A Deep-Time Perspective of Land-Ocean Linkages in the Sedimentary Record

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Abstract

It is increasingly important to understand and predict how marine environments respond to changes in climate and sea level and to variability in sediment flux from rivers. The dynamics of these factors occur over several orders of temporal magnitude and, under favorable geologic conditions, contribute to long-lived sediment accumulation. Thus, stratigraphic successions along continental margins are archives of these environmental changes and can be used to reconstruct land-ocean linkages, which provide important context for shorter-term and future modifications to this critical zone. Here, we discuss an integrated approach to the analysis of deep-time sediment archives ($>10^6$ years) that considers the entire system, from eroding catchments where sediment is produced to subsiding basins where sediment accumulates. This holistic approach is presented within the framework of fundamental concepts about sedimentary-basin analysis and stratigraphic characterization through a combination of foundational literature and studies that represent the state of the art.

INTRODUCTION

A comprehensive understanding of the land-ocean transition and its changes through the Earth's history is critical to marine science. Marine environments and habitats in coastal areas, continental shelves, and the deep sea are significantly influenced by the geologic evolution of continental margins. Reconstructions of paleoenvironmental conditions on continental margins provide important context for addressing issues related to modern processes and for improving predictions about this spatially complex and dynamic environmental transition (Natl. Res. Counc. 2010).

Continental-margin paleoenvironments are accessible through the stratigraphic record, an archive of the Earth's history with which marine scientists can investigate land-ocean linkages across geographic space and through geologic time. This archive is constructed largely from continental material. The transfer of particulate and dissolved material from land to ocean impacts the physical, chemical, and biological systems in the marine realm. Temporally, the processes associated with material transfer occur over several orders of magnitude, from events observable at human timescales (such as river floods and storms) to changes that occur over tens of millions of years. Sediment erosion, transport, and deposition are recorded by stratigraphic successions that are preserved in and make up the structure of continental margins.

This article reviews fundamental concepts of sedimentary-system analysis with an emphasis on the scientific value of deep-time records ($>10^6$ years) contained within continental-margin stratigraphic successions. Our goal is to provide a broad review of both foundational concepts and the state of the art related to land-ocean linkages that are relevant to marine scientists. We focus on the transport, deposition, and stratigraphic preservation of particulate material (sediment); however, many of the salient points are relevant to land-to-ocean transfer of nutrients, terrestrial carbon, and dissolved material as well.

THE SEDIMENTARY SYSTEM

Sedimentary systems begin in mountainous upland catchments, where sediment is liberated from bedrock through weathering processes and transported via hillslope and channel erosion by streams and rivers (**Figure 1**) (Allen 2008). Under the influence of gravity, sediment moves from these dominantly erosional areas to lower-relief and lower-elevation areas typified by a combination of sediment transport and deposition, such as river and floodplain systems. These intermediate, or transfer, zones transition seaward to areas dominated by sediment deposition and, importantly, long-lived accumulation, burial, and lithification of sediment into sedimentary rock. Sedimentary basins (discussed in detail below) are the principal repositories for the sediment that survives into the rock record. The preserved terminus of a given sedimentary system is always a sedimentary basin but not always in the marine realm (e.g., closed terrestrial drainage basins such as the Great Basin in the western United States and the Tarim Basin in western China). Here, we focus on the more numerous and volumetrically important sedimentary systems that terminate in the ocean, typically at the margins of continents.

The recognition that the production and subsequent deposition of sediment across the Earth's surface are linked in space and through time is not a novel idea in Earth science (Hutton 1788); however, in recent years there has been increasing interest in research focused on the thorough documentation and quantification of this linkage (e.g., Anthony & Julian 1999, Goodbred 2003, Romans et al. 2009, Carter et al. 2010, Covault & Graham 2010). Characterizing the dynamics and history of a complete sedimentary system is inherently interdisciplinary because sediment production occurs in eroding mountain belts, whereas sediment deposition occurs in subsiding basins that may be in either terrestrial or marine realms or, commonly, in basins crossing the land-ocean

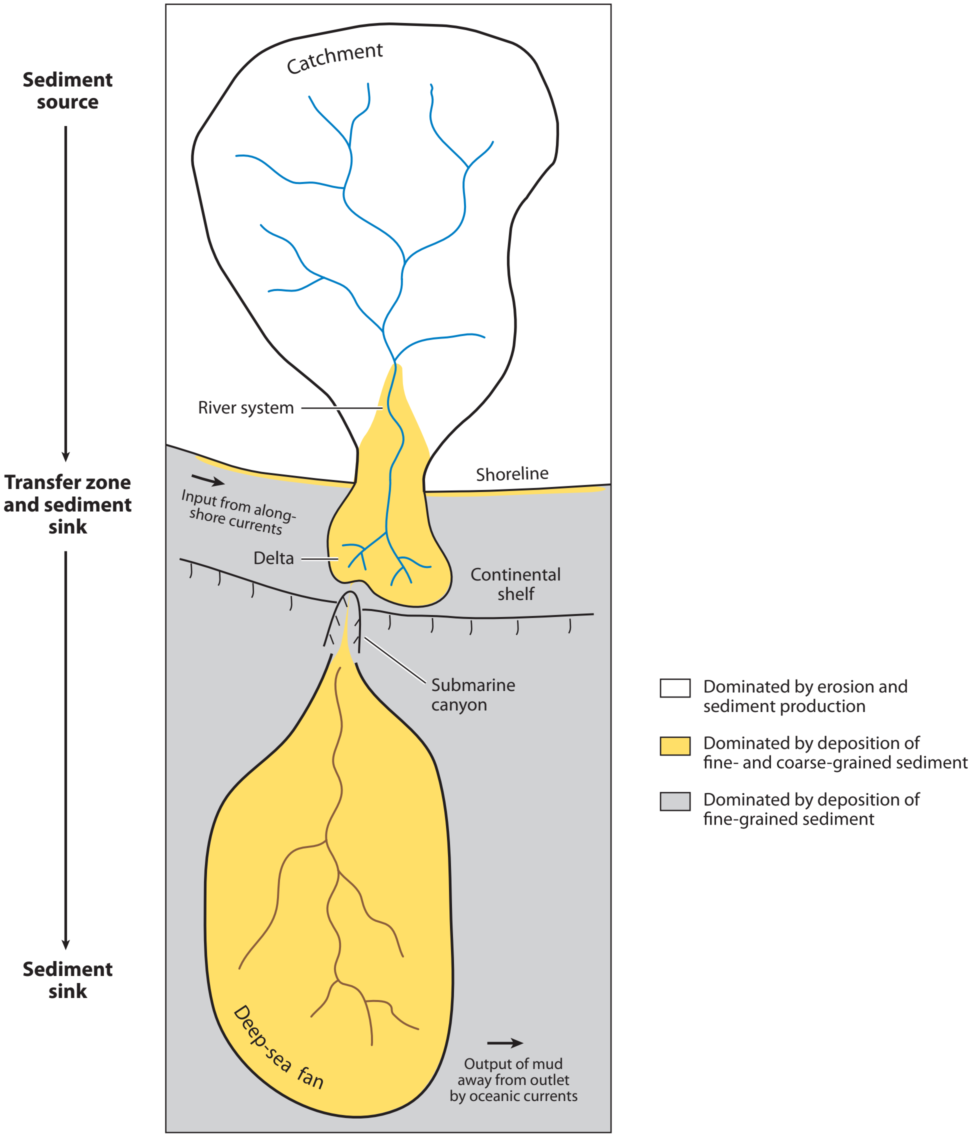

Figure 1

Map-view generalization of a complete sedimentary system from upland drainage basins, in which sediment is produced through weathering and erosion, to terrestrial lowland and marine-sediment sinks. The delta zone can also be expressed as an estuary, barrier system, or wave-dominated shoreline system (see **Figure 2**). Adapted from Schumm (1977).

boundary. To that end, disciplines as diverse as geomorphology, sedimentology, stratigraphy, oceanography, geochemistry/biogeochemistry, ecology, and others are being integrated with the aim of developing a more comprehensive understanding of material transfer through a sedimentary system.

The sedimentary-system concept, commonly referred to as source to sink, is advantageous when considering land-ocean linkages because of its inherent emphasis on connections across

