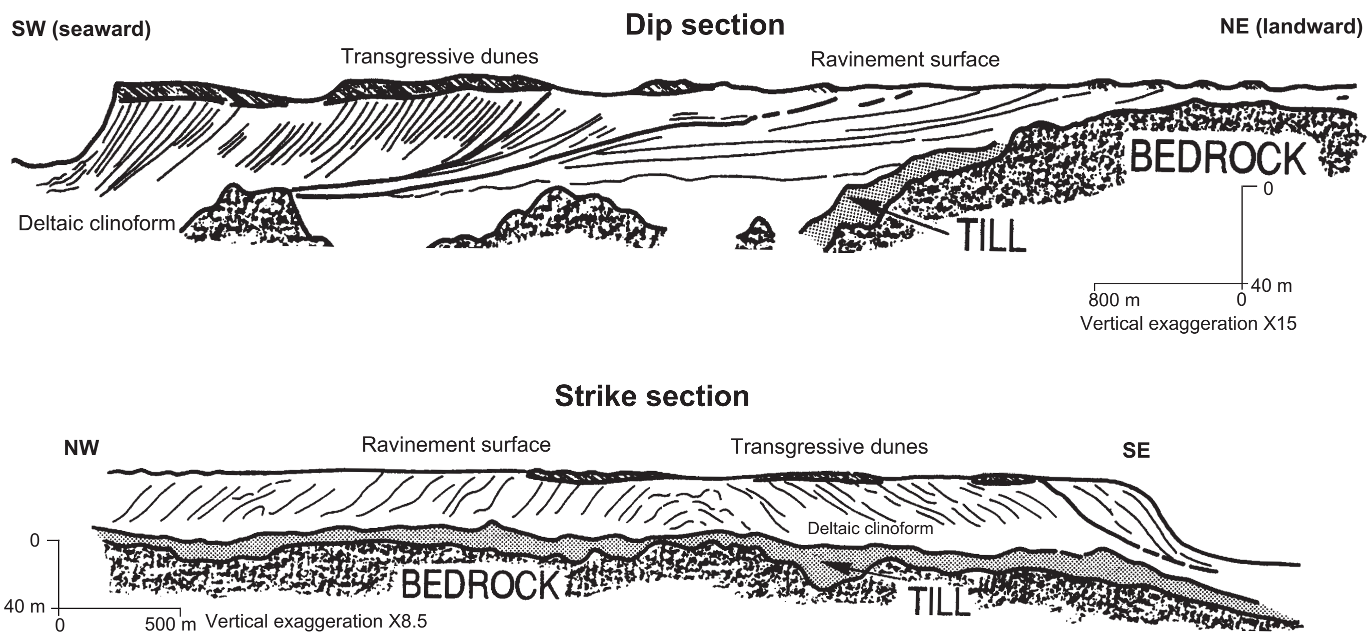

FIG. 8.—High-resolution seismic line drawings of Holocene Natashquan Delta, Gulf of St. Lawrence, Canada. Dip section (upper diagram) shows top-truncated and seaward-dipping clinoforms, whereas strike section (lower diagram) emphasizes bidirectional offlapping of these clinoforms (after Hart and Long, 1996).

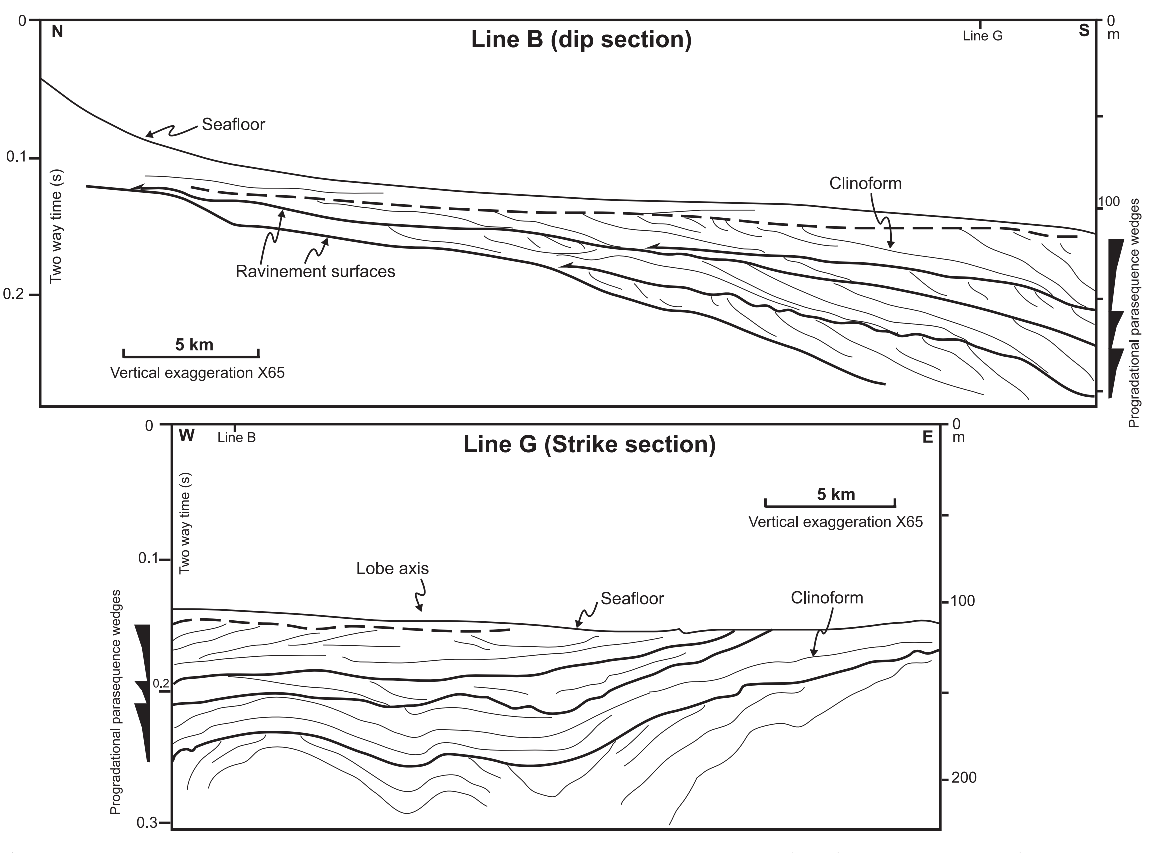

FIG. 9.—High-resolution seismic line drawings of late Pleistocene lowstand wedges off the Rhone Delta, French Mediterranean. Each regressive parasequence wedge shows seaward-dipping clinoforms in dip section (upper diagram) and bidirectional clinoforms in strike section (lower diagram) (modified after Tesson et al., 1993).

