*Sedimentology* (2000), **47** (Suppl. 1), 2–48

# Fluvial responses to climate and sea-level change: a review and look forward

MICHAEL D. BLUM* and TORBJÖRN E. TÖRNQVIST†
**Department of Geosciences, University of Nebraska – Lincoln, 214 Bessey Hall, Lincoln, NE 68588-0340, USA (E-mail: mblum1@unl.edu)*
*†Department of Earth and Environmental Sciences, University of Illinois at Chicago, 845 West Taylor Street, Chicago, IL 60607-7059, USA (E-mail: tor@uic.edu)*

**ABSTRACT**

Fluvial landforms and deposits provide one of the most readily studied Quaternary continental records, and alluvial strata represent an important component in most ancient continental interior and continental margin successions. Moreover, studies of the long-term dynamics of fluvial systems and their responses to external or 'allogenic' controls, can play important roles in research concerning both global change and sequence-stratigraphy, as well as in studies of the dynamic interactions between tectonic activity and surface processes. These themes were energized in the final decades of the twentieth century, and may become increasingly important in the first decades of this millennium.

This review paper provides a historical perspective on the development of ideas in the fields of geomorphology/Quaternary geology vs. sedimentary geology, and then summarizes key processes that operate to produce alluvial stratigraphic records over time-scales of $10^3$–$10^6$ years. Of particular interest are changes in discharge regimes, sediment supply and sediment storage en route from source terrains to sedimentary basins, as well as changes in sea-level and the concept of accommodation. Late Quaternary stratigraphic records from the Loire (France), Mississippi (USA), Colorado (Texas, USA) and Rhine–Meuse (The Netherlands) Rivers are used to illustrate the influences of climate change on continental interior rivers, as well as the influence of interacting climate and sea-level change on continental margin systems.

The paper concludes with a look forward to a bright future for studies of fluvial response to climate and sea-level change. At present, empirical field-based research on fluvial response to climate and sea-level change lags behind: (a) the global change community's understanding of the magnitude and frequency of climate and sea-level change; (b) the sequence-stratigraphic community's desire to interpret climate and, especially, sea-level change as forcing mechanisms; and (c) the modelling community's ability to generate numerical and physical models of surface processes and their stratigraphic results. A major challenge for the future is to catch up, which will require the development of more detailed and sophisticated Quaternary stratigraphic, sedimentological and geochronological frameworks in a variety of continental interior and continental margin settings. There is a particular need for studies that seek to document fluvial responses to allogenic forcing over both shorter ($10^2$–$10^3$ years) and longer ($10^4$–$10^6$ years) time-scales than has commonly been the case to date, as well as in larger river systems, from source to sink. Studies of Quaternary systems in depositional basin settings are especially critical because they can provide realistic analogues for interpretation of the pre-Quaternary rock record.

**Keywords** Climate change, fluvial sedimentology, Quaternary geology, sea-level change, sequence stratigraphy.

## INTRODUCTION

Studies of continental stratigraphic records, Quaternary and ancient, were energized in the final decades of the twentieth century by two somewhat distinct trends that emerged within the geosciences. First, there was increasingly widespread recognition that human activities were altering climatic and environmental conditions over very short time-scales. Since the stratigraphic record is the only empirical record of global change (Burke *et al.*, 1990), studies of the magnitude and frequency of past global changes, Quaternary and ancient, were seen as a means to provide a context for observed historical trends and predicted near-future conditions. Second, development of sequence-stratigraphic concepts and methods (e.g. Vail *et al.*, 1977; Jervey, 1988; Posamentier & Vail, 1988; Posamentier *et al.*, 1988) provided a potential unifying framework for much of sedimentary geology, especially coastal and marine strata, but their application to continental deposits has been controversial.

At a basic level, global change and sequence-stratigraphic research have in common a focus on changes in process through time in response to external forcing, and it is hard to envisage any scenario for the first decades of this millennium in which these issues will be less important. In addition, an important third trend has begun to emerge, as there is now a deeper appreciation of the magnitude and frequency of tectonic activity in plate boundary, continental interior and passive margin settings, and relationships between tectonic activity and surface processes (e.g. Molnar & England, 1990; Molnar *et al.*, 1993; Merritts & Ellis, 1994; Pinter & Brandon, 1997; Burbank & Pinter, 1999). This third trend will further energize studies of continental records, since integrative models of this kind must be tested against, and refined by, studies of Quaternary and ancient strata.

Fluvial landforms and deposits provide one of the most readily studied Quaternary continental records, and alluvial strata represent an important component in most ancient continental interior and continental margin successions. Moreover, modern fluvial environments are critical to human activities, and ancient fluvial deposits are important repositories for hydrocarbons, groundwater and other resources. Studies of the long-term dynamics of fluvial systems, and their responses to external or 'allogenic' controls, therefore have a broad range of applications. This paper provides an overview of fluvial responses to climate and sea-level change, and attempts to: (a) develop a historical perspective; (b) outline a basic process framework, with illustrations of fluvial responses to climate and sea-level change from Late Quaternary contexts; and (c) suggest key areas of emphasis for the first decades of this millennium.

## HISTORICAL STARTING POINTS

Studies of fluvial responses to climate and sea-level changes have evolved somewhat differently within the fields of geomorphology and Quaternary geology vs. sedimentary geology.

### Geomorphology and Quaternary geology

Several concepts from the late 1800s and early 1900s have played key roles in studies of fluvial response to climate and sea-level change. One of these was base level, defined by Powell (1875) as the lower limit to which rivers can erode their valleys, with his 'grand' or ultimate base level corresponding to sea-level. A second concept was that of the graded stream, which Gilbert (1877) suggested was adjusted in terms of channel slope, or longitudinal profile, so that the available discharge could transport the amount of sediment supplied by the drainage network, and the channel bed was neither aggrading nor degrading. Mackin's (1948) discussion of the graded stream is better known and more detailed, and also focused on equilibrium long profiles that are adjusted to prevailing conditions of discharge and sediment load.

One of the first empirical studies of fluvial response to climate change was by Penck & Brückner (1909), whose examination of terraces along tributaries to the Danube in southern Germany gave birth to the concept of four Pleistocene glacial–interglacial cycles. This model for Quaternary climate change remained dominant until the development of oxygen-isotope records from ocean basins in the 1960s and 1970s, and confirmation of the Milankovitch theory of glaciation (Hays *et al.*, 1976). Critical to the present discussion, Penck & Brückner (1909) linked aggradation to glacial-period sediment supply, and incision with floodplain abandonment and terrace formation to interglacial periods (Fig. 1A). By contrast, Lamothe (1918) in the Somme Valley of France, and Fisk (1944) in the Lower Mississippi Valley of the USA, focused on the role of glacio-eustasy. Fisk's (1944) well-known model suggested valley incision, floodplain abandonment and terrace formation during sea-level fall and lowstand, followed by valley aggradation during transgression and highstand (Fig. 1B,C).

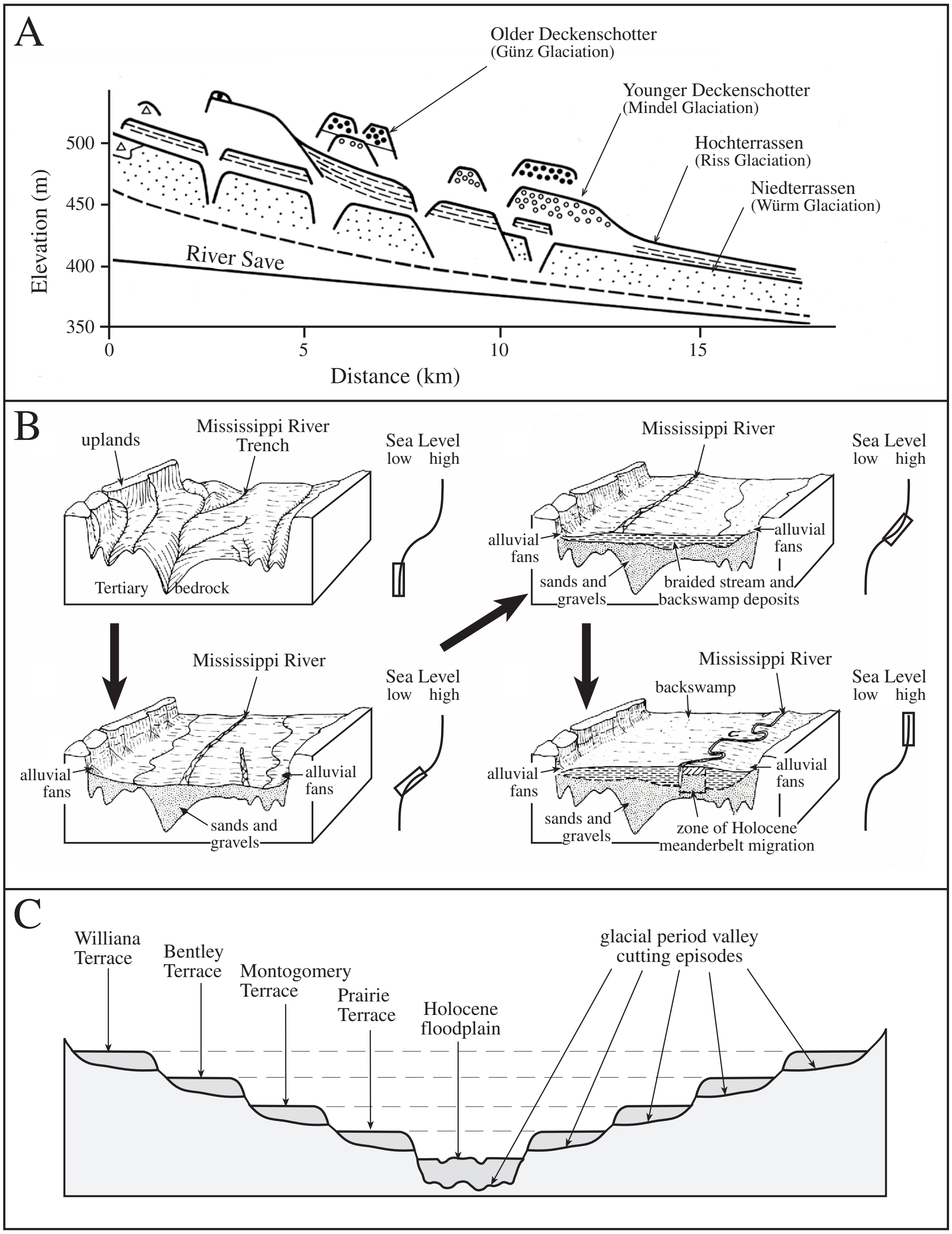



**Fig. 1.** (A) Penck & Brückner's (1909) model for terraces in southern Germany, linking aggradation to glacial cycles, and incision to interglacials (adapted from Bowen, 1978; original from Penck & Brückner, 1909). (B) Fisk's (1944) model for valley development during an individual eustatic cycle, illustrating cutting during sea-level fall, and the different stages of filling during sea-level rise and highstand. (C) Fisk's model for terraces of the Gulf Coastal Plain in Louisiana (USA), linking incision to glacial cycles, and aggradation to interglacials (B and C modified from Fisk, 1944).

This 'continental interior' vs. 'continental margin' dichotomy, or a focus on upstream vs. downstream controls depending on study area location, was still prevalent in the last decades of the twentieth century.

### *Upstream controls in continental interiors*

As described by Butzer (1980), a 'glacial' vs. 'interglacial' dichotomy, following Penck & Brückner (1909), also persisted for some time, and it was commonly assumed that present floodplains represented the Holocene, the first terrace was from the last Pleistocene glacial, the second terrace was from the penultimate glacial, and so on. Clear turning points can be traced to the development of radiocarbon dating (Libby, 1952) and to the hydraulic geometry studies of Leopold & Maddock (1953). Radiocarbon dating techniques provided an opportunity to develop chronological frameworks for climate change from palaeobiological and other indicators, and, independently, for alluvial successions. Moreover, the effective limits of radiocarbon eventually served to focus attention on the last full-glacial and the Holocene (last 20 kyr). Leopold & Maddock (1953), by contrast, initiated a generation of efforts that developed quantitative relations between discharge regimes, sediment load and measures of channel geometry (e.g. width, depth, sinuosity, meander wavelength, slope).

Several papers from the 1960s illustrate the immediate impact of hydraulic geometry. Among these are Schumm's (1965) general model for fluvial response to climatic change, Dury's (1965) studies of 'underfit' streams and Schumm's (1968a) discussion of the concept of channel metamorphosis, based on studies of the Murrumbidgee River, south-eastern Australia (Fig. 2). A subsequent series of influential papers by Schumm and colleagues in the 1970s and early 1980s served to caution against developing general models for fluvial response to climate change. In concise summaries of this work, Schumm (1977, 1991) notes the importance of: (a) spatial and temporal scale; (b) convergence of responses given different external forcing mechanisms; (c) divergence of response following similar external inputs; (d) differential sensitivity of fluvial systems to external controls due to differing thresholds for change; and (e) complex response due to internal system dynamics. These issues suggest that fluvial responses to climate change may be geographically circumscribed, nondeterministic and nonlinear.

Many of these ideas are reflected in review papers by Knox (1983, 1996) and Starkel (1987, 1991), and Bull's (1991) monograph. Knox (1983), for example, summarized the Holocene record from the USA, and argued that climate change produces time-parallel discontinuities in alluvial successions over broad areas, even though the direction of change may differ between regions. He suggested this could be due to the way changes in global atmospheric circulation are manifested regionally, and/or the intrinsic characteristics of each system. Starkel (1987, 1991) also recognized the variability of fluvial response to climate change over the last 15 kyr, and differentiated classes of European rivers on the basis of relationships between tectonic highlands, Pleistocene ice extent, the former periglacial region, isostatic rebound and sea-level change. Starkel's papers emanated from international projects that demonstrate increased interest in fluvial systems and climate change during the last two decades (Gregory, 1983; Gregory *et al.*, 1987,

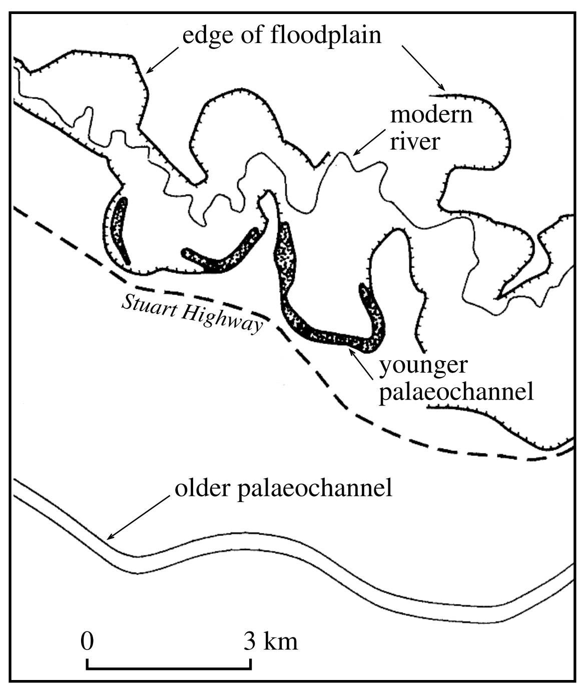



**Fig. 2.** Concept of channel metamorphosis, introduced by Schumm (1968a) based on studies of the Murrumbidgee River, Australia. Map shows modern highly sinuous Murrumbidgee River, vs. older channel with larger meanders, and an even older low-sinuosity channel (adapted from Schumm & Brakenridge, 1987; original from Schumm, 1968a).

1996; Starkel *et al.*, 1991; Branson *et al.*, 1996; Benito *et al.*, 1998).

### *Downstream controls in continental margins*

Fisk's (1944) investigations of the Lower Mississippi Valley coupled valley evolution to glacio-eustasy and changes in stream gradients, and played a fundamental role in development of models for fluvial response to sea-level change. According to Fisk, the valley was deeply incised and swept clean of sediments to a point some 1000 km upstream from the present Gulf of Mexico shoreline due to increased channel gradients during the Last Glacial Maximum sea-level lowstand. Braided-stream surfaces formed when gradients decreased during latest Pleistocene to middle Holocene sea-level rise, with a transition to a meandering regime during the late Holocene sea-level highstand. Fisk's model was so influential that many workers assigned successively older terraces in the lower reaches of river valleys to successively older interglacials. Extreme examples of this type of thinking can be found in studies along the Gulf Coast of the USA that inferred short-lived periods of sea-level rise for terraces that did not fit into the standard model of four glacial–interglacial cycles (e.g. Bernard & Leblanc, 1965).

Further empirical studies of continental margin systems have been less visible, perhaps because of the perceived power of Fisk's model. It is therefore appropriate that the Mississippi has played a role in reassessment of fluvial responses to sea-level change. Saucier's (1994, 1996) work, for example, shows that the Mississippi was never completely excavated, and did not feel the effects of sea-level change as far upstream as Fisk had envisaged. Saucier also assigned braided-stream surfaces to the last glacial period, and suggested they record fluvial responses to glacially induced changes in discharge and sediment load, whereas the transition to a meandering regime occurred in the earliest Holocene with the loss of a glacial source for sediment and water.

A variety of conceptual, experimental and theoretical models of river response to base-level change appeared in the 1970s and 1980s. Leopold & Bull (1979), for example, used observations from modern rivers to suggest the upstream effects of base-level rise were limited, whereas Begin *et al.* (1981) and Begin (1988) used flume studies coupled with a diffusion-based model to show that vertical lowering of base-level (as along a fault block) results in long-profile lowering by nickpoint migration at rates that diminish in the upstream direction. Slingerland & Snow (1988) developed a numerical sediment-transport model to simulate long-profile evolution in response to base-level fall, and suggested a series of complex autogenic oscillations of cutting and filling might result from a single allogenic perturbation. At a broader conceptual level, Summerfield (1985) suggested the influence of sea-level fall will vary with geometric relationships between the slope of the coastal plain and the slope of the shelf as it becomes emergent (Fig. 3). For example, Brown & Wilson (1988) and Leckie (1994) discuss the Canterbury Plains of New Zealand, where aggradation occurred during glacial periods because of newly exposed shelf gradients that were less

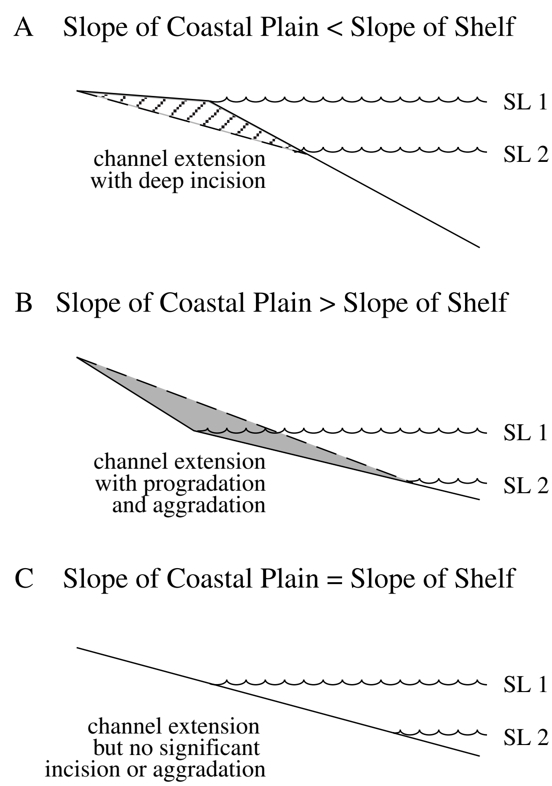



**Fig. 3.** Model for fluvial response to sea-level fall as a function of coastal plain and shelf gradients. (A) Incision through coastal prism (depositional shoreline break) due to steeper gradients exposed on the inner shelf as sea-level falls; (B) aggradation and progradation due to sea-level fall across a shelf that has a gradient shallower than the coastal plain; (C) channel extension with little incision, other than that necessary to contain the channel itself, due to no gradient differences between coastal plain and exposed shelf during sea-level fall. Adapted from Summerfield (1985).

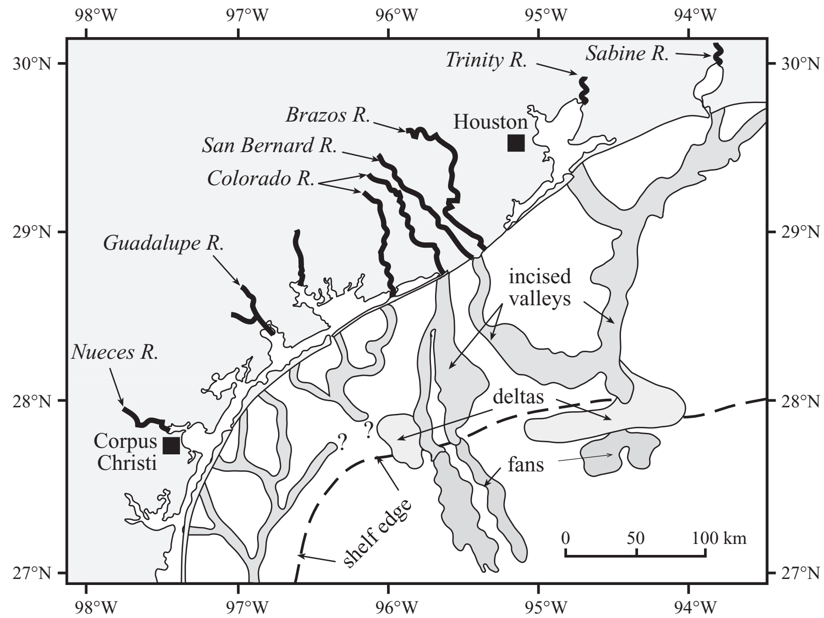



**Fig. 4.** Valleys and deltas of the north-west Gulf of Mexico shelf during the last full-glacial period, as identified in high-resolution seismic data (adapted from Suter & Berryhill, 1985; Anderson *et al.*, 1996).

steep than the permanently subaerial alluvial plains.

Most recently, workers have examined interactions between upstream climatic and downstream sea-level controls in the lowermost reaches of coastal plain rivers. As discussed later, these efforts have concentrated on rivers of the Texas Gulf Coastal Plain (USA) and on the Rhine–Meuse of The Netherlands. The 1980s and 1990s also witnessed the emergence of high-resolution seismic-stratigraphic studies on continental shelves. Suter & Berryhill (1985), for example, demonstrated channel extension and delta progradation across the Gulf of Mexico shelf during the last sea-level fall and lowstand. Subsequent work by others continued to document the extent and variability of fluvial channels and deltaic strata on the shelves and at shelf edges (Fig. 4). Important examples include work by Morton & Suter (1996) and Anderson *et al.* (1996) for the north-western Gulf of Mexico (USA), and Tesson *et al.* (1993; also Tesson & Gensous, 1998) for the Rhone shelf of the Medditeranean.

## Sedimentary geology

Eustatic sea-level change played an important role in explanations of cyclicity in pre-Quaternary sedimentary rocks during the first two-thirds of the twentieth century (e.g. Wanless & Weller, 1932; Sloss, 1963; Wheeler, 1964). However, a period of waning enthusiasm for sea-level change accompanied development of plate tectonics on one hand, and facies models on the other (Dott, 1992), such that studies in the 1960s and 1970s commonly focused on tectonic activity coupled with autogenic processes to explain stratal patterns. Sedimentary geologists have also long recognized the importance of climate in the production of sediments, as well as the range of depositional systems, environments and facies, but attempts to explain changes in alluvial successions through time with reference to climate change are a recent innovation.