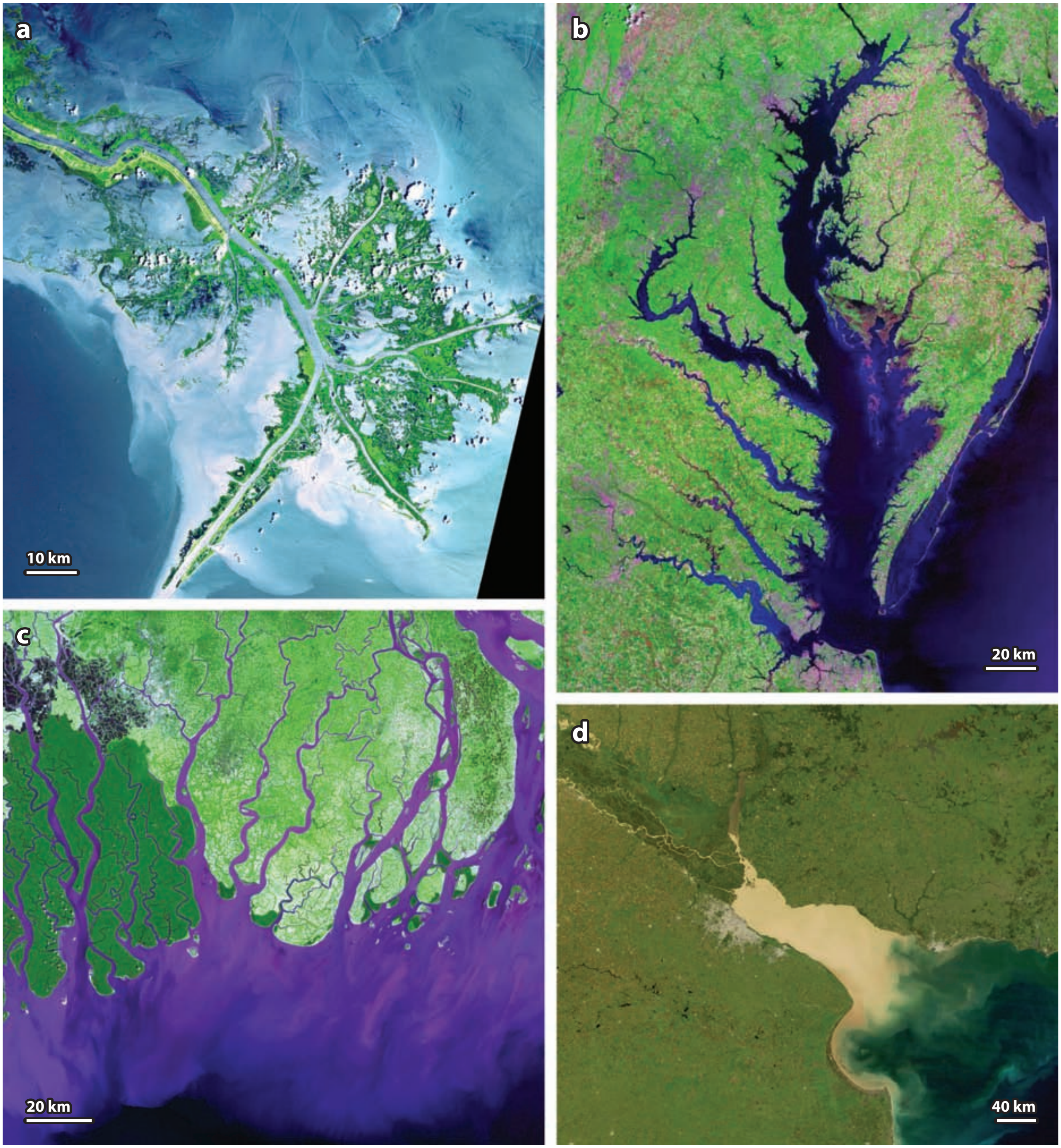

Figure 2

Examples of the land-ocean interface in modern sedimentary systems: (*a*) the seaward limit of the river-dominated Mississippi River delta, United States; (*b*) the Chesapeake Bay estuary, United States; (*c*) the tidally influenced Ganges River delta, Bangladesh; and (*d*) the Río de la Plata estuary (confluence of Río Paraná and Río Uruguay), Argentina and Uruguay. All images from NASA.

distinct segments within the system [articulated for terrestrial systems by Schumm (1977); the source-to-sink terminology first appeared in the literature in the 1990s]. The land-ocean interface is expressed in a variety of sedimentary-system configurations on the modern Earth surface (**Figure 2**). Numerous factors influence whether a river mouth is characterized by a delta, estuary, barrier system, or other shoreline system. These factors include the size and relief of the catchment, rates of sediment production from the catchment, volume of sediment deposited in the terrestrial segments, flux of sediment at the river mouth, strength of marine currents/waves, salinity contrast, climatic regime, physiographic configuration of the margin (e.g., narrow versus wide continental shelves), and other aspects of geologic history (Bhattacharya 2006).

The land-ocean interface also represents an important boundary in terms of the processes responsible for transporting and depositing sediment. The varying morphologies of river-mouth environments influence and are influenced by marine processes such as tides and waves. A classic example of this is the subdivision of delta types into river dominated, tide dominated, and wave dominated, which was introduced by Galloway (1975). Detailed study of modern river-delta environments has demonstrated that such a classification scheme can overlook important processes or conditions. However, simple conceptual models of depositional systems are useful as a basis for comparison and as a hypothesis-testing tool when reconstructing paleogeography from the sedimentary rock record (Walker 1984, Walker & James 1992), as discussed in more detail below.

Land-ocean linkages are major fluxgates in a sedimentary system, inevitably affecting the local to regional marine realm. Consider, for example, the Mississippi River delta. It currently delivers up to 400 Mt (441,000,000 tons) of sediment to its mouth and 140 Mt (154,000,000 tons) of solutes to the marine waters of the Gulf of Mexico annually (Milliman & Farnsworth 2011). The shoreline of the modern delta has advanced seaward by nearly 50 km in the past 3,000 years (Frazier 1967, Boyd et al. 1989, Bhattacharya & Walker 1992), replacing marine environments with marginal-marine to nonmarine environments. Thus, the net sediment transport is seaward, despite the sediment moved landward by rare events such as Hurricane Katrina in 2005 (Keen et al. 2006). Ultimately, seaward sediment flux, as illustrated in exaggerated fashion by the Mississippi River delta (**Figure 2*a***), accounts for the vast volume of sediment that accumulates to blanket the continental margins of the world.

SEDIMENTARY SYSTEMS IN THE ROCK RECORD

Complete sedimentary systems are not preserved in the geologic record. At the scale of the entire system, net-erosional segments inherently are not preserved over geologic timescales because those areas are subject to denudation. That material is exported to downstream locations where the mass eroded is balanced by the mass deposited (plus material in solution). As one landscape is degraded, another is constructed with the removed material. Moreover, the depositional landscapes are themselves only partially represented. The morphologies of depositional systems as we observe them on the modern Earth surface are rarely, if ever, preserved in the geologic record. The stratigraphic architecture (patterns of sediment layering) represents a morphology that results from a history of depositional and erosional processes over many orders of temporal magnitude. In other words, stratigraphy represents time-averaged depositional system morphology.

The recognition that preserved strata contain an archive of continental-margin evolution through the Earth's history is foundational to the science of geology. Based on interpretations of sedimentary deposits from marine environments, early works by Hutton (1788) and Lyell (1833) concluded that ancient seas must have covered present-day terrestrial landscapes. The presence of continental, coastal, and marine-sedimentary deposits stacked on top of one another led to the recognition that their corresponding environments, and thus the sea level with it, must have shifted landward and seaward over time (Walther 1894). However, the accumulation and preservation of these depositional environments are neither uniform across the Earth's surface nor steady through time.

Plate Tectonics and Sedimentation

The long-term preservation of depositional segments of sedimentary systems occurs in sedimentary basins. A cursory examination of a global map of marine-sediment thickness reveals the uneven distribution along the world's continental margins (**Figure 3**). For example, the difference between the eastern and western continental margins of North America and South America is considerable. At first order, these differences can be ascribed mainly to the plate-tectonic setting and evolution of the margins. Areas of the Earth's crust that are actively subsiding create space (known as accommodation) for sediment to accumulate and are the principal repositories of sediment. However, some deeply subsided areas, notably the ocean trenches, are devoid of significant volumes of sedimentary fill even though they occur directly adjacent to mountainous topography and an ample

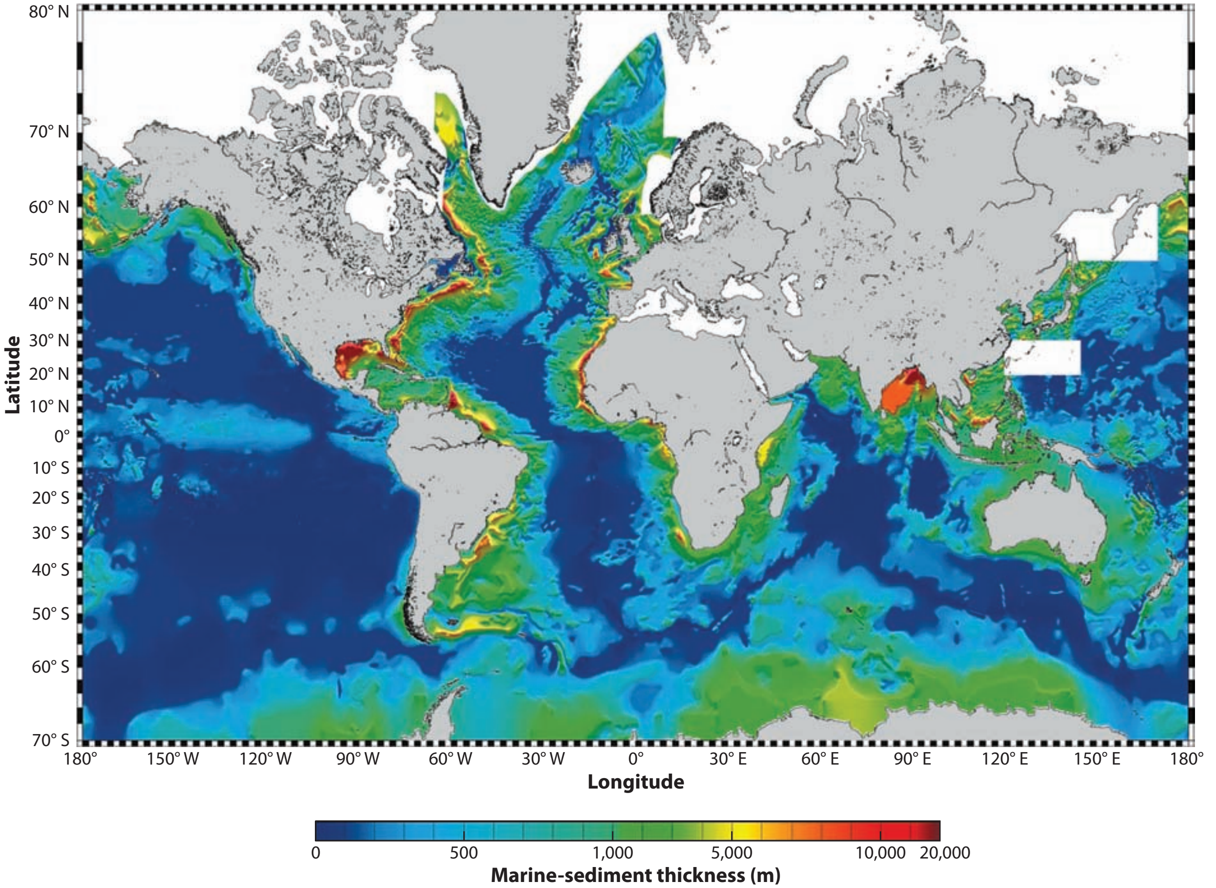

Figure 3

Global map showing total thickness of marine sediment. The nonuniform distribution of sediment along continental margins is primarily a result of plate-tectonic configuration/history and the location of significant sediment sources. Adapted from Divins (2003).

potential supply of sediment (e.g., northern Chile; **Figure 3**). In such cases, understanding the tectonic processes and the interdependence of sedimentation, climate, and topography is critical (Molnar & England 1990, Métivier et al. 1999, Burbank & Anderson 2011).