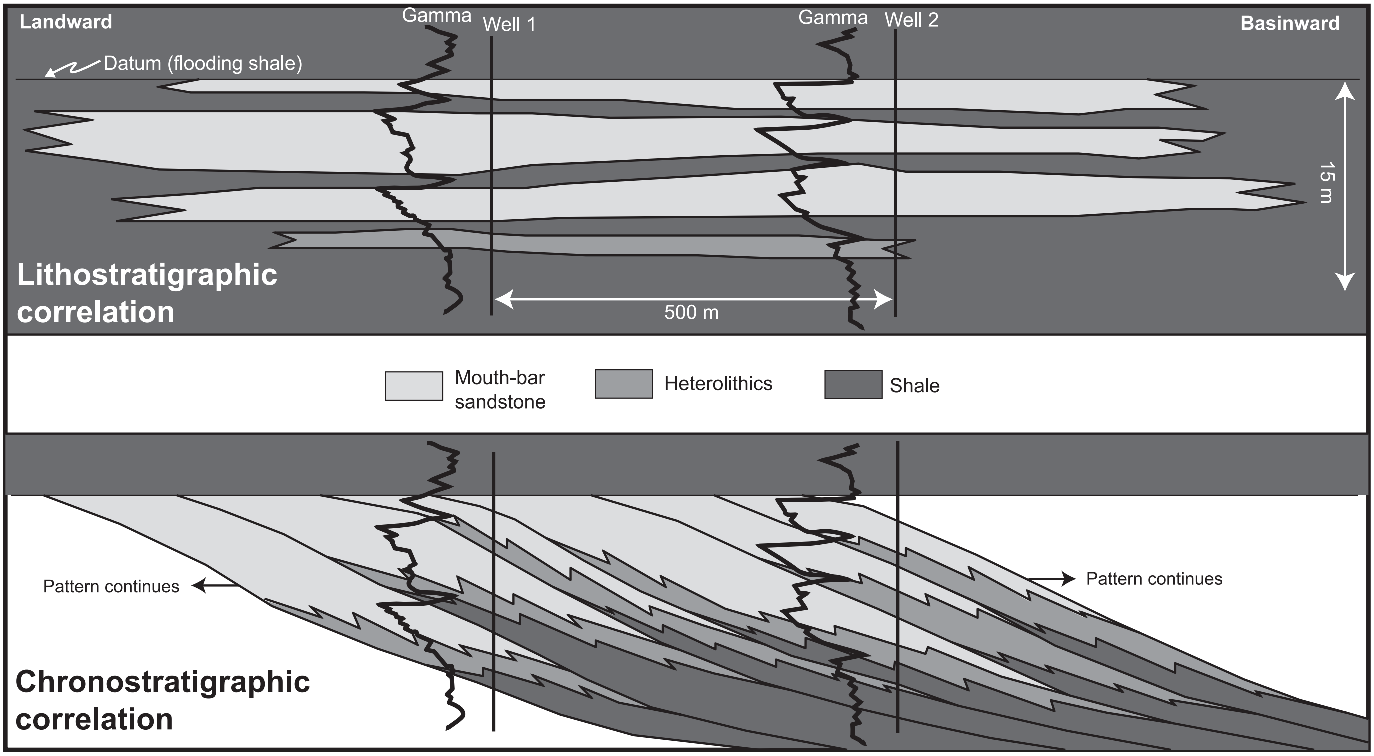

FIG. 10.—Subsurface model of well-log correlation in a lacustrine deltaic environment along depositional dip. Lithostratigraphic correlation (upper diagram) assumes no dip in sand bodies towards basin, whereas chronostratigraphic correlation (lower diagram) assumes basinward-dipping clinoforms. Chronostratigraphic model better predicts reservoir behavior. Note that correlation lengths of many beds are below the well spacing (modified after Ainsworth et al., 1999).

that lithologic properties (i.e., facies) follow the inclined reflectors (i.e., clinoforms) that are generally assumed to follow bedding, and do not form flat, layer-cake units. These examples also suggest that the deltaic facies architecture seen in high-resolution seismic cross sections through Quaternary delta systems resembles the stratal architecture seen in the ancient outcrop examples presented above.

Another example is based on subsurface well-log data in a lacustrine delta (Fig. 10). Ainsworth et al. (1999), in the Sirikit oilfield, Thailand, illustrated the difference between lithostratigraphic (i.e., layer-cake facies) and chronostratigraphic (i.e., inclined bedding) correlation of subsurface wireline logs in delta-front mouth-bar deposits. The chronostratigraphic correlation better predicts fluid-flow behavior, particularly in terms of perforation strategy and recovery factor of the oilfield (Ainsworth et al., 1999). Although the detailed geometry of clinoforms in lacustrine settings may be different from that in marine settings, this example demonstrates the general notion that the deltaic strata dip basinward.

Tye et al. (1999) also used production data and horizontal-well data to verify the presence of dipping delta-front sandstones interfingering with marine prodelta shales in the Permo-Triassic Ivishak deposits in the super-giant Prudhoe Bay field in Alaska. Previous layer-cake stratigraphic schemes were unable to explain the complex production behavior of these deltaic strata.