There is little question that plate tectonics plays the overriding role in organization of landmasses into sediment source regions, transport routes and sedimentary basins, and is thus primarily responsible for the accumulation of thick successions of alluvial strata. The following discussion refers readers to Miall (1996) for a comprehensive discussion of the role of tectonic activity in the development of alluvial successions, and instead highlights alternative trends from the last three decades. Of greatest significance is the emergence of sequence-stratigraphic models and their emphasis on the interwoven concepts of sea-level, base level and accommodation. Most recently, workers have begun to examine links between alluvial successions and climate change.

### *Sea-level, base level and accommodation*

Development of sequence-stratigraphic concepts, beginning with publications of Vail and colleagues from Exxon Production Research in *AAPG Memoir 26* (Payton, 1977) initiated a wave of research into the responses of depositional systems to sea-level change. Publication of the first Exxon cycle charts (Vail *et al.*, 1977) gave rise to new views on the pervasiveness of sea-level changes through geological time.

The origins of this wave of research, as it pertains to 'fluvial sequence stratigraphy', lagged behind development of the general model, and can be traced to *SEPM Special Publication 42* (Wilgus *et al.*, 1988), which contained two papers that catalysed discussion over the next decade. The first was by Jervey (1988) which introduced the term 'accommodation' as the space available below base level for sediments to accumulate, a function of eustatic sea-level change and subsidence (i.e. relative sea-level change). The second was by Posamentier & Vail (1988), in which fluvial response to sea-level change played a prominent role in the development of conceptual models for 'systems tracts', the basic building blocks in the Exxon model. Their process framework rests on the premise that rivers adjust longitudinal profiles in response to sea-level change, and they argued that: (a) widespread fluvial deposition characterizes the early stages of relative sea-level fall; (b) valley incision and sediment bypass characterizes the late stages of sea-level fall and lowstand; and (c) filling of valleys occurs during transgression and highstand.

The Exxon views on sequence stratigraphy have been carefully scrutinized, accepted by some, and criticized by others (e.g. Galloway, 1989; Miall, 1991, 1996; Helland-Hansen & Gjelberg, 1994; Shanley & McCabe, 1994). Some criticisms are grounded on scientific shortcomings, but others reflect an unfortunate use of genetic terminology for Exxon systems tracts (see Van Wagoner, 1995a, for a historical perspective), as well as contradictions within and between publications from the Exxon group as a whole. For example, numerous figures in Posamentier & Vail (1988) show widespread fluvial deposition during sea-level fall, but the text commonly infers fluvial incision and sediment bypass during that time. Moreover, Posamentier & Vail (1988) illustrate the development of systems tracts with respect to eustasy, and/or various combinations of eustasy and subsidence. By contrast, Van Wagoner *et al.* (1988) provide an operational view that follows the original definition by Mitchum *et al.* (1977), and systems tracts are 'defined objectively' on the basis of key bounding surfaces, position within a sequence, stratal geometry and facies associations, and the 'terms lowstand and highstand are not meant to imply a unique period of time or position on a cycle of eustatic or relative change of sea-level'.

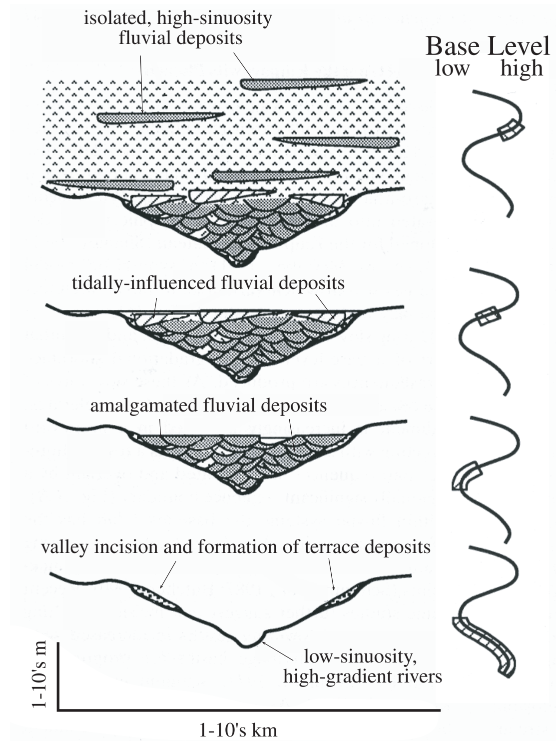



**Fig. 5.** Shanley & McCabe's (1993, 1994) model for development of depositional sequences in mixed fluvial–coastal–marine strata of the Cretaceous Western Interior basin of the USA, in response to base-level change. They illustrate the concept of incision and sediment bypass during base-level fall that is common to many sequence stratigraphic models, followed by valley filling, first with amalgamated fluvial deposits, then tidally influenced strata and finally low net-to-gross fluvial deposits.

Nevertheless, *SEPM Special Publication 42* resulted in a flurry of interest in the concepts of sea-level, base level and accommodation, and in how fluvial and other continental systems fit within the mostly marine-derived sequence-stratigraphic model (see the review by Shanley & McCabe, 1994). 'Incised valleys' emerged as a focus of attention; according to Van Wagoner *et al.* (1990), 'incised valleys' contain significant erosional relief, truncate older strata, juxtapose fluvial or estuarine sandstone on marine deposits, and define a significant basinward shift of facies due to relative sea-level fall. Dalrymple *et al.* (1994) defined two types of 'incised valleys', those

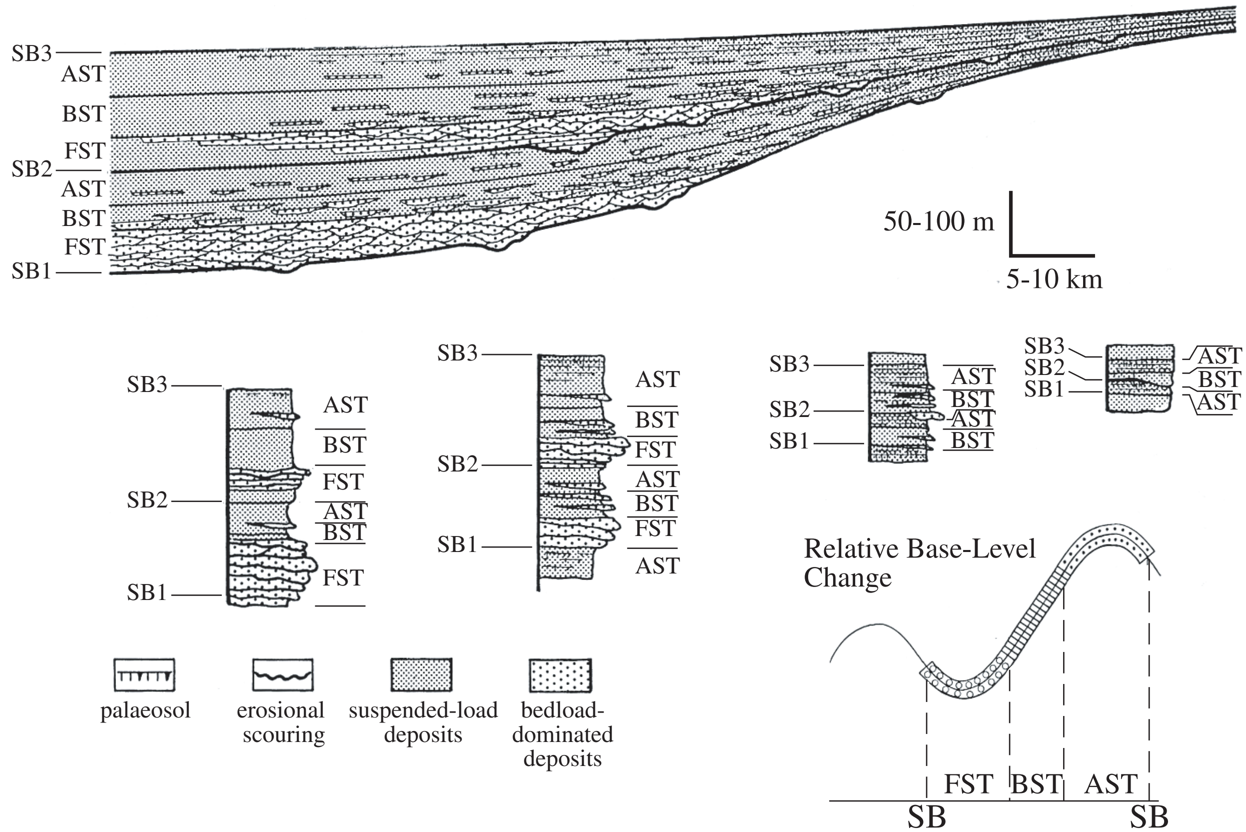



**Fig. 6.** Hinterland depositional sequence model of Legarreta and colleagues, based on Cretaceous nonmarine strata in Argentina. FST = forestepping systems tract, BST = backstepping systems tract, AST = aggradational systems tract, SB = sequence boundary. Downdip is to the left. Modified from Legarreta & Uliana (1998).

formed by relative sea-level fall, and those formed in response to some other mechanism. They argued the first type should have sequence boundaries at their base and will be filled by predictable successions of fluvial and estuarine facies due to relative sea-level rise (Zaitlin *et al.*, 1994), whereas the second type will be difficult to recognize since they may occur within a succession of fluvial strata, and have no significance in the Exxon sequence-stratigraphic sense.

A variety of explanatory models for fluvial sequence stratigraphy have been published that focus on linking fluvial and nearshore marine strata. Shanley & McCabe (1991, 1993, 1994) recognized depositional sequences based on interbedded fluvial and marine strata from the Cretaceous of the Western Interior foreland basin of Utah (USA). Their interpretations are grounded on correlations between alluvial strata and coeval shorelines that step basinward or landward, as well as recognition of systematic vertical changes in sandbody amalgamation and/or isolation (Fig. 5). Posamentier & Allen (1993) proposed a variant on the standard sequence model that applies to foreland basins, whereas Howell & Flint (1996) discussed active extensional settings. Van Wagoner (1995b) developed a detailed model for Cretaceous foreland basin strata of the Book Cliffs in Utah (USA) that, among other things, has served as a catalyst for debate in the literature (see Yoshida *et al.*, 1998; Van Wagoner, 1998) and, more informally, among the sedimentology community as a whole.

Fully nonmarine models have been proposed as well. Legarreta & Uliana (1998) propose a model for Mesozoic continental basins in Argentina that includes: (a) a coarsening-upwards 'forestepping' systems tract that is laterally confined and dominated by amalgamated channel sandstones; (b) a fining-upwards 'backstepping' systems tract; and (c) an 'aggradational' systems tract (Fig. 6). Wright & Marriott (1993) propose a generic model that is not based on actual examples, but incorporates systems tracts terminology and emphasizes relationships between alluvial architecture, palaeosols and changes in accommodation that relate specifically to floodplain sedimentation. Gibling & Bird (1994) and Aitken & Flint (1995), among others, use Carboniferous examples from Canada and the USA to discuss overall sequence architecture, the role of palaeosols, and the recognition, variability and importance of 'interfluve' sequence boundaries. Most recently, Martinsen *et al.* (1999) use the accommodation to sediment supply ratio (A/S ratio) described in Muto & Steel (1997) to interpret changes in alluvial architecture.

## *Climate change*

Studies that link fluvial deposition to climate change in the pre-Quaternary record are relatively sparse when compared with the volume of literature on fluvial responses to sea-level or base-level change that has been generated following introduction of sequence-stratigraphic concepts. By far the most common theme is the interpretation of ancient climate from individual features (e.g. palaeosols) within alluvial successions, as opposed to interpretations of fluvial response to climate change. Much of this work is summarized by Parrish (1998) and not repeated here. Instead the discussion below focuses on examples where workers have specifically interpreted depositional responses to climate change.

A number of workers have inferred climate change as a control based on transitions between fluvial and other strata. Over time-scales of $10^6$–$10^7$ years, Olsen & Larsen (1993) suggest the Late Devonian of East Greenland can be subdivided into depositional complexes similar in concept to Exxon's systems tracts. Interpreted changes from braidplain environments to terminal fluvial systems that pass laterally to aeolian environments, then to a meandering stream-dominated setting were attributed to shifts towards more arid and then more humid conditions. A number of studies also interpret transitions between fluvial and other strata due to climate changes over time-scales of $10^4$–$10^5$ years (Milankovitch scales). These include Cojan's (1993) work on Upper Cretaceous to Palaeocene fluvial and lacustrine strata in the Provence Basin of southern France, Yang & Nio's (1993) studies of Permian Rotliegendes strata of the Dutch North Sea, Clemmensen *et al.*'s (1994) summary of interbedded fluvial and aeolian rocks of Permian to Triassic age in the UK, and Dubiel *et al.*'s (1996) discussion of interfingering fluvial and aeolian strata within the Permian Cutler Group of the western USA.

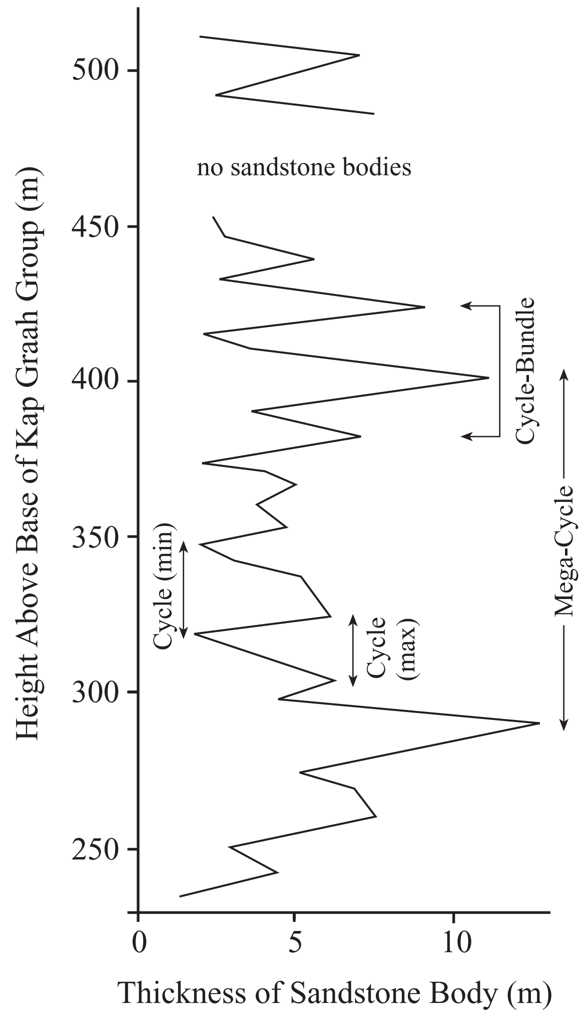



**Fig. 7.** Interpreted cyclical changes in sandbody thicknesses deposited by meandering rivers from the Andersson Land Formation, Devonian Kap Graah Group of East Greenland (after Olsen, 1994). Cycle (min) indicates cycles defined by minimum thicknesses, whereas Cycle (max) indicates the opposite definition. Mega-cycles are interpreted to reflect the Milankovitch eccentricity period, calculated at 95 kyr for the Devonian, whereas individual cycles are interpreted to represent precessional periods of 17 or 20 kyr.

Changes within fully alluvial successions have been ascribed to the influence of Milankovitch-scale climate changes as well. Olsen (1990, 1994), for example, examined the Late Devonian Andersson Land Formation of east Greenland, the axial meandering stream-dominated complex described above. He identified two scales of cyclicity in the thickness of channel sand bodies, which were interpreted to represent climatically controlled changes in discharge regimes at Milankovitch-scale periodicities of 100 kyr and ~20 kyr (Fig. 7). Smith (1994) suggested that changes in channel sandbody geometry, sand-to-mud ratios, sediment accumulation rates and types of palaeosols in Plio-Pleistocene strata from Arizona (USA) occurred during a tectonically quiescent period and might instead reflect climate changes.

Modelling fluvial responses to climate change in the pre-Quaternary record has not been common practice, but a number of important efforts can be identified. Perlmutter & Matthews (1989) propose a cyclostratigraphic model that emphasizes Milankovitch-scale climate change superimposed on tectonically driven basin evolution. Key model components include weathering and sediment production, discharge regimes, and transport efficiency as they relate to variations in climate, as well as how these factors control the spatial patterns of clastic environments and temporal evolution of clastic successions. Paola *et al.* (1992) use a diffusion-based model to examine the roles of sediment flux, rates of subsidence, changes in sediment grain-size (gravel vs. sand) and water supply on patterns of deposition in foreland basins at time steps of $10^7$ and $10^5$ years. This study is not specifically concerned with causal mechanisms, but the authors note that sediment flux, changes in grain-size and variations in water supply can have several causes, including climate change. Variations in sediment flux and grain size are important in both time steps, with both resulting in progradation or retrogradation of gravel fronts. By contrast, cyclical changes in water supply play a significant role in shorter time steps only, resulting in progradational cycles during time periods when water supply is increasing. Paola *et al.* (1992) suggest that over time-scales of $10^5$ years (Milankovitch time-scales), patterns of deposition for foreland basin settings most closely reflect surface processes, whereas over longer time-scales basin subsidence and other tectonically controlled factors become dominant.

## GENERAL PROCESS FRAMEWORK

Promising avenues of research lie at the interface between Quaternary and ancient fluvial systems, especially studies of fluvial responses to climate and sea-level changes at time-scales of $10^6$ years or less. The following section focuses on how rivers produce stratigraphic records over these time-scales; the section concentrates on alluvial channels because of their mobile beds and banks, the rapidity with which such systems can respond to allogenic controls, and the fact that such rivers provide the common link between Quaternary and ancient records.

### Channel geometry and depositional style

Process-based interpretations of fluvial responses to climate and sea-level change should be linked in some way to controls on the mutually dependent variables of channel geometry and depositional style. Numerous discussions of alluvial channel process and form, as well as fluvial depositional processes and systems, are readily available elsewhere and not repeated here (e.g. Knox, 1976; Leopold & Bull, 1979; Richards, 1982; Miall, 1985, 1995, 1996; Schumm, 1985; Ferguson, 1987; Nanson & Croke, 1992; Bridge, 1993a,b, 1995; Orton & Reading, 1993; Van den Berg, 1995; Brierley, 1996; Nanson & Knighton, 1996; Knighton, 1998; Fielding, 1999). Instead, four fundamental relationships can be distilled from this body of literature: (a) cross-sectional and plan view geometry of a 'graded stream' is adjusted to prevailing discharge regimes and sediment loads, and maintains a statistically constant size and shape over some interval of time ($10^2$–$10^3$ years); (b) fluvial facies and depositional systems are linked to channel geometry through the spatial distribution of depositional landforms and environments; (c) changes in the relationship between discharge and sediment load result in changes in one or more geometric variables, for example width, depth, width-to-depth ratio, sinuosity or slope; and (d) changes in channel geometry result in changes in the lateral and vertical distribution of depositional environments and facies.

### Aggradation and degradation: changes in sediment storage

Aggradation or degradation often accompanies changes in channel geometry and depositional style, and results in changes in sediment storage per unit valley length due to changes in channel bed and floodplain elevation. Width-averaged bedload transport rates ($q_s$) reflect stream power per unit channel length, $\Omega = \gamma QS$ (where $\Omega$ = stream power, $\gamma$ = specific weight, $Q$ = discharge and $S$ = channel bed slope;

Bagnold, 1973). Channel beds aggrade when sediment supply exceeds maximum bedload transport rates, degrade when the reverse is true and maintain stable long profiles when there is a balance between stream power and sediment supply (Fig. 8).

Theoretical models to describe aggradation or degradation are widely published in the engineering, geomorphological and sedimentological literature (e.g. Torres & Jain, 1984; Wyroll, 1988; Paola *et al.*, 1992; Leeder & Stewart, 1996). Such models are ultimately based on the sediment continuity equation, which can be written in its simplest one-dimensional form as:

$$dz/dt + dq_s/dx = 0 \qquad (1)$$

where $z$ = bed elevation, $t$ = time, $q_s$ = width-averaged sediment transport rate and $x$ = distance along the channel. For a channel bed that is in equilibrium ('graded') and neither aggrading nor degrading, $dz/dt = 0$, hence $dq_s/dx = 0$. From this simple relationship, three end-member situations for aggradation can be derived: (a) sediment overloading (holding discharge constant) from an upstream point source (typical of an alluvial fan) will result in a downstream-tapering wedge of channel-bed aggradation (i.e. the 'downfilling' of Schumm, 1993); (b) sediment overloading from upstream and lateral sources (drainage network feeding a main valley axis) will result in a relatively constant thickness of channel-bed aggradation; and (c) base-level rise under conditions of constant sediment supply will result in downstream decreases in sediment transport rates, and downstream increasing rates of channel-bed aggradation (the 'backfilling' of Schumm, 1993). Degradation can be triggered in a variety of ways, and from both upstream and downstream directions, but always results in channel incision and floodplain abandonment, net sediment removal, and production of an unconformity.

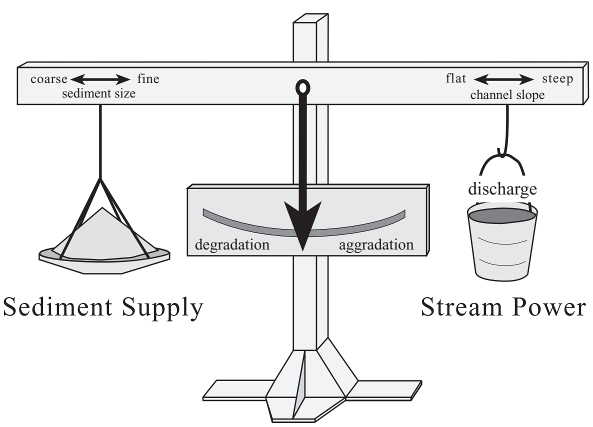



**Fig. 8.** Balance model for aggradation and degradation of alluvial channels, emphasizing changes in the relationship between discharge and sediment supply. Channels aggrade when sediment supply exceeds transport capacity of the discharge regime, and degrade when the reverse is true. Redrawn from a widely circulated diagram that originated as an unpublished drawing by W. Borland of the USA Bureau of Reclamation, and was based on an equation by Lane (1955).

A simple two-dimensional view of channel-bed aggradation and degradation is shown in Fig. 9A, but may be complicated by a number of factors. For example, under equilibrium conditions channels could migrate laterally but undergo no significant aggradation or degradation, which translates into no net change in sediment storage. This does not mean that a stable stream cannot leave behind a deposit, since lateral migration of a channel belt results in cannibalization of older sediments and emplacement of new deposits. In this case, interpretation of true aggradation and development of multistoried channel belts vs. simple lateral migration is not a simple issue, and should be grounded on observations of deposit thicknesses that exceed the vertical distance between the maximum depth of autogenic scour (Salter, 1993) and the upper limit to floodplain accretion as a channel belt migrates laterally. For example, recent studies demonstrate that depths of autogenic scour at flow confluences and at channel bends can be up to five times deeper than the mean channel depth (Best & Ashworth, 1997), and depths of scour can be significantly below contemporary sea-level positions.

Perhaps equally important are cases where there is little, if any, change in channel-bed elevation, but floodplain height increases or decreases (e.g. Blum & Valastro, 1994; Fig. 9B). For example, floodplain abandonment can take place without significant channel incision due to a reduction in peak discharges and overbank flooding. Lateral migration of a channel belt then produces a basal erosional unconformity that traces laterally up to soils that developed on the abandoned floodplain surface. By contrast, formerly stable terrace surfaces can be buried by renewed overbank flooding if flood magnitudes increase. Finally, changes in channel-bed and floodplain elevation may occur at different rates, and in some instances in opposite directions (cf.

Tebbens *et al.*, 1999), due to changes in channel geometry. This variety of possible geometric responses suggests that inferences of fluvial aggradation and/or incision are less than straightforward, and should be based on evidence that bears on changes in both channel-bed and floodplain elevations, wherever possible.