More generally, however, it is possible to view the Earth's major continental-margin sediment accumulations in terms of tectonic setting (**Figure 4**). Long-term subsidence occurs near plate boundaries and areas associated with the boundary between continental and oceanic crust. Subsidence history and geometry are first-order controls on the basin-scale patterns of sediment distribution. The three general types of plate boundaries important for the development of sedimentary basins are divergent (rift zones), convergent (subduction and collisional zones), and transform (strike-slip fault zones).

Sedimentary basins at divergent plate boundaries. A divergent plate boundary begins as a continental rift zone (e.g., the modern East African Rift) dominated by extensional deformation, the development of stretched continental crust, and abundant normal faults (**Figure 4*a***). This crustal thinning creates rift basins that fill with sediment deposited in nonmarine and/or lake environments (Leeder 1995). The continued rifting of the continent creates a spreading center and incrementally generates thinner and denser oceanic crust, which results in an area of even greater subsidence and, ultimately, marine incursion and connection to the global ocean.

The further development of a divergent plate boundary leads to a full oceanic basin flanked by passive continental margins (**Figure 4*b***). A passive margin is termed such because, although it is the boundary between continental and oceanic crust, at this stage in its evolution it is far from active tectonic processes at the divergent boundary. The present-day relationship between the eastern continental margin of North America and the spreading center of the Mid-Atlantic Ridge, approximately 3,000 km to the east, is a prime example. Space available for sediment accumulation is inherited primarily from the continental-oceanic crust transition, resulting in a sedimentary prism overlapping the margin. If sediment accumulation is significant and sufficiently long lived, loading due to sediment overburden contributes additional subsidence and thus attracts more sediment (Reynolds et al. 1991) (**Figure 4*b***). The lack of major tectonic reorganization results in nearly uninterrupted accumulation of continentally derived sediment for tens to hundreds of millions of years, making passive-margin sedimentary-basin fill one of the most important long-term archives of land-ocean linkages.

Sedimentary basins at convergent plate boundaries. Convergent plate boundaries, also commonly referred to as active margins, are areas where two tectonic plates collide; they can be subdivided into two general types, subduction zones and continental collision zones, both of which create mountain-belt systems and associated sedimentary basins. Convergent-margin basins are inherently more tectonically complex than passive margins. The interplay of tectonics and sedimentation is a dominant control on basin evolution and thus the focus of research aimed at unraveling those controls (e.g., Clift 2006, Strecker et al. 2007, Whipple 2009). Additionally, the life span of convergent-margin basins that record land-ocean linkages is typically shorter than that of passive-margin basins because of the inevitable tectonic consumption associated with subduction and collision. A comparison of the marine-sediment thicknesses of the western and eastern continental margins of South America emphasizes the difference between convergent-margin basins and passive margins, respectively (**Figure 3**). Thus, using the sedimentary fill of convergent-margin basins to examine land-ocean linkages requires a robust understanding of the tectonic history. A comprehensive discussion of the tectonic processes of convergent margins and their influence on basins is beyond the scope of this review; interested readers are referred to Busby & Ingersoll (1995) and Busby & Azor (2012).

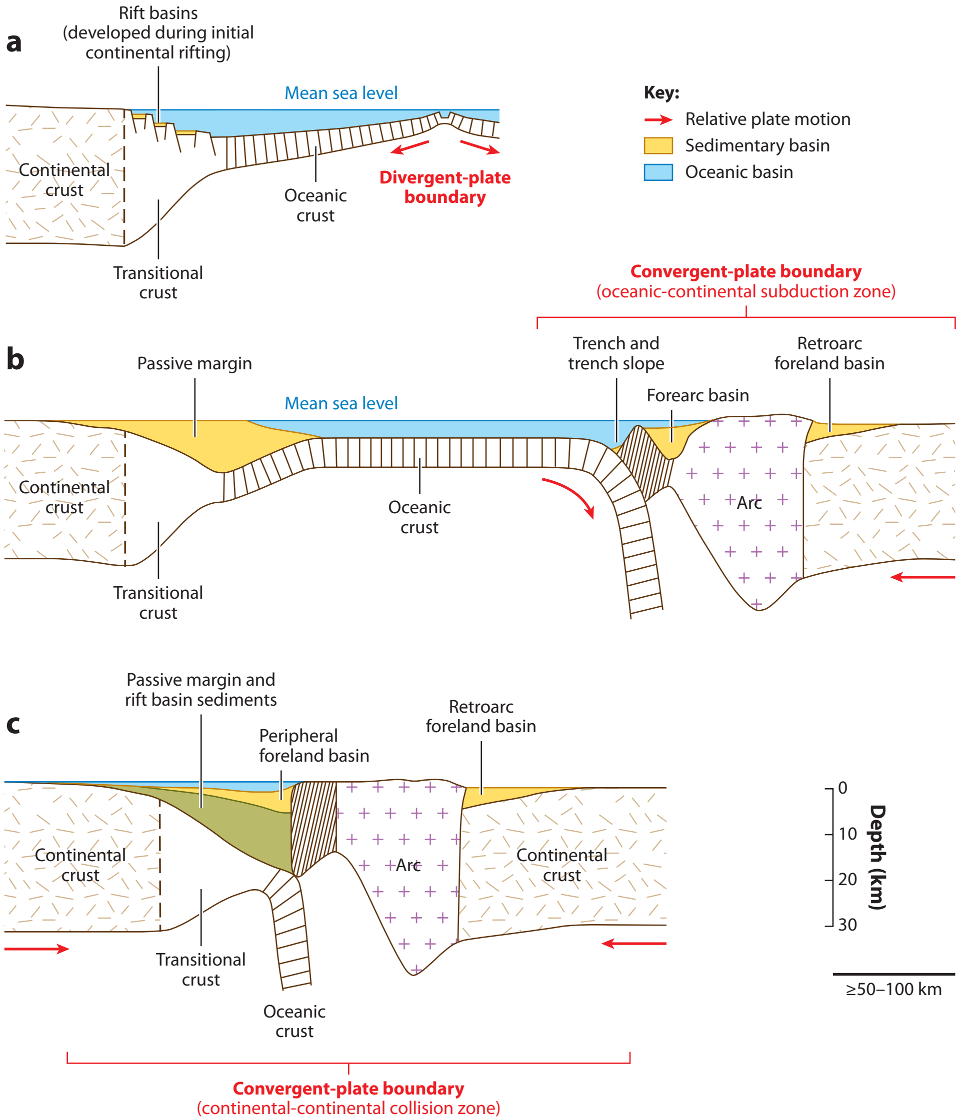

Figure 4

Schematic cross sections of the Earth's crust depicting the relationship between plate-tectonic configurations and associated sedimentary basins. (*a*) Rift basins preserved on one side of a rifted margin associated with a midocean ridge divergent plate boundary. (*b*) Passive-margin sequences deposited at the transition from continental to oceanic crust (*left*) that was produced in an earlier rifting phase, along with oceanic-continental convergent-margin basins (*right*) associated with a subduction-zone system. The oceanic-oceanic subduction-zone system is not shown. (*c*) Continental-continental convergent system and its associated basins. Note that these schematic cross sections are oriented parallel to divergent/convergent tectonic processes and thus do not depict transform-margin configurations. Adapted from Dickinson (1974).

Subduction zones are characterized by the underthrusting of an oceanic plate beneath a continental plate, which forms a continental volcanic arc and mountain-belt system. The subduction of an oceanic plate under another oceanic plate forms an island arc system and associated sedimentary basins (Marsaglia 1995); these systems are not included in this review for the sake of brevity and to maintain the emphasis on land-ocean linkages. The most important types of sedimentary basins that develop in association with oceanic-continental subduction zones are trenches and trench-slope basins, forearc basins, and retroarc foreland basins (**Figure 4*b***).

Trenches mark the boundary between a subducting oceanic plate and the overriding plate and can be significant repositories of terrigenous sediment. In some cases, the sediment supply is so voluminous that it overfills the accommodation, obscuring the characteristic trench morphology on the seafloor (e.g., the Cascadia subduction zone in northwest North America; Underwood & Moore 1995). In other cases, trenches lack significant sediment accumulation because the supply of continentally derived material is low and/or it is trapped in basins in landward positions. Trench-slope basins are relatively small areas of accommodation within the deforming accretionary wedge that develops between the trench and the continental plate. Using the sedimentary archive from these basins to examine system-scale history is challenging because the basin fills are commonly intensely deformed, if not effectively destroyed, after deposition as a result of continued subduction (Clift & Vannucchi 2004, Underwood & Moore 2012).

Forearc basins are elongate, margin-parallel areas of subsidence positioned landward of the trench and seaward of the active volcanic arc (**Figure 4*b***). The mechanisms, geometry, and history of subsidence for forearc basins vary significantly, thus making it difficult to treat them systematically in terms of sedimentary fill patterns and the occurrence of marine deposits (Dickinson 1995). Additionally, and similarly to the above-mentioned trench/trench-slope basins, the long-term preservation of forearc-basin fills is rare because of the intense deformation associated with subduction zones. However, if the fill is preserved as a result of subsequent tectonic reorganization, then forearc-basin successions can contain valuable information about ancient land-ocean linkages [e.g., the Talara Basin of Peru (Fildani et al. 2008) and the California Great Valley (Dickinson & Rich 1972, DeGraaff-Surpless et al. 2002)].

Retroarc foreland basins are termed such because they are positioned in the continental interior "behind" the active volcanic arc (**Figure 4*b***). Subsidence is caused primarily by tectonic loading due to an actively developing fold-thrust belt (uplifting mountain belt) at the boundary between the arc and the continent (DeCelles & Giles 1996). Owing to their position on the continental crust, the sedimentary fills of retroarc foreland basins are typically dominated by nonmarine deposits (Jordan 1995). However, during periods of high global sea level, such as during the Late Cretaceous (~100–65 Mya), vast continental areas were flooded, connecting retroarc foreland basins to the global ocean and preserving a record of land-ocean linkages [e.g., the Book Cliffs of Utah (Van Wagoner et al. 1990) and the Magallanes Basin of Chile (Romans et al. 2011)].

Continental collisional plate boundaries are characterized by the convergence of two continental plates (**Figure 4*c***). The collision of the Indian subcontinent with Asia to form the Himalayan mountain belt is the archetypal example. Peripheral foreland basins typically develop atop transitional crust associated with the boundary with oceanic crust that has already subducted (Miall 1995a). Thus, **Figure 4** can be viewed as a sequence, showing the transformation of a subduction zone (**Figure 4*b***) into a collisional zone (**Figure 4*c***) as a result of the closure of the ocean basin. Similar to the subsidence of foreland basins in the retroarc position, the dominant subsidence mechanism in peripheral foreland basins is tectonic loading from the overriding fold-thrust belt and underthrusting of the lower plate. The sedimentary fill of a peripheral foreland basin varies depending on tectonic evolution, but is typically characterized by a succession of deep-marine deposits overlain by shallow-marine and, ultimately, nonmarine deposits (Ricci Lucchi 1986, Miall 1995a). The sedimentary fills of both peripheral and retroarc foreland basins are commonly incorporated into the fold-thrust belt, which results in uplift and exhumation, exposing the stratigraphy as surface outcrops available for detailed examination.

Sedimentary basins at transform plate boundaries. Transform plate boundaries are characterized by a long-lived strike-slip fault zone where two plates move in opposite directions horizontally (e.g., the San Andreas Fault zone in California and Baja California, Mexico). Bends in the trace of the main fault and/or geometric configurations between the main fault and secondary faults create localized areas of extension and subsidence commonly referred to as pull-apart basins (Nilsen & Sylvester 1995). These basins are typically small and may be characterized by internal drainage. Bounded by faulted steep margins, alluvial fans are common basin-margin depositional systems in strike-slip basins. Depending on the climate, basin centers may host environments that range from lakes to evaporative salt flats.

Plate tectonics and sediment supply. In addition to creating the repositories of long-term sediment accumulation, plate-tectonic processes create the supply of material that is moved from source to sink. The uplift of the Earth's crust into mountain belts drives the exhumation and erosion of bedrock and, ultimately, the production of sediment. Plate-tectonic setting and evolution shape onshore topography, influence continental drainage divides, focus fluvial drainages into major trunk streams, and can localize those trunk drainages in the same geographic positions for 10^6–10^7 years along passive margins (Potter 1978). In such cases, long-lived deltas, such as those of the Mississippi, Niger, and Amazon Rivers, accrue and profoundly affect land-ocean linkages. The tectonic processes characteristic of active margins (i.e., convergent and transform plate boundaries) result in catchments that can be quite small in area but that have relatively high relief and correspondingly high sediment yields (Mulder & Syvitski 1995, Milliman & Farnsworth 2011). Active tectonics also create dynamic and quickly changing landscapes that can result in the abrupt reorganization of source-to-sink pathways by stream capture/piracy and/or drainage diversion (Bishop 1995). Although the tectonic setting and activity are clearly major factors, it is worth noting that the climatic regime (e.g., precipitation/runoff, rainfall severity, vegetation) of a sedimentary system also plays an important role in the nature of source-to-sink sediment flux (Milliman & Farnsworth 2011).

Sediment Preservation and the Nature of the Stratigraphic Record

The deep-time geologic archives of land-ocean linkages with the highest fidelity are those where a sedimentary system and a continental-margin sedimentary basin have coexisted on the Earth's surface for a significant duration ($>10^6$ years). The concepts of plate tectonics and sedimentary-basin development reviewed above provide context regarding the nature of preserved strata at the scale of continental margins; however, shorter-term and more localized factors influence sediment accumulation and preservation at finer scales. The temporal variability of factors such as sediment flux to the basin, the grain-size distribution of available sediment, the nature of marine currents, and changes in global sea level—to name just a few—influence the stratigraphic distribution of distinct types of sedimentary deposits. The variability of spatial aspects within depositional systems such as channel network patterns, channel dimensions, river- and channel-mouth morphology, and the nature of important process boundaries (e.g., confined-to-unconfined flow transition) also influence preserved patterns. The stratigraphic architecture is a consequence of the combined influence of sediment deposition and preservation.

A comprehensive review of the history of stratigraphic theory is beyond the scope of this review (interested readers are referred to Ager 1980, Dott 1992, Emery & Myers 1996, and

Catuneanu et al. 2009); however, brief commentary here provides valuable context for general marine scientists. Concepts related to the nature of stratigraphic preservation that were discussed in detail by Grabau (1913) and Barrell (1917) and later expanded upon by others, especially Wheeler (1958, 1964) and Sloss (1963), are arguably the foundation of the modern science of stratigraphy. The concept of base level, as discussed by Powell (1875) following his efforts to map the western United States, refers to the lowest level to which a landscape can erode (e.g., a river incising into a landscape to reach sea level). Wheeler (1964) expanded on this idea, distinguishing Powell's geomorphic base level from stratigraphic base level, which emphasizes both degradation (erosion) and aggradation (deposition) at the Earth's surface relative to an equilibrium surface. Thus, a region of the Earth's surface that is aggrading is essentially filling this available space, or accommodation, until a new equilibrium is reached. Accommodation within a basin varies at multiple spatial scales and through time as important boundary conditions and forcings such as subsidence rate and sea level fluctuate. Accommodation is only part of the picture, however, as this space must be filled with sediment to create stratigraphy.

Thus, understanding the history and interaction of accommodation and supply, even in a relative and qualitative sense, aids the reconstruction of paleoenvironments from the stratigraphic record. Although there is still considerable debate in the literature regarding what controls stratigraphic patterns (discussed in more detail below), the distillation of fundamental factors into accommodation and supply, and understanding how they change in space and time, permits further investigation. The following sections build on this theory in more detail and with examples.

CONTINENTAL-MARGIN STRATIGRAPHY

Facies Models and Architectural Element Analysis

Conceptual models of component depositional systems guide the examination of land-ocean linkages within continental-margin stratigraphic successions. **Figure 5** depicts a generalized sedimentary-system profile from source to sink with an emphasis on zones that are characterized by deposition and, potentially, burial and long-term preservation. These zones are discriminated by characteristic sedimentary processes and associated deposits, which are largely a function of their positions on the profile. Identification of these characteristic deposit types, referred to as

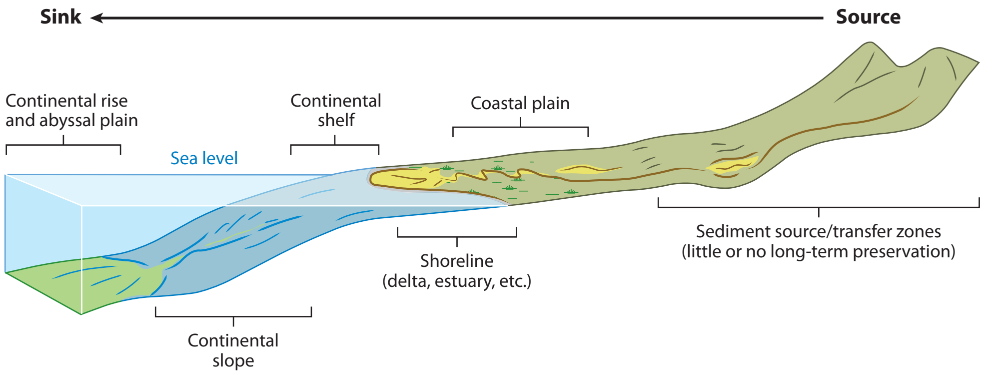

Figure 5

Generalized diagram of a sedimentary-system profile showing the relative positions of the depositional systems (coastal plain, shoreline, continental shelf, continental slope, and continental rise and abyssal plain) that stack to construct continental-margin successions.

facies, and interpretation of the depositional environment they represent are used to reconstruct the profile characteristics. Thus, the linkage of terrestrial and marine environments observed on the modern Earth surface is maintained in facies models of the depositional profile.

Facies models combine features of recent sediments and ancient sedimentary rocks into idealizations that represent sedimentary environments. These generalizations attempt to distill the most important aspects of a depositional environment into a model that can be used as a basis of comparison, a guide for future observations, a predictor, and a basis for integrated interpretation (Walker 1984, Walker & James 1992). An understanding of the processes related to sediment transport and deposition is embedded within this approach. For example, facies models for delta systems emphasize the overall coarsening-upward grain-size pattern of a vertical succession, which is the result of the coarser-grained delta top building out over the finer-grained delta front (Bhattacharya 2006). Although not all locations in a delta will have this vertical pattern, it provides a general hypothesis to be tested with more information. Facies models for other environments—including coastal plain rivers, shoreline/shoreface systems, shallow continental shelves, and deep-sea fans—differ in their details but are comparable in that they attempt to generalize the stratigraphic pattern that results from depositional system evolution (Posamentier & Walker 2006).

Facies analysis is enhanced through the characterization of the 3D configuration of sedimentary bodies. This approach, commonly referred to as architectural element analysis (e.g., Miall 1985), has grown significantly over the past two decades as a result of research focused on large outcrop belts with 3D control and the increasing acquisition and availability of high-resolution 3D seismic-reflection data. Although the traditional facies model approach acknowledged the 3D complexity of deposits, the recent focus on stratigraphic architecture, especially the characterization of planform patterns, has led to a wealth of explicit examples that test and improve conceptual models (e.g., Sylvester et al. 2012). Moreover, the emphasis on 3D architecture has led to improved quantitative documentation of stratigraphic patterns, which helps constrain novel stratigraphic modeling approaches (e.g., McHargue et al. 2011, Sylvester et al. 2011).

Facies and architectural approaches to stratigraphic characterization are typically applied at scales ranging from fundamental sedimentary structures that are millimeters to decimeters thick to mappable sedimentary bodies that are several to tens of meters thick and tens to hundreds of square kilometers in area. Paleoenvironmental reconstructions at this scale of the sedimentary record most closely resemble the types of depositional landscapes observed on the modern Earth surface (**Figure 2**) and are the building blocks of larger-scale stratigraphic patterns that represent longer-term land-ocean dynamics.

Sequence Stratigraphy

Continental margins with appreciable and long-lived sediment delivery from river systems result in the long-term seaward advance of the shoreline. This net-accumulative history creates thick successions of strata (up to 10 km or more; **Figure 3**) with an overall seaward-stepping, or progradational, stratigraphic pattern. A consequence of the long-term outbuilding of a margin is that shorter-term fluctuations of land-ocean sedimentary dynamics are recorded. However, the coastal-plain-to-abyssal-plain profile shown in **Figure 5** is not preserved in a simple, straightforward manner. **Figure 6** shows a schematic depiction of stratigraphic preservation in thickness and time of coastal-to-marine depositional environments through several cycles of sea-level rise (transgression) followed by sea-level fall (regression) (Lemon 1990). The facies and architectural analysis methods described above lead to interpretations of the depositional environment, which in this simplified example is characterized by no deposition on land, sand deposition at the coast, and mud deposition offshore. These spatially linked environments shift landward and seaward

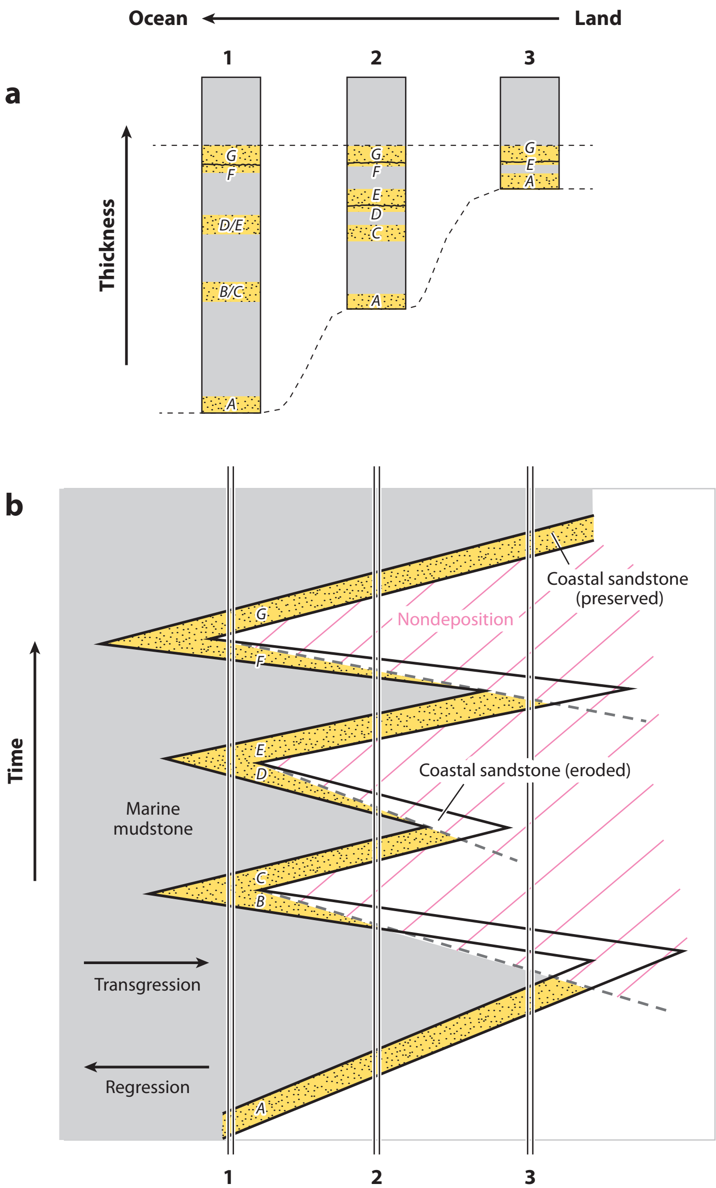

Figure 6

Schematic depiction of stratigraphic preservation in (*a*) thickness and (*b*) time of coastal-to-marine depositional environments through several cycles of sea-level rise (transgression) followed by sea-level fall (regression). Differential deposition/nondeposition combined with differential preservation of deposited sediment results in multiple lithologic units of similar facies that may not correlate in time. Also note that mappable lithologic formations are deposited not in an instant but rather through geologic time. For a larger-scale depiction of continental-margin depositional zones, see **Figure 5**. Adapted from Lemon (1990).

in correspondence with changes in relative sea level. Moreover, deposited sediment in this example is removed by erosion during subsequent regressions. The resulting stratigraphic stacking shows that, in general, more landward positions have lower preservation potential relative to more seaward positions. Differential stratigraphic preservation significantly impacts the temporal correlation of environments and, thus, reconstructions of land-ocean linkages.

Although simple, the hypothetical example in **Figure 6** lays the foundation for the concepts of sequence stratigraphy, which emphasizes the relationship between stratigraphic surfaces and facies architecture within a chronological framework (Catuneanu et al. 2009). The oil industry's widespread application of reflection seismology to image the subsurface of sedimentary basins in the 1960s–1970s provided explicit views of stratigraphy at scales that previously could only be inferred. This technological innovation quickly helped to advance the theory and interpretations discussed by Wheeler (1958, 1964), Sloss (1963), and others with more direct observations and measurements. The seismic-stratigraphy research group at Exxon was most visible in this regard, publishing a series of influential papers in American Association of Petroleum Geologists Memoir 26 (Vail et al. 1977) that laid the groundwork for sequence stratigraphy as a practical method used by applied geoscientists to subdivide strata. A comprehensive review of sequence stratigraphic concepts and methods is beyond the scope of this review; for a recent discussion of the standardization of methods and terminology, readers are referred to Catuneanu et al. (2009).

Sequence stratigraphy is founded on the identification of stratal terminations on 2D seismic-reflection profiles that define surfaces with regional chronostratigraphic significance (**Figure 7**). These surfaces bound relatively conformable packages of strata that exhibit systematic internal stacking patterns related to land-ocean linkages (seaward stepping versus landward stepping).

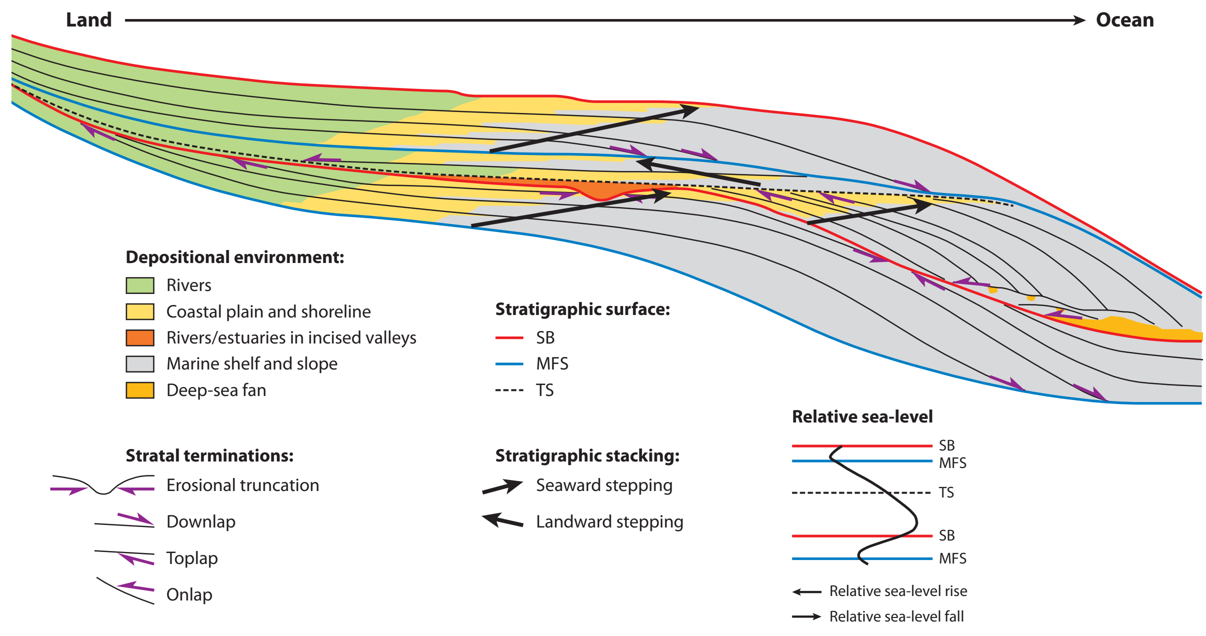

Figure 7

Idealized stratigraphic cross section of basin-margin sequence development. Surfaces with chronostratigraphic importance—the sequence boundaries (SBs; *red lines*), maximum flooding surfaces (MFSs; *blue lines*), and transgressive surface (TS; *black dashed line*)—are identified based on stratal terminations observed in seismic-reflection data and/or abrupt vertical changes in facies observed in wellbore or outcrop data. Adapted from Van Wagoner (1990), which built upon concepts in Vail et al. (1977).

Concepts based largely on patterns documented in seismic-reflection data were subsequently expanded upon with wellbore and outcrop data and with modeling approaches (e.g., Wilgus et al. 1988, Van Wagoner et al. 1990). There are differing views on which type of surface defines the fundamental sequence, with Vail et al. (1977) and successors emphasizing unconformities, or sequence boundaries, and Galloway (1989) stating that flooding surfaces better define the sequence. The details of this debate aside, the important point is that the methods of sequence stratigraphy combine facies and surfaces to characterize and interpret the history of continental-margin sedimentation.

Similarly to the above-mentioned methods of facies and architectural analysis, the more recent emphasis on 3D characterization of stratigraphy tests and challenges the 2D geometries depicted in **Figure 7**. However, the sequence stratigraphy paradigm remains an important tool for testing hypotheses about continental-margin evolution (Exped. 313 Sci. 2010) and reducing uncertainty in applied sedimentary geology. The resolution of fossil biozones and radiometric dating in the Phanerozoic (<540 Mya) typically allows for the discrimination of sequences at 10^5–10^6 years. Recent statistical methods advanced by Peters (2006), termed macrostratigraphy, build on the tenets of sequence stratigraphic theory and provide a quantitative framework for examining longer-term patterns (10^7–10^9 years) in the sedimentary record. The interpretations and associated debate in the literature regarding the controls on observable patterns, which are critical for using these archives to reconstruct events and conditions in the Earth's history, are discussed in a separate section below.

Continental-Margin Stratigraphy in the Subsurface

The largest and longest-lived continental-margin sedimentary archives on Earth are on modern passive margins (**Figure 3**). Because these sedimentary archives are in the subsurface, accessing them requires the integration of geophysical remote sensing (typically reflection seismology) with log and/or core data from wellbores if available for facies calibration and chronology. Two-dimensional seismic-reflection profiles tens to hundreds of kilometers long and oriented orthogonal to the shoreline can be used to image and map the stratigraphic evolution of continental-margin successions. For example, the continental margin of eastern North America offshore of New Jersey clearly shows the seaward-stepping evolution of shelf-to-basin profiles that have built out over the past ~60 million years (**Figure 8*a***) (Steckler et al. 1999). In this case, the correlation of sequence stratigraphic architecture with horizons of known or inferred age (obtained from scientific or industry wellbores) permits the calculation of margin growth rates and a closer examination of the effects that forcing mechanisms such as subsidence, sea-level change, and climate have on stratal patterns (Steckler et al. 1999).

The advent of 3D reflection seismology and its increasing importance in subsurface characterization have been the most significant data-driven advancements in stratigraphy in decades. Prior to the availability of 3D seismic-reflection data, stratigraphic characterization emphasized vertical profiles and cross-sectional patterns. The idealized sequence stratigraphic model shown in **Figure 7** is founded on a 2D cross-sectional architecture. Planform patterns can be reconstructed or inferred based on 1D and 2D data, in some cases to a very accurate degree (e.g., in dense wellbore sampling), but these are interpretations and thus have uncertainty. Three-dimensional seismic-reflection data provide more explicit views of planform stratigraphy, also referred to as seismic geomorphology (Posamentier & Kolla 2003). Uncertainty still exists with these data, but it is related to the velocity characteristics of the subsurface, the associated seismological response, and the resolution rather than extrapolation from sparse control points. The morphology that can be imaged within a stratigraphic interval, especially in the shallow subsurface, provides an

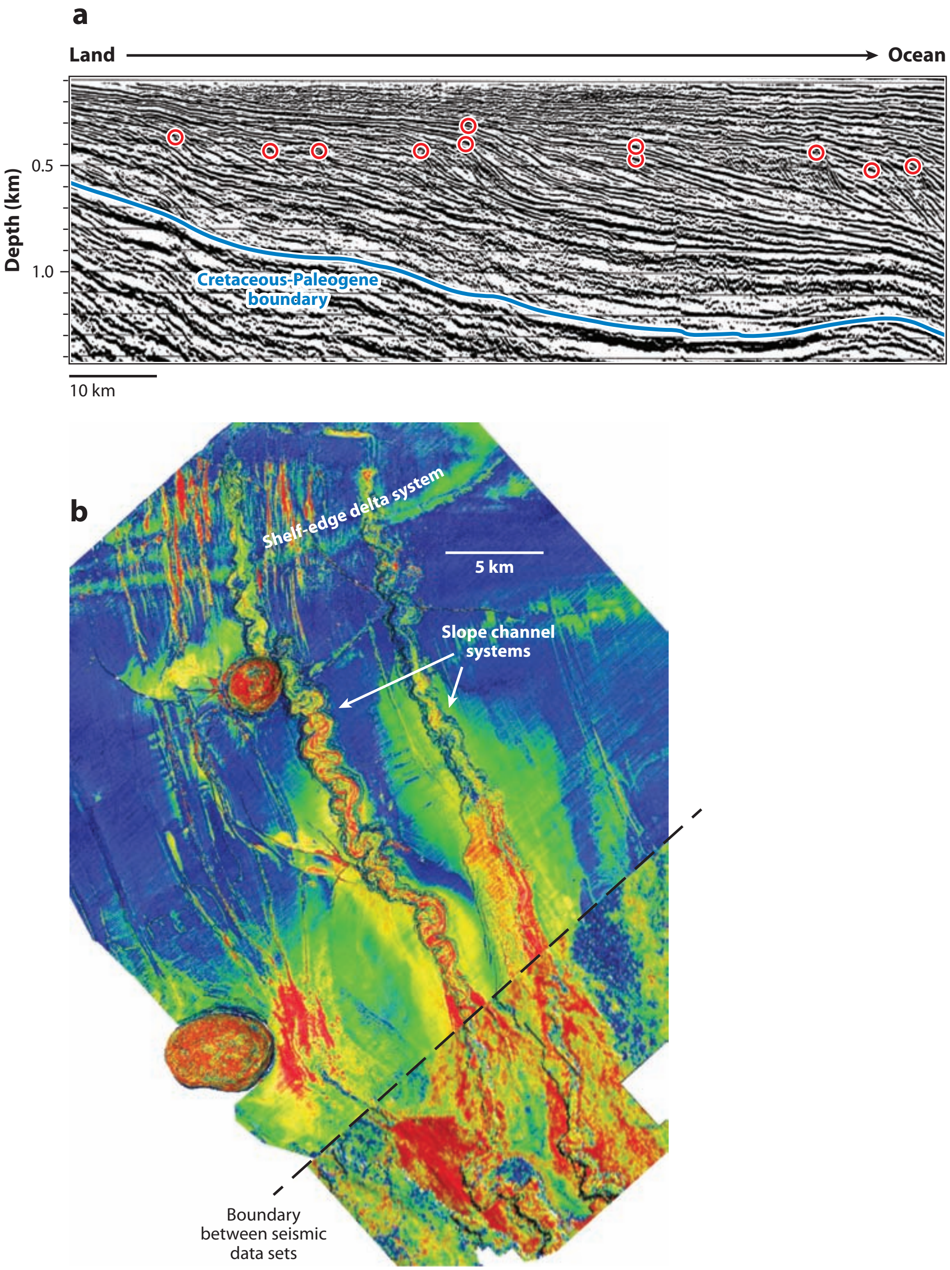

Figure 8

(*a*) Two-dimensional seismic-reflection profile of the New Jersey continental margin showing seaward-stepping sequences that have built out over the past ~60 million years. Data and image from Steckler et al. (1999); the red circles (interpretation by the authors) denote the positions of shelf-edge, or rollover, zones along preserved coastal-plain-to-continental-slope depositional profiles. (*b*) Plan-view image of a mapped stratigraphic surface in 3D seismic-reflection data showing preserved shelf-edge deltas (*near top*) transitioning to delta-slope channels. Red and yellow represent higher amplitudes and likely sandy sediment; green and blue represent lower amplitudes and likely muddy sediment. Adapted from Sylvester et al. (2012).

opportunity to examine the pathways of land-to-ocean sediment transfer in unprecedented detail (**Figure 8*b***) (Sylvester et al. 2012).

Basin-Margin Stratigraphy in Outcrops

Basin-margin successions that have been uplifted into mountain belts and exposed on land as outcrops provide an opportunity to observe sedimentary architecture in great detail. Well-exposed strata permit the examination of relationships that are impossible to map with low-resolution and/or sparse subsurface data. In the past 10–15 years, sustained efforts to map and characterize particularly large outcrop belts have allowed the integration of detailed facies analysis with basin-scale patterns typical of seismic-stratigraphic studies (e.g., Bhattacharya & Tye 2004, Flint et al. 2011, and Romans et al. 2011, among many others). The outcrops that most directly provide a record of land-ocean linkages are those characterized by alternating packages of terrestrial and marine strata (**Figure 9**). High-resolution measurement and mapping of the land-ocean transition, as well as linked depositional segments both up-system and down-system, within a robust stratigraphic framework have greatly improved our understanding of the types of relationships observed in **Figure 8*a*** (e.g., Johannessen & Steel 2005, Hubbard et al. 2010).

An important consideration, however, is that the majority of well-exposed outcrops linking terrestrial and marine depositional systems are from foreland basins that developed on continental or transitional crust (**Figure 4**). Outcrops of foreland-basin successions are so common because of long-lived fold-thrust propagation and the incorporation of earlier basin fills into the uplifting mountain belt. Such basin margins are distinct from true continental margins that mark the boundary between continental and oceanic crust. Passive-margin successions can also be uplifted into mountain belts (e.g., suture-zone development during the closing of an oceanic basin), but this typically results in significant structural deformation and/or metamorphism, which hinders detailed stratigraphic characterization. Thus, it is necessary to place high-resolution patterns of land-ocean linkages derived from outcrop studies into the proper basin and tectonic context (**Figure 4**).

Drivers of Continental-Margin Stratigraphic Patterns

Understanding the controls on patterns in the sedimentary record is critical if we are to use this record to inform models and predictions of environmental change in marine and coastal environments (Natl. Res. Counc. 2010). Relating stratigraphic patterns to changes in accommodation and sediment supply is helpful in terms of conceptualizing the forcings that drive observable stacking patterns (**Figure 7**), but what controls changes in accommodation and supply? Classical sequence stratigraphy emphasizes the methodology and objective criteria for delineating sequences in seismic-reflection, wellbore, and outcrop data. However, in their detailed summary of seismic-stratigraphic interpretation methodology, Vail et al. (1977) concluded that the primary driver of the sequence architecture was change in global sea level, or eustasy—that is, preserved shoreline or shelf-edge deposits stacked in seaward- and landward-stepping patterns in continental-margin successions were interpreted to reflect corresponding sea-level falls and rises. The interpretation that eustasy controls sequence stacking patterns led to widespread correlation and the creation of a global sea-level chart for the past ~250 million years (Haq et al. 1987). This interpretation also led to important critical reviews of methodologies for reconstructing sea-level history and spirited debate regarding whether it is even possible to extract a global sea-level record from stratigraphy (e.g., Burton et al. 1987).

The terms for the conformable packages between surfaces defined by stratal terminations (**Figure 7**) are directly associated with their relationship to sea level (lowstand, highstand,

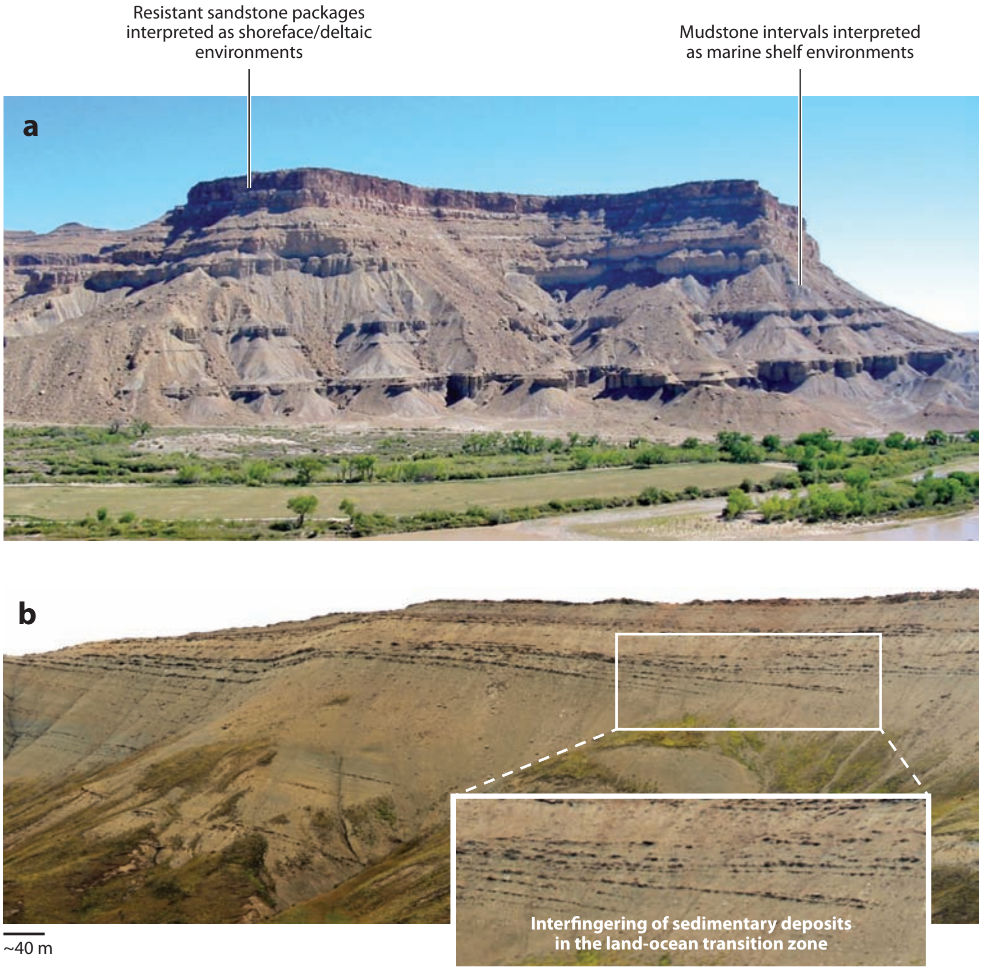

Figure 9

(*a*) Alternating shoreface/deltaic deposits (resistant sandstone benches) and offshore marine shelf deposits (slope-forming gray mudstone intervals) of the Upper Cretaceous Blackhawk Formation, Book Cliffs, Utah, United States. Note the overall upward-coarsening and upward-thickening of sandstone packages, which are interpreted to reflect longer-term building out of the land-ocean transition zone superimposed on higher-frequency cycles of transgression-regression. (*b*) Interfingering of deltaic sandstone beds and marine mudstone in the Upper Cretaceous Dorotea Formation, Cerro Cazador, Chile. Note the sandstone beds dipping from left to right and pinching out (*inset*), which are interpreted to represent a preserved segment in the land-ocean profile. Photos taken by the authors.

and transgressive systems tracts) (Wilgus et al. 1988, Van Wagoner et al. 1990). However, as Posamentier & Allen (1993) and others have pointed out, the sea-level variability recorded by stratigraphy is more correctly referred to as relative sea level, as it represents relative transgression or regression at any one position along the profile, which can be affected by eustatic changes and local vertical movement of the Earth's surface (sediment compaction or tectonic subsidence/uplift). For example, the margin of a rapidly subsiding basin can experience increased marine accommodation through time and thus develop a transgressive stacking pattern in the absence of any change in global sea level.

The debate about the nature of eustatic fluctuations in the geologic record motivated research investigating the influence of tectonic processes on the development of stratigraphic cycles. Tectonic processes related to flexural loading, intraplate stresses, and regional crustal loading are all interpreted to play an important role in the creation/destruction of accommodation at timescales of 10^5–10^7 years, which are important timescales for the idealized sequence shown in **Figure 7** (Miall 1995b). Recent research on patterns of coastal uplift, driven by a combination of glacio-isostatic rebound and other tectonic processes over the past ~100,000 years, has shown that uplift rates can exceed rates of global sea-level rise, thus creating a local relative sea-level fall during transgressions (Pedoja et al. 2011). At more regional scales, numerical modeling suggests that mantle convection can induce vertical movements in the lithosphere and thus changes in accommodation comparable to the rates, durations, and magnitudes generated by eustatic cycles (Petersen et al. 2010). The relationship of sea level to the components of the sequence stratigraphic model is important because of the implicit predictions. For example, recent work on Quaternary (<2 Mya) to modern sedimentary systems has shown that delivery of sand from the coastal zone to the deep sea can occur at any sea-level stand, including the current highstand, and along both active and passive margins (Covault & Graham 2010). This is in contrast to the idealized sequence model, which emphasizes that when active submarine fan growth occurs, it does so during lowstand conditions.

Variability in sediment supply is also thought to have a significant effect on sequence stacking patterns. Sediment production is ultimately controlled by the climate and tectonics that work to erode bedrock in the hinterland (Allen 2008). The climatic regime (e.g., precipitation/runoff, rainfall severity, vegetation) in modern sedimentary systems is known to have a significant influence on measured sediment fluxes to the ocean (Milliman & Farnsworth 2011). Conceptually, if the rate of sediment supply to a depositional system outpaces the rate of accommodation creation (from eustasy, subsidence, or a combination), then the system will build basinward and vice versa. However, this relationship is only relative and cannot be used to reliably reconstruct paleosediment flux. An additional consideration is that complex feedbacks between accommodation and supply can develop in some settings. The salt-withdrawal minibasins on the Gulf of Mexico continental slope, for example, capture and accumulate land-derived sediment, which induces rapid subsidence through loading and the creation of new accommodation, which captures more sediment, and so on (e.g., Prather et al. 1998).

Developing a quantitative understanding of how sediment flux influences depositional patterns would be a significant advancement, but this has been difficult to achieve because of the relatively low resolution of chronological constraints in deep time. Additionally, the extrapolation of sediment accumulation rates measured from modern systems to bedding patterns in ancient systems is hampered by well-known statistical biases (Sadler 1981). Analysis of Quaternary sedimentary systems—which affords higher temporal resolution through dating techniques such as radiocarbon, optically stimulated luminescence, and cosmogenic radionuclides, among numerous others (Walker 2005)—is a valuable approach for addressing these issues [e.g., the river system response to climate and sea-level change (Blum & Tornqvist 2000) and the source-to-sink sediment budget at timescales of 10^4 years (Covault et al. 2011)].

Much of the research on stratigraphic controls in the 1980s and 1990s focused on the trinity of eustasy, tectonics, and climate and their effects on variability in accommodation and/or sediment supply. More recently, studies using scaled-down experimental sedimentary systems have emphasized processes and resultant depositional patterns intrinsic to the system. The self-organizing processes within sedimentary systems—referred to as autogenic dynamics sensu Paola et al. (2009), and first articulated by Beerbower (1964)—can create patterns in preserved deposits that closely resemble those of stratigraphic cycles created by external forcings. The archetypal example of autogenesis is the threshold behavior of distributary channel switching, or avulsion, on deltas. Experiments with constant supply and accommodation show that distributary channels extend, backfill, and avulse systematically in space and time, resulting in cyclical patterns in the stratigraphy that might erroneously be interpreted as recording sea-level variability (Hoyal & Sheets 2009).

The findings from experimental research have focused the debate about stratigraphic pattern controls on the discrimination of autogenic dynamics from external, or allogenic, forcings such as eustasy, tectonics, and climate (e.g., Jerolmack & Paola 2010). The conclusion that a significant part of the stratigraphic record could be noise is obviously an important hypothesis to test going forward. Paola et al. (2009) postulated that autogenic processes might be more important at high temporal frequencies and allogenic forcings more influential over longer periods. However, recent work examining sedimentary-system response to climatic fluctuation has shown that preserved depositional patterns can be directly tied to millennial-scale (Romans et al. 2009) and decadal-scale (Aalto et al. 2003) climate forcings. Moreover, the timescales at which autogenic dynamics is the dominant driver might be greater than previously thought (e.g., Wang et al. 2011), thus increasing the temporal overlap at which autogenic and allogenic forcings operate and confounding our ability to distinguish their relative contributions. Future research should build on these findings and aim to better characterize and understand the interactions and feedbacks between autogenic and allogenic forcings instead of attempting to discriminate one or the other. Ultimately, the continued integration of observations and measurements from well-constrained natural sedimentary systems with improved dynamic models incorporating physical laws of sediment transport and deposition will provide opportunities to more accurately test and predict the relationship of controls to stratigraphic patterns (Paola et al. 2009).

In summary, active research and vigorous debate in the literature about the controls on patterns in the sedimentary record underscore the importance of the scientific problem. Understanding the complex and interdependent process-response relationships in sedimentary-system evolution is a priority for Earth surface researchers (Natl. Res. Counc. 2010). Marine scientists interested in using sedimentary archives to examine paleoenvironments and understand the influence of past climatic and oceanographic conditions on marine systems will be impacted by the findings from the increasingly interdisciplinary field of sedimentary-system analysis.

SUMMARY: A DEEP-TIME PERSPECTIVE OF LAND-OCEAN LINKAGES

Paleoenvironmental context, whether it is for the past few millennia or deep into the past hundreds of millions of years, is critical for many problems in marine science. For example, various time-series data for annual to decadal processes in the marine realm are more meaningful when viewed within the context of longer-term environmental change. Such context is provided by the sedimentary record, which can be used to reconstruct land-ocean linkages and dynamics through the Earth's history. However, sediment accumulation does not passively record ancient environments; rather, it actively shapes them by linking numerous Earth system components (Peters 2006). A holistic approach to stratigraphic analysis that considers the entire sedimentary system, from uplifting and eroding catchments where sediment is produced to subsiding basins where sediment accumulates, provides additional insight and constraints compared with considering only a part of the system.

Sedimentary-system analysis of geologically young to modern systems has the ability to explicitly map the sediment pathways and more accurately relate landscape evolution to forcings such as climate, sea-level change, and tectonics using ever-improving Quaternary geochronometric tools. Sedimentary-system analysis in deep time (>1–2 million years old) becomes more

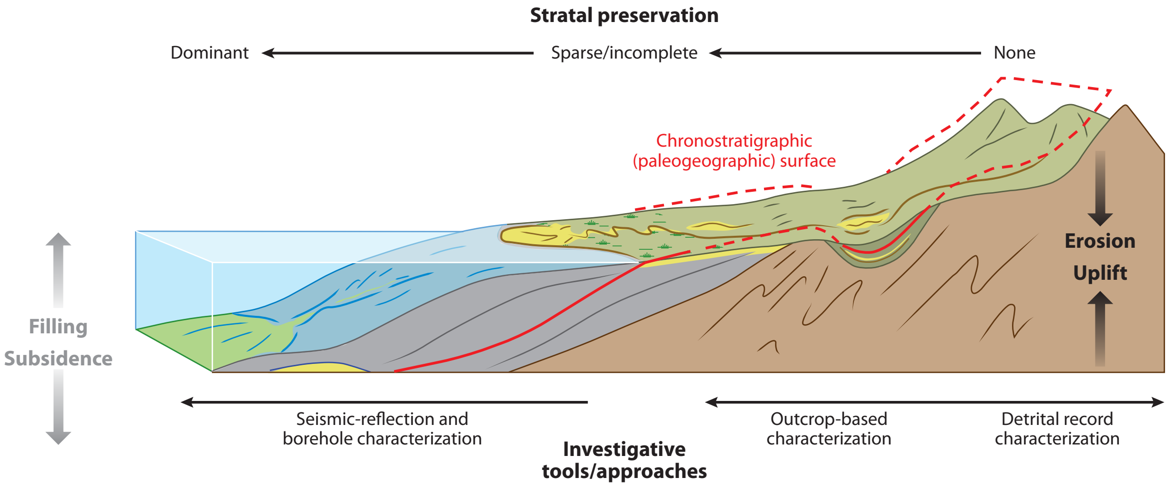

Figure 10

Schematic depiction of a long-lived (more than tens of millions of years) source-to-sink system along a basin margin (prior to significant tectonic regime change). Preservation potential increases overall in more basinward positions. The red line represents a single time line in the evolution of the system. An ongoing scientific challenge is to better integrate studies and results that use different tools, approaches, and types of data in different parts of a system. For the general positions of depositional systems, see **Figure 5**.

challenging because the net-erosional segments that produced the sediment are not preserved (**Figure 10**). However, methods such as geochronology and thermochronology of detrital minerals reveal information about sediment source areas that are long since eroded. Such methods, when fully integrated with facies and architectural analysis and sequence stratigraphy, are leading to more accurate, and more quantitative, characterizations of ancient sedimentary-system evolution (for a review of the state of the art for detrital record techniques and applications, see Busby & Azor 2012 and references therein).

FUTURE ISSUES

1. Improved documentation of erosion/exhumation and transfer/deposition rates, derived from better-resolved absolute age dating, is needed across a broad range of timescales, as are improved measurement (calculation, estimation) methods for material fluxes into and out of sedimentary-system segments.
2. Detailed and quantitative linkage of erosional and depositional segments in various types of Quaternary sedimentary systems (where process rates can more accurately be determined) is needed. These understandings, in turn, will better inform interpretations of much more ancient systems.
3. The complex combination of controls on observed stratigraphic patterns remains to be unraveled, and the autogenic/allogenic dichotomy must be addressed by using both experiments and data from natural systems to test the hypothesis that noise overwhelms the record.

4. It will be important to gain a better understanding of how the signals of various forcings propagate through the system. For example, to what extent are processes and history at the land-ocean interface recorded in the stratigraphy of depositional systems far from the coast (e.g., either up-system in terrestrial river systems or down-system in submarine fan systems)?
5. Taking full advantage of 3D seismic-reflection data will help improve understanding of planform stratigraphic patterns. Applying these data to this problem will require the development of robust quantitative geomorphic metrics, and more studies are needed linking cores with remotely sensed data (for facies calibration and chronology).
6. To what extent does the current interglacial highstand (the present-day condition of submerged continental shelves) bias our understanding of preserved land-ocean linkages in deep time? Similarly, to what extent does the Quaternary "icehouse" climatic regime, which is characterized by high-frequency and high-magnitude global sea-level fluctuations, bias our understanding of preserved land-ocean linkages in deep time?
7. Most of the marine stratigraphic record is mud(stone), but the transport/deposition processes of mud are still poorly understood compared with those of coarser material.
8. Continued research should aim at more robustly integrating numerical models of the physics of sediment transport with those that simulate basin-filling patterns. Similarly, improved integration is needed between studies characterizing natural systems and those using experiments (physical or numerical) to test hypotheses about fundamental controls on patterns.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

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In this review, we have distilled ideas from a large and interconnected community of scientists accrued over many decades of research. The research cited here emphasizes what we regard as particularly important papers and undoubtedly overlooks research considered influential by others. We acknowledge the fact that our approach and experience in sedimentary geology have a significant influence on the perspectives presented here, for which we are solely responsible. We hope the reader appreciates the challenge of preparing such a broad review. We thank Andrea Fildani, Jake Covault, Steve Hubbard, Julie Fosdick, Tim McHargue, and the late Bill Normark for illuminating discussions about sedimentary geology over the past several years.

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Errata

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