Lastly, numerical models of deltas also predict basinward-inclined clinoforms. Tetzlaff and Harbaugh (1989), using SEDSIM3 software, modeled a Mio-Pliocene delta in a reservoir in the Gulf of Mexico. The dip-oriented cross section of the simulated deposits (total 10,000 years) shows a series of offlapping clinoforms down which lithofacies interfinger with each other in a progressively decreasing grain-size trend (Fig. 11). The numerical models predict facies dislocations across bed boundaries, just as in the outcrop examples presented above.

RECORRELATION OF MODERN DELTAS WITH A FEW WELL CORES

Unlike in outcrop, the lateral relationship of a sedimentary deposit is not directly observable in well data if not supplemented by seismic data. Therefore, subsurface interpretation and correlation of well data depends on preestablished assumptions (i.e., stratigraphic and architectural models). Recent subsurface studies of modern deltas rely on widely separated well cores commonly supplemented with chronometric analysis (e.g., ^{14}C, luminescence dating). For example, Ta et al. (2002a) and Ta et al. (2002b) compiled a superb data set on the Mekong River Delta in southern Vietnam based on several well cores taken from the delta plain. They analyzed and dated the core sediments to interpret the Holocene evolution of the Mekong Delta. Figure 2 of Ta et al. (2002b) shows the regional subsurface interpretation of the Mekong Delta along two depositional-dip cross sections. However, their depiction follows Scruton (1960) in that similar but diachronous facies are drawn with solid lines that cut across the timelines obtained from chronometry. We have redrawn one of their dip sections (section AB, Fig. 12A), applying the concept of bedding correlation, incorporating the assumption that beds and facies-dislocations parallel the time lines, and using our

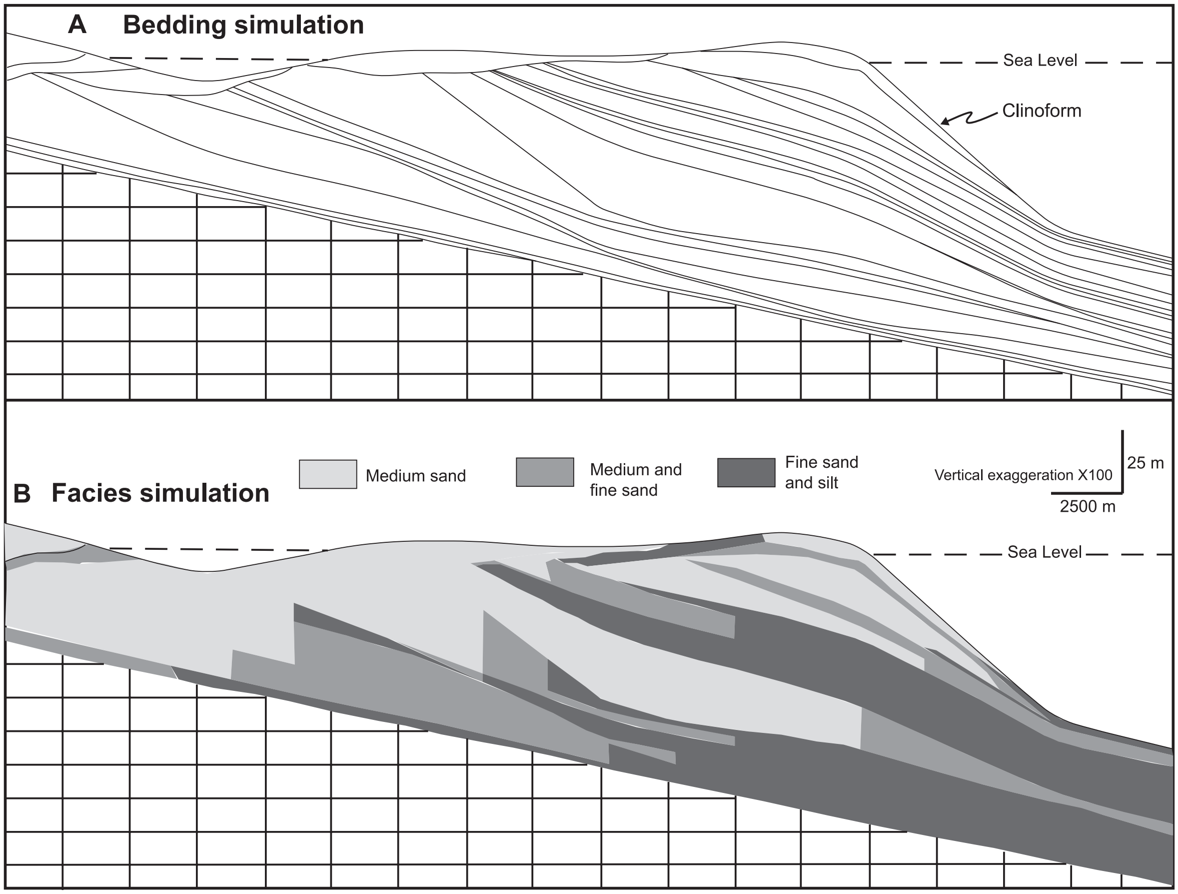

FIG. 11.—Computer modeling of a prograding delta. **A)** Bedding simulation emphasizes seaward-dipping clinoforms. Each individual bed represents 400 years, totaling 10,000 simulated years. **B)** Simulation of lithofacies (sediment composition) demonstrates that facies follow beds and interfinger with each other down the clinoforms (modified from Tetzlaff and Harbaugh, 1989).

outcrop and seismic examples as a guide (Fig 12B). A number of mostly upward-coarsening and a few upward-fining bedsets can be identified in the cored sections. Only the more prominent bedset cycles are marked in Figure 12B. The boundaries of the coarsening-upward bedsets are demarcated by a landward shift of facies indicating an abrupt reorganization of environments. Therefore, these surfaces may represent intra-parasequence "minor flooding surfaces". These boundaries are picked and correlated through the cross section with the idea that clinoforms dip seaward and should roughly follow time lines. However, the internal detail of this facies and bed correlation may vary depending on how many of these bedset boundaries one is able to pick. Figure 12B matches the outcrop and seismic examples of prograding deltas described above, while the data in Fig. 12A are consistent with that in Fig. 12B. In the same way, the dip section XY of Ta et al. (2002a) can be redrawn to show a more facies-architectural representation of the subsurface geology.

The modern Yangtze River delta, China, has been studied extensively by Hori et al. (2001) and Hori et al. (2002), primarily on the basis of three well cores from the present-day delta plain. These studies also used the Scruton model of delta progradation (as quoted in their text), the result of which is a lithostratigraphic representation of the subsurface delta facies geometry (Fig. 13A). Our bedding correlation approach suggests a more complex interpretation of the facies architecture of the Yangtze delta. We have recorrelated their data, using concepts outlined in this paper, yielding a significantly different bedding architecture of the subsurface Yangtze delta (Fig. 13B).

In a more simplified regional longitudinal cross section of the Mahakam Delta, Woodroffe (2000) also showed a very traditional lithostratigraphic correlation of diachronous facies units bounded by solid lines (Fig. 14A). The inclusion of ^{14}C age dates allows us to reinterpret the internal geometry of this delta in Figure 14B, which suggests a more complex intertonguing than could be rationalized with the lithostratigraphic depiction.

We do not wish to suggest that the correlations originally depicted in the above Quaternary examples are wrong. Indeed, depiction of bed-scale facies architecture was not a stated goal of most of these studies. Drawing a straight line between lithofacies is the most parsimonious and in some ways least interpretive, objective approach. Rather, we suggest that our chronostratigraphic bedding correlation approach, guided by our experience working with outcrop and seismic data, provides a potentially more realistic interpretation. Our more complex correlations may have a varying uncertainty and error depending on the correlation length (i.e., well spacing), but we believe that they present an overall more accurate depiction of the organization of beds and facies in these deltas. Depending on the scientific and practical objectives, this approach may nevertheless provide a more useful result, as we discuss below.

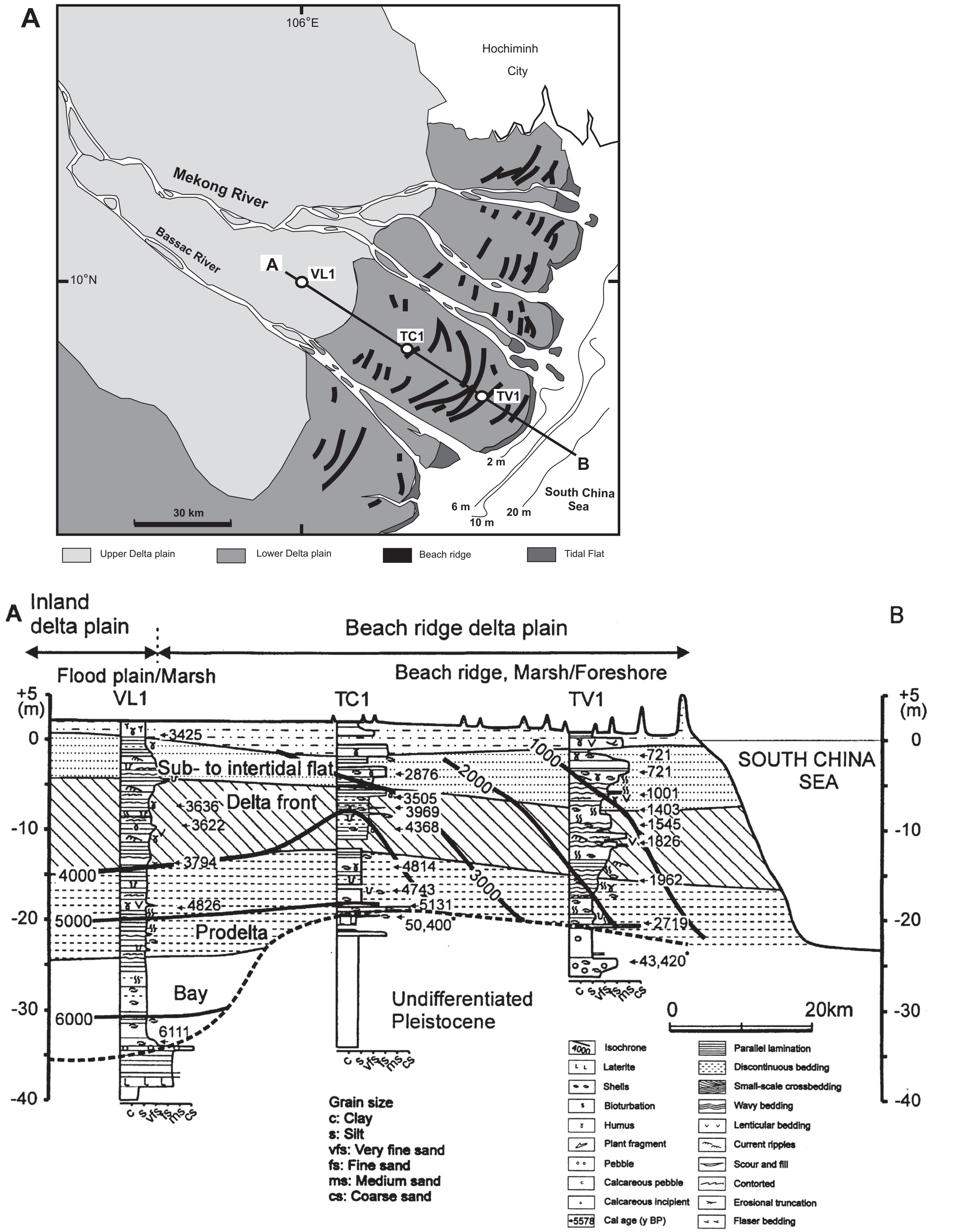

FIG. 12.—**A)** Depositional-dip-oriented subsurface correlation of cores through the Mekong River Delta as presented by Ta et al. (2002b) (lower diagram is reprinted with permission from Elsevier).

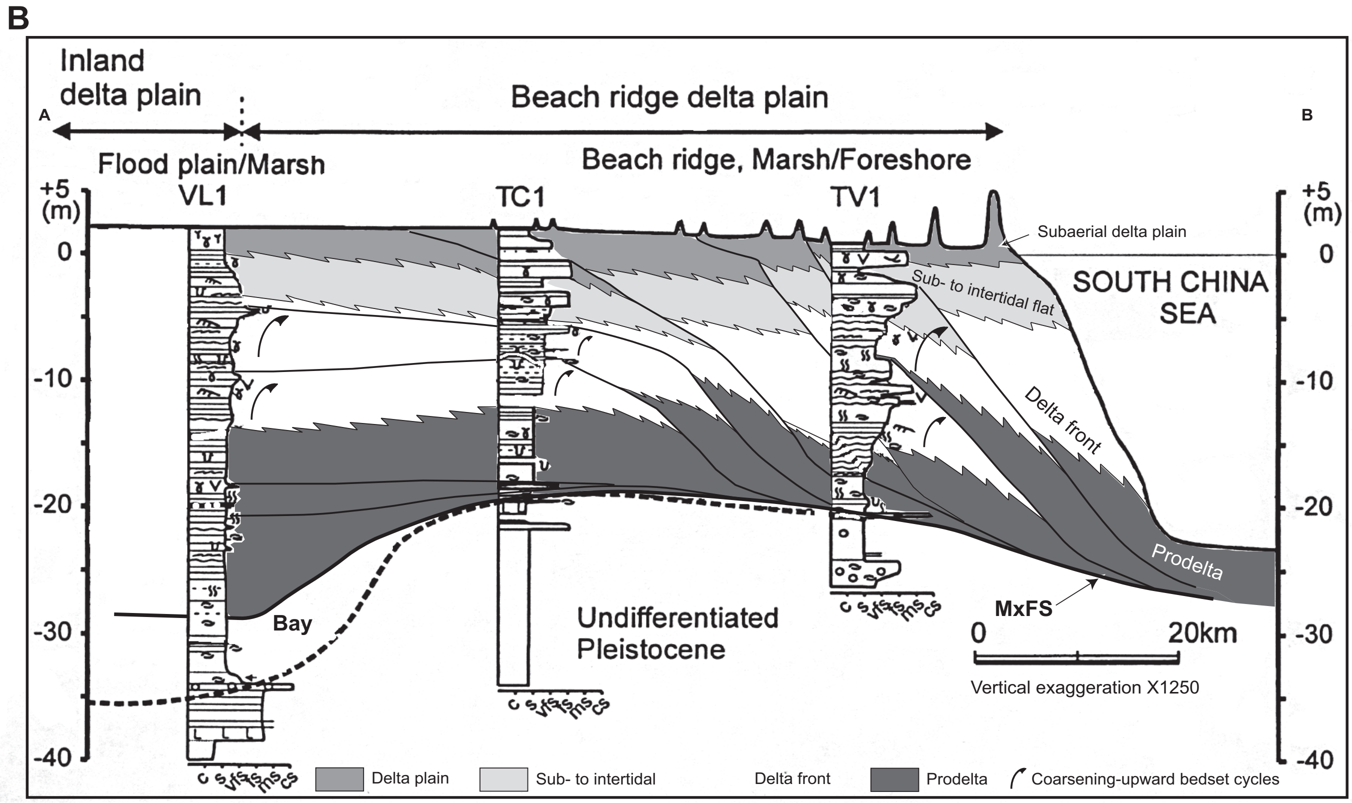

FIG. 12 (continued).—**B)** Reconstruction of Part A applying the technique of bedding correlation. See text for discussion. Note that the dip of the present-day delta front surface is 0.115°.

DISCUSSION

Modern analogs can play a vital role in understanding ancient deltaic systems. Studies of modern deltas, unlike those of ancient counterparts, begin with a reasonably complete plan view of the distribution of environments and facies. The subsurface distribution of these environments, however, must be interpolated from widely spaced cores, unless high-resolution seismic or other subsurface imaging data (e.g., GPR data) are available. In subsurface studies of ancient deposits, especially in petroleum basins where well logs are available, the inverse problem must be solved. The plan-view distribution of facies must be reconstructed from correlation (interpolation) between wells followed by the mapping of units on the basis of a series of correlated well picks to identify the scale of the delta. Sequence stratigraphic, allostratigraphic, and facies architectural concepts are increasingly employed by the sedimentologic community, and layer-cake-type correlations are increasingly viewed as being of less use in various applications (e.g., Van Wagoner et al., 1990; Posamentier and Allen, 1993; Tye et al., 1999; Ainsworth et al., 1999). The assumption of facies interfingering is very widely made, and nearly all sequence stratigraphic cross-sectional cartoons of deltas use the shazam line to demarcate the boundary between offshore, prodelta mudstone and delta-front sandstones. Detailed bed-scale interpretation of units is generally more difficult in the subsurface, because of a lack of chronometric control of sufficiently high resolution. In certain cases, pressure data or other type of fluid-flow engineering data can help the subsurface geologist determine connectivity of beds, and has been used to identify clinoform strata in prograding delta complexes (e.g., Sullivan et al., 1997; Tye et al., 1999). Outcrop-analog datasets are routinely used as "training images" in providing a conceptual basis for correlating subsurface datasets, as we have attempted to show above. More recent numerical models of deltas also show that the bed-scale architecture controls the broader-scale facies architecture.

The recorrelation of modern-delta examples presented in the previous section (Figs. 12B, 13B, 14B) differ significantly from their original versions (Figs. 12A, 13A, 14A). The original correlations depict layer-cake facies that prograded largely horizontally and uninterruptedly during the last 6 kyr of delta evolution. The modified versions suggest a more complex progradational history and "trajectory" of facies. The bedding correlation depicts a number of seaward-dipping clinoform-bounded units, which likely consist of distinct bedsets that define 10–1000 year intervals. Most of these bedset cycles show coarsening-upward facies successions bounded by minor flooding surfaces (and their correlative surfaces) associated with a minor landward shift of facies. The abrupt facies changes at the bedset boundaries may relate to mouth-bar switching, intra-lobe avulsion of distributary channels, minor fluctuations of relative sea level, and/or physiographic change or climatic change in the upstream drainage basin. For example, in case of the Mekong delta, Ta et al. (2002b) showed that over the last 6–7 kyr delta progradation was not constant. They suggested that the delta evolved from a "tide-dominated" to a "mixed tide-wave-dominated" system, and that depositional loci shifted laterally through time. In the Yangtze delta, Hori et al. (2001) showed that during the last 7 kyr a series of *en echelon* mouth bars were developed and then abandoned, and that a dramatic increase in

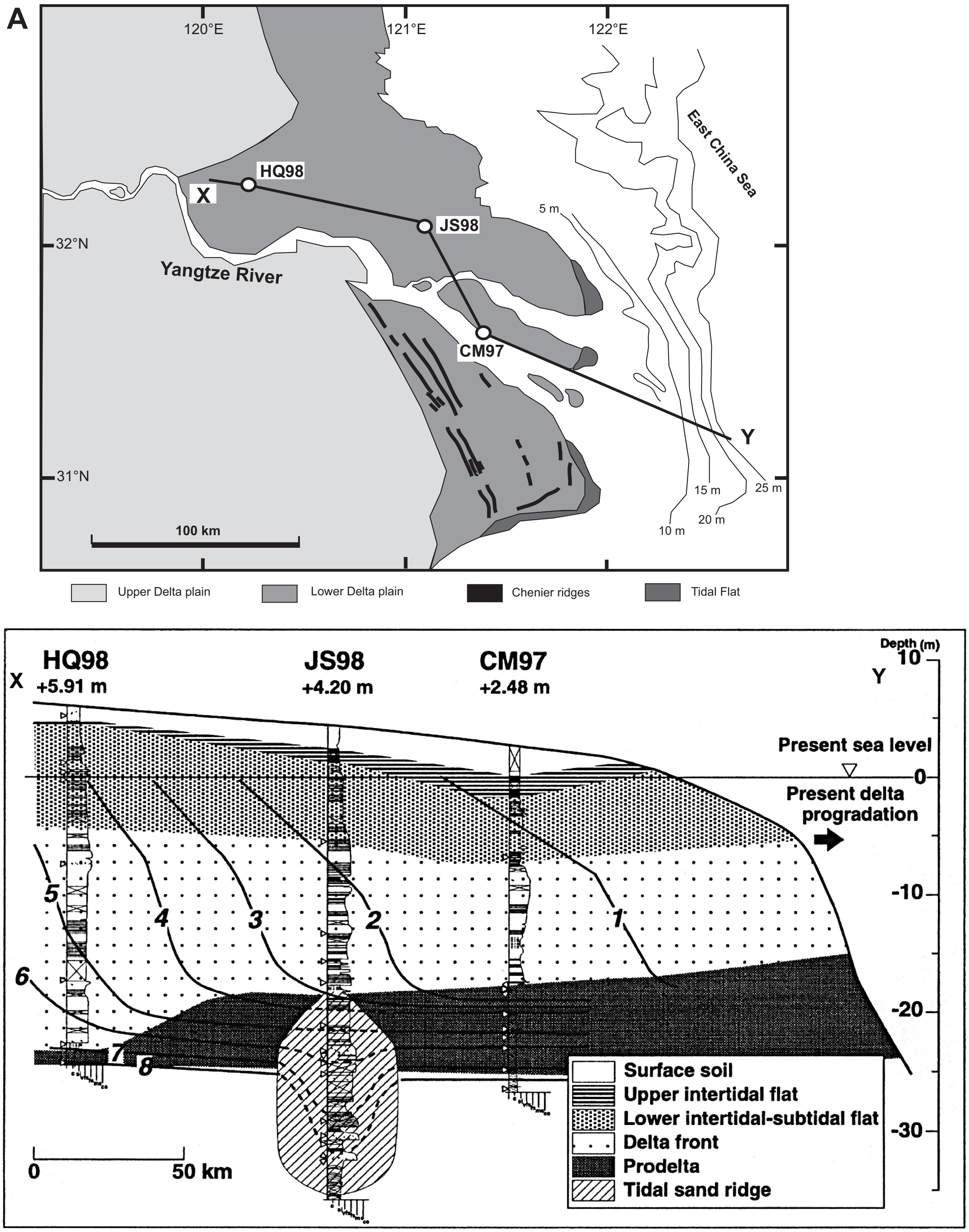

FIG. 13.—**A)** Subsurface geology of the Yangtze River delta illustrated by Hori et al. (2001) following the model of Scruton (1960). Isochron lines are in kyr BP (lower diagram is reprinted with permission from Elsevier). **B)** Alternate correlation incorporating concepts of bedding geometry reconstructed from Part A. Note that the dip of the present-day delta-front surface is 0.039°. See text for discussion.

B

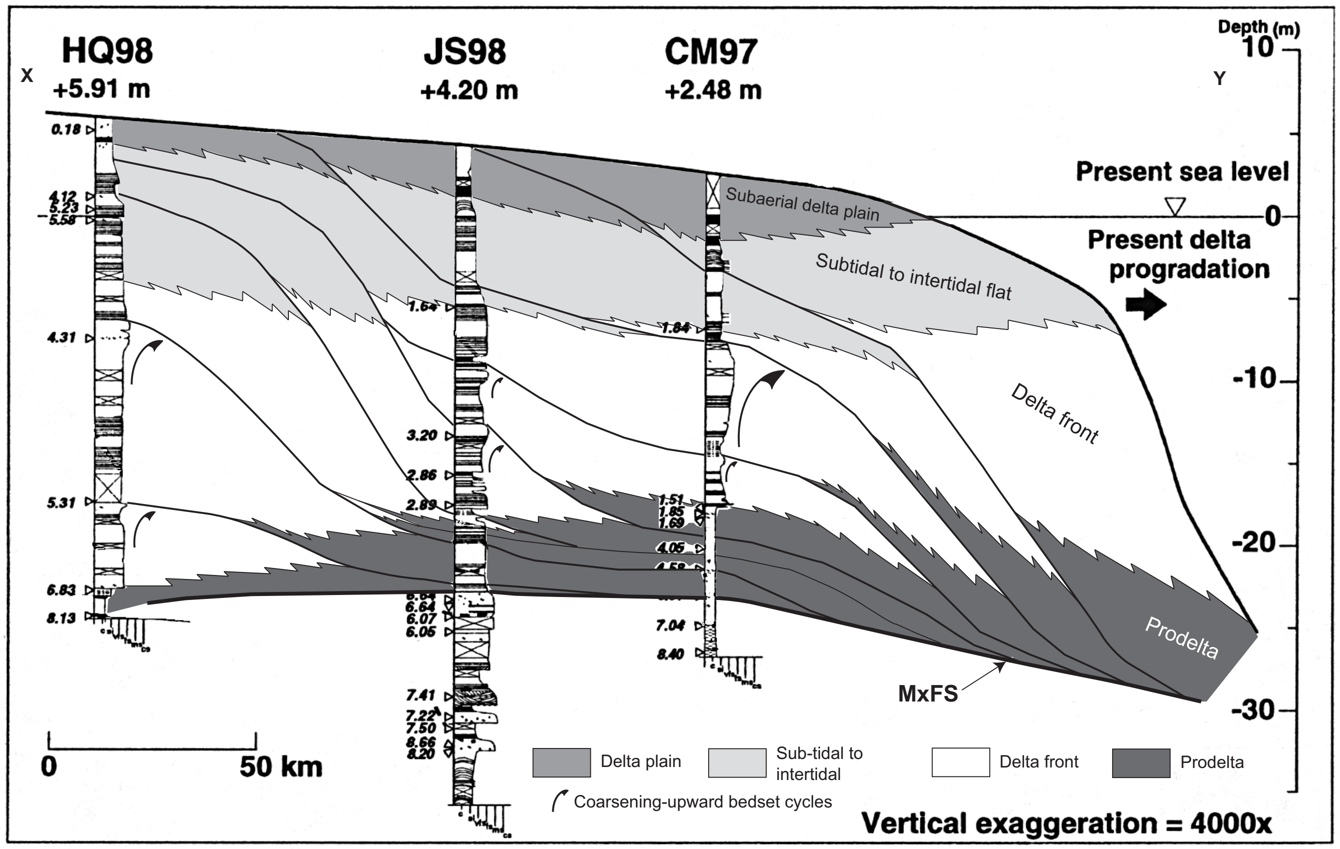

FIG. 13 (continued).—**B)** Alternate correlation incorporating concepts of bedding geometry reconstructed from Part A. Note that the dip of the present-day delta front surface is 0.039°. See text for discussion.

sediment supply occurred at 2 ka. All of these phenomena are likely to contribute to the development of intra-parasequence bedset boundaries across which facies dislocations may have occurred (Figs. 12B, 13B). Incorporation of bedding correlation, based on correlation of distinctive bedsets within an upward-coarsening deltaic facies succession, may help to identify phases of delta evolution in cross sections and lead to a more comprehensive 3-D picture of the entire delta. Because the hierarchies of planform morphometric elements, facies architectural elements, and stratigraphic subdivisions of a single delta are so far poorly understood, bedding correlation of modern deltas can help us in establishing and generalizing these hierarchies.

The recorrelated diagrams (Figs. 12B, 13B, 14B) show significant differences in the cross-sectional arrangement of sands and muds, which would potentially result in very different fluid-flow behavior. The original lithostratigraphic environmental facies correlations (Figs. 12A, 13A, 14A) show homogeneous and layer-cake facies units that could be interpreted to suggest horizontally layered sandy aquifers (delta-front sand). The recorrelated versions (Figs. 12B, 13B, 14B) show considerably more compartmentalization, with complex aquifers partially separated by prodelta mudstone facies, which would represent potential aquitards. For example, judging from Figure 13A, delta-front sandstones could be modeled as a single flow unit, where seawater may invade freely into the aquifer. In contrast, using Figure 13B, sea-water invasion of the subsurface aquifer would likely be retarded by a muddy aquitard associated with a landward shift of prodelta facies across the bedset boundary of the two bedset cycles shown at core TV1. In coastal regions, the withdrawal of fresh ground water without causing the invasion of salt water is a grave concern, and depends on accurate prediction of aquifer geometry.

Reservoir characterization of petroleum fields routinely shows that dislocations of facies, and hence reservoir properties, typically occur across clinoforms (i.e., time lines) and do not form flat, throughgoing "flow units" (Begg et al., 1996; Tye et al., 1999; Ainsworth et al., 1999; White et al., in press). The architecture of shale beds is especially important because of their variable effects in controlling reservoir behavior (Willis and White, 2000; White et al., in press). Like the control of facies-scale architecture of deltas on reservoir geology, many of the predictions of the subsurface aquifer geometry of modern delta systems also require detailed knowledge of the 3-D distribution of porous sands and impermeable muds. Clearly, as we have attempted to show, these can be quite different depending on the way in which beds and facies are correlated and depicted (Figs. 10, 12, 13, 14). This information may be pivotal for hydrogeologists trying to model Quaternary aquifers in coastal regions.

CONCLUSIONS

Earlier models of deltas (e.g., Scruton, 1960; Fig. 1A) indicated a diachronous lithostratigraphy with solid lines between

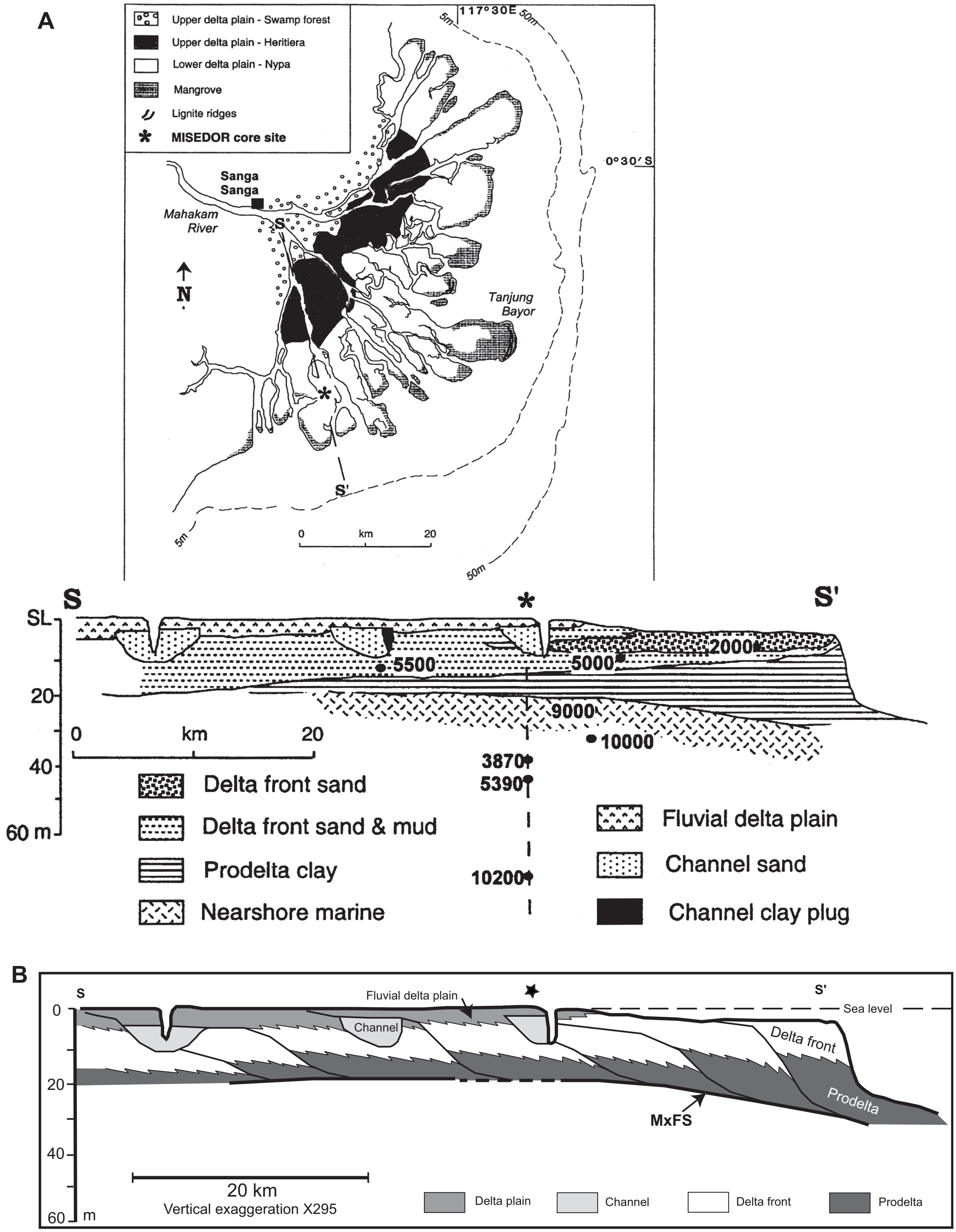

FIG. 14.—**A)** Longitudinal cross section of the Mahakam Delta illustrating highly diachronic lithostratigraphy (from Woodroffe, 2000) (reprinted with permission from Elsevier). **B)** Reconstruction of the facies architecture of Part A using bedding-correlation concepts. Note that the dip of the present-day delta-front surface is 0.122°.

diachronous facies units, leading to a potentially oversimplified depiction of the geometry and architecture of deltas. The most prominent features of deltaic deposits are the seaward-dipping inclined beds known as clinoforms. This concept, although not new, can be applied in subsurface correlation of cores from modern deltas. Broadly, lithofacies and bedding should follow time lines rather than forming tabular sheets. Facies dislocations commonly occur across bedset boundaries. Diachronous facies boundaries should be drawn as "shazam lines" to indicate that boundaries of this kind are gradational and intertonguing rather than sharp.

We have attempted to redraw some of the published diagrams on modern deltas using the concept of chronostratigraphic bedding correlation, and using seismic and outcrop examples as guide. We suggest that these recorrelations are a more accurate (although not necessarily more precise, because of large correlation length) depiction of the internal geometry of deltas that should be considered if details about facies architecture are required. These correlations may allow more accurate determination of the evolution and growth pattern of deltas with respect to time by identifying repetitive development of bedset cycles. They also may provide a more accurate basis for predicting reservoir and aquifer behavior.

It is acknowledged that the same level of resolution presented in our outcrop examples may not be achievable in subsurface, especially in a large modern delta with widely separated cores; however, the method of bedding correlation can be applied conceptually and at least crudely, irrespectively of the data base. We understand that our subsurface recorrelations are inherently model-driven and conceptual in nature. However, outcrop and seismic analogs are routinely used as guides to correlate subsurface well data, and in this paper we have taken this approach in recorrelating subsurface core data from Quaternary delta systems.

ACKNOWLEDGMENTS

Funding for this research was provided by the U.S. Department of Energy DOE Grant # DE-FG0301ER15166. Additional support was provided by the University of Texas Quantitative Sedimentology Research Consortium, of which BP and Chevron/Texaco are members. The authors are especially grateful to Joe Lambiase, Liviu Giosan, and Yoshiki Saito for their constructive criticism in reviewing the manuscript. All shortfalls in interpretations, and especially the recorrelations, are solely the responsibility of the authors. This is contribution number 1047 of the Geosciences Department, University of Texas at Dallas.

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