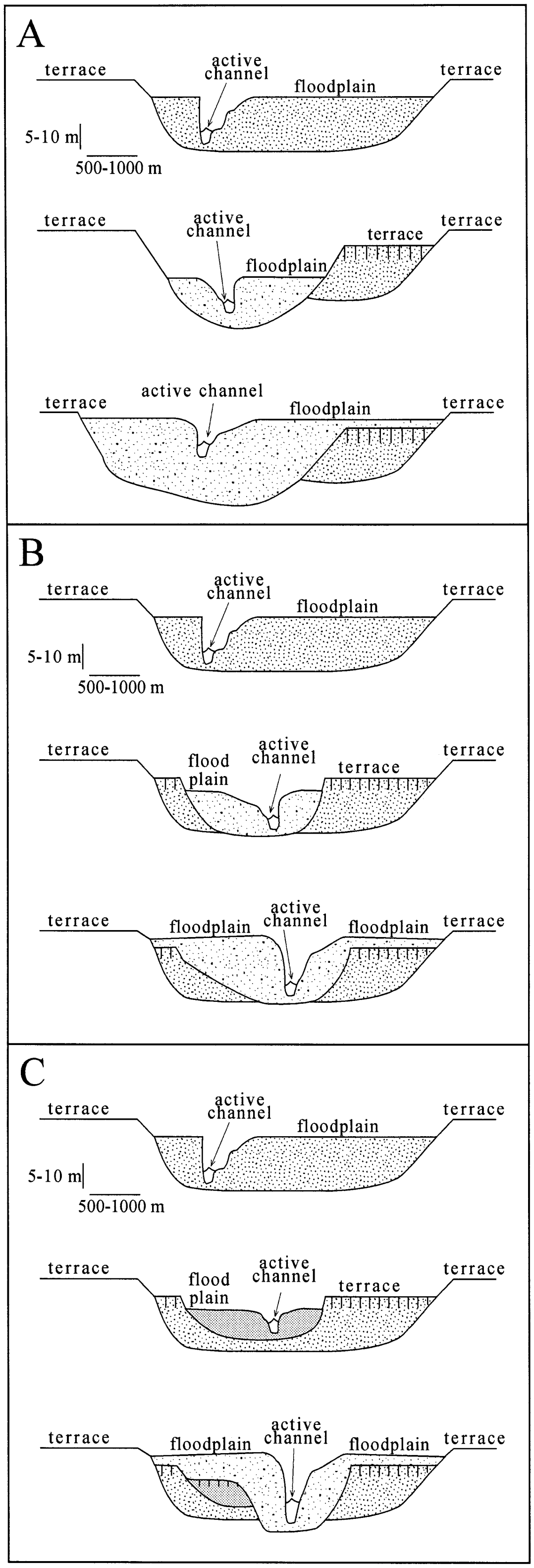



**Fig. 9.** Changes in sediment storage within valley cross-sections, and possible stratigraphic results. Each scenario begins with lateral migration of a single-story channel belt. (A) Channel-bed degradation and floodplain abandonment with terrace formation, then channel-bed aggradation to produce a multistory channel belt, with floodplain deposition over previously stable terrace surfaces characterized by palaeosols (hachures). (B) Reduction in channel size, floodplain abandonment and terrace formation without significant channel-bed degradation, then channel enlargement with floodplain deposition over previously stable terrace surfaces characterized by palaeosols. (C) Significant reduction in channel size accompanied by channel-bed aggradation, floodplain abandonment and terrace formation, followed by channel enlargement accompanied by channel-bed degradation and floodplain deposition over previously stable terrace surfaces characterized by palaeosols.

## Controls on changes in discharge, sediment supply and sediment storage

Changes in channel geometry, depositional style and net sediment storage are dependent variables over time-scales of interest here, and reflect prevailing conditions of discharge and sediment supply. What controls changes in discharge and sediment supply over these time-scales?

### *Discharge regimes*

Alluvial channel size reflects the volume of water that must be transmitted on a relatively frequent basis, with recurrence intervals for channel-forming discharges that range from 1 to 30 years (Williams, 1978; Knox, 1983; Lewin, 1989). Overviews of flood characteristics in various climates can be found in Baker *et al.* (1988), McMahon *et al.* (1987, 1992) and Waylen (1996), whereas Pazzaglia *et al.* (1998) discuss possible relationships between rates of uplift, rates of erosion, river long profiles and flood hydrographs. Critical to the present discussion is the potential impact of climate change on flood magnitude and frequency, and how this might vary to the extent that global climate change impacts different river systems in the same or different ways.

In this context, Knox (1983) summarizes a variety of historical period data that illustrate how climate change can impact flood regimes of individual rivers. For small drainages in the mid-latitude USA, he shows that flood discharge per unit area increases (holding recurrence intervals constant) with decreasing precipitation due to decreases in vegetation cover and corresponding increases in surface runoff. Moreover, he uses a long time series of annual floods from the upper Mississippi River to illustrate relationships between flood magnitudes and independently identified changes in global atmospheric circulation. These data show that circulation changes have significant impacts on the magnitude of rare events (recurrence intervals > 10 years), but lesser impact on more frequent floods (Fig. 10). More recently, Knox (1987, 1993) documents changes in middle to late Holocene channel-forming and extreme floods, and concludes that minor changes in climate produced changes in bankfull discharges ranging from 70 to 130% of present-day values.

Another important approach is illustrated by Probst (1989), who examines the spatial structure of runoff fluctuations from larger European rivers during the historical period, and shows periods with positive and negative deviations from long-term averages. Most commonly all rivers varied in-phase, but at other times runoff regimes of rivers within present-day oceanic and continental regimes (Rhone, Loire, Garonne, Seine and Rhine) were out-of-phase with rivers in the core Mediterranean region of southern Europe (Ebro, Guadalquivir and Po). From these relationships, it might be envisaged that discharge regimes in the two areas should respond simultaneously to global climate change, but in different directions due to the regional manifestations of changes in global atmospheric circulation. Similar in-phase and out-of-phase relationships between regional precipitation changes and changes in atmospheric circulation are well documented (e.g. Lau, 1988; Hurrell, 1995; Rogers, 1997; Dai *et al.*, 1997).

In aggregate, these studies serve to illustrate four points that are of particular relevance. First, changes in atmospheric circulation through time have a direct impact on the magnitude and frequency of floods. Second, these changes are not directly proportional to increases or decreases in precipitation, but are instead buffered by other variables that influence runoff rates, especially vegetation. Third, flood regimes are especially sensitive to changes in climatic inputs, such that small changes in climate can significantly increase or decrease flood magnitudes. Finally, responses of flood regimes to climate change should be geographically circumscribed since global changes in circulation may result in simultaneous changes in discharge regimes everywhere, but some regions will be out-of-phase with others in terms of the direction of change.

## *Sediment supply*

Routing of sediments in river systems is a topic that resides at the interface between studies of modern processes, Quaternary landscape evolution and development of the pre-Quaternary stratigraphic record. Hovius & Leeder (1998) note that sedimentary basins record erosion of the continents, whereas drainage networks are the

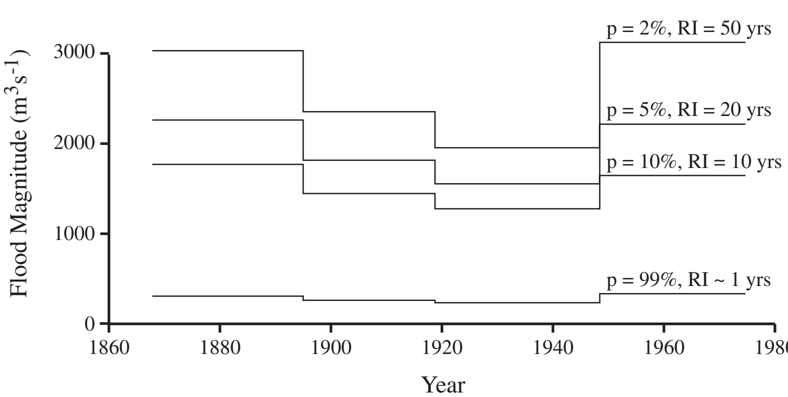



**Fig. 10.** Changes in flood magnitudes due to changes in atmospheric circulation, Mississippi River at St. Paul, Minnesota, USA (after Knox, 1983). Data represent a time series of all floods that exceeded 368 $m^3 s^{-1}$, and was disaggregated into time periods defined by dominant types of atmospheric circulation (meridional vs. zonal). Flood probabilities were then calculated for each period, with p = the probability that a flood with a given magnitude will be equalled or exceeded in any given year, and RI = average recurrence interval.

'negative imprint' of this same record, and their existence must be inferred from stratigraphic data. Especially pertinent, then, are the allogenic controls on erosion from upland source terrains and delivery to depositional basins.

There is a long history to discussions of climatic controls on sediment supply, with studies by Langbein & Schumm (1958) and Fournier (1960) among the first to develop quantitative relationships between climate, erosion and sediment yield. Langbein & Schumm (1958), in particular, indicate that sediment yield increases with increasingly effective precipitation through the arid to semi-arid transition, then decreases towards more humid climates due to the increasing importance of vegetation. Compilations by Walling & Webb (1983, 1996) suggest the Langbein & Schumm (1958) curve may be applicable for the midcontinent USA where it was derived, but when other climate regimes, especially subtropical and tropical, are taken into account then sediment yield increases with precipitation at values greater than ~ 1000 mm $yr^{-1}$. Because of the mitigating effect of vegetation in each of these relationships, they are most applicable for that part of Earth history when land plants have been common. In the absence of land plants, sediment supply would most likely increase as precipitation increases (e.g. Schumm, 1968b).

There is an equally long history to discussions of relationships between sediment yield and measures of relief or rates of uplift. Indeed, Walling & Webb's (1983, 1996) compilations show the highest rates of sediment yield in orogenic belts that surround the Pacific Ocean. Moreover, specific sediment yields (yields per unit area) decrease as drainage area increases, which emphasizes the importance of small and steep catchments for sediment production. Milliman & Syvitski (1992), for example, show that up to 80% of sediments delivered to the oceans is derived from small catchments within active orogens, and suggest that sediment yield is a log-linear function of drainage area and maximum elevation.

Hovius (1998) presents the most comprehensive study of sediment supply to date, based on examination of 97 intermediate and large drainage basins around the world. He indicates that specific sediment yield can be estimated using the following empirical relationship:

$$\ln E = -0{\cdot}416 \ln A + 4{\cdot}26 \times 10^{-4} H + 0{\cdot}15 T + 0{\cdot}095 T_R + 0{\cdot}0015 R + 3{\cdot}58 \quad (2)$$

where $E$ is specific sediment yield (t $km^{-2}$ $yr^{-1}$), $A$ is drainage basin area ($km^2$), $H$ is mean height (relief) of the drainage basin (m), $T$ and $T_R$ are mean annual temperature and annual temperature range (°C), and $R$ is specific runoff (mm $km^{-2}$ $yr^{-1}$). This equation explains only 49% of the observed variance and, although vegetation was not considered, Hovius suggests that inclusion of other variables does not substantially improve the explanatory power. Hovius (1998) also uses Milliman & Syvitski's (1992) larger data set to show that specific sediment yield varies with tectonic setting and rates of rock uplift, with contractional orogens far outpacing other settings, and low-relief cratons yielding very low values.

To the extent that drainage area, tectonic setting, average rates of uplift and total relief remain relatively constant for individual river systems over time-scales of $10^3$–$10^5$ years, Hovius' (1998) equation suggests significant variations in specific sediment yields with changes in climatic parameters such as temperature and runoff. However, Leeder *et al.* (1998) model erosion rates and discharge regimes during the late Pleistocene full-glacial and the Holocene, contrasting the USA Basin and Range province with the Mediterranean region, and in doing so illustrate a key point that deserves emphasis. In much the same way as changes in discharge regimes can vary regionally, Leeder *et al.* (1998) show the same global climate change can produce out-of-phase responses for the Basin and Range and Mediterranean regions, when measured in terms of runoff and sediment yield, sediment flux to the depositional basin, relative changes in lake or sea-level and development of a stratigraphic record (Fig. 11). In addition to the above, an important factor that cannot be gleaned readily from the present interglacial world is the high rates of erosion and sediment production that accompanies widespread glaciation (e.g. Hallet *et al.*, 1996).

### *Sediment storage en-route to depositional basins*

At any point in time, there is a disparity between the liberation of sediments from uplands and sediment yields past some point in the drainage network. The difference is related to sediments that are temporarily stored in the drainage network as colluvial, alluvial fan and fluvial deposits. This amount can be considered in the context of the sediment delivery ratio (Walling, 1983),

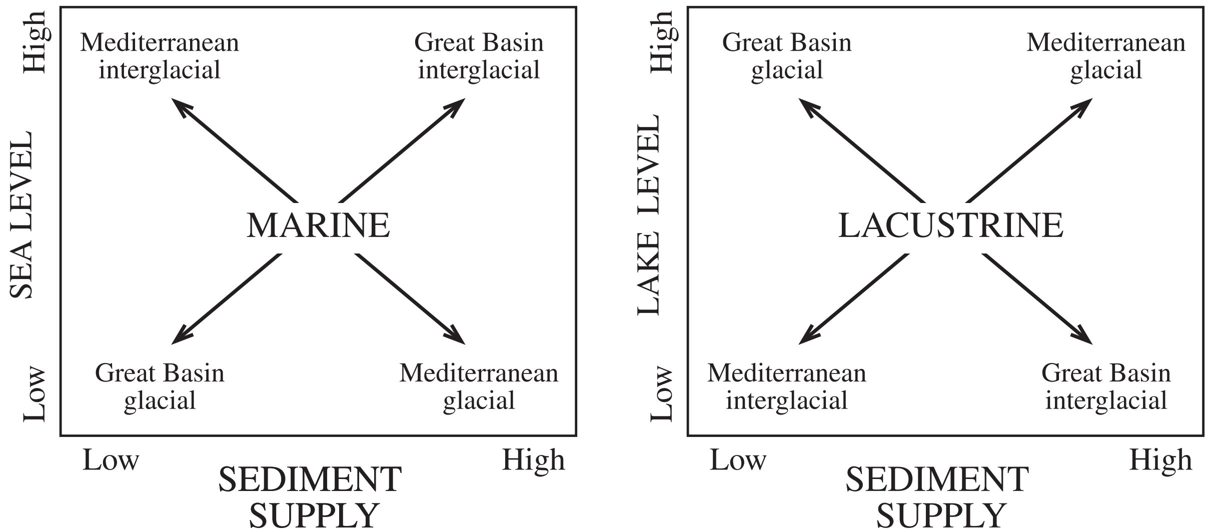



**Fig. 11.** Model for changes in sediment supply in Mediterranean vs. USA Great Basin climates during glacial and interglacial periods. Diagram on left illustrates conditions that might apply to a marine basin, whereas diagram on the right illustrates conditions for a lacustrine basin. Both diagrams illustrate a succession of possible out-of-phase responses. After Leeder *et al.* (1998).

defined as $S_d = S_y/ER$, where $S_y$ is sediment yield past a given point in the drainage network, and $ER$ equals total erosion from the drainage basin above that point.

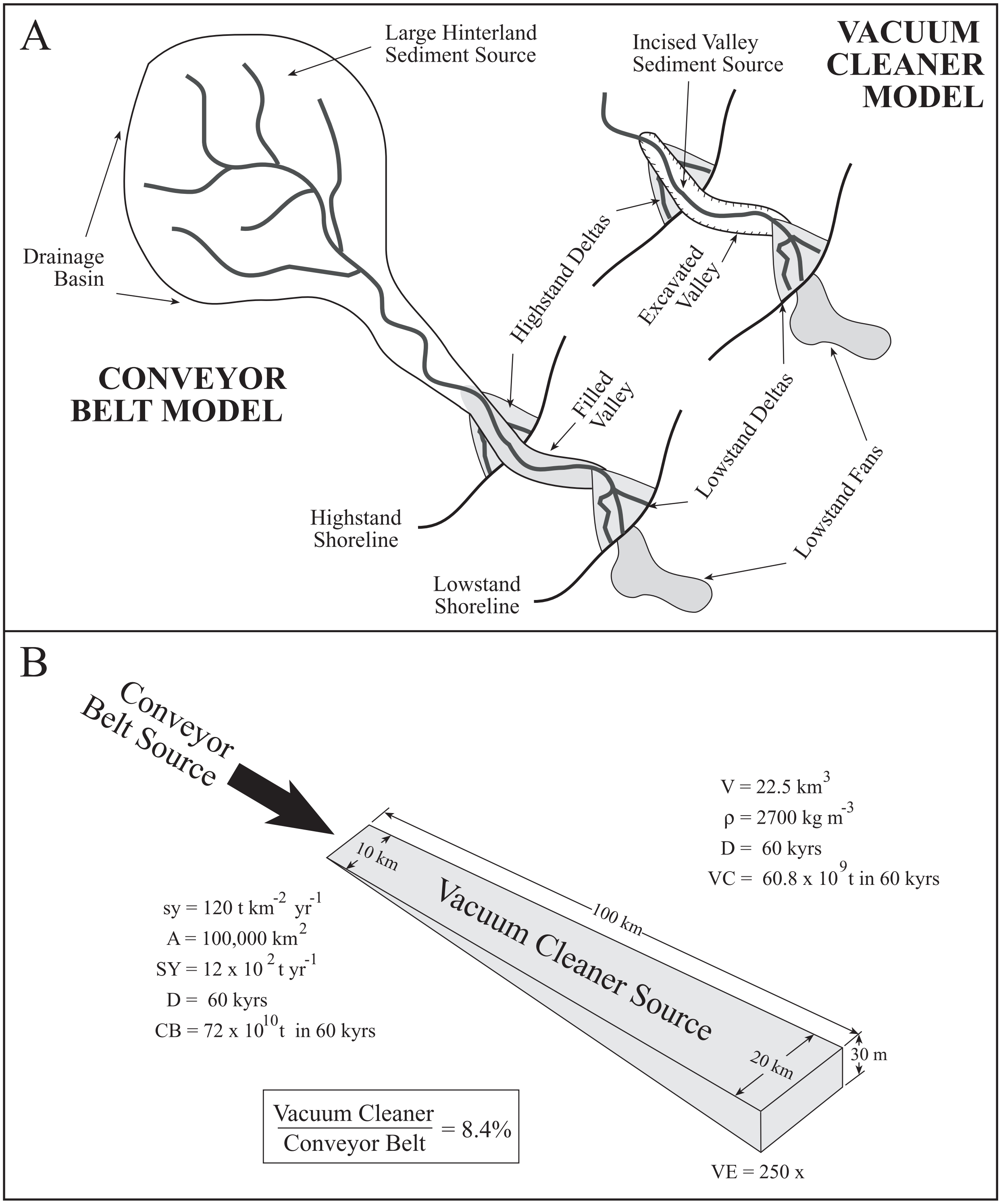
Compilation of sediment delivery ratios from a variety of settings indicates that they typically decrease as drainage area increases and stream gradients decrease, with very high values for very small drainage basins, and values as low as 0·1–0·2 for drainage areas $> 1000\ \mathrm{km}^2$ (Walling, 1983). Data from modern settings are strongly biased by human activities that have increased rates of erosion, increased sediment storage within small catchments and trapped sediments within artificial reservoirs. For example, Meade *et al.* (1990) note that roughly 10% of all sediment eroded from the conterminous USA presently reaches the ocean basins, but up to 20% of all sediment is trapped by reservoirs constructed on a few large rivers. As a result, continent-wide sediment delivery of 20–30% ($S_d = 0{\cdot}2$–$0{\cdot}3$) or more may be more representative.

Changes in the sediment delivery ratio can significantly imprint the stratigraphic record. Hovius' (1998) view that drainage networks are the negative imprint of basin filling would correctly imply that basin margin sediment delivery over geological time must approach 100%. It follows that over shorter periods of time, individual segments, or perhaps entire drainage networks, must have delivery ratios greater than average values, and must in some cases be greater than 1 during periods when previously stored sediments are flushed basinward.

**Fig. 12.** (A) Contrasts between 'vacuum cleaner' vs. 'conveyor belt' models for sediment supply to basin margins. The vacuum cleaner derives all sediment from more distal parts of the basin by means of excavation of a valley at the basin margin, whereas the conveyor belt relies on sediment delivery from a large hinterland drainage network, and does not require deep incision with complete sediment bypass during sea-level fall. (B) Calculation of relative contribution of vacuum cleaner vs. conveyor belt model, using the palaeovalley fill from the last glacial cycle of the Colorado River, Texas, as an example. Dip and strike dimensions and thickness of palaeovalley fill based on data presented in Blum (1993) and Aslan & Blum (1999), with data on sediment supply taken from Hovius (1998). For vacuum cleaner calculation, V = volume of palaeovalley fill, ρ = average density of earth materials, D = duration of glacial cycle falling stage and lowstand (kyr), and VC = mass of sediments produced by complete excavation of the valley over duration D. For conveyor belt calculation, sy = specific sediment yield (tons $\mathrm{km}^{-2}\,\mathrm{yr}^{-1}$), A = drainage area ($\mathrm{km}^2$), SY = total sediment yield from drainage network (t $\mathrm{yr}^{-1}$), D = as above. For both calculations, CB = mass of sediments delivered from the conveyor belt during time interval D.

*Role of sea-level change*

The following discussion asks a simple question – exactly how does sea-level change affect a fluvial system? To begin, it is difficult to envisage how sea-level or base-level change can have a significant impact on discharge regimes or liberation of sediments, since these are mostly upstream-controlled. Nevertheless, since much of the literature implies relative sea-level



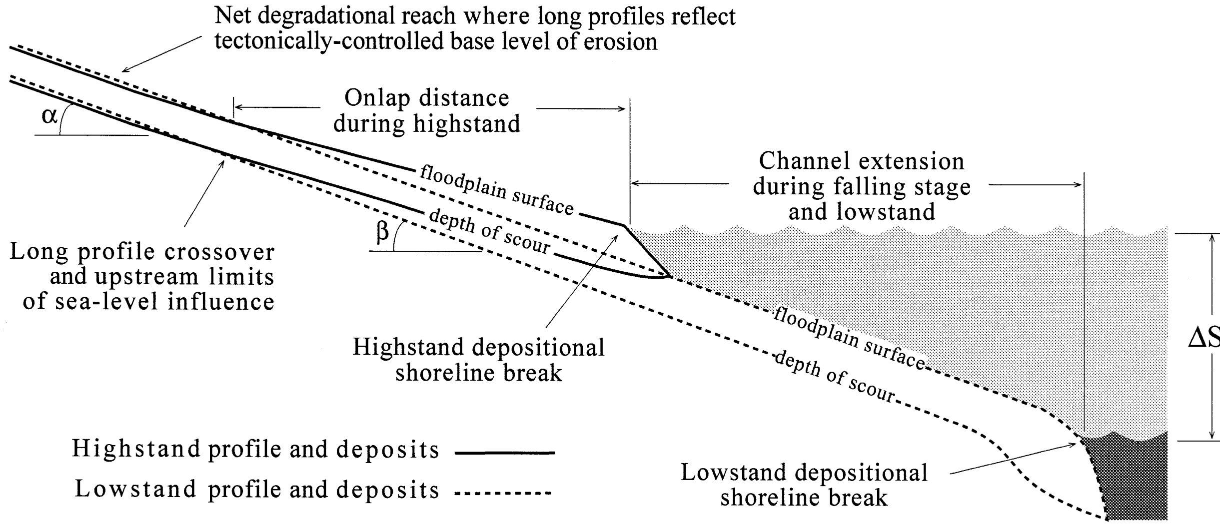



**Fig. 13.** Definition sketch for fluvial response to sea-level change along a continental margin with a distinct highstand depositional shoreline break. Diagram illustrates concepts of channel extension during sea-level fall and lowstand, vs. upstream limits of onlap during sea-level rise and highstand. Also, average slope of the channel above the limits of sea-level influence is shown as changes, and reflect a long-term tectonically controlled base-level of erosion.

controls over sediment supply, it is important to first look at what sea-level change does not do.

Nowhere is confusion more apparent than in sequence-stratigraphic models for 'incised valleys' (hereafter valleys or palaeovalleys, since all valleys are incised, by definition) that assume relative sea-level fall produces incision, and an upstream-propagating wave of stream rejuvenation, which produces sediments that entirely bypass the coastal plain and newly emergent shelf to provide a critical volume of sediment for systems tracts further basinward. This is referred to here as a 'vacuum cleaner' model for sediment supply, as contrasted with a 'conveyor belt' model, where sediments are continuously delivered to the basin margin from a large inland drainage (Fig. 12A). Figure 12(B) illustrates these models with reference to the Colorado River, Texas Gulf Coast (USA), and shows that the volume of sediments produced by complete 'vacuum cleaner' excavation of a valley during the last glacio-eustatic falling stage and lowstand would be an order of magnitude less than the total volume delivered by the 'conveyor belt' during that same interval of time.

The 'vacuum cleaner' model has intellectual roots in Fisk (1944), yet subsequent work in the Lower Mississippi Valley clearly shows that complete sediment bypass was not the case (e.g. Saucier, 1994, 1996; Blum *et al.*, 2000). The same can be said for other large fluvial systems of the Gulf Coastal Plain of the USA (Blum *et al.*, 1995; Blum & Price, 1998), for large rivers of southern Europe such as the Rhone and Po (Mandier, 1988; Amorosi *et al.*, 1999), the Rhine–Meuse system in north-west Europe (e.g. Pons, 1957; Berendsen *et al.*, 1995; Kasse *et al.*, 1995; Törnqvist, 1998) and the Nile (Stanley & Warne, 1993). In fact, it is difficult to find an example where complete sediment bypass in response to base-level fall has actually been documented on Quaternary river systems that have significant hinterland drainage areas and discharge to a depositional basin. Hence, to the extent that Quaternary systems provide ground-truth for sequence-stratigraphic models, the body of evidence actually points in a different direction. These conclusions are supported by modelling results of Leeder & Stewart (1996), which demonstrate that high rates of sediment supply can overcome base-level fall, and result in progradation without significant incision.

Given a continental margin setting with a pronounced depositional shoreline break (Fig. 13), and a shelf that is as steep or steeper than the coastal plain, why should rivers not completely bypass sediments during sea-level fall? Simply put, given the influx of sediments from the 'conveyor belt', complete sediment bypass of a coastal plain and shelf during sea-level fall would require significant downstream increases in slope and stream power ($\beta > \alpha$ in Fig. 13), and corresponding downstream increases in rates of sediment transport. In most cases, some incision through a highstand depositional shoreline break takes place as the channel extends across the newly exposed shelf (Posamentier *et al.*, 1992; Blum, 1993; Talling, 1998; Törnqvist *et al.*, 2000), with corresponding net removal of previously stored sediment, but it seems unlikely that the depth of incision will produce slopes that exceed those further upstream from the limits of sea-level influence (i.e. $\beta > \alpha$ is not likely). Hence if the valley upstream from the limits of long profile adjustment aggrades due to sediment overloading, or laterally migrates due to equilibrium conditions, this mode of behaviour is simply translated further basinward. Periods of complete sediment bypass should only occur when sediment supply from upstream sources decreases relative to maximum sediment transport rates, such that the valley further upstream is also incising.

On the other hand, sea-level rise along a continental margin with the configuration described above (Fig. 13) results in channel shortening, decreases in the distance over which sediments can be stored and, in most cases, flattening of channel slope. Discharge is conserved, but reductions in slope will result in corresponding downstream decreases in stream power and sediment transport rates. These conditions result in net valley aggradation that in turn may play a significant role in adjustments of channel geometry and depositional style (discussed more fully below). However, even within long periods of overall net valley aggradation driven by sea-level rise (time-scales of $10^3$–$10^4$ years), significant intervals of incision and/or sediment bypass can occur if sediment supply decreases relative to stream power, as shown by Blum (1990, 1993) for the Colorado River of the Texas Gulf Coast (USA), Törnqvist (1998) for the Rhine–Meuse and Blum *et al.* (2000) for the Lower Mississippi Valley.

Turning back to the original question, the fundamental responses to sea-level change appear to be channel extension or shortening, coupled with changes in the elevation of channel bases and floodplain surfaces, in order to keep pace with a shoreline that is advancing or retreating and changing its elevation. All other adjustments take place within this context, and should be regarded as nondeterministic, since they depend on alluvial valley, coastal plain, shoreface and shelf gradients (see Fig. 3), discharge and sediment supply from the drainage network and local physiographical factors. With respect to the latter, Leckie (1994) provides an example from the Canterbury Plains of New Zealand, where incision has occurred during Holocene sea-level rise because of steep alluvial plain gradients in combination with high-energy wave attack. Moreover, Schumm (1993), Wescott (1993) and Ethridge *et al.* (1998) note that fluvial systems possess several degrees of freedom by which they can adjust channel parameters to changes in base level, a discussion not repeated here.

Many recent papers (e.g. Butcher, 1990; Nummedal *et al.*, 1993; Posamentier & Weimer, 1993; Schumm, 1993; Koss *et al.*, 1994; Merritts *et al.*, 1994; Shanley & McCabe, 1994; Leeder & Stewart, 1996) have emphasized the issue of how far inland sea-level actually controls fluvial incision and aggradation. Again, Fisk's (1944) work in the Lower Mississippi Valley has been extremely influential, postulating eustatic control more than 1000 km upstream from the modern shoreline. This view has been challenged by more recent studies in the same area (e.g. Saucier, 1994, 1996) that, in turn, are now cited as critical evidence in numerous recent reviews (Shanley & McCabe, 1994; Emery & Myers, 1996; Miall, 1996, 1997; North, 1996). Shanley & McCabe (1993) propose strong generalizations, suggesting that sea-level control typically extends 100–150 km updip from the coeval shoreline. However, in most of these studies it is not clear how the landward limit of sea-level control is actually defined.

For this paper, and for the purposes of discussion and comparison, the landward limit is defined as the upstream extent of coastal onlap due to sea-level rise (see Fig. 13). In late Quaternary contexts, this consists of the intersection between the modern floodplain and the floodplain surface from the Last Glacial Maximum (~ 20 ka), and is not necessarily the same as the landward extent of incision due to sea-level fall (cf. Ethridge *et al.*, 1998). By contrast, the basinward limit of sea-level influence is defined as the maximum distance of channel extension and delta progradation during sea-level fall. Table 1 summarizes a variety of data from fluvial systems from Europe and the Gulf Coastal Plain of the USA. These data suggest the landward limit of onlap due to sea-level rise correlates to hinterland sediment supply, and is inversely related to the gradient of the onlapped floodplain surface. Accordingly, this distance is highly variable and ranges from at least 300–400 km

**Table 1.** Relationship between drainage area, onlapped lowstand floodplain gradient and aggradation distance for six late Quaternary fluvial systems. Channel extension and onlap distances are measured with respect to the average highstand shoreline. Data from the Rhone taken from Mandier (1988) and Tesson *et al.* (1993).

| River system | Drainage area ($km^2$) | LGM floodplain gradient ($cm\ km^{-1}$) | LGM channel extension (km) | Holocene onlap distance (km) |
|---|---|---|---|---|
| Nueces (Texas, USA) | 40 000 | 50 | > 200 | 40 |
| Trinity (Texas, USA) | 50 000 | 20 | 150 | 90 |
| Rhone (France) | 99 000 | 130 | 50–60 | 100 |
| Colorado (Texas, USA) | 100 000 | 80 | 100–120 | 90 |
| Rhine–Meuse (The Netherlands) | 254 000 | 25 | 800 | 150 |
| Mississippi (Louisiana, USA) | 3 344 000 | 15 | 150 – 200* | > 300 – 400 |

* The present birdfoot delta is also extended close to this amount.

for the low-gradient, high-sediment-supply Mississippi River, to ~40 km for steep-gradient, low-sediment-supply systems like the Nueces River of the Texas Gulf Coastal Plain. Channel extension during lowstand reflects shelf physiography, and ranges from 800 km or so for the Rhine, 100–200 km for rivers of the Texas Gulf Coastal Plain (Colorado, Trinity, Nueces), to very short distances for the Mississippi, since it now discharges to the shelf edge. The Rhine is a special case, since during the last lowstand it flowed across the very low-gradient North Sea, then was diverted south-westward through the Strait of Dover and discharged to the Atlantic (Gibbard, 1995; Bridgland & D'Olier, 1995).

### *Role of accommodation*

Few would argue that the concept of accommodation plays a critical role in sedimentology in the new millennium. This section again asks a basic question: what exactly is accommodation?

To begin, many workers recognize that Jervey's (1988) definition of accommodation uses a 'stratigraphic' (as opposed to 'geomorphic') definition of base level that can be traced to Barrell (1917), Sloss (1962) and Wheeler (1964) among others. These differing definitions for base level are not trivial. The geomorphic view defines the lower limits to erosion, and extends upstream from sea-level into the subaerial landscape as a 'base level of erosion' that defines the graded longitudinal profile (see Bull, 1991), but has no significance offshore beyond the fluvial system. By contrast, the stratigraphic definition defines the upper limits to deposition, and was intended to be used in marine systems as well. However, as Wheeler (1964) noted, stratigraphic base level does not control anything – it is not a cause but an effect. In the fluvial context, stratigraphic base-level changes in response to changes in geomorphic base level (lake or sea-level), climate-related and geomorphic parameters (flood magnitudes, sediment supply, channel geometries, etc.) and rates of uplift or subsidence. It follows from the above that accommodation is not exactly a control either. Instead, increases or decreases in accommodation are at least in part a response to changes in geomorphic base level, which defines the lower limits to accommodation, and in fluvial contexts the upper limits are defined by changes in discharge regimes and sediment supply as they control equilibrium floodplain heights.

It also seems that accommodation, as it is commonly used, somewhat imprecisely mixes processes that operate over a range of rates and temporal scales; it is difficult to reconcile the time-scales over which sediments are deposited in the first place, whether or not those deposits will be preserved in the stratigraphic record, and the manner in which ancient alluvial successions are interpreted in terms of changes in accommodation or an accommodation/sediment supply ratio. It may be more precise to consider these issues in much the same manner as Kocurek & Havholm (1993) and Kocurek (1998), who differentiate 'accumulation' vs. 'preservation' space in the context of aeolian sequences. In a fluvial context, accumulation space ('process-scale' or real-time accommodation) would be the volume of space that can be filled within present process regimes, and is fundamentally governed by the relationship between stream power and sediment load, and how this changes in response to geomorphic base level. However, preservation in the stratigraphic record occurs when subsidence lowers these deposits below possible depths of incision and removal. As accumulations subside towards this depth, the probability of preservation increases, but it is only assured when this depth is reached. Hence preservation space (net accommodation?) lies below the maximum depths of incision. For a continental margin, like that shown in Fig. 13, preservation space would lie below the lowstand longitudinal profile.

Accommodation as a term in the vocabulary of sedimentary geology is certainly here to stay. However, it might be most useful to use accommodation explicitly in the same manner as Kocurek & Havholm (1993) and Kocurek (1998) use accumulation space, and future discussions should be explicit about deposition- vs. preservation-scale processes, since they operate at different rates, as well as over different time-scales, but ultimately result in what is preserved in the stratigraphic record. While accommodation remains a useful concept, the stratigraphic concept of base level is the same as the upper limits of accommodation – it is not a control on anything, has outlived its usefulness, and it should simply be abandoned.

## MAGNITUDE AND FREQUENCY OF CLIMATE AND SEA-LEVEL CHANGE

Fluvial systems respond to climate changes within their catchments and/or relative sea-level changes that occur at their mouths. Over time-scales of interest here, climate change occurs because of global-scale changes in radiation balance and atmospheric or ocean circulation, and sea-level changes have a globally coherent 'eustatic' component. However, global-scale changes are manifested in specific regions in a variety of ways. The following section outlines key elements of climate and sea-level change, as viewed from the Quaternary vs. the Phanerozoic.

### The Quaternary

The Quaternary provides a unique perspective on the dynamism of the Earth's climate and oceanographic systems, and has been the subject of intense study over the past three decades. Recent publications that summarize records and mechanisms of Quaternary climate and/or sea-level change include Crowley & North (1991), Broecker (1995), Pirazzoli (1996), Lowe & Walker (1997) and Bradley (1999).

The most significant development in Quaternary palaeoclimatology over the last 3–4 decades has been the new picture of glacial–interglacial cycles that emerged from studies of oxygen-isotope records in deep-sea sediments (e.g. Shackleton & Opdyke, 1973; Imbrie *et al.*, 1984; Chappell & Shackleton, 1986; Shackleton, 1987). Isotope records are responsible for the widespread acceptance of the Milankovitch theory of climate change (Hays *et al.*, 1976; Imbrie & Imbrie, 1979), and provide a model for major changes in global climate and ice volume, as well as the corresponding eustatic component of sea-level over the last several millions of years (see the recent review by Pillans *et al.*, 1998). There has been a high-amplitude 100-kyr periodicity to full glacial–interglacial cycles during the middle to late Pleistocene, but lower amplitude 40-kyr cycles dominated prior to that. One important implication pertains to the concept of 'average conditions', since only a small percentage of the last $10^6$ years resembled full interglacial (present-day) or full glacial (20 ka) conditions (with eustatic sea-level at −120 to −130 m). As noted by Porter (1989), up to 80% of any middle to late Pleistocene 100-kyr glacial cycle witnessed global temperatures that were cooler than full interglacial conditions, but not as cold as a full glacial, and eustatic sea-level was at −15 to −85 m (Fig. 14A).

More recently, work on ice cores and the marine record shows that significant climate changes at scales of $10^3$ and $10^4$ years are superimposed on the 100-kyr glacial–interglacial cycles discussed above (e.g. Johnsen *et al.*, 1992; Bond *et al.*, 1993, 1997; Grootes *et al.*, 1993; Bond & Lotti, 1995; Behl & Kennett, 1996), and provides an exciting picture of the complexity of the last glacial, as well as the Pleistocene–Holocene transition. 'Dansgaard–Oeschger cycles' (D-O cycles), for example, consist of abrupt warming over a period of decades to centuries, followed by cooling trends that last 1–2 kyr. D-O cycles are themselves bundled together into cooling trends that last 10–15 kyr ('Bond cycles'), culminate with massive iceberg discharges and deposition of large quantities of ice-rafted debris into the North Atlantic ('Heinrich events'), and are followed by abrupt warming (Fig. 14B). The causal mechanisms for these cycles are not completely understood, but they must in some way reflect the internal dynamics, and feedback within, the coupled atmosphere–cryosphere–ocean system (Bradley, 1999), and their effects are propagated around the ocean basins via

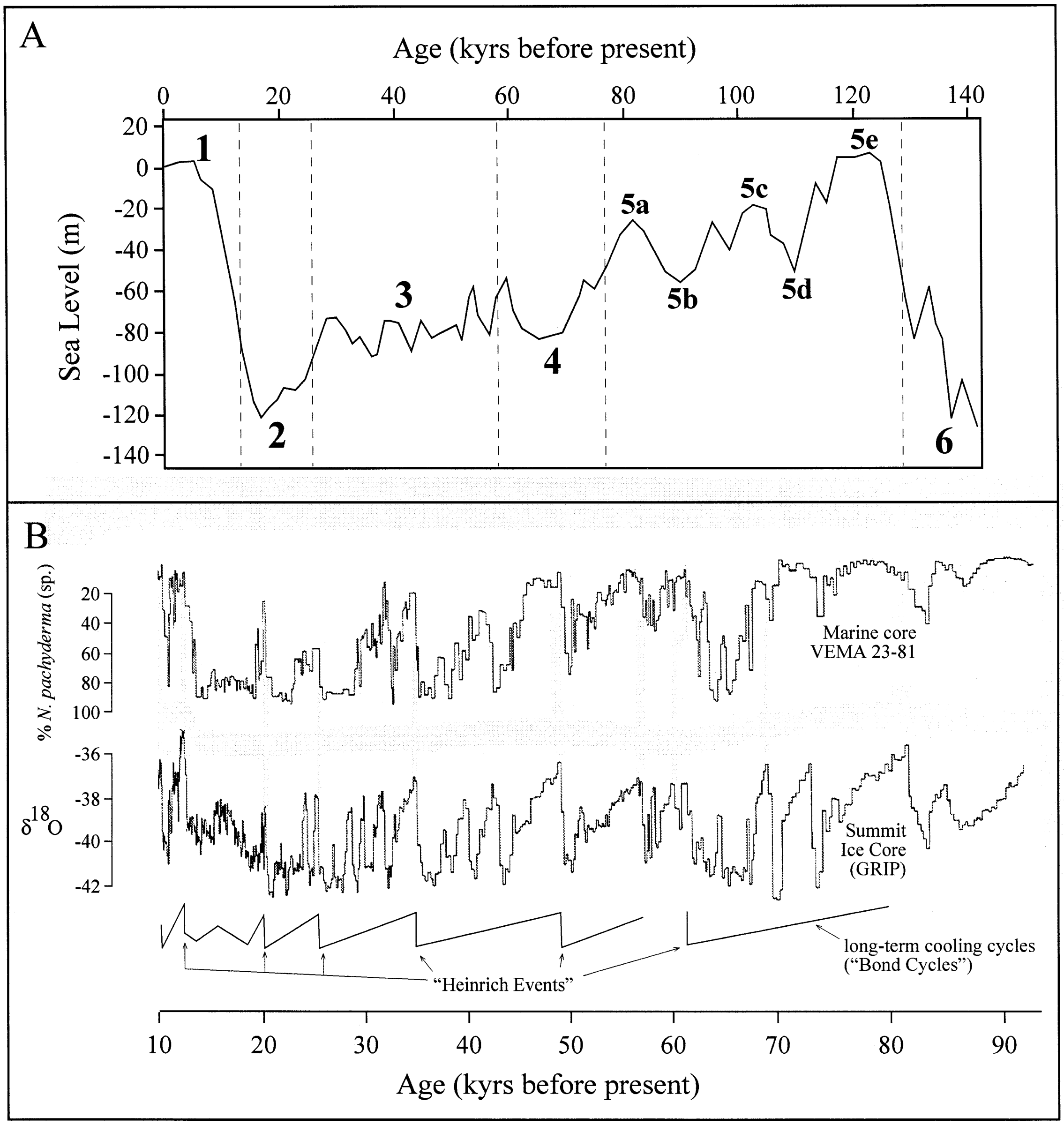



**Fig. 14.** (A) Eustatic sea-level curve based on precision U–Th dating of corals from Huon Peninsula, Papua New Guinea (after Chappell *et al.*, 1996), with oxygen isotope stages (boundaries shown by dashed lines). (B) Comparison of the proportion of the planktonic coldwater foraminifera *Neogloboquadrina pachyderma* (sinistral) in marine core VM 23–81 (after Bond *et al.*, 1993).

impacts on the large-scale thermohaline circulation and formation of North Atlantic deep water (Broecker, 1997).

Regional climate changes are more complex than the global picture due to the way global changes in atmospheric circulation are manifested in different regions; for the last 20 kyr, many regions show significant departures in magnitude and/or direction from global climatic trends (COHMAP Project Members, 1988; Wright *et al.*, 1993; Kutzbach *et al.*, 1997). Local sea-level changes also most commonly depart from eustasy in both rate and magnitude, and sometimes in direction, due to local to regional tectonics, mantle response to accumulation and melting of ice sheets, glacio- and hydro-isostatic deformation of coastlines, and migration of ocean water mass to geoidal lows (Tushingham & Peltier,

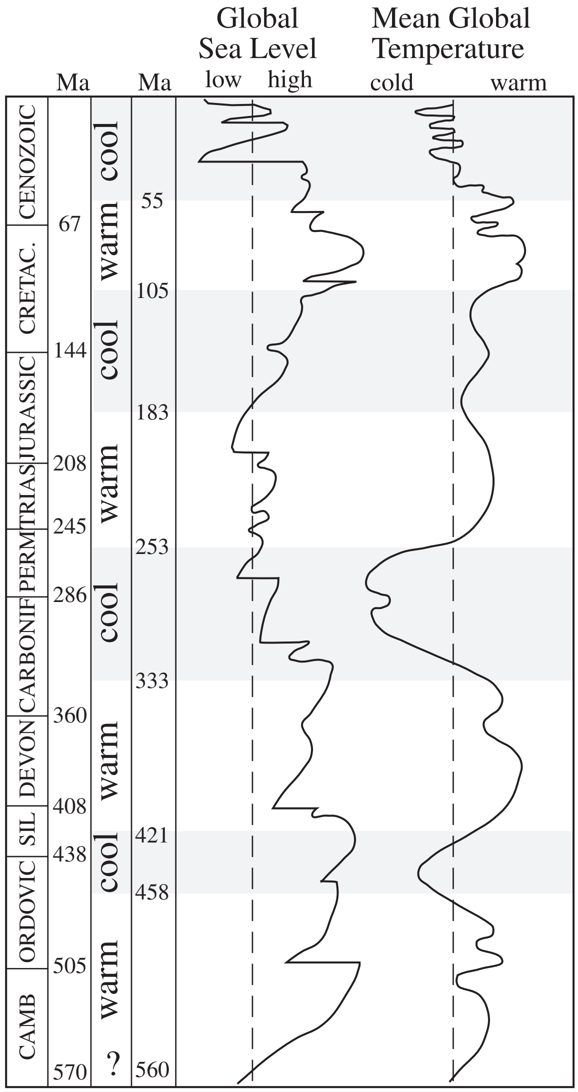



**Fig. 15.** Estimated eustatic sea-level and global temperature changes through the Phanerozoic, illustrating warm and cool modes. Adapted from Frakes *et al.* (1992).

1992; Lambeck, 1993; Fleming *et al.*, 1998; Peltier, 1998). Strong eustatic signatures may be present at some localities, but all sea-level change is essentially relative.

## Pre-Quaternary

A broad range of climate and sea-level change is evident from the Phanerozoic record (Frakes, 1979; Crowley & North, 1991; Frakes *et al.*, 1992; Parrish, 1998), and only small parts of this record may resemble the Quaternary 'ice-house'. Perhaps the most important distinction within the Phanerozoic is between what Frakes *et al.* (1992) refer to as alternating 'warm' and 'cool' modes with average durations of 50 Myr, and the long-wavelength cycles of relative sea-level change evident in Haq *et al.* (1987, 1988; Fig. 15). For the purposes of this paper, such climate changes are initiated by the agglomeration and break-up of supercontinents, and/or by migrations of landmasses into different latitudinal belts, and are beyond the time-scales of interest here.

Of great interest, however, are the externally forced cyclical climate and sea-level changes that might go on within these longer-term modes. For example, there is little reason to believe that Milankovitch-scale radiation-forced changes have not been significant throughout the Phanerozoic (Barron & Moore, 1994), even though their periodicity, amplitudes and phase relations may have changed. Indeed, calculations by Berger *et al.* (1989) and Berger & Loutre (1994) show that wavelengths of the present 100 kyr eccentricity cycle have varied little since 500 Ma, whereas the obliquity (currently 41 kyr) and precessional (currently 23 and 19 kyr) components were shorter at 500 Ma (~ 30 kyr, 19 and 16 kyr, respectively) due to changes in Earth–Moon distance and day length. Even though Milankovitch-scale changes were present throughout the Phanerozoic, they operated within a context defined by plate tectonics and long-term evolution of the biosphere. Accordingly, this type of external forcing should have different manifestations in cold modes, when continental landmasses were located in more polar latitudes and glaciation was widespread, than in warm modes when evidence for significant glaciation is lacking (Frakes *et al.*, 1992).

Two caveats should be kept in mind. First, Broecker (1997) stresses the possible amplification of relatively limited orbital forcing by changes in the ocean thermohaline circulation during considerable parts of Phanerozoic history. Second, and equally important, is the amplification or suppression of flood regimes that occurs even with minor changes in climate, and the manner by which such changes are manifested in channel geometry, fluvial depositional styles, sediment transport rates and changes through time in net sediment storage. The key question is how to recognize pre-Quaternary fluvial responses to climate change, sea-level change, or some combination of the two, and disentangle them from tectonic effects or autogenic processes.

## FLUVIAL RESPONSE TO CLIMATE AND SEA-LEVEL CHANGE: RECOGNITION

Potential fluvial responses to climate and sea-level change vary by position within the system, and the ability to store sediment over various lengths of time. At one extreme are the high stream powers and high sediment delivery ratios common in the upper reaches of drainage networks. To the extent that these settings often possess bedrock channels with discontinuous floodplains, and short residence times for sediment as a whole, there is little potential for records of fluvial response to climate change that span significant lengths of time ($>10^4$ years). By contrast, lower-gradient mixed bedrock/alluvial valleys with significant drainage areas ($>10^3$ km$^2$) commonly have continuous floodplains and low sediment delivery ratios. These settings typically show long-term rates of incision that may outpace rates of rock uplift (Hovius, 1999), and serve as the 'conveyor belts' for sediment delivery to basin margins, with sediment residence times measured in multiples of $10^4$–$10^6$ years. As a result, mixed bedrock/alluvial valleys commonly contain records of fluvial landscape evolution over late Cenozoic time-scales, but have little to no actual preservation space.

Alluvial valleys within subsiding basins represent the opposite extreme, and provide the critical link between Quaternary and ancient systems. Present-day continental interior basins occur within tectonically active drylands, where drainage integration has not proceeded to the extent that fluvial systems reach marine basins, or in subsiding reaches of fluvial systems that are en-route to a marine basin. Rift and pull-apart basins of the arid western USA provide examples of the former, whereas the Himalayan foreland provides an example of the latter. Continental margin systems are numerous, but much of the present-day landscape is drained by a relatively few large, long-lived rivers (e.g. Potter, 1978) that discharge to passive margins or flooded forelands, whereas smaller fluvial systems typically drain to rifted or sheared margins. Sediments delivered to basins enter preservation space when they subside below maximum depths of incision, but until that time they can be remobilized by a variety of processes, and transported out of the basin (continental interior) or elsewhere within the basin (both continental interior and continental margin settings).

### Types of response

Fluvial responses to climate and sea-level change can be disaggregated into stratigraphic, morphological and sedimentological components. As defined here, stratigraphic responses (stratigraphic architecture) are produced by aggradation due to increasing accumulation space, degradation as accumulation space decreases and lateral migration when there is no change in accumulation space. These types of responses serve to differentiate the larger-scale aspects of alluvial successions that mostly reflect allogenic controls (climate change, sea-level change, tectonic activity). Lower-gradient mixed bedrock/alluvial valleys typically contain flights of downward-stepping terraces and underlying fills that demarcate long-term valley incision punctuated by relatively short periods ($10^3$–$10^4$ years) of lateral migration and perhaps minor aggradation. Fluvial systems in subsiding basins are characterized by just the opposite, long-term net aggradation, punctuated by relatively short periods ($10^3$–$10^4$ years) of incision and/or lateral migration. Stratigraphic responses are perhaps best defined in terms of unconformity-bounded stratigraphic units of varying scale (i.e. the 'allostratigraphic units' of the North American Commission on Stratigraphic Nomenclature, 1983; see also Walker, 1990, 1992; Autin, 1992; Blum & Valastro, 1994); definition of allostratigraphic units is independent of lithological characteristics, but should include: (a) basal erosional unconformities that trace laterally and upwards, eventually truncating older landscape or palaeolandscape elements that are commonly defined by palaeosols; and (b) upper boundaries that represent intact or truncated former floodplain surfaces that are/were defined by palaeosols or coals (Fig. 16).

For lower-gradient mixed bedrock/alluvial valleys, the vertical separation between allostratigraphic units reflects the frequency of responses to allogenic forcing, but also must correlate to long-term rates of uplift; with increasing rates of uplift, the preservation of older units becomes increasingly fragmentary. By contrast, for continental margin systems, vertical separation between allostratigraphic units reflects the frequency of responses, sediment supply and relative sea-level change (eustasy vs. subsidence), and with increasing rates of subsidence, preservation in the stratigraphic record becomes increasingly likely. Two scenarios highlight this relationship. First, contrast slowly subsiding vs.

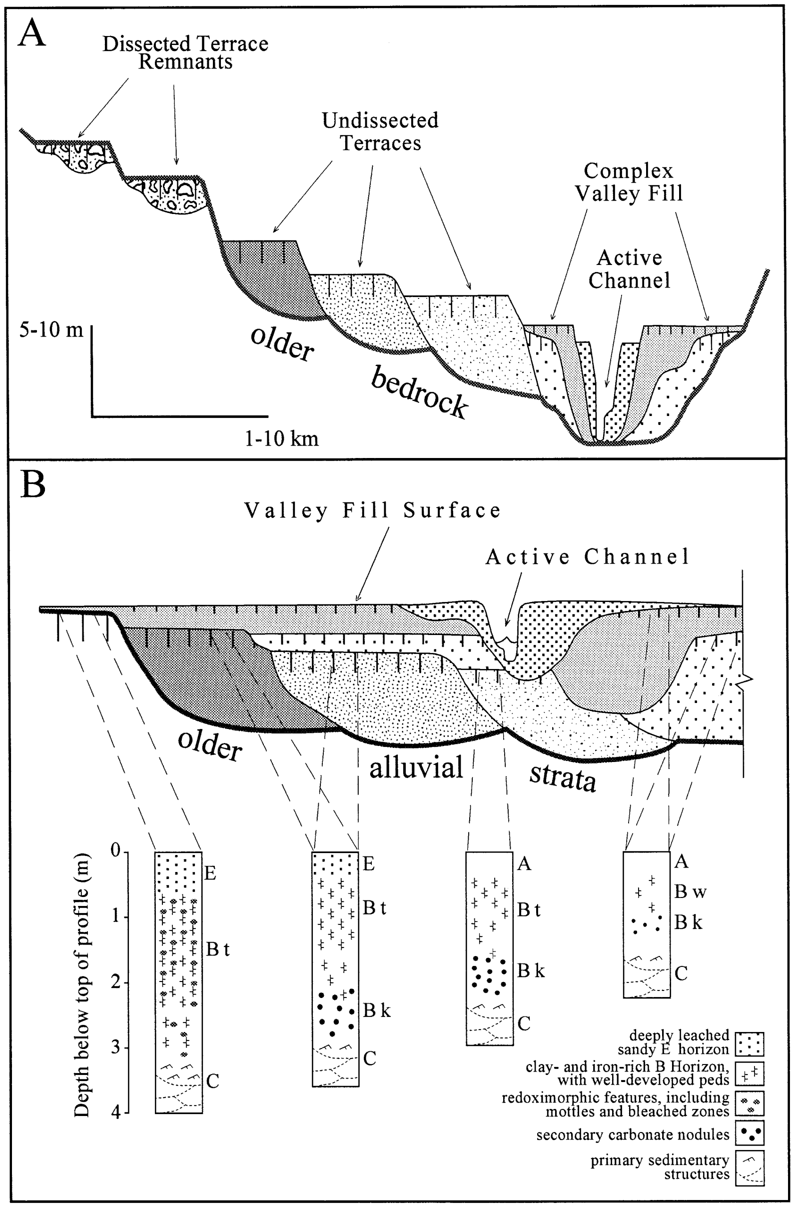



**Fig. 16.** Concept of allostratigraphic units of varying scale (scale bar applies to both diagrams, and vertical hatchures represent soil profiles with the relative degree of soil development represented by length of hatchure). (A) Mixed bedrock/alluvial valley setting, with flights of downward-stepping terrace surfaces and underlying fills, and a complex valley fill with multiple allostratigraphic units. Older and higher terraces are commonly discontinuous and dissected, with significant thicknesses of strata removed; they also may represent long periods of time, and multiple lateral migration, aggradation and incision events within a limited elevation range that are not readily differentiated due to degree of preservation. Younger mostly intact terraces and the complex valley fill may represent the last glacial cycle. (B) Continental margin situation, where sea-level has fallen then risen, resulting in downward-stepping then aggradational successions of allostratigraphic units bounded by palaeosols. Vertical hatchures represent palaeosols and, in each diagram, the solid grey line encloses a single 100-kyr glacial–interglacial cycle. In (B), the relative degree of palaeosol development is shown schematically by the length of the hatchure (sandy facies only, with muddy facies slightly different), and is a proxy for the duration of subaerial exposure before burial. As defined here, unconformities that bound allostratigraphic units are equivalent in concept to the higher-order bounding surfaces of Miall (1996), the basal valley fill unconformity in (B) would be a strongly time-transgressive equivalent to the Exxon sequence boundary as classically defined, and the well-developed alluvial plain palaeosol would be equivalent to the 'interfluve sequence boundaries' discussed by various workers. After the work of Blum & Price (1998) on the Colorado River, Texas (USA).

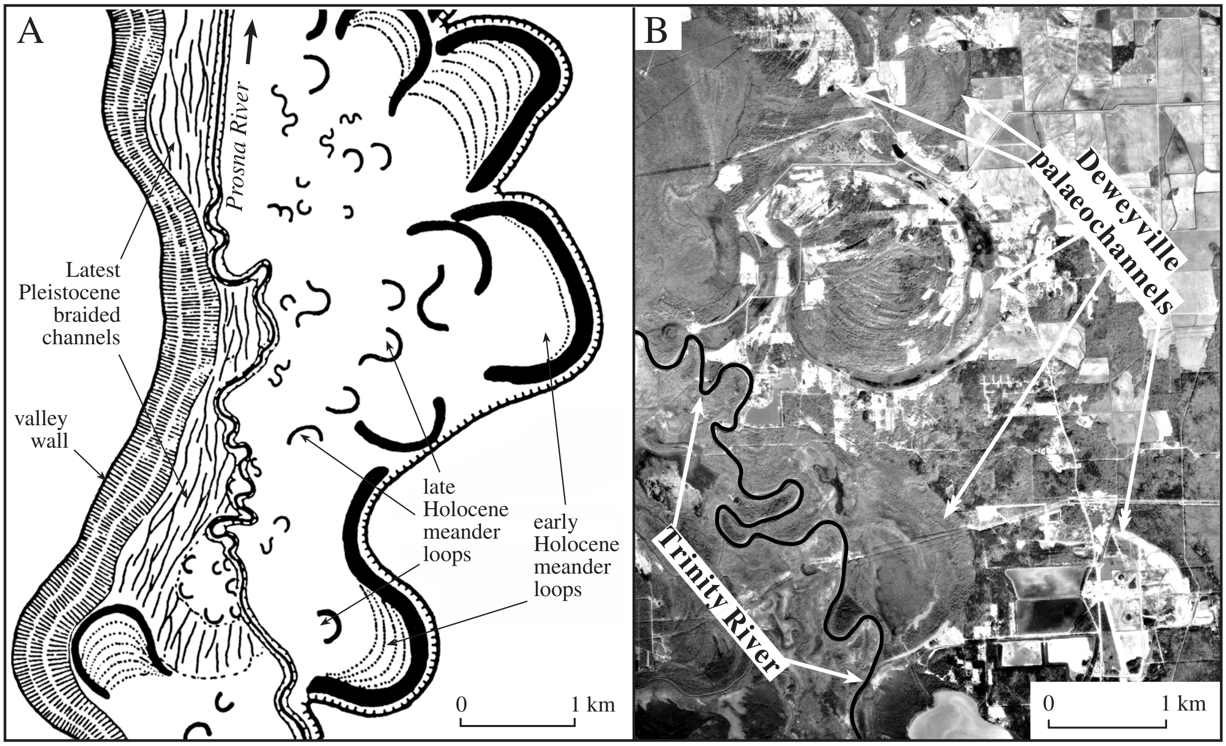



**Fig. 17.** (A) Channel changes in plan-view interpreted for the Prosna River in Poland (after Schumm & Brakenridge, 1987; original from Kozarski & Rotnicki, 1977), with latest Pleistocene braided channels, followed by large early Holocene meandering channels, and small late Holocene meandering channels. (B) Contrast between palaeochannels (Deweyville allostratigraphic units) from the last glacial cycle (OIS 2–4) and the modern channel of Trinity River, Texas Gulf Coastal Plain (see Blum *et al.*, 1995).

rapidly subsiding continental margins during eustatic sea-level fall; relative sea-level fall will be greater along the slowly subsiding margin, hence vertical separation of allostratigraphic units will be significantly greater. Second, during eustatic sea-level rise, relative rates of rise will be significantly greater along the rapidly subsiding margin, as will vertical separation of allostratigraphic units. Indeed, in rapidly subsiding settings, key stratigraphic markers like palaeosols may not form during eustatic sea-level fall due to lack of separation between units, or during eustatic sea-level rise due to continuous deposition and burial.

Morphological responses reflect changes in channel geometry, and occur within the context provided by differentiation of allostratigraphic units. Clear and unambiguous recognition of plan-view changes is limited to Late Quaternary examples, where channel patterns are preserved on terrace surfaces. Examples include braided to sinuous single-channel transitions that occurred along many European rivers (Fig. 17A; Starkel, 1991), and changes in meander dimensions within single-channel systems of the Texas Gulf Coast (Fig. 17B; Blum *et al.*, 1995). In theory, changes in cross-sectional dimensions (width, depth, width-to-depth ratio) can be recognized in both Quaternary and ancient settings, although in practice a number of complicating factors arise (see Ethridge & Schumm, 1978; Williams, 1987; Rotnicki, 1991; Wohl & Enzel, 1996). A well-studied Holocene example is provided by Knox (1987, 1993), who cored a large number of palaeochannel fills from small streams in Wisconsin (USA) to establish changes in channel cross-sectional area through time. A promising technique for the future may be the estimates of palaeochannel depth from detailed descriptions of the heights of cross-strata and strata sets. This method is based on establishment of relationships between thicknesses of preserved cross-strata and the dimensions of parent bedforms (Best & Bridge, 1992; Bridge, 1997; Leclair *et al.*, 1997), coupled with empirical relations that relate dune height to palaeoflow depth.

As defined here, sedimentological responses can be viewed within the context of alluvial

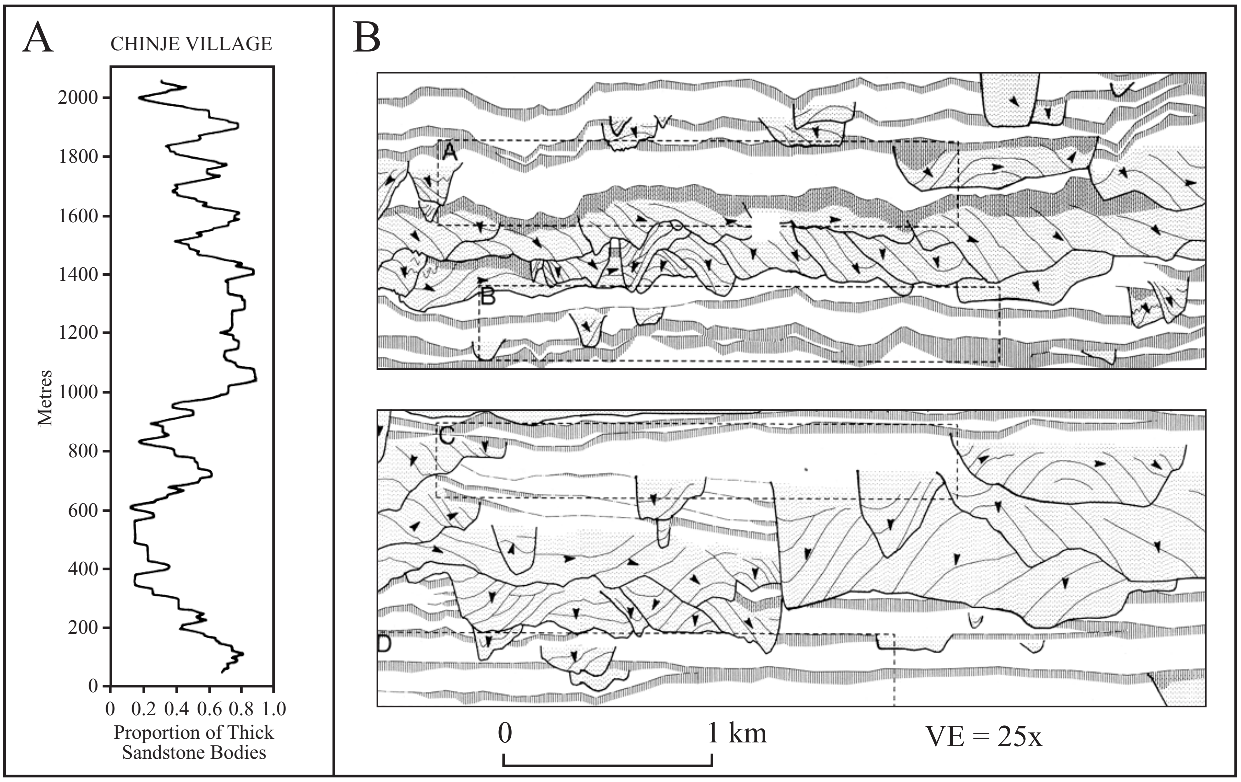



**Fig. 18.** (A) Proportion of thick sandstone bodies in the Siwalik succession at Chinje Village, Pakistan, relative to mudstone-dominated intervals. The diagram illustrates changes in sandstone proportions through time at several possible levels of cyclicity (after Willis, 1993b). (B) Line drawings of palaeosol-bounded stratigraphic units in the Siwalik succession. Stippled pattern illustrates sandbodies, white indicates mudstones, vertical hatchures indicate palaeosols and arrows indicate palaeocurrent directions (after Willis & Behrensmeyer, 1994).

architecture, initially described as the geometry, proportion and spatial distribution of different types of fluvial deposits (Leeder, 1978; Allen, 1978). Sedimentological responses reflect changes in channel geometry and the spatial distribution of depositional environments, and also occur within the context provided by differentiation of allostratigraphic units and bounding unconformities, or stratigraphic architecture as defined here. Sedimentological responses can be defined in a number of ways, depending on the types of data available, and range from simple descriptions of textural changes to detailed description and quantification of changes in the proportions of different lithofacies, facies associations and bounding surfaces. Outstanding detailed descriptions of alluvial strata can be found in the series of papers that discuss the Neogene Siwalik succession of northern Pakistan (Willis, 1993a,b; Willis & Behrensmeyer, 1994; Khan *et al.*, 1997; Zaleha, 1997). Among the many characteristics highlighted are successions of palaeosol-bounded floodplain facies, and quasi-cyclical vertical changes in mean grain-size and the proportions of thick sandstone bodies relative to muddy floodplain facies (Fig. 18).

Palaeosols deserve special mention (Wright, 1986; Retallack, 1986, 1990; Mack *et al.*, 1993; Birkeland, 1999), and a critical issue is the degree to which palaeosols represent allogenic or autogenic controls. There is, for example, a long history to the use of palaeosols to subdivide and correlate flights of Quaternary terraces and underlying fills; a key underlying premise in studies of this kind is the soil chronosequence and how soil profiles are increasingly well developed with increasing durations of subaerial exposure (see Birkeland, 1999, for a recent summary). By contrast, studies of Holocene soils as analogues for pre-Quaternary strata (e.g. Aslan & Autin, 1998), or pre-Quaternary palaeosols themselves (e.g. Allen, 1974; Leeder, 1975; Bown & Kraus, 1987; Kraus, 1987; Willis & Behrensmeyer, 1994; Behrensmeyer *et al.*, 1995), have more commonly focused on how palaeosol characteristics are related to aggradation rates, distance to active channel belts or floodplain hydrology. However, the advent of sequence stratigraphy has drawn attention to the use of palaeosols as key stratigraphic markers that trace from interfluves into adjacent palaeovalleys, and therefore serve as sequence-bounding unconformities (e.g. Wright & Marriott, 1993; Gibling & Wightman, 1994; Aitken & Flint, 1996; Blum & Price, 1998; McCarthy & Plint, 1998). Moreover, it is important to realize that palaeosols with lesser degrees of development, or perhaps different characteristics, may serve as boundaries to smaller-scale allostratigraphic units (e.g. Blum & Price, 1998; see Fig. 16B). Indeed, most important from a stratigraphic point of view may be differences in the duration of periods of nondeposition and the degree of development of pedogenic characteristics, which may provide an index of the timescales over which different allostratigraphic units form. Clearly, palaeosols deserve close scrutiny in the future.

## FLUVIAL RESPONSE TO CLIMATE CHANGE: EXAMPLES

Recognition of fluvial response to climate change in continental interiors often becomes a question of spatial and temporal scale, the degree of temporal resolution possible given existing dating methods and predilection of the investigator for autogenic (everything is 'complex response') vs. allogenic (everything is climate change) controls. There are few 'smoking guns' for any particular model, and within the Quaternary community, standards for correlation of changes in alluvial successions increase with decreasing age, such that debate can ensue regarding discrepencies of $10^1$–$10^2$ years as the age of deposits approach the period of historical monitoring. On the one hand it seems unlikely that autogenic mechanisms can result in mappable stratigraphic units that can be traced over significant distances within, or correlated between, river systems, whereas on the other hand there is every reason to assume that fluvial systems are sensitive to climatically controlled changes in discharge and sediment load. However, there is also every reason to assume that: (a) fluvial response to global climate change will vary spatially such that different regions may be out of phase; and (b) the frequency of adjustments to global climate change will vary between river systems due to different thresholds for change, i.e. differential sensitivity.

Because of the numerous uncertainties, the most convincing studies interpret chronologically controlled alluvial stratigraphic frameworks within the context of independent records of climate change. A number of reviews or regional syntheses have been published, with most focusing on the last 20 kyr and often concerning small systems. These include Knox's (1983) summary of Holocene records from the USA, Bull's (1991) documentation of Quaternary histories for several fluvial systems in the western USA & New Zealand, Starkel's (1991) summary of late Pleistocene and Holocene changes in European rivers, Bravard's (1992) summary of late Pleistocene and Holocene data from France (especially the Rhone), Macklin & Lewin's (1993) discussion of Holocene records in England, Schirmer's (1995) discussion of central European (mostly German) rivers during the last 20 kyr and Knox's (1996) overview of global records from the last 20 kyr. There is no reason to provide an additional review here; instead, two case studies are used to demonstrate contrasting styles of fluvial responses to climate change.

### Loire River, France

The Loire is one of the larger rivers in Europe, with a drainage area of ~ 120 000 km$^2$. The Loire is typical of many mid-latitude continental interior fluvial systems in that it has a flight of downward-stepping terraces and underlying fills that demarcate long-term valley incision punctuated by relatively short periods of lateral migration and minor aggradation.

Recent work by Straffin *et al.* (2000) in the upper Loire recognized five allostratigraphic units from the last glacial period (oxygen-isotope stages 2–4; hereafter OIS 2–4) through the Holocene (OIS-1; Fig. 19). Terrace surfaces with braided channel traces occur at elevations of 17 and 12 m above the modern low-water channel and define the upper boundaries to two glacial-age allostratigraphic units (T6 and T5). Underlying fills are 6–10 m in thickness, and interpreted to represent high concentrations of coarse sand and gravel along valley axes under periglacial climatic conditions, and moderate-magnitude floods produced by snowmelt runoff. Inter-vening periods of valley incision represent diminished sediment supply due to increased slope stability, and/or perhaps increased flood magnitudes and sediment transport capacity associated with moderately warm periods. The last significant period of valley incision corresponds to the latest

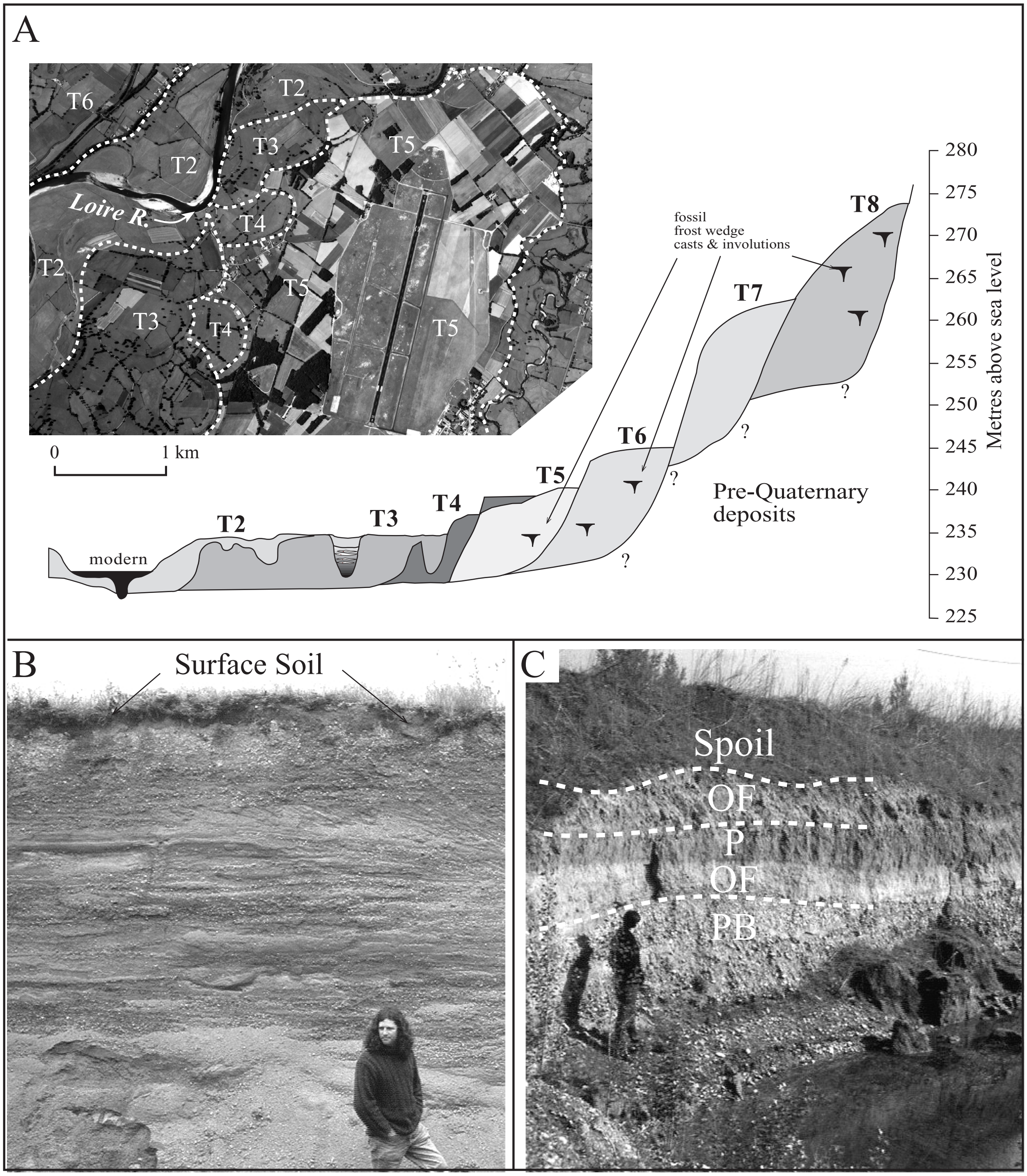



**Fig. 19.** (A) Aerial photo and schematic geomorphic and stratigraphic cross-section from a portion of the Loire River, France, illustrating large late Pleistocene braided stream surfaces (T5) and Holocene surfaces with clear high-sinuosity single-channel traces (modified from Straffin *et al.*, 2000). (B) Typical glacial period facies, with sets of trough cross-strata, but no overbank facies (unit T5 in (A)). (C) Typical late Holocene facies, illustrating overbank facies with palaeosols resting on point bar gravel (unit T2 in (A)). PB = point bar gravel, OF = overbank fine sand, P = weakly developed palaeosol.

Pleistocene–Holocene transition, and Holocene allostratigraphic units are part of a complex valley fill, some 5–7 m in thickness, that was deposited by a succession of single-channel systems of varying sinuosity. Early to middle Holocene units display high-sinuosity meandering planforms, whereas late Holocene units have lower sinuosity channels (Fig. 19A).

Stratigraphic, morphological and sedimentological responses of the Loire to climate change during the last glacial cycle can be discussed at two contrasting scales. First, as is the case for many larger European rivers, transition from a glacial to interglacial climate produced fundamental transformations in channel geometry and depositional style. Glacial-age units record deposition by braided channels, and systematically lack fine sandy and muddy overbank strata (Fig. 19B), whereas Holocene units were deposited by sinuous single channels, and contain appreciable thicknesses of fine-grained overbank facies (Fig. 19C). Second, high-amplitude, low-frequency adjustments characterized the relatively long glacial period, with only two extended periods of sediment storage punctuated by episodes of valley incision over a period of 50–60 kyr. By contrast, low-amplitude, high-frequency adjustments have been typical of the relatively short Holocene, with little if any net valley incision or net changes in sediment storage, and only minor adjustments in channel geometry. However, relatively frequent changes in climatically controlled flood regimes have resulted in alternating periods of floodplain stabilization with soil development vs. high-magnitude flooding and burial of palaeosols by overbank facies.

Over longer time periods, records of fluvial activity in the Loire are strongly biased in favour of the long glacial periods, whereas short interglacial periods like the Holocene would seem to have a low potential to be recorded in the landscape. This type of situation may be typical of many continental interior river systems in the unglaciated mid-latitudes and subtropics.

### Mississippi River, USA

The Mississippi River served as the principal conduit for meltwater and sediment discharging from the southern margins of Pleistocene ice sheets, and the Lower Mississippi Valley (LMV) provides an example of the response of a large, long-lived, low-gradient fluvial system to the growth and decay of ice sheets. Indeed, landforms and deposits of the LMV (Fig. 20A) testify to the scale, complexity and dynamism of this continental-scale fluvial system, as do the changing interpretations through time.

Blum *et al.* (2000) used stratigraphic relations between chronologically controlled loess units and subjacent fluvial deposits to provide a model for LMV history (Fig. 20B) that differs from both Fisk (1944) and Saucier (1994). In this model: (a) major braided stream surfaces are either late Illinoian (OIS 6) or late Wisconsin age (OIS 2); (b) there is little evidence for preserved fluvial deposits from the last interglacial period (OIS 5) through much of the valley; and (c) deposits from the early Wisconsin substage (OIS 4) are preserved in protected settings only. At a finer level of detail, a difference in elevation of up to 5 m between three successive late Wisconsin terraces indicates that large braided stream surfaces were rapidly constructed, incised and abandoned in response to high-frequency fluctuations in the delivery of meltwaters and outwash from the former ice margin and the drainage of large proglacial lakes. The tremendous volumes of meltwaters during this time also resulted in the simultaneous occupation of two large-scale channel courses (Western and Eastern Lowlands), as well as breaching of a new bedrock gap (Thebes Gap) through which the modern river flows. Subsurface data are not sufficient to distinguish allostratigraphic units; however, from surface mapping, three major units might be inferred to represent the last deglaciation (a period of 10–12 kyr) within the main valley and in overflow courses (Fig. 20C).

Unlike the Loire, where flights of terraces record long-term valley incision punctuated by relatively short periods ($10^4$ years) of lateral migration and minor aggradation, the stratigraphic, morphological and sedimentological record of the low-gradient LMV at any point in time will always be biased in favour of the most recent period of deglaciation. Maximum floodplain elevations of only 100 m can be found at distances of 1000 km upstream from the present highstand shoreline, so there is little opportunity for long-term progressive downcutting and development of terrace flights, and strata from the penultimate glacial period (OIS 6) are only preserved due to the wholesale abandonment of that channel course in favour of the present combined Mississippi–Ohio valley. Within the context of these longer-term controls, large fluctuations in discharge and sediment loads delivered from the ice margin during deglaciation serve to ensure that relatively short periods of time (~ 10 kyr) at the end of successive 100-kyr glacial cycles (late OIS 6 and late OIS 2) dominate the landscape, and deposits from earlier parts of a glacial cycle or previous interglacial periods are not widely preserved.

## Pre-Quaternary records

As discussed above, several examples of pre-Quaternary fluvial response to climate change have been described in the literature. It is clear that records of this kind must be more widespread than presently interpreted, but reasonable confidence in such interpretations is hampered by a number of factors. Among these, the temporal resolution provided by existing dating techniques is the most obvious and most important limitation. High-resolution palaeomagnetic chronologies, for example those of the Neogene Siwalik succession (Khan *et al.*, 1997), permit calculation of average time periods represented

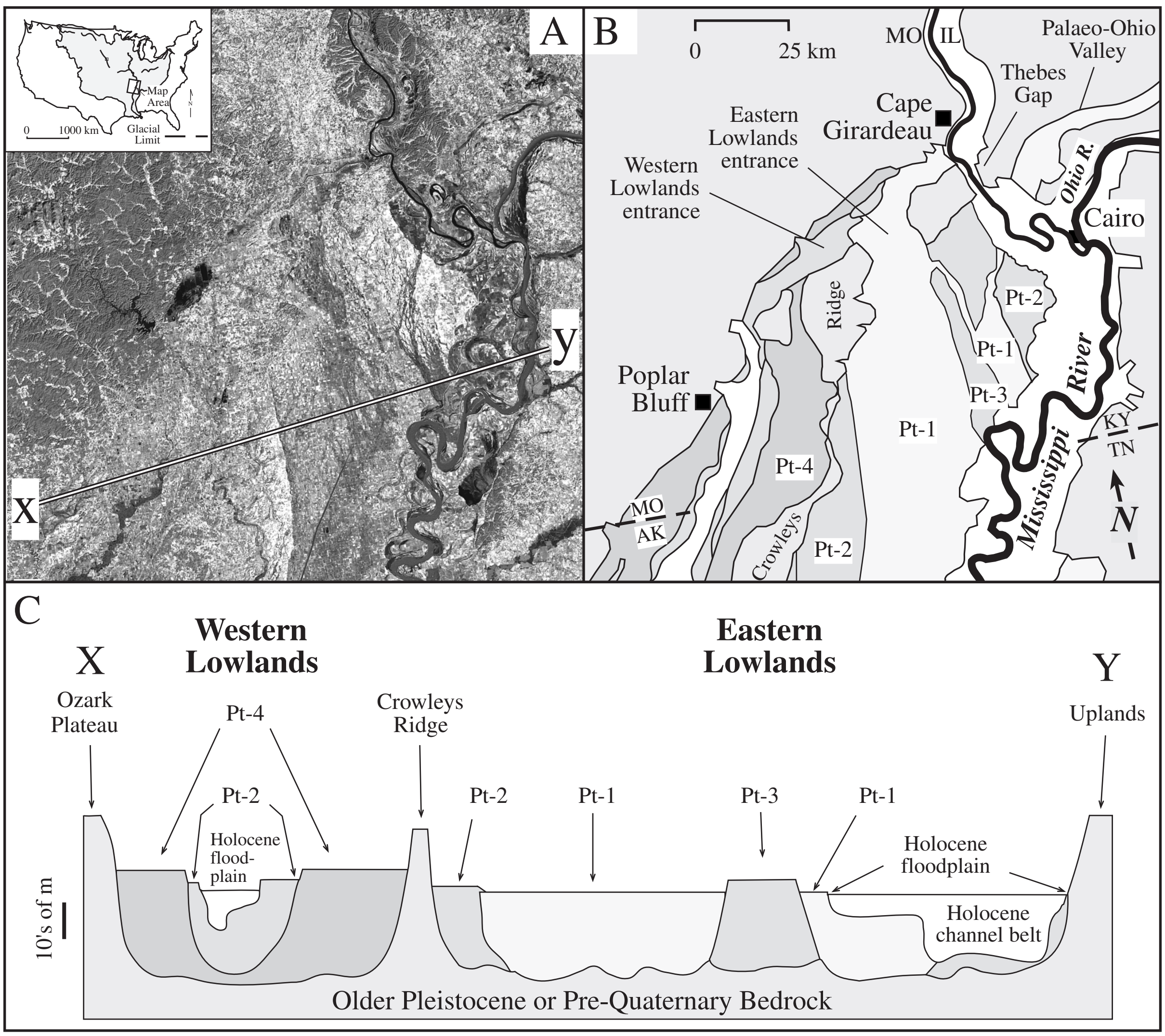



**Fig. 20.** (A) Landsat image of northern part of the Lower Mississippi alluvial valley (USA), with braided late Pleistocene vs. sinuous meandering Holocene channel belts. (B) Surficial geological map of the area shown in (A). (C) Schematic cross-section of inferred stratigraphic relationships along x–y in (A). Pt-4 = loess-covered terrace and underlying glacio-fluvial deposits from the OIS 6 glacial period, Pt-3 = terrace and underlying glacio-fluvial deposits from the OIS 2 full-glacial period, Pt-2 and Pt-1 = braided stream surfaces and underlying deposits from the OIS 2 late-glacial period. Thicknesses of deposits are schematic only, but data in Saucier indicates 50–60 m is not uncommon. Holocene floodplain in Western Lowlands represents deposits of smaller streams that head on the Ozark Plateau to the west. After Blum *et al.* (2000).

by specific unconformity-bounded intervals of deposition that are well within the Milankovitch scale, and would seem to offer the best chance to evaluate fluvial responses to climate change. Within relatively well-constrained successions such as these, periods of incision and floodplain abandonment with formation of palaeosols, as well as changes in channel morphology and depositional style that occur across unconformities (especially when defined in part by palaeosols), are excellent candidates for interpreting fluvial responses to climate change.

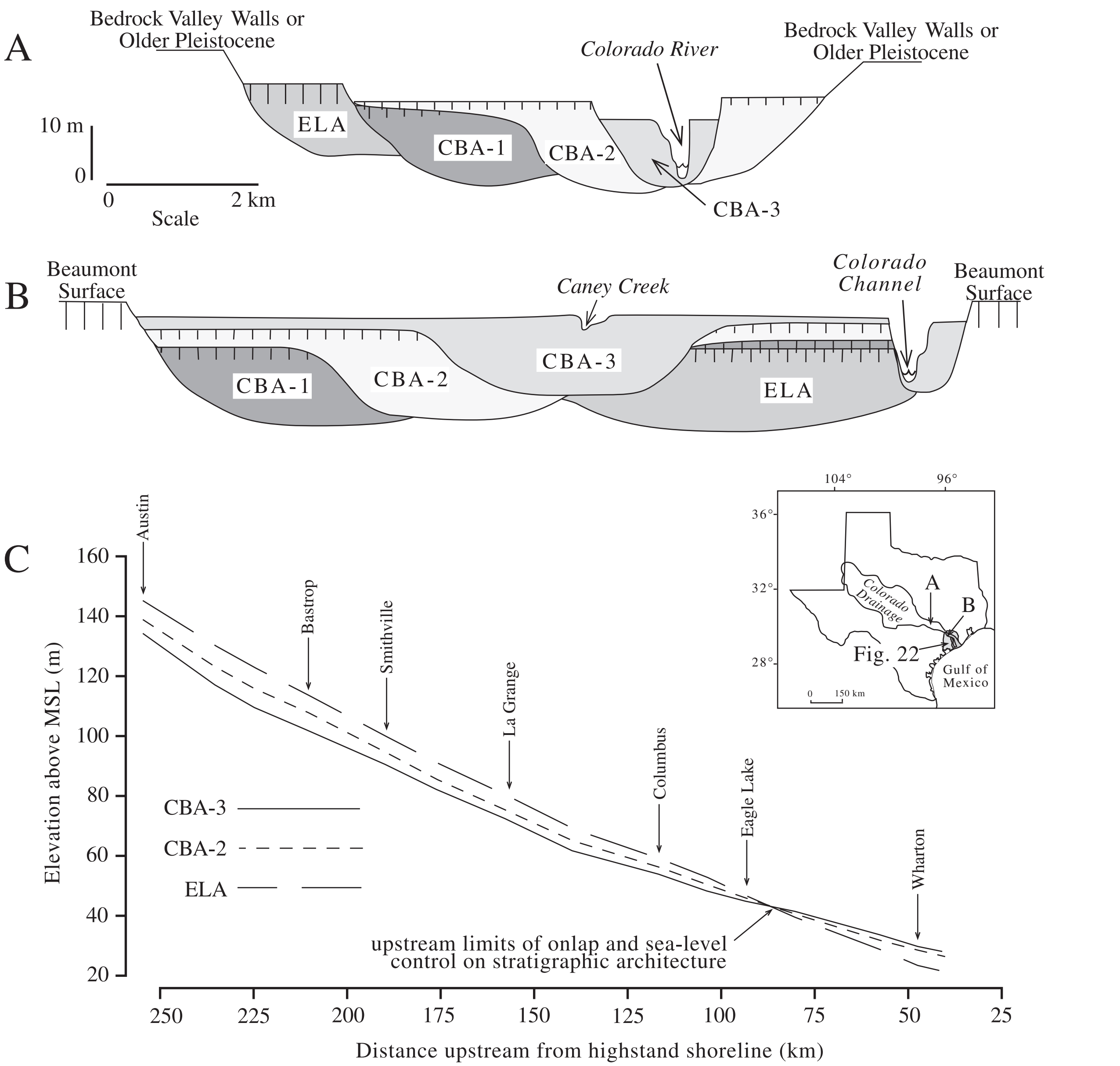



**Fig. 21.** Schematic cross-sections of the late Pleistocene and Holocene valley fill of the Colorado River, Texas Coastal Plain, illustrating downstream persistence of allostratigraphic units with downstream changes in stacking patterns. (A) The bedrock-confined degradational valley near La Grange, Texas, and (B) the lower valley near Wharton. Beaumont surface is the last interglacial highstand surface (see Fig. 21A), ELA = Eagle Lake Alloformation of late Pleistocene full-glacial age, whereas CBA-1–3 = Columbus Bend Alloformation Members 1–3, of latest Pleistocene and Holocene age. Caney Creek was the active channel until 200–300 years ago, when the lower 90 km avulsed to its present position. (C) Long profiles for ELA, CBA-2 and CBA-3, illustrating crossover point, and upstream limits of onlap. Inset map shows locations for (A) and (B), with long profile in (C) extending between these two locations. Modified from Blum & Price (1998).

## FLUVIAL RESPONSES TO CLIMATE AND SEA-LEVEL CHANGE: EXAMPLES

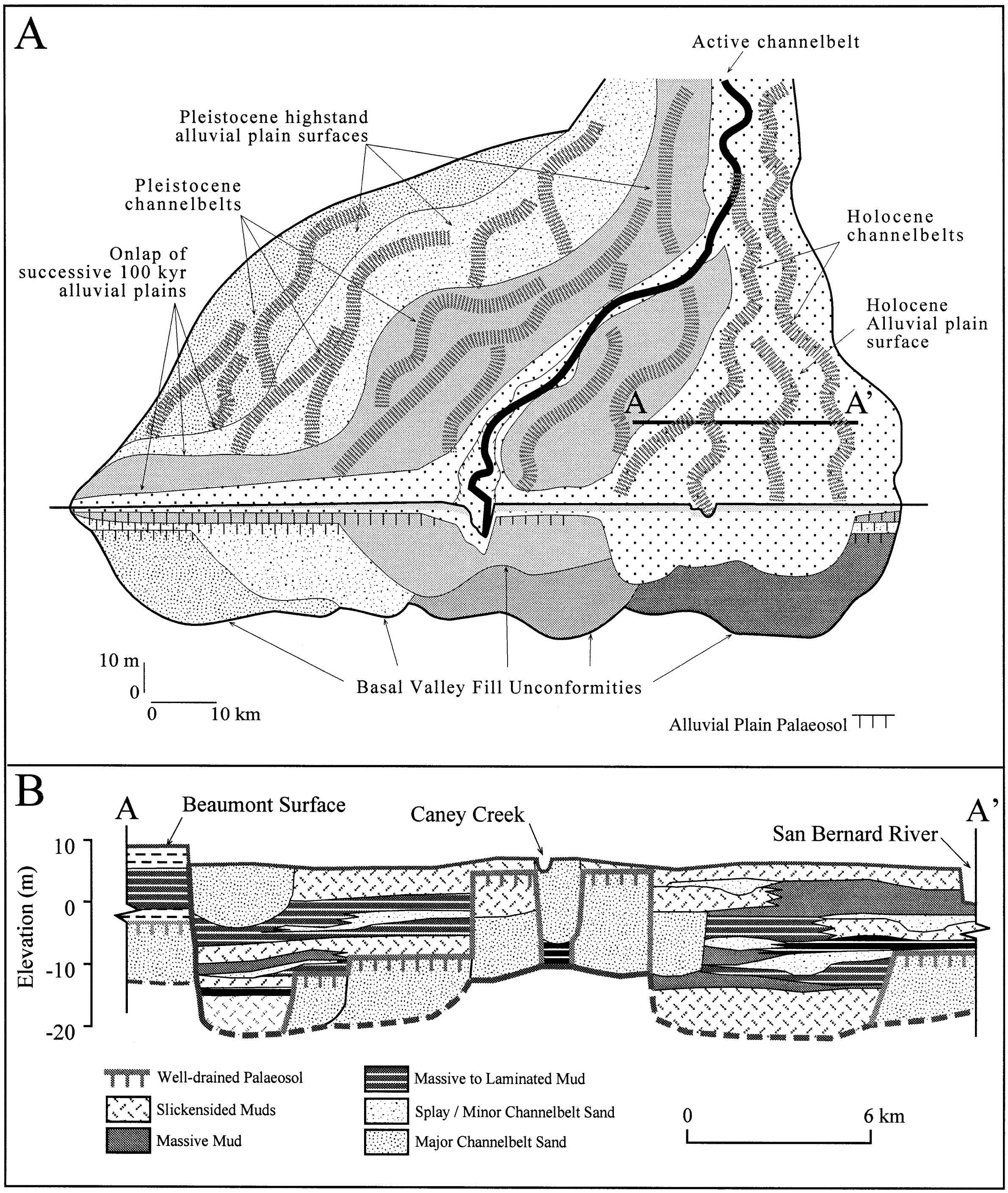
At some point upstream, fluvial systems become completely independent of high-frequency ($<10^6$ years) sea-level change. However, the reverse is not true, and there is no point moving in the downstream direction where the influence of climate and climatically controlled changes in discharge and sediment supply can go to zero – if it does not rain, nothing happens. Moreover, since glacio-eustasy is a function of climate change, it seems likely that some sort of autocorrelation will arise between the effects of climate vs. sea-level change. It follows from the above that continental margin fluvial systems must in some way reflect the influence of both controlling mechanisms, although in some cases the influences of sea-level change and subsidence may overwhelm the recognizable signature of other factors. Nevertheless, Quaternary systems in continental margin settings provide unique opportunities to isolate the nature of these interactions, as discussed in the two case studies below.

### Colorado River, Texas

From studies of late Pleistocene and Holocene strata of the Colorado River, Gulf Coastal Plain of Texas (USA), Blum (1993) defined interactions between climate and sea-level change in terms of: (a) the downstream continuity of allostratigraphic units and component facies as a reflection of climatic controls; and (b) the corresponding downstream changes in stratigraphic architecture as a reflection of the increasing influence of sea-level change (Fig. 21). Subsequent work confirms these relationships for palaeovalleys that span the last 300–400 kyr (Blum & Price, 1998). Individual palaeovalleys correspond to 100-kyr glacial–interglacial cycles, and are partitioned by lowering of sea-level below highstand depositional shoreline breaks, when channels incise and valley axes become fixed in place as they extend across the subaerially exposed shelf. During falling stage and lowstand, multiple episodes of lateral migration, minor aggradation and degradation occur within the extended valleys in response to climatic controls on discharge and sediment supply. Transgression and highstand then results in channel shortening, and valleys begin to fill; as valley filling nears completion, overbank facies spread laterally and bury soils that developed on the downdip margins of the previous highstand alluvial plain. Complete valley filling promotes avulsion, with relocation of valley axes before the next sea-level fall, such that successive 100-kyr palaeovalley fills have a distributary pattern (Fig. 22A). Individual palaeovalleys range from 15 to 20 m in thickness at the updip limits of sea-level influence, to $>35$ m at the present highstand shoreline, whereas they extend 15–40 km along strike.

Within individual unconformity-bounded palaeovalley sequences, alluvial architecture reflects interactions between changes in climate and sea-level (Fig. 22B). During the glacial period, regional climate was more temperate than today and the shoreline was in a midshelf position or further basinward. Allostratigraphic units from this time period consist of amalgamated channel-belt sands with few overbank facies, and are bounded by well-drained palaeosols; these units can be 10–15 m in thickness, and extend 2–5 km along strike. Transition to the interglacial period resulted in increases in sea surface size and temperature, 'subtropical' land surface temperatures, and deeper inland penetration of tropical moisture, that in turn produced increases in the depth and flashiness of floods. Superimposed on this overall trend were higher-frequency climate changes as well (Toomey *et al.*, 1993). As a result, multiple episodes of aggradation, lateral migration and some incision with sediment bypass occurred contemporaneously with the late stages of transgression and sea-level highstand, but in response to climatic controls on discharge regimes and sediment supply. Even in upstream reaches, beyond any influence of sea-level, Holocene units contain an abundance of fine-grained overbank facies (as was the case for the Loire as well), and sand bodies are less amalgamated (Blum & Valastro, 1994; Blum *et al.*, 1994). These characteristics are enhanced within the lower valley by a forced shortening of channels and flattening of gradients.

Aslan & Blum (1999) also show that in far downstream reaches, rates of valley filling and style of avulsion during sea-level rise and highstand play a strong role in alluvial architecture. During early transgression, when the shoreline is still some distance basinward, avulsion occurs by reoccupation of abandoned falling stage and lowstand channels, with erosion and reworking of older channel-belt sands (Fig. 23A). By contrast, accumulation space is rapidly generated as the shoreline moves closer, rates of valley filling increase and avulsion occurs by repeated diversion into floodplain depressions. This produces successions of massive to laminated floodbasin muds that encase thin (< 5 m) ribbon-like crevasse channels and thin (< 2–3 m) sheet-like splay sands (Fig. 23B), and comprise up to 50% of the total valley fill (comparable to the 'avulsion deposits' of Smith *et al.*, 1989). Deposits of individual avulsions are separated by massive to slickensided muds or buried soil horizons that represent periods of slow sediment accumulation or floodplain stability between episodes of avulsive deposition. As filling of accumulation space nears completion, avulsion by channel reoccupation again becomes the dominant process, and again results in amalgamated channel belts



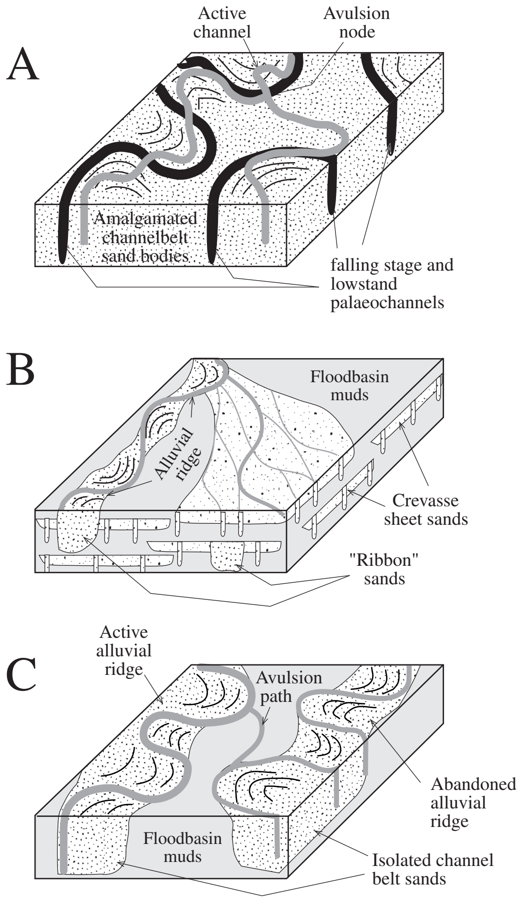



**Fig. 23.** Model for changes in avulsion styles during valley filling in response to sea-level rise. (A) Avulsion by reoccupation of falling stage and lowstand channels during early stages of valley filling, when rates of floodplain aggradation are very low. (B) Avulsion by frequent crevassing into floodplain depression in response to rapid increases in accumulation space that correspond to high rates of sea-level rise. (C) Avulsion by reoccupation of older channel belts, when sea-level highstand has been reached, and accumulation space is nearly filled (after Aslan & Blum, 1999).

(Fig. 23C). During the most recent avulsion, the Colorado River abandoned its valley from the last glacial cycle, and reoccupied a Pleistocene channel belt from the previous interglacial highstand (see Fig. 22A).

## Rhine–Meuse Rivers, The Netherlands

Studies of the Rhine–Meuse Rivers during the last glacial cycle also clearly document interactions between upstream and downstream controls. During much of the last glacial (OIS 2–4) the Rhine mouth was located beyond the Strait of Dover, up to 800 km downstream from the present shoreline (Gibbard, 1995; Bridgland & D'olier, 1995), and direct sea-level influence was limited to reaches that are now submerged in the English Channel. Throughout the glacial cycle as a whole, periglacial conditions with sparse vegetation and continuous permafrost alternated with a temperate climate comparable to present-day, and it is generally assumed that sediment supply to the Rhine and Meuse was considerably higher when periglacial conditions prevailed (e.g. Vandenberghe, 1995). Recent work by Törnqvist *et al.* (2000) suggests that during the sea-level fall associated with OIS 4, substantial deposition occurred near the present Dutch shoreline despite net incision, similar to the Colorado River, as described above. The Rhine and Meuse were also predominantly aggrading braided systems during the Last Glacial Maximum sea-level lowstand (OIS 2, 25–13 ka; Kasse *et al.*, 1995), and climate change continued to play a paramount role during deglaciation as sea-level rose rapidly. As examples, during the relatively warm Bølling–Allerød interstadial (the last D-O Cycle), which corresponds to extreme rates of eustatic sea-level rise (meltwater pulse 1 of

**Fig. 22.** (A) Perspective map view and schematic cross-section of Pleistocene (Beaumont Formation) and Holocene alluvial plains of the Colorado River, Texas, illustrating large-scale stratigraphic architecture dominated by multiple cross-cutting incised valley fills. Individual valley fills are interpreted to represent 100 kyr glacial–interglacial cycles based on physical stratigraphic relations, mostly downdip onlap and burial of successively older alluvial plain palaeosols, especially the onlap of floodplain facies and palaeosols from one highstand by floodplain facies and palaeosols from successively younger highstands. A series of thermoluminescence ages support these age relations. The Holocene alluvial plain surface was recently abandoned, when the channel avulsed to reoccupy an older Pleistocene meanderbelt. Location shown in inset map of Fig. 21. After Blum & Price (1998). (B) Interpreted post-Beaumont valley fill cross-section along line A–A′, based on a series of continuous cores with 2 km spacing. Lowstand channelbelt sandbody equivalent to ELA in Fig. 20, whereas strata that overlie well-drained palaeosols are equivalent to CBA (individual members not differentiated). After Aslan & Blum (1999).

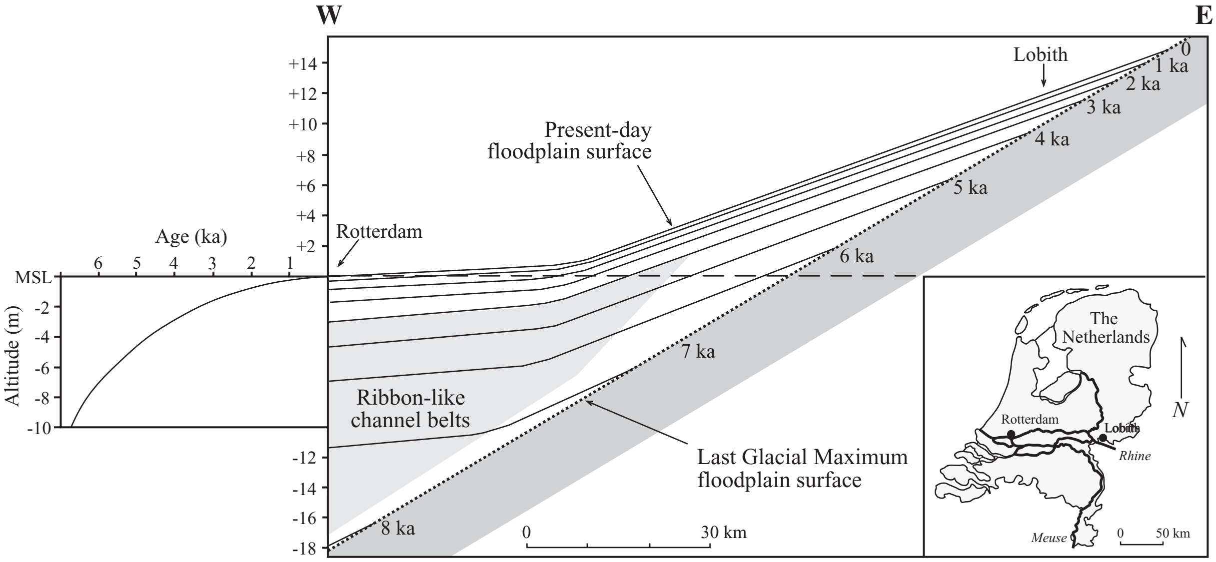



**Fig. 24.** Holocene rise of the (ground)water table in the Rhine–Meuse Delta as a function of relative sea-level rise (relative sea-level curve indicated to the left; mainly after Van de Plassche, 1982), primarily based on ~100 $^{14}$C ages of basal peats (Van Dijk *et al.*, 1991). Spacing of the (ground)water gradient lines (isochrons with ages) define rates of creation of accumulation space. Ribbon-like channel belts encased in thick, organic-rich overbank successions dominate downdip areas, whereas sheet-like channel belts are typical of conditions with lower rates of increase in accumulation space. Note the intersection point between the Last Glacial Maximum and modern longitudinal profiles to the far east, representing the landward limit of onlap.

Fairbanks, 1989), as well as during the earliest part of the Holocene (meltwater pulse 2), the Rhine–Meuse incised in response to reductions of sediment supply due to re-establishment of dense vegetation (Pons, 1957; Kasse *et al.*, 1995; Berendsen *et al.*, 1995; Törnqvist, 1998).

Well-documented rates of rise in (ground)-water tables in the present Rhine–Meuse delta during the middle to late Holocene are interpreted as a proxy for sea-level rise (Van Dijk *et al.*, 1991; Fig. 24), which is in turn interpreted to have played a prominent role in the development of alluvial architecture. The database for interpretation of the Holocene record includes > 200 000 boreholes (an average of 50–100 boreholes km$^{-2}$) plus some 1000 radiocarbon ages (e.g. Berendsen, 1982; Törnqvist, 1993; Berendsen *et al.*, 1994), and permits unparalleled documentation of changes in alluvial architecture through time. For the middle Holocene, prior to 4 ka, rates of sea-level controlled (ground)water-table rise were very high (typically > 1·5 mm yr$^{-1}$). The record from this time consists of a succession of anastomosed (Törnqvist, 1993) or straight (Makaske, 1998) distributaries with ribbon-like channel belts (width-to-thickness ratios < 15) encased in lacustrine muds and organics (Van der Woude, 1984), and avulsion frequency was very high (Törnqvist, 1994). By contrast, meandering single-channel distributaries with sheet-like channel belts (width-to-thickness ratios > 50) and more homogeneous overbank deposits have dominated the late Holocene sea-level highstand, and avulsion frequency was significantly less. There are striking similarities between the middle to late Holocene Rhine–Meuse, the Texas Gulf Coast examples described above and recent re-evaluations of the middle to late Holocene of the Lower Mississippi Valley (Aslan & Autin, 1999).

## Pre-Quaternary records

How can interactions between climate and sea-level change be recognized in the pre-Quaternary record? The bad news is that interactions defined by the downstream continuity of allostratigraphic units and component facies, with corresponding downstream changes in stratigraphic architecture, may be difficult to identify. For example, the intersection between lowstand and highstand floodplain surfaces defined along both the Texas Coast and in

The Netherlands will not be preserved, which may be typical of most passive margin settings where subsidence rates decrease landward. Indeed, as a general rule, stratigraphic units deposited during falling stage to lowstand should occur deeper within palaeovalley fills, and stand the best chance of preservation, whereas strata deposited during highstand will more commonly be removed during subsequent sea-level falls (cf. Törnqvist, 1995; Blum & Price, 1998; Törnqvist *et al.*, 2000). However, the good news is there is no reason to assume that interactions between climate and sea-level change will not occur, and downstream continuity of strata should be the rule, not the exception. Moreover, future interpretations of these interactions will at least in part rely on the well-tested method of developing modern analogues, only at 'sequence' time-scales (see discussion below).

In this context, it is worthy of note that models developed from the pre-Quaternary record (e.g. Shanley & McCabe, 1991, 1993, 1994; Wright & Marriott, 1993; Olsen *et al.*, 1995; Currie, 1997; Zhang *et al.*, 1997) infer relationships between alluvial architecture and sea-level change that are very similar to what is observed in Late Quaternary successions. Although details differ (compare Shanley & McCabe, 1993; Wright & Marriott, 1993), a common pattern would be amalgamated high net-to-gross channel belts that rest on what is interpreted to be a sequence boundary, and overlain by isolated ribbon-like sand bodies that are encased in laterally extensive mudstone-dominated successions. Many workers have interpreted the sequence boundary to reflect incision and sediment bypass during sea-level fall, and the amalgamated character of overlying sand bodies reflects low accommodation, whereas the more isolated sand bodies upsection reflect increasing accommodation due to relative sea-level rise and/or highstand. For the Late Quaternary examples discussed above, the basal palaeovalley unconformity would be interpreted as a composite erosion surface, cut during multiple periods of incision alternating with lateral migration and minor aggradation during falling stage and lowstand. Moreover, the contrast between laterally amalgamated and more isolated sand bodies that interfinger with mud-rich successions reflect fundamentally different glacial vs. interglacial climate regimes, respectively, upon which are superimposed sea-level controls on overall palaeovalley-fill architecture.

## SYNTHESIS AND A LOOK FORWARD

The discussion above has addressed the history of research on fluvial responses to climate and sea-level change, outlined a basic process framework for investigations of this kind, and provided examples of fluvial response to climate and sea-level change from work on Quaternary systems. The Mississippi River, which has long played an important role in the fluvial community, can be used to illustrate a key concept that may play a role in the future. In a previous summary of Mississippi River response to glaciation and deglaciation, Wright (1987) noted that an idealized model would predict some crossover point where aggradation due to glacial sediment loading gives way downstream to incision due to glacio-eustatic lowstand. Wright recognized that this crossover is more conceptual than real; the synthesis here takes this a step further and suggests this crossover is best viewed as a metaphor for how workers in different settings, Quaternary and ancient, have focused on causal mechanisms that reside in their own backyard. A bright future for studies of fluvial response to climate and sea-level change can be envisaged for the new millennium, one that will become increasingly integrative with respect to both upstream and downstream controls, as well as how they operate in tandem to produce the landscape and stratigraphic record. This review concludes by suggesting some key issues for the future.

### Quaternary systems

The first 2–3 decades of this millennium should be an exciting time to study Quaternary fluvial systems, with challenges that await at both ends of the temporal scale. On the one hand, it will be important to keep pace with research in high-frequency climate and sea-level change. For example, how do fluvial systems respond to the Dansgaard–Oeschger events that are so prominent in records from Greenland and the North Atlantic? Holocene records clearly show that river systems respond in dramatic fashion to relatively subtle climate changes, but are there upper limits to the frequency of responses that can be interpreted from the late Pleistocene and Holocene stratigraphic record, and were river systems during the glacial period as sensitive to rapid climate changes as their interglacial counterparts? To date, much of the high-profile, well-funded work has focused on documentation of climate changes *per se*. However, humans live on, and interact with, the Earth's surface, which has received considerably less attention and funding. Understanding the spatial dimensions and significance of high-frequency climate and sea-level changes, and their effects on surface processes, will require more precise, systematically defined, whole-system (from source to sink) and/or regional stratigraphic and geochronological frameworks than are now widely available.

On the other hand, it is equally important to study longer-wavelength cycles of fluvial landscape evolution. It is fair to say that most detailed research on fluvial response to climate change during the last 3–4 decades has focused on the last 20 kyr. While important, this relatively short period encompasses only the tail end of a single 100-kyr glacial to interglacial cycle. Very little is actually known about fluvial responses to complete glacial–interglacial cycles, or how the first 70–80% of the last cycle have preconditioned fluvial processes during the last 20–30% of the cycle. A number of studies have begun to address fluvial responses to climate change at Milankovitch scales. Antoine (1994), for example, uses stratigraphic relationships between loess sheets and fluvial deposits in the Somme Valley of France to develop a relative-age geochronological framework, and then infers cycles of aggradation, degradation and terrace formation at the 100-kyr scale. Bridgland (1994) also infers 100-kyr cyclicity for terraces of the Thames in England. Moreover, terraces of the Meuse in the southern Netherlands span the entire Quaternary, and have been used to develop numerical models of long-term fluvial response to climate change and tectonic uplift, suggesting 100-kyr cycles of aggradation and incision (Veldkamp & Van den Berg, 1993). Investigations such as these also provide an opportunity to link studies of fluvial response to climate and sea-level change over longer time-scales with new ideas on relationships between tectonics and surface processes (e.g. Burbank & Pinter, 1999).

Two issues emerge as fundamental to future advancements in understanding the responses of Quaternary fluvial systems to climate and sea-level change over both shorter and longer time-scales. First, there is a clear need to develop and apply more sophisticated geophysical techniques to explore three-dimensional relationships at both the stratigraphic and alluvial architecture scales. Applications of ground-penetrating radar (GPR) and shallow high-resolution seismic will become increasingly important in this regard. GPR has, for example, been applied in a number of fluvial contexts, but mostly at the alluvial architecture scale, and more specifically with reference to internal structure at the channel bar scale (e.g. Huggenberger, 1993; Bridge *et al.*, 1995, 1998). Future applications of high-resolution geophysical techniques in Late Quaternary continental strata are not without problems, especially at the stratigraphic architecture scale, but may prove to be essential for developing linkages between continental strata and the high-resolution records that have been, and will continue to be, documented for alluvial–deltaic strata on the now submerged shelves. This, in turn, must play a critical role in developing an understanding of the relative importance of upstream vs. downstream controls at both the stratigraphic and alluvial architecture scales, and the evolution of fluvial systems from source to sink.

Second, and equally important, is a corresponding need to develop, refine and apply new dating techniques. Radiocarbon has served as the clear reference standard for almost five decades, and has had a profound impact on understanding the dynamics of terrestrial systems over the last 20–30 kyr. However, many records remain poorly constrained because they lack organic matter in key stratigraphic contexts, and the time period covered by radiocarbon represents only 30–40% of a single glacial–interglacial cycle. On the near horizon, application and refinement of the various luminescence techniques seem to offer the most promise. In theory, luminescence techniques measure the time elapsed since sand- and silt-sized grains were exposed to solar radiation during transport, and can provide numerical ages for deposits within the middle to late Pleistocene and Holocene. For fluvial deposits, optically stimulated luminescence (OSL) has considerable advantages over the older technique of thermoluminescence (TL), since only minutes of exposure are required during transport (Duller, 1996; Aitken, 1998). Both TL and OSL have been used in fluvial contexts; examples include TL dating of fluvial deposits in the Lake Eyre basin of Australia (Nanson *et al.*, 1988, 1992), Murrumbidgee River palaeochannels in south-eastern Australia (Page *et al.*, 1996), Saharan wadi systems (Blum *et al.*, 1998) and Texas Gulf Coast fluvial deposits (Blum & Price, 1998), as well as OSL dating of fluvial deposits of the Ebro drainage in Spain (Fuller *et al.*, 1998), the Loire in France (Straffin *et al.*, 2000) and the Rhine–Meuse in The Netherlands (Törnqvist *et al.*, 2000).

### Pre-Quaternary systems

Two fundamental issues can be identified that should play a role in interpretations of fluvial responses to high-frequency (time-scales of $10^4$–$10^6$ years) climate and sea-level change in the pre-Quaternary record. First, future interpretations must at least in part rely on the development of 'sequence-scale' Quaternary analogues. There is, at present, a paucity of good analogues that: (a) extend beyond the relatively short latest Pleistocene and Holocene period into geologically resolvable time-scales (multiples of $10^4$–$10^6$ years); (b) include depositional basin settings where preservational processes operate; and (c) describe fluvial responses to allogenic controls in sedimentological terms that facilitate recognition in the ancient record. Further detailed study of Quaternary analogues may also provide a mechanism by which cross-fertilization of methods and perspectives from geomorphology and sedimentology can occur, and traditional disciplinary and other barriers can be dismantled.

Second, and perhaps more difficult, will be changes in the philosophy of interpretation. It seems clear that the development of sequence stratigraphy resulted in a paradigm shift with respect to how sedimentologists view the responses of fluvial systems to sea-level change. However, the same intellectual hurdle has yet to be crossed with respect to the significance of climate change, which both causes and covaries with sea-level, and is one of the dominant controls on changes in sediment delivery to depositional basins through time. Clear recognition and interpretation of fluvial responses to climate change certainly remains difficult, and for the time being may require well-constrained geochronological frameworks that demonstrate rates of change comparable to known climate forcing functions, coupled with an approach where possible alternatives are eliminated and the only one that remains must be the most viable. However, part of the hurdle will involve a willingness to explicitly consider climate change as a forcing mechanism; for example, many features described in ancient successions are remarkably similar in scale and kind to that observed in Late Quaternary records, but they are commonly interpreted in terms of autogenic variation superimposed on tectonic controls. No analogues clearly demonstrate, as opposed to assume, this particular model, and the assumption of autogenic variation may not be as justified today as it might have been in the past given present views on the magnitude, frequency and significance of climate change.

### Importance of modelling

Although modelling efforts are discussed elsewhere in this issue (Paola, 2000), it seems clear that integration of different 'fluvial' models will be a major challenge for the near future (cf. Nystuen, 1998). As appropriately stated by Paola in this issue, presently available numerical models should be considered temporary building blocks that will ultimately merge together. Four broad classes of models can be distinguished: (a) the predominantly autogenic and exclusively aggradational numerical models of alluvial architecture (e.g. Bridge & Leeder, 1979; Mackey & Bridge, 1995; Heller & Paola, 1996); (b) sequence-stratigraphic models that focus on incision and/or aggradation in downdip parts of the fluvial system (e.g. Nummedal *et al.*, 1993; Leeder & Stewart, 1996); (c) numerical models that focus primarily on long-term fluvial incision and/or sediment production in the hinterland (Veldkamp & Van den Berg, 1993; Leeder *et al.*, 1998); and (d) the unscaled and scaled physical (analogue) models that have provided important qualitative insight into fluvial responses to varying rates and directions of sea-level change (Wood *et al.*, 1993, 1994; Koss *et al.*, 1994; Paola, 2000), or how alluvial architecture varies with aggradation rate (e.g. Ashworth *et al.*, 1999).

In the future, linkage of models that focus on both continental interiors and continental margins (e.g. Veldkamp & Van Dijke, 1998), as well as integrating model results with real-world data (e.g. Leeder *et al.*, 1996), must become increasingly important so as to more clearly understand relations between sediment production, transport and deposition at time-scales that reside at the interface between the traditional interests of geomorphologists/Quaternary geologists and sedimentary geologists ($10^3$–$10^6$ years). As noted by Paola in this issue, model development can proceed at higher rates than field studies; hence the first decades of this millennium offer significant opportunities for new and creative field-based investigations that are designed to constrain and validate quantitative models.

## ACKNOWLEDGEMENTS

We appreciate the invitation from the *Sedimentology* editorial board to write this paper.

Comments by Peter Friend, Mike Leeder and editor Jim Best were very helpful. We also appreciate numerous discussions with our various collaborators, students and colleagues, but stress that this is a selective review that reflects our own perspectives on the subject matter.

## REFERENCES

**Aitken, J.F.** and **Flint, S.S.** (1995) The application of high-resolution sequence stratigraphy to fluvial systems: a case study from the Upper Carboniferous Breathitt Group, eastern Kentucky, USA. *Sedimentology*, **42,** 3–30.

**Aitken, J.F.** and **Flint, S.S.** (1996) Variable expressions of interfluvial sequence boundaries in the Breathitt Group (Pennsylvanian), eastern Kentucky, USA. In: *High Resolution Sequence Stratigraphy: Innovations and Applications* (Ed. by J. A. Howell and J. F. Aitken), *Spec. Publ. Geol. Soc.*, **104,** 193–206.

**Aitken, M.J.** (1998) *An Introduction to Optical Dating*. Oxford University Press, Oxford.

**Allen, J.R.L.** (1974) Studies in fluviatile sedimentation: implications of pedogenic carbonate units, Lower Old Red Sandstone, Anglo-Welsh outcrop. *Geol. J.*, **9,** 181–208.

**Allen, J.R.L.** (1978) Studies in fluviatile sedimentation: an exploratory quantitative model for the architecture of avulsion-controlled suites. *Sedim. Geol.*, **21,** 129–147.

**Amorosi, A., Colalongo, M.L., Fusco, F., Pasini, G.** and **Fiorini, F.** (1999) Glacio-eustatic control of continental-shallow marine cyclicity from Late Quaternary deposits of the southeastern Po Plain, northern Italy. *Quat. Res.*, **52,** 1–13.

**Anderson, J.B., Abdulah, K., Sarzalejo, S., Siringin, F.** and **Thomas, M.A.** (1996) Late Quaternary sedimentation and high-resolution sequence stratigraphy of the East Texas Shelf. In: *Geology of Siliciclastic Shelf Seas* (Ed. by M. De Batist and P. Jacobs), *Spec. Publ. Geol. Soc.*, **117,** 95–124.

**Antoine, P.** (1994) The Somme valley terrace system (northern France); a model of river response to Quaternary climatic variations since 800,000 BP. *Terra Nova*, **6,** 453–464.

**Ashworth, P.J., Best, J.L., Peakall, J.** and **Lorsong, J.A.** (1999) The influence of aggradation rate on braided alluvial architecture: field study and physical scale-modelling of the Ashburton River gravels, Canterbury Plains, New Zealand. In: *Current Research in Fluvial Sedimentology: Proceedings of 6th International Conference on Fluvial Sedimentology* (Ed. by N. D. Smith and J. J. Rogers), *Spec. Publ. Int. Assoc. Sediment.*, **28,** 333–346.

**Aslan, A.** and **Autin, W.J.** (1998) Holocene flood-plain soil formation in the southern lower Mississippi Valley: Implications for interpreting alluvial paleosols. *Geol. Soc. Am. Bull.*, **110,** 433–449.

**Aslan, A.** and **Autin, W.J.** (1999) Evolution of the Holocene Mississippi River floodplain, Ferriday, Louisiana: insights on the origin of fine-grained floodplains. *J. Sedim. Res.*, **69,** 800–815.

**Aslan, A.** and **Blum, M.D.** (1999) Contrasting styles of Holocene avulsion, Texas Gulf Coastal Plain. In: *Current Research in Fluvial Sedimentology: Proceedings of 6th International Conference on Fluvial Sedimentology* (Ed. by N. D. Smith and J. J. Rogers), *Spec. Publ. Int. Assoc. Sediment.*, **28,** 193–209.

**Autin, W.J.** (1992) Use of alloformations for definition of Holocene meanderbelts in the middle Amite River, southeastern Louisiana. *Geol. Soc. Am. Bull.*, **104,** 233–241.

**Bagnold, R.A.** (1973) The nature of saltation and bedload transport in water. *Proc. Royal Society, London*, **322A,** 473–504.

**Baker, V.R., Kochel, R.C.** and **Patton, P.C.** (Eds). (1988) *Flood Geomorphology*. John Wiley, New York.

**Barrell, J.** (1917) Rhythms and the measurement of geological time. *Geol. Soc. Am. Bull.*, **28,** 745–904.

**Barron, E.J.** and **Moore, G.T.** (1994) *Climate Model Application in Palaeoenvironmental Analysis*. SEPM Short Course no. 33.

**Begin, Z.B.** (1988) Application of diffusion-erosion model to alluvial channels which degrade due to base-level lowering. *Earth Surf. Proc. Landf.*, **13,** 487–500.

**Begin, Z.B., Meyer, D.F.** and **Schumm, S.A.** (1981) Development of longitudinal profiles of alluvial channels in response to base-level lowering. *Earth Surf. Proc. Landf.*, **6,** 49–68.

**Behl, R.J.** and **Kennett, J.P.** (1996) Brief interstadial events in the Santa Barbara basin, NE Pacific, during the past 60 kyr. *Nature*, **379,** 243–246.

**Behrensmeyer, A.K., Willis, B.J.** and **Quade, J.** (1995) Floodplains and palaeosols of Pakistan Neogene and Wyoming Palaeogene deposits: a comparative study. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **115,** 37–60.

**Benito, G., Baker, V.R.** and **Gregory, K.J.** (Eds). (1998) *Palaeohydrology and Environmental Change*. John Wiley, Chichester.

**Berendsen, H., Hoek, W.** and **Schorn, E.** (1995) Late Weichselian and Holocene river channel changes of the rivers Rhine and Meuse in the Netherlands (Land van Maas en Waal). *Palâoklimaforschung*, **14,** 151–171.

**Berendsen, H.J.A.** (1982) De genese van het landschap in het zuiden van de provincie Utrecht, een fysisch-geografische studie. *Utr. Geogr. Studies*, **25,** 1–255.

**Berendsen, H.J.A., Faessen, E.L.J.H.** and **Kempen, H.F.J.** (1994) *Zand in Banen. Zanddiepte-Attentiekaarten van het Gelders Rivierengebied*. Provincie Gelderland, Arnhem.

**Berger, A., Loutre, M.F.** and **Dehant, V.** (1989) Astronomical frequencies for pre-Quaternary palaeoclimate studies. *Terra Nova*, **1,** 474–479.

**Berger, A.** and **Loutre, M.F.** (1994) Astronomical forcing through geologic time. In: *Orbital Forcing and Cyclic Sequences* (Ed. by P. L. de Boer and D. G. Smith), *Spec. Publ. Int. Assoc. Sediment.*, **19,** 15–24.

**Bernard, H.A.** and **Leblanc, R.J.** (1965) Resume of the Quaternary Geology of the Northwestern Gulf of Mexico Province. In: *The Quaternary of the United States* (Ed. by H. E. Wright and D. G. Frey), pp. 137–185. Princeton University Press, Princeton.

**Best, J.L.** and **Ashworth, P.J.** (1997) Scour in large braided rivers and the recognition of sequence stratigraphic boundaries. *Nature*, **387,** 275–277.

**Best, J.L.** and **Bridge, J.S.** (1992) The morphology and dynamics of low amplitude bedwaves upon upper stage plane beds and the preservation of planar laminae. *Sedimentology*, **39,** 737–752.

**Birkeland, P.W.** (1999) *Soils and Geomorphology*. Oxford University Press, New York.

**Blum, M.D.** (1990) Climatic and eustatic controls on Gulf Coastal Plain fluvial sedimentation: an example from the Late Quaternary of the Colorado River, Texas. In: *Sequence Stratigraphy as an Exploration Tool: Concepts and Practices* *in the Gulf Coast* (Ed. by J. M. Armentrout and B. F. Perkins) Gulf Coast Section of the Society of Economic Palaeontologists and Mineralogists Foundation, Proceedings of the 11th Annual Research Conference, pp. 71–83.

**Blum, M.D.** (1993) Genesis and architecture of incised valley fill sequences: a Late Quaternary example from the Colorado River, Gulf Coastal Plain of Texas. In: *Siliciclastic Sequence Stratigraphy: Recent Developments and Applications* (Ed. by P. Weimer and H. W. Posamentier), *Mem. Am. Assoc. Petrol. Geol.*, **58,** 259–283.

**Blum, M.D.** and **Price, D.M.** (1998) Quaternary alluvial plain construction in response to interacting glacio-eustatic and climatic controls, Texas Gulf Coastal Plain. In: *Relative Role of Eustasy, Climate, and Tectonism in Continental Rocks* (Ed. by K. W. Shanley and P. J. McCabe), *Spec. Publ. Soc. Econ. Paleont. Miner.*, **59,** 31–48.

**Blum, M.D.** and **Valastro, S. Jr** (1994) Late Quaternary sedimentation, Lower Colorado River, Gulf Coastal Plain of Texas. *Geol. Soc. Am. Bull.*, **106,** 1002–1016.

**Blum, M.D., Toomey III, R.S.** and **Valastro, S. Jr** (1994) Fluvial response to Late Quaternary climatic and environmental change, Edwards Plateau of Texas. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **108,** 1–21.

**Blum, M.D., Morton, R.A.** and **Durbin, J.M.** (1995) 'Deweyville' terraces and deposits of the Texas Gulf Coastal Plain. *Trans. Gulf Coast Assoc. Geol. Soc.*, **45,** 53–60.

**Blum, M.D., Kocurek, G., Deynoux, M., Swezey, C., Lancaster, N., Price, D.** and **Pion, J.-C.** (1998) Quaternary wadi-lacustrine-aeolian depositional cycles and sequences, Chott Rharsa Basin, Tunisia. In: *Quaternary Deserts and Climatic Change* (Ed. by A. S. Alsharhan, K. Glennie, G. L. Whittle and C. G. St. C. Kendall), pp. 539–552. Balkema Press, Rotterdam.

**Blum, M.D., Guccione, M.J., Wysocki, D.A.** and **Robnett, P.C.** (2000) Late Pleistocene evolution of the Central Mississippi Valley, Southen Missouri to Arkansas. *Geol. Soc. Am. Bull.*, **112,** 221–235.

**Bond, G., Broecker, W., Johnsen, S., McManus, J., Labeyrie, L., Jouzel, J.** and **Bonani, G.** (1993) Correlations between climate records from North Atlantic sediments and Greenland ice. *Nature*, **365,** 143–147.

**Bond, G., Showers, W., Cheseby, M., Lotti, R., Almasi, P., Demenocal, P., Priore, P., Cullen, H., Hajdas, I.** and **Bonani, G.** (1997) A pervasive millennial-scale cycle in North Atlantic Holocene and glacial climates. *Science*, **278,** 1257–1266.

**Bond, G.C.** and **Lotti, R.** (1995) Iceberg discharges into the North Atlantic on millennial time scales during the last glaciation. *Science*, **267,** 1005–1010.

**Bowen, D.Q.** (1978) *Quaternary Geology*. Pergamon Press, Oxford.

**Bown, T.M.** and **Kraus, M.J.** (1987) Integration of channel and floodplain suites, I. Developmental sequence and lateral relations of alluvial paleosols. *J. Sedim. Petrol.*, **57,** 587–601.

**Bradley, R.S.** (1999) *Paleoclimatology*. Academic Press, San Diego.

**Branson, J., Brown, A.G.** and **Gregory, K.J.** (Eds). (1996) Global Continental Changes: The Context of Palaeohydrology. *Spec. Publ. Geol. Soc. London,* **115.**

**Bravard, J.-P.** (1992) Rapport no. 2: Les rythmes d'evolution morphologique des vallèes Francaises au Tardiglaciaire et l'Holocene. *Bull. Assoc. Geographes Francais.*

**Bridge, J.S.** (1993a) Description and interpretation of fluvial deposits: a critical perspective. *Sedimentology*, **40,** 801–810.

**Bridge, J.S.** (1993b) The interaction between channel geometry, water flow, sediment transport and deposition in braided rivers. In: *Braided Rivers* (Ed. by J. L. Best and C. S. Bristow), *Spec. Publ. Geol. Soc. Lond.*, **75,** 13–71.

**Bridge, J.S.** (1995) Description and interpretation of fluvial deposits: a critical perspective. *Sedimentology*, **42,** 382–389.

**Bridge, J.S.** (1997) Thickness of sets of cross-strata and planar strata as a function of formative bedwave geometry and migration, and aggradation rate. *Geology*, **25,** 971–974.

**Bridge, J.S.** and **Leeder, M.R.** (1979) A simulation model of alluvial stratigraphy. *Sedimentology*, **26,** 617–644.

**Bridge, J.S., Alexander, J., Collier, R.E.L., Gawthorpe, R.L.** and **Jarvis, J.** (1995) Ground-penetrating radar and coring used to document the large-scale structure of point-bar deposits. *Sedimentology*, **42,** 839–852.

**Bridge, J.S., Collier, R.E.L.** and **Alexander, J.** (1998) Large-scale structure of Calamus River deposits (Nebraska, USA) revealed using ground-penetrating radar. *Sedimentology*, **45,** 977–986.

**Bridgland, D.R.** (1994) *Quaternary of the Thames. Geological Conservation Review Series 7.* Chapman & Hall, London.

**Bridgland, D.R.** and **D'olier, B.** (1995) The Pleistocene evolution of the Thames and Rhine drainage systems in the southern North Sea Basin. In: *Island Britain: a Quaternary Perspective* (Ed. by R. C. Preece), *Spec. Publ. Geol. Soc.*, **96,** 27–45.

**Brierley, G.J.** (1996) Channel morphology and element assemblages: A constructivist approach to facies modelling. In: *Advances in Fluvial Dynamics and Stratigraphy* (Ed. by P. A. Carling and M. R. Dawson), pp. 263–298. John Wiley, Chichester.

**Broecker, W.S.** (1995) *The Glacial World According to Wally*. Eldigio Press, Palisades.

**Broecker, W.S.** (1997) Thermohaline circulation, the achilles heel of our climate system: Will man-made CO2 upset the current balance? *Science*, **278,** 1582–1588.

**Brown, L.J.** and **Wilson, D.D.** (1988) Stratigraphy of Late Quaternary deposits of the northern Canterbury Plains. *NZ J. Geol. Geoph.*, **31,** 305–335.

**Bull, W.B.** (1991) *Geomorphic Responses to Climate Change*. Oxford University Press, Oxford.

**Burbank, D.W.** and **Pinter, N.** (1999) Landscape evolution: the interactions of tectonics and surface processes. *Basin Res.*, **11,** 1–6.

**Burke, K., Francis, P.** and **Wells, G.** (1990) Importance of the geological record in understanding global change. *Palaeogeogr. Palaeoclimatol. Palaeoecol. (Glob. Plan. Change Sect.)*, **89,** 193–204.

**Butcher, S.W.** (1990) The nickpoint concept and its implications regarding onlap to the stratigraphic record. In: *Quantitative Dynamic Stratigraphy* (Ed. by T. A. Cross), pp. 375–385. Prentice Hall, Englewood Cliffs.

**Butzer, K.W.** (1980) Holocene alluvial sequences: problems of dating and correlation. In: *Timescales in Geomorphology* (Ed. by R. A. Cullingford, D. A. Davidson and J. Lewin), pp. 131–142. John Wiley, New York.

**Chappell, J.** and **Shackleton, N.J.** (1986) Oxygen isotopes and sea-level. *Nature*, **324,** 137–140.

**Chappell, J., Omura, A., Ezat, T., McCulloch, M., Pandolfi, J., Ota, Y.** and **Pillans, B.** (1996) Reconciliation of late Quaternary sea-levels derived from coral terraces at Huon Peninsula with deep sea oxygen isotope records. *Earth Planet. Sci. Lett.*, **141,** 227–236.

**Clemmensen, L.B., Øxnevad, I.E.I.** and **De Boer, P.L.** (1994) Climatic controls on ancient sedimentation: some late Palaeozoic and Mezosoic examples from NW Europe and the Western Interior of the USA. In: *Orbital Forcing and Cyclic Sequences* (Ed. by P. L. de Boer and D. G. Smith), *Spec. Publ. Int. Assoc. Sediment.*, **19,** 439–457.

**COHMAP Project Members.** (1988) Climatic changes of the last 18,000 years: Observations and model simulations. *Science*, **241,** 1043–1052.

**Cojan, I.** (1993) Alternating fluvial and lacustrine sedimentation: tectonic and climatic controls (Provence Basin, S. France, Upper Cretaceous/Palaeocene). In: *Alluvial Sedimentation* (Ed. by M. Marzo and C. Puigdefabregas), *Spec. Publ. Int. Assoc. Sediment.*, **17,** 425–438.

**Crowley, T.** and **North, G.R.** (1991) *Palaeoclimatology*. Oxford University Press, New York.

**Currie, B.S.** (1997) Sequence stratigraphy of nonmarine Jurassic–Cretaceous rocks, central Cordilleran foreland-basin system. *Geol. Soc. Am. Bull.*, **109,** 1206–1222.

**Dai, A., Fung, I.Y.** and **Del Genio, A.D.** (1997) Surface observed global land precipitation variations during 1900–88. *J. Clim.*, **10,** 2943–2962.

**Dalrymple, R.W., Boyd, R.** and **Zaitlin, B.A.** (Eds) (1994) History of research, types and internal organisation of incised-valley systems: Introduction to the Volume. In: *Incised-Valley Systems: Origin and Sedimentary Sequences* (Ed. by R. W. Dalrymple, R. Boyd and B. A. Zaitlin), *Spec. Publ. Soc. Econ. Paleont. Miner.*, **51,** 3–10.

**Dott, R.H. Jr** (1992) An introduction to the ups and downs of eustasy. In: *Eustasy: the Historical Ups and Downs of a Major Geological Concept* (Ed. by R. H. Dott, Jr), *Geol. Soc. Am. Mem.*, **180,** 1–16.

**Dubiel, R.F., Huntoon, J.E., Condon, S.M.** and **Stanesco, J.D.** (1996) Permian deposystems, palaeogeography, and palaeoclimate of the Paradox Basin and vicinity. In: *Palaeozoic Systems of the Rocky Mountain Region* (Ed. by M. W. Longman and M. D. Sonnenfeld), pp. 427–444. Rocky Mountain Section, SEPM.

**Duller, G.A.T.** (1996) Recent developments in luminescence dating of Quaternary sediments. *Progr. Phys. Geogr.*, **20,** 127–145.

**Dury, G.H.** (1965) Principles of Underfit Streams. *United States Geol. Surv. Prof. Pap.*, **452-A**.

**Emery, D.** and **Myers, K.J.** (Eds). (1996) *Sequence Stratigraphy*. Blackwell Science, Oxford.

**Ethridge, F.G.** and **Schumm, S.A.** (1978) Reconstructing palaeochannel morphologic and flow characteristics: methodology, limitations and assessment. In: *Fluvial Sedimentology* (Ed. by A. D. Miall), *Can. Soc. Petrol. Geol. Mem.*, **5,** 703–721.

**Ethridge, F.G., Wood, L.J.** and **Schumm, S.A.** (1998) Cyclic variables controlling fluvial sequence development: Problems and perspectives. In: *Relative Role of Eustasy, Climate, and Tectonism in Continental Rocks* (Ed. by K. W. Shanley and P. J. McCabe), *Spec. Publ. Soc. Econ. Paleont. Miner.*, **59,** 17–29.

**Fairbanks, R.G.** (1989) A 17,000-year glacio-eustatic sea-level record: influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature*, **342,** 637–642.

**Ferguson, R.** (1987) Hydraulic and sedimentary controls of channel pattern. In: *River Channels: Environment and Process* (Ed. by K. S. Richards), pp. 17–29. Blackwell Science, Oxford.

**Fielding, C.R.** (1999) Varieties of fluvial form: the relevance to geologists of an expanded reality. In: *Varieties of Fluvial Form* (Ed. by A. J. Miller and A. Gupta), pp. 497–505. John Wiley, Chichester.

**Fisk, H.N.** (1944) *Geological Investigation of the Alluvial Valley of the Lower Mississippi River*. Mississippi River Commission, Vicksburg.

**Fleming, K., Johnston, P., Zwartz, D., Yokoyama, Y., Lambeck, K.** and **Chappell, J.** (1998) Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites. *Earth Planet. Sci. Lett.*, **163,** 327–342.

**Fournier, F.** (1960) *Climat et Erosion: la relation entre lı́erosion du sol par lı́eau et les precipitations atmospheriques*. Presse Universitaire de France.

**Frakes, L.A.** (1979) *Climates Throughout Geologic Time*. Elsevier, Amsterdam.

**Frakes, L.A., Francis, J.E.** and **Syktus, J.I.** (1992) *Climate Modes of the Phanerozoic*. Cambridge University Press, Cambridge.

**Fuller, I.C., Macklin, M.G., Lewin, J., Passmore, D.G.** and **Wintle, A.G.** (1998) River response to high-frequency climate oscillations in southern Europe over the past 200 k.y. *Geology*, **26,** 275–278.

**Galloway, W.E.** (1989) Genetic stratigraphic sequences in basin analysis I: architecture and genesis of flooding-surface bounded depositional units. *Am. Assoc. Petrol. Geol. Bull.*, **73,** 125–142.

**Gibbard, P.L.** (1995) The formation of the Strait of Dover. In: *Island Britain: a Quaternary Perspective* (Ed. by R. C. Preece), *Spec. Publ. Geol. Soc.*, **96,** 15–26.

**Gibling, M.R.** and **Bird, D.J.** (1994) Late Carboniferous cyclothems and alluvial paleovalleys in the Sydney Basin, Nova Scotia. *Geol. Soc. Am. Bull.*, **106,** 105–117.

**Gibling, M.R.** and **Wightman, W.G.** (1994) Palaeovalleys and protozoan assemblages in a Late Carboniferous cyclothem, Sydney Basin, Nova Scotia. *Sedimentology*, **41,** 699–719.

**Gilbert, G.K.** (1877) *Report on the Geology of the Henry Mountains*. Government Printing Office, Washington, DC.

**Gregory, K.J.** (Ed). (1983) *Background to Palaeohydrology*. John Wiley, Chichester.

**Gregory, K.J., Lewin, J.** and **Thornes, J.B.** (Eds). (1987) *Palaeohydrology in Practice*. John Wiley.

**Gregory, K.J., Starkