Introduction

NEW DIRECTIONS IN DELTAIC STUDIES

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INTRODUCTION

Deltas are amongst the most environmentally and economically important coastal sedimentary environments. Twenty-one of the world's 25 largest rivers, which deliver 31% of total fluvial sediment reaching the ocean, have well-expressed deltas developed at the open coast (Milliman and Meade, 1983; Meade, 1996). Deltas have high natural and agricultural productivity, rich biodiversity, and an abundance of waterways that provide easy means of transportation. As a result, ~ 25% of the world's population lives on deltaic coastlines and wetlands (Syvitski et al., in press). Furthermore, deltas act as filters, repositories, and reactors for a suite of continental materials including sediments, organic carbon, nutrients, and pollutants, significantly affecting both the regional environment at the continent–ocean boundary as well as global biogeochemical cycles (e.g., Keil et al., 1997; Aller and Blair, 2004; McKee et al., 2004). However, deltas are fragile geomorphic features, which can change dramatically with modest modifications in boundary conditions. Their complex morphology is the result of a dynamic equilibrium between fluvial discharge, marine energy conditions, accommodation, and the overall geological framework. In spite of the importance of deltas, a quantitative understanding of deltaic deposition is limited, because of their intrinsic complexity (see, e.g., Overeem et al., this volume). Progress in our ability to model and manage deltas depends strongly on a better understanding of the fundamentals of system-scale sediment dynamics. Sustained monitoring of various forcing factors affecting the deltaic morphology, as well as acquisition of new detailed information on deltaic depositional history, are necessary to provide quality datasets for quantitative modeling.

Studies of deltas lag behind research in both fluvial and deep-water depositional systems, as well as more geomorphologically oriented land studies. This knowledge lag reflects both a reorientation of the petroleum industry in the last two decades toward deep-water systems, as well as the difficulty of working across the shoreline with the traditional tools used for oceanographic or land-based work. However, deltaic studies are experiencing a renewed focus, because of their global importance in environmental and other societal concerns. This volume stems from a special session: "Deltas: Old and New", held at the Annual Geological Society of America conference in October 2002, that was convened to highlight these new directions in deltaic research.

VOLUME LAYOUT

The book is organized into three major areas. The first section includes several conceptual papers, including an overview of numerical modeling of deltas (Overeem et al.) and a paper that describes the concept of using outcrop analogs and high-resolution seismic data to provide a conceptual basis for the correlation of core data (Gani and Bhattacharya). The third paper in this section represents the first comprehensive synthesis of the ichnology of deltas (MacEachern et al.). The last contribution in this section presents the first comprehensive review of tide-influenced river deltas (Willis).

The second section presents several examples of ancient delta systems, primarily outcrop examples, ranging in age from Cretaceous to Tertiary, with the first two examples from the outcrop exposures in the Cretaceous interior of North America (Olariu et al. and Hampson and Howell). Tertiary-age deltas are represented by a study that focuses on the shelf–slope transition in seismic-scale outcrops in Spitsbergen, Norway (Plink-Björklund and Steel). Neogene deltas from Russia are presented by Davies et al., who discuss the Amur delta on Sakhalin Island, and Kroonenberg et al., who focus on the oil-producing paleo–Volga delta in the Caspian Sea. The Volga paper includes a comparison between the Neogene and present-day delta and provides a link to section three of the present volume.

The third and last section includes the largest number of papers, and assembles several studies of modern deltas, including summary papers on the Ganges–Brahamaputra mega-delta in India (Kuehl et al.), the Danube delta (Giosan et al.), the Burdekin in Australia (Fielding et al.), and the Godavari in India (Rao et al.). Ta et al. provide an overview of the Mekong based on the results of an extensive and ongoing coring program. Results from more than a decade of study on the Gulf of Mexico lowstand deltas is presented by Anderson. In the same region, the paper by Kulp et al. revisits the Mississippi, discussing the role of waves in delta development. The links between subaerial and subaqueous delta development is explored for the Po delta by Correggiari et al. A pair of papers from the Netherlands (Stouthamer and Cohen) focuses on avulsions and groundwater-level reconstructions in the extensively studied Rhine–Meuse delta system. Nonmarine deltas are represented in the paper by Smith et al., who discuss the development of a lacustrine, wave-dominated delta in Lake Athabasca, Canada. The geographical distribution of delta case studies, both ancient and modern, is presented in Fig. 1.

CONCEPTS AND REVIEWS

The past century has seen major decreases in discharge to the world's deltaic coastlines, whereas storm patterns and wave climate have changed, as a consequence of anthropogenic effects, combined with global warming. In order to manage world resources, more accurate, predictive, numerical models will be needed. Robust models require testing against field examples.

River Deltas—Concepts, Models, and Examples
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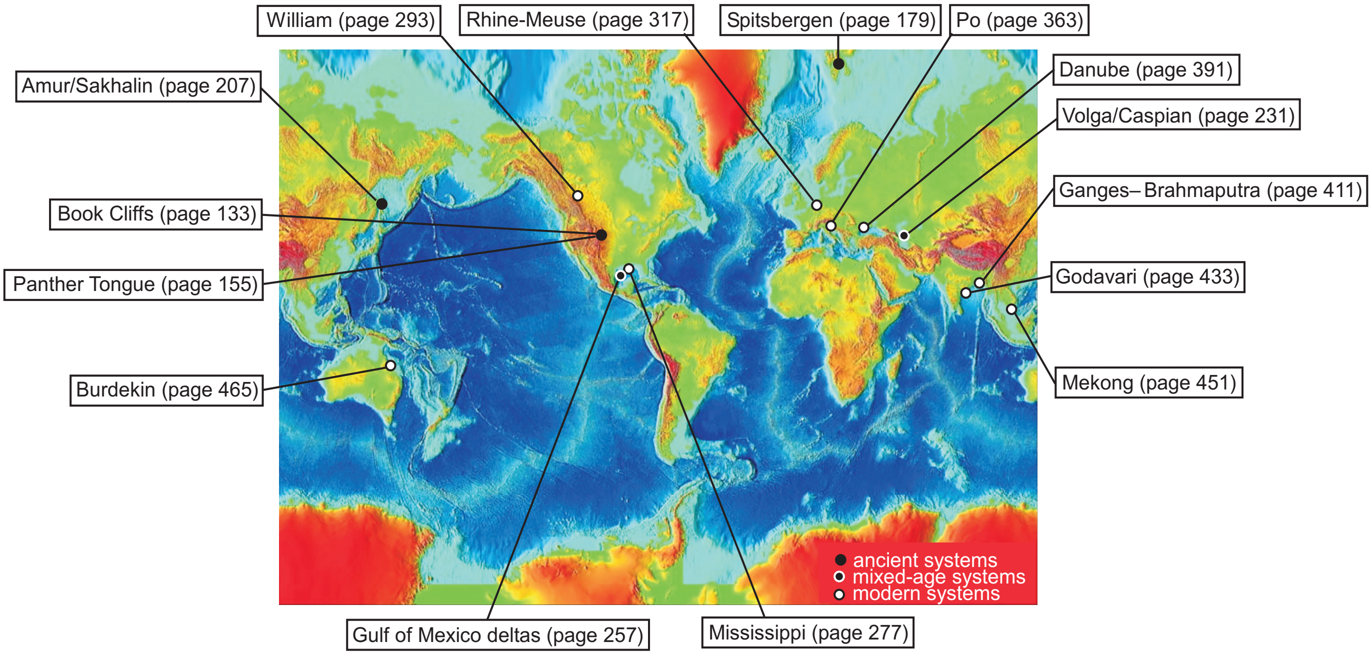

FIG. 1.—Geographical distribution of deltas (ancient and modern) discussed in detail in papers published in this volume. The starting pages in this volume for papers discussing specific systems are indicated in parentheses for each delta. Topography and bathymetry is from the National Geophysical Data Center (www.ngdc.noaa.gov). Concept and review papers in the first section of this volume discuss in brief other deltas not represented herein.

The opening paper by Overeem et al. reviews the state of the art in 3D numerical modeling of deltas. One ultimate goal of modeling is to provide quantitative estimates of shoreline progradation and retreat; in the case of deltas, modeling has to account for a larger number of processes than on other clastic coasts. Development of modeling routines for floodplain dynamics, longshore transport, as well as increasing the ability to model multiple grain-size classes are identified as priorities. Because most sedimentation in deltas occurs during relatively rare river flood events, one practical solution for modeling the growth of deltas is to adopt coarser time steps for nonflood conditions, while using finer time steps during "sedimentary events". From the perspective of subsurface fluid resources (i.e., water, and oil and gas), the internal organization of porous sandy elements versus flow-retarding muddy elements is crucial. The authors underscore that a key need for developing predictive deltaic sedimentation models is the improvement of the 3D characterization of modern delta systems to provide high-quality test cases against which numerical models can be calibrated. Depending on the nature of the modeling tool, but especially when event-scale features are to be incorporated, bed-scale, 3D field examples with detailed chronological control are necessary.

The Gani and Bhattacharya paper illustrate techniques for more chronostratigraphic correlations of the 3D facies architecture of modern delta systems using concepts and models developed by the petroleum industry. These concepts derive from analysis of high-resolution seismic and outcrop cliff photomosaics and are applied to the reinterpretation and correlation of cores from several recently published modern delta examples. They follow with a discussion of the implications of the different correlation styles for reservoir and aquifer connectivity and the construction of bed-scale numerical models. The use of bed-scale stratigraphy links back to the event-style numerical models presented by Overeem et al. (this volume).

The MacEachern et al. paper provides the first comprehensive synthesis of the ichnology of deltas. It covers the theory of interaction of various deltaic processes on trophic behavior, as well as illustrations of various diagnostic forms and assemblages from the ancient rock record. River plumes (whether hypopycnal or hyperpycnal) represent a major stress on infauna, including salinity, sunlight, and suspended sediment. The more stressful environments tend to favor short-lived, opportunistic, trophic generalists, resulting in trace-fossil suites that show low diversity and typically low abundance, compared to nondeltaic shelves, which favor more specialized behaviors resulting in a greater variety and abundance of forms, and generally higher levels of bioturbation. The paper emphasizes that ichnology is an increasingly important tool in interpretation and analysis of sedimentary facies and environments, although there remain far too few studies of the ichnology of modern delta systems. This is somewhat unfortunate, because cores from modern systems commonly are more amenable to analysis of the actual trace makers as well as the trace fossils (e.g., Ta et al., this volume), whereas a detailed chronology at various time scales is simultaneously available via radioisotope techniques (e.g., ^{10}Be, ^{210}Pb, ^{137}Cs, radiocarbon) or OSL dating. Studies of the ichnology of modern delta systems are essential to help calibrate relationships between environments and ichnofacies. In addition, better integration of the biology and process sedimentology provides a whole new dimension in looking at the relationship between biosphere and lithosphere, and can be relevant in measuring sedimentation rates, carbon cycling, and other key environmental parameters.

The paper by Willis provides a thorough review of tide-influenced river deltas, including a discussion of modern processes and ancient examples. He emphasizes the role of tidal reworking of sands in building submerged bars and dunes that overlap in scale, leaving a complex hierarchy of large-scale cross stratification in the sedimentary record. In this context, interpretation of cross stratification in tidal systems becomes more difficult than generally acknowledged because of the inability to distinguish cross stratification formed by prograding tidally modulated mouth bars deposited in a few meters water depth from tidal "sandwaves" that migrate in considerably deeper water. Willis also points out that sequence stratigraphic divisions defined by large-scale shifts in facies belts associated with key surfaces are difficult to resolve in tide-influenced deltas, where both autogenic changes (e.g., in sediment supply, in tidal currents) as well as allogenic processes (e.g., sea-level changes) produce pronounced facies variations and significant erosion at similar scales.

ANCIENT SYSTEMS

Hampson and Howell reexamine the well-known Cretaceous Books Cliffs succession, focusing on detailed facies architectural analysis and 3D reconstruction of environments. Previous regional stratigraphic studies have interpreted these deposits as wave-dominated shorefaces, but Hampson and Howell use geomorphic measures of the shape of the shoreline (lobate versus straight), areal proportion of fluvial deposits, and spacing of river channels to determine the overall contribution of rivers to shoreline progradation. They suggest that rivers were critical in feeding the Book Cliffs shorefaces, and show that they contain specific, more fluvially influenced components. They also suggest that rivers were spaced from 1 to 68 km apart, compared to modern strandplains, where rivers may be spaced up to 130 km apart. They also provide a test of the asymmetric wave-influenced delta model (Bhattacharya and Giosan, 2003; Giosan et al., this volume) and show that river channels are deflected south by persistent longshore drift, and consequently show a distinct updrift–downdrift asymmetry, as predicted by the model. The wave dominance of these systems inhibits major transgression caused by autogenic avulsions, and the authors interpret major parasequence-bounding transgressions to reflect allogenic controls.

Olariu et al. present one of the first papers that uses digital, photogeological techniques integrated with GPR data and more traditional sedimentological techniques to describe the detailed facies architecture of a proximal delta-front sandstone body, the Cretaceous Panther Tongue sandstone in Utah. The authors show that the delta front contains thin, shallow "terminal" distributary channels, associated with more sheet-like to lens-shaped distal bar sandstones. An abundance of structureless to graded beds suggests a highly river-dominated delta that was possibly hyperpycnal. The landward margins of the distributary channels show good evidence for upstream accretion, suggesting that backfilling is a potentially important process in growth and abandonment of distributary channels.

Plink-Björklund and Steel describe seismic-scale outcrop examples of Eocene shelf-edge deltas in Spitsbergen. Detailed facies architectural analysis, integrated with regional stratigraphy, allows them to compare the difference in deltas formed when the shelf edge was fully exposed (Type 1 sequence) to times when the shelf edge was not fully exposed (Type 2 sequence). They suggest that the lack of basin-floor fans in the Type 2 examples reflect higher rates of sediment fallout near the shelf edge during slow sea-level falls that effectively armor the shelf edge and prevent deep incision. The interpreted outcrop panels show a complex hierarchy of inclined beds organized into clinothem sets, which in turn group into systems tracts and sequences. Erosion surfaces occur at the scale of beds, individual distributary channels, as well as more regional amalgamated channel belts, that define the major sequence boundaries. The paper is particularly valuable in that the outcrops allow a full integration of analysis at every stratal scale, from individual beds at the facies scale, to regional sequences. The virtually 100% exposure leaves very little to interpolate. They also make a conclusion similar to that of Anderson (this volume), that rapidly deposited deltas at or near the shelf edge may not have linked submarine fans. High sediment supply can cause the shelf to aggrade, and cause rivers to avulse and lobes to switch laterally, rather than cut into the shelf edge and bypass sediment to deeper water.

The Davies et al. paper presents the first detailed outcrop data on the Neogene Paleo-Amur sand-rich delta deposits, exposed on Sakhalin Island, Russia, and sourced from the Asian continent. They present a detailed description of the facies and facies successions, which are placed into the regional lithostratigraphic framework. The authors interpret the distribution of sands as controlled by both geological structure and longshore-drift transport, suggesting that these are wave-dominated delta systems. Deltaic sandstones on Sakhalin Island are associated with a significant, but poorly understood, hydrocarbon province.

The paper by Kroonenberg et al. compares the sediments of the ancient, Neogene Productive Series of the Paleo–Volga Delta with the modern system discharging into the Caspian Sea. The ancient succession was deposited into an extremely rapidly subsiding but relatively narrow part of the basin during a major lowstand. A large canyon, several hundred meters deep, feeds this lowstand system. The modern Volga is essentially a highstand delta, deposited on an extremely low-gradient and contrastingly wide shallow shelf, which results in more than 800 outlets, the largest of which are less than 4 m deep. Sedimentation rates in the modern delta are about 1 mm/yr, compared to 4 mm/yr for the older Productive Series. The Caspian was essentially brackish to nonmarine for most of its Neogene History, and thus represents a good example of a highly cyclic, continental-scale lacustrine delta.

MODERN DELTAS

An exceptionally dense and well-resolved seismic and lithostratigraphic dataset is presented by Anderson, who discusses the development of shelf-margin deltas during the last glacioeustatic cycle for several river systems discharging into the Gulf of Mexico. This paper represents an instructive transition from the studies of ancient deltas, where chronological constraints are minimal, to Holocene deltas, where radiocarbon dating allows high-resolution integration of sedimentation patterns, sea-level curves, and climate records. Anderson uses biostratigraphy and isotope stratigraphy to move beyond the range of the radiocarbon method that is used for the youngest part of the deposits. Shelf deltas built diachronously in the Gulf of Mexico throughout the falling stage of sea level, rather than at the maximum lowstand when the sea level actually reached the shelf margin. Rivers like the Colorado and the Rio Grande had relatively stable courses on the shelf during sea-level fall and built lowstand deep-sea fans. In contrast, the higher-discharge Brazos River, as well as rivers feeding the Western Louisiana shelf, wandered onto the shelf through avulsions prior to the maximum lowstand and did not produce associated fans (see also Plink-Björklund and Steel, this volume). These high-discharge deltas reached the shelf edge before maximum eustatic lowstand and subsequently shifted laterally, infilling the shelf, rather than bypassing sediment to deep-water systems at maximum eustatic lowstand. The location of the sequence boundary associated with the maximum eustatic lowstand is not straightforward to detect, and cannot be determined simply on the basis of stratal patterns.

Kulp et al. reassess the role played by waves and longshore transport in the development of the Mississippi delta plain. Historically, delta lobes of the Mississippi have been treated as river-dominated depocenters. However, analysis of headlands along the south-central delta plain reveals sandy coastal lithosomes containing regressive beach ridges, which suggest that waves have been more influential than previously proposed. Marine reworking of earlier-formed headlands is interpreted to have provided the sand that was captured downcoast by younger progradational distributaries building wave-influenced lobes. Besides its fundamental significance in understanding the detailed facies architecture of deltas, the distribution of sand-rich lithosomes has important practical implications: it influences subsidence patterns that are vital to predicting locations of future shoreline erosion and wetland loss, and it is essential to locate sands needed for shoreline renourishment projects. Kulp and colleagues make a key observation that waves and river plumes interact quasi-continuously (see also Giosan et al., this volume), such that wave-formed sands may be interbedded with river-dominated facies throughout the deposit, as opposed to more traditional view that tended to assume that deltas went through a river-dominated phase, during progradation, followed by wave reworking during transgression (e.g., Boyd and Penland, 1988).

Smith et al. studied the William River lacustrine wave-dominated delta in Lake Athabasca, Canada, which has been building since ~ 9800 cal years BP. The reduced scale of the delta makes it ideal for a comprehensive study of its morphology and internal stratigraphy. Another appeal of the William delta is the fact that it evolved in the absence any major, direct human intervention. The potential for extracting high-resolution records of storm and flood frequency from lacustrine deltaic deposits is illustrated by the ground-penetrating radar stratigraphy that shows offlapping clinoform bedsets. The authors relate the bedsets to annual to decadal storms. Several gently dipping ravinement surfaces are interpreted to have been produced by severe storms with a millennial-scale periodicity. On the basis of a radiocarbon chronology and luminescence dates on beach ridges, the frequency of these large storms appears to have increased toward the present.

In examples of deltas in Europe, studies by Stouthamer and by Cohen utilize the most detailed Holocene paleogeographic reconstruction ever undertaken—of the Rhine–Meuse delta system, which is based on interpretation of ~ 200,000 borehole descriptions collected over 25 years (Berendsen and Stouthamer, 2001). Stouthamer tackles changes in avulsion style and their influence on alluvial architecture at the entire scale of the delta, focusing for the first time on channel reoccupations. Avulsion by diversion into floodbasins, with a limited number of reoccupations, was prevalent during the period of rapid sea-level rise in the early and mid Holocene, when rivers discharged into the North Sea at various locations through a fragmented system of coastal barriers. In contrast, in the late Holocene, channel reoccupation and avulsion frequency was found to increase, controlled by increases in the local sedimentation rates (within-channel and/or on natural levees). This change in the avulsion style and regime occurred during a period of slow relative sea-level rise and, therefore, low regional aggradation rates. Detection of reoccupied channel belts require detailed paleogeographic reconstructions, because they cannot be distinguished, using stratigraphy alone, from channel belts that experienced discharge fluctuations. As also documented in the papers by Anderson and by Plink-Björklund and Steel, Stouthamer (this volume) shows that times of rapid sediment supply are frequently associated with more rapid avulsions.

Cohen takes a geostatistical approach to analyze groundwater markers (mostly basal peats) from the same Rhine–Meuse dataset. The analysis shows that the construction of the coastal prism is not determined exclusively by sea-level changes. Until the late Holocene, the relatively fast eustatic sea-level rise controlled the backfilling of the coastal lagoon in the Rhine–Meuse valley system. In contrast, fluvial discharge is responsible for the continued backfilling in the upper delta, even after it had been superseded by delta progradation in the central area. The barrier-protected lagoon acted as a sediment trap for fluvial sediments, but the rapid progradation expected for a delta building in a quiescent bayhead environment was somewhat delayed by creation of accommodation via regional and local subsidence. Locally, higher aggradation rates were probably related to changes in groundwater flow rates. The contributions by Stouthamer and Cohen illustrate well the advantages provided by exhaustive chronostratigraphic databases that can be employed in statistical analyses and, further, in modeling of the complex response of a delta to upstream and downstream controls as well as local vs. far-field forcing mechanisms.

Correggiari et al. combine historical cartography on the subaerial Po delta and detailed seismic-stratigraphic and core data collected on the Adriatic shelf to correlate the late Holocene offshore prodelta architecture to onshore phases of delta growth and retreat. High-frequency climatic change, autocyclic avulsions, and anthropogenic factors, acting on typically short time scales, led to alternating phases of rapid advance and abandonment of multiple deltaic lobes. Changes in the forcing parameters are also reflected by frequent shifts in morphology of individual lobes or morphologic reorganizations at the scale of the entire delta (e.g., from supply-dominated to wave-dominated during the Little Ice Age due to climatically modulated changes in sediment discharge and/or reflecting anthropogenic intervention in the drainage basin). The morphological variability preserved on land is also reflected in the prodelta architecture, where changes in the relative importance of distributaries and lateral shifts in sediment entry points led to the construction of prodelta lobes that overlap through low-angle downlap or onlap surfaces. Overall, a marked asymmetry of the delta–prodelta system is observed, resulting from a preferential sediment dispersal downdrift of each individual delta mouth. Prodelta deposits are either shingled individual lobes made of amalgamated flood layers (alternation of fine-grained sand or silt/mud), reflecting changes in the relative importance of feeding distributaries, or massive silts preserved in "cut-and-fill" features that were deposited during phases of major prodelta-lobe construction. The latter type of deposits probably record catastrophic flood events, similar to the channels observed in outcrops examples of Plink-Björklund and of Steel and Olariu et al. (this volume).

Giosan et al. discuss morphodynamics-based models for the development of wave-influenced lobes of the Danube delta, while providing a comprehensive review of the research undertaken over the last 150 years in this region. A reassessment of a previous radiocarbon chronology of the Danube delta suggests that it started to prograde outside a barrier-protected embayment around 6,000 years BP, rather than 9,000 years ago as previously proposed. Morphodynamics of the open-coast Danube delta, as well as of the nondeltaic coast situated downdrift, has largely been determined by the interaction between fluvial deposition and the strong southward wave-induced longshore drift. The resulting river-mouth morphodynamics is highly nonlinear, involving multiple feedbacks among subaerial deltaic progradation, deposition on the subaqueous delta, current and wave hydrodynamics, and wave–river plume interactions. In spite of this complexity, the morphology at the mouth exhibits a tendency to self-organize that is reflected and preserved by the facies architecture of wave-influenced lobes (see also Bhattacharya and Giosan, 2003). An established paradigm for other coastal environments, morphodynamics should be consistently employed in the study of deltas for both a full understanding of deltaic deposition in modern deltas as well as for detailed process-based reconstructions of deltaic architecture.

Kuehl and colleagues' review of extensive work on the Ganges–Brahmaputra system reveals the complex interaction between the multitude of factors controlling the development of a large river delta. They identify tectonics as a strong control on the sedimentation in the subaerial delta, which is compartmentalized in subsiding basins and uplifting terraces. Coarse-caliber sediments delivered by the rivers are responsible for a high rate of avulsion influencing the development of the delta plain. In contrast to other Holocene deltas that started to prograde after sea-level rise decelerated (8,500–6,500 years ago; Stanley and Warne, 1994), a monsoon-modulated doubling of the already enormous sediment load carried by the Ganges and Brahmaputra led to an additional phase of progadation between 11,000 and 7,000 years ago. Subaerial and subaqueous progradation of Ganges–Brahmaputra delta has built a compound clinoform across the shelf, a feature that appears to relate to an energetic regime on the shelf. However, the presence of a major canyon dissecting the shelf in front of the delta has been a limiting factor in the growth of the subaqueous delta.

A first comprehensive review on the Godavari delta is presented by Rao et al. The variable morphology exhibited by different lobes of the delta is the result of the complex interplay between variations in river discharge, wave climate, and location of a distributary mouth relative to other previous or contemporaneously evolving delta lobes. Strong wave-induced longshore transport is responsible for episodes of river-mouth deflection and development of barrier islands and spits, leading to a diversification of depositional environments and trapping of fine sediments on the delta plain.

Ta et al. used borehole data from the Mekong delta plain to study the response of the river-influenced coastal depositional system to sea-level changes since the last glacial maximum. After the Mekong delta aggraded and prograded out of its valley, between 8,000 and 3,000 years ago, its morphology changed from tide-dominated to wave-influenced in character. Increased exposure of the delta coast to waves, once it prograded outside the sheltered embayment, is a probable cause for this morphologic reorganization, although additional monsoon-modulated influences, such as a decrease in river discharge and/or an increase in wave energy, are not excluded. In the wave-influenced phase of the delta evolution, longshore transport of river-derived sediment led to the formation of an extensive mangrove and mudflat sector downdrift of the Mekong River mouths that expanded the delta plain with more than a third of its initial areal extent.

The Fielding et al. paper provides a thorough overview of the Burdekin delta in Australia, integrating surficial mapping, core, seismic, and ground-penetrating radar data. The Holocene delta formed by progradation and abandonment of at least thirteen lobes over the past 8–10 ky. The authors found that the delta platform consists of river-mouth-bar deposits that form the bulk of the deltaic deposits. The dominance of river-mouth-bar deposits suggests that the delta has primarily been constructed by major river floods, challenging previous interpretations that the Burdekin is a wave-dominated system or a "mixed energy" delta. Beach ridges and spits that are clearly indicative of significant wave activity and strong longshore drift are, however, volumetrically insignificant, despite the fact that they impart a "classic" wave-dominated plan view. The paper makes an important point that interpretation of internal facies patterns based on plan-view morphology, although practiced for many years, must be done with caution. The flood-deposited mouth bars commonly have sharp, scoured bases that reflect high shear stresses of flood events rather than forced regressions or wave scour, which are commonly invoked processes to explain sharp-based mouth bars and shoreface sandstones in the ancient record (e.g., Plint, 1988; Posamentier et al., 1992).

NEW DIRECTIONS

Deltas build at one of the most dynamic internal boundaries of sediment-dispersal systems: the shoreline. In contrast to most other coasts, deltas are largely accumulative depositional systems, where paleoenvironmental information from the receiving basin as well as from the upstream drainage basin is preferentially buried, providing the best chance for preservation in the stratigraphic record. A recent trend in sedimentary research emphasizes a holistic systems approach toward studying depositional systems—the so-called "source-to-sink" strategy (e.g., Nittrouer and Driscoll, 1999; Kuehl et al., 2003)—devised to better deconvolve the paleoenvironmental information preserved by these systems. This approach is justified by the need to explore the full range of responses of a sediment-dispersal system to external forcing (e.g., tectonics, hydrology, sea-level change, and other climate-modulated parameters) and internal controls (e.g., avulsions, morphodynamics), but also for identifying components of the system that need further study. Intrinsic controls typically result from feedbacks developed among components of a sediment-transfer system, but in contrast to external controls they have received far less attention.

In the original sequence stratigraphic literature, sequences were largely interpreted assuming constant sediment supply, slowly or linearly varying subsidence (i.e., tectonics), with more complex and rapid stratigraphic changes attributed to eustasy (e.g., Posamentier et al., 1988; Van Wagoner et al., 1988). Clearly, climate and sediment discharge are not constant in most of the systems studied in this volume. Indeed, varying sediment supply is seen as a major control on both small-scale facies architectural patterns and on the position of larger-scale systems tracts and sequence boundaries. In future studies of deltas, changes in sediment supply can no longer be ignored or assumed to be constant. The relationship between sea level, climate change, and the stratal record remains a main topic for future research, particularly in the context of global change.

Invited papers for the "Concepts and Reviews" section of the present volume extensively discuss several areas where research will likely focus in the future; these include delta types that have less developed facies models (tide-influenced deltas reviewed by Willis), concepts that have already gained acceptance in the study of ancient deltas or in the petroleum industry that should be extended to modern systems (ichnological approaches reviewed by MacEachern et al., this volume, and the use of bed-scale stratigraphy reviewed by Gani and Bhattacharya, this volume), and the role of modeling in testing scenarios about deltaic development and stratigraphic architecture (reviewed by Overeem et al., this volume).

Case studies of ancient and modern deltas from this volume collection are representative of several other distinct directions in recent deltaic research that reflect legitimate concerns for the fragile environment of deltas, but also by the recognition that deltaic deposits are untapped repositories of high-resolution paleoenvironmental information.

Paleohydrology

Most paleoclimate reconstructions focus on temperature, but for understanding fluvial, deltaic, and coastal dynamics, reconstructions of past hydrological variability are more important, especially given the emerging recognition that stratal patterns are strongly controlled by climate. Several papers in this volume document or suggest that changes in river water and sediment discharge have had system-wide effects on delta sedimentation, irrespective of eustatic and tectonic controls. Kuehl et al. (this volume) show that the Ganges–Brahmaputra mega-delta started to prograde earlier than most of the world's modern deltas because of a doubling of the sediment discharged by the rivers under a monsoon-intensified regime. Fielding et al. (this volume) demonstrate that the Burdekin delta has been constructed primarily by flood-related processes. Climatically modulated changes in discharge of the Po River led to morphologic reorganizations at the scale of the entire delta during the Little Ice Age (Corregiari et al., this volume). Lack of synchronous changes in river discharge to balance changes in wave energy resulted in a late Holocene reorganization of the Mekong delta (Ta et al., this volume). Extreme floods are also the probable cause for the "cut-and-fill" features preserved on the Po prodelta and in the ancient examples presented by Olariu et al. (this volume) and Plink-Björklund and Steel (this volume). Anderson (this volume) shows that it was primarily sediment supply rather than eustasy that dictated when and where rivers on the Gulf Coast built their shelf deltas during the falling stage of sea level of the last glacial cycle. Plink-Björklund and Steel (this volume) also conclude that high sediment supply can cause the shelf to aggrade, and cause rivers to avulse and lobes to switch laterally, rather than cut into the shelf edge and bypass sediment to deeper water.

Although distributary channel networks in deltas are fundamental factors in controlling the architecture of deltas, their development has rarely been studied. Avulsions and bifurcations are the primary processes responsible for development of channel networks. Rather than being a function of regional aggradation as previously proposed, avulsions appear to be controlled by a suite of factors that include coastal evolution and local aggradation rate, which is determined mainly by discharge and sediment load (Stouthamer, this volume). Coarse-caliber sediments delivered by the Ganges and Brahmaputra are responsible for a high rate of avulsion influencing the development of that delta plain (Kuehl et al., this volume). The number of distributary channels in a delta appear to be controlled by length of river and by the delta gradient (Syvitski et al., in press). Several papers in this volume, however, identify the discharge partitioning among distributaries as another important aspect regulating the number and pattern of distributaries. A larger share of the Danube discharge has allowed the Chilia distributary to build a typical river-dominated lobe in an atypical wave-dominated environment (Giosan et al., this volume). The morphology and facies distribution of both the subaerial and the subaqueous lobes of the Po delta have been dependent on the discharge of individual distributaries (Corregiari et al., this volume). Similar links between morphology and discharge are proposed by Rao et al. (this volume) for the Godavari delta. Future paleohydrological reconstructions as well as the hydrological monitoring of modern rivers should address explicitly the partition of discharge among distributary channels in a delta as well as the links between discharge and avulsions.

Morphodynamics

Morphodynamics of deltaic coasts and shelves has been a less explored aspect in the evolution of deltas, although the morphodynamic paradigm has been widely used in coastal studies (e.g., Carter and Woodroffe, 1994; Cowell et al., 2004). Feedbacks between the evolving morphology of a delta and basinal hydrodynamics remain inadequately known, as are the interactions between contemporaneous lobes within a delta (e.g., Komar, 1973; Wright, 1985; Cowell et al., 2004) or the influence exerted by a delta on the dynamics of adjacent nondeltaic coasts and vice versa (e.g., Penland and Suter, 1989; Aslan et al., 2003; Corregiari et al., this volume). While there has been much recent progress in understanding suspended-sediment deposition from river plumes (e.g., Syvitski and Bahr, 2001; Geyer et al., 2004), the dynamics of coarse sediments at river mouths (Wright, 1977) has received little attention recently, in large part because of the inability of conventional techniques to provide direct reliable measurements.

Existing morphodynamic models (e.g., Komar, 1973; Cowell et al., 2003) identify rotation of the shoreline as the principal phenomenon associated with delta development. Shoreline rotation is responsible for changes in longshore drift along deltaic coasts. Several other hydrodynamic–morphodynamic feedback loops are related to bedload sedimentation at river or distributary mouths. The hydraulic groin effect of river plumes (Todd, 1969; Komar, 1973, Dominguez et al., 1983; Dominguez et al., 1996; Giosan, 1998) is accompanied by the groin effect of the subaqueous delta or of the delta plain (see Giosan et al., this volume, and Kulp et al., this volume). The development of a shallow subaerial delta platform, strongly offset to the downdrift direction, helps dissipate waves reaching the platform (Giosan et al., this volume), leading to entrapment of sediment on the platform. Giosan et al. (this volume) also suggest that wave reworking of flood deposits on the subaqueous delta platform can lead to recurrent emergence of barrier islands at its offshore edge. Longshore transport, intensified and guided by the new coast along the barrier, leads to a rapid expansion of the subaqueous delta in the alongshore direction. Another effect of river-mouth bedload sedimentation is presented by Olariu et al. (this volume). They present evidence that the landward margins of the "terminal" distributary channels from the Cretaceous Panther Tongue sandstone show good evidence for upstream accretion, suggesting that backfilling is a potentially important process in growth and abandonment of distributary channels. Morphodynamic aspects of delta development are also discussed by Rao et al. for the Godavari delta, Ta et al. for the Mekong, Corregiari et al. for the Po delta, and Fielding et al. for the Burdekin. Hampson and Howell (this volume) apply morphodynamic insights for a better interpretation of ancient deltas. The role of longshore sediment transport in delta development is also discussed by Davies et al. (this volume).

Morphodynamics of adjacent nondeltaic clastic coasts can also have a surprising limiting effect on deltaic sedimentation. Several papers in this volume emphasize the role of coastal processes in building transgressive sandy barriers at the mouths of embayments (see papers by Stouthamer, Cohen, Corregiari et al, Giosan et al., and Kulp et al., this volume). In a first phase, in many cases a delta develops as a bayhead system in these barrier-protected embayments. After reaching the open coast, the delta morphology and stratigraphic architecture change drastically as a result of changes in energy of the receiving basin.

A better understanding of the mechanisms for distal, fine-grained subaqueous deltaic deposition is also acutely needed (e.g., Kuehl et al, this volume; Corregiari et al., this volume). Whereas modeling indicates that deltaic clinoform dip profiles are a function of wave climate and riverine sediment supply (e.g., Friedrichs and Wright, 2004), Kuehl and colleagues suggest that a coarse sediment caliber, in addition to a high energy level on the shelf, may be responsible for the formation of a double clinoform on the Ganges–Brahmaputra shelf. Corregiari et al (this volume) build on previous research on clinoforms on the Adriatic shelf (e.g., Cattaneo et al., 2003) to address the detailed structure of the diffusion-dominated part of the Adriatic mud wedge, close to the Po mouths. The prodelta deposits are either shingled individual lobes made of amalgamated flood layers (alternation of fine-grained sand or silt and mud), reflecting changes in the relative importance of feeding distributaries, or massive silts preserved in "cut-and-fill" features that were deposited during phases of major prodelta lobe construction. Studies of the subaqueous part of deltas, especially the fine-grained prodeltas (e.g., Asioli et al., 2003; Oldfield et al., 2003), hold strong promise for paleohydrological and other paleoclimatical reconstructions, guaranteeing that this topic will remain high on future research agendas (e.g., Syvitski and Trincardi, in press). The study by Corregiari et al. (this volume) emphasizes well the level of detail necessary for understanding of deposition of deltaic clinoforms for developing meaningful paleoenvironmental reconstructions.

Current process-based models for deltaic deposition emphasize variations in the proportion of wave, tide, and river influence that are thought to be the primary control on delta morphology and facies architecture (Wright and Coleman, 1973; Coleman and Wright, 1975; Galloway, 1975). However, papers herein and elsewhere (e.g., McManus, 2002; Bhattacharya and Giosan, 2003) show that the morphology and facies of a delta or delta lobe are dynamically responding to changes in all three controlling parameters. One challenge for future deltaic research is the reconstruction of past wave climates and tidal characteristics that have affected delta-hosting basins, in a complement to paleohydrological reconstructions. High-resolution geophysical and sedimentological surveys such as the one presented by Smith et al. (this volume) for the William River delta is one avenue for reconstructions of storm frequency. Hydrodynamical modeling can be used successfully in reconstructions of tidal regime (e.g., Uehara et al., 2002). Morphodynamic analysis and modeling is another promising approach for reconstructing basinal regimes. Bhattacharya and Giosan (2003) suggested that the asymmetry in morphology and facies in wave-dominated deltas indicates a relatively strong wave-driven longshore transport. This model is applied by Hampson and Howell (this volume) to the classic storm-wave-dominated shorefaces of the Book Cliffs, which are reinterpreted here as asymmetric, wave-influenced prograding deltaic complexes, with a significant longshore drift component. Asymmetry of successive lobes as well as the development of baymouth barriers in the Danube delta are interpreted by Giosan et al. as an indication of a strong and sustained southward-directed longshore transport, suggesting that the wave climate along the delta coast has not changed dramatically in the last 5,000–6,000 years.

Bed-Scale Facies Architecture and Sequence Stratigraphy

The last two decades of deltaic studies have seen a major emphasis on the more regional sequence stratigraphic analysis. As sequence stratigraphy matures, there is a significant opportunity for more detailed sedimentological and facies architectural studies to be conducted within an established sequence stratigraphic framework. For example, the papers by Hampson and Howell, Olariu et al., and Gani and Bhattacharya provide detailed analysis of facies architectural elements in the otherwise stratigraphically well-studied Book Cliffs of Utah. These studies focus on specific sedimentologic aspects, such as the internal organization of distributary channels and the relationships of channel facies elements to other shoreline elements, such as beach and foreshore deposits. The Plink-Björklund and Steel paper is a good example of analysis of a deposit at all stratal scales, from sedimentologic to sequence stratigraphic. Studies and datasets of these kinds allow a more robust examination of the links between allogenic and autogenic controls on delta development.

Facies architectural analysis of delta systems remains, however, an immature field compared to the study of fluvial (e.g. Miall, 1996) and deep-water (e.g., Bouma and Stone, 2000) systems. The papers by Plink-Björklund and Steel, Olariu et al., Hampson and Howell, and Gani and Bhattacharya provide examples of the bed-scale facies approach, but more detailed studies are needed to fully characterize and define what the critical architectural elements are in deltaic depositional systems. Such studies are essential for reservoir characterization studies as well as for interpreting ancient systems.

As Willis (this volume) points out, the relationship between bed forms and bar forms, and corresponding cross-stratal expression, is well established for fluvial systems, but analysis is not trivial in tidal and marine systems. Clearly, a better integration of modern process sedimentology and facies architectural analysis of both modern and ancient systems, along with accurate paleo-water-depth analysis, is needed to fully interpret tidally influenced shallow marine depositional systems.

The paper by Gani and Bhattacharya (this volume) suggests that bed-scale facies architectural correlations of modern delta systems may be achievable, especially where data of other kinds, such as seismics or age-control, exist, (e.g., Ta et al., this volume, and Anderson, this volume). Future core-based studies of modern deltas should be integrated with seismic or GPR data (as presented in the case studies of the William and Burdekin deltas in this volume) and apply concepts derived from other disciplines, such as sequence stratigraphy. In addition, ichnological analysis on cores from modern deltas would provide critical environmental information for detailed interpretations of deltaic deposition (MacEachern et al., this volume).

Lastly, controls on sequences are clearly the result of a complex interplay between eustasy, tectonics, and sediment supply. These factors are not necessarily independent. Increased uplift in the drainage basin may induce an increase in sedimentation rate. Eustatic changes are a result of climate change, but they can also lead to regional changes in precipitation patterns, wave climate, tidal circulation, and even tectonics. Better predictive models will require accurate information about all controlling parameters, instead of simplistic assumptions.

CONCLUSION

Deltas represent one of the most important depositional systems at the critical boundary between land and sea. Understanding of the dynamics of this boundary is essential for people living near or along the coast, as well as for those who depend on resources associated with modern or ancient deltas. Research on deltas is witnessing a revitalization, fueled by these societal concerns, but also by programs that seek to integrate and promote a dialogue across disciplines studying separated segments of the "source-to-sink" sediment-dispersal systems. As the Earth's population continues to grow and the Earth's climate changes, there will be an ever greater need to better manage coastlines, to efficiently and safely exploit resources associated with deltas, and to preserve their unique ecosystems. This collection of papers represents an attempt to bring together current ideas and to pose questions for the next generation of deltaic studies.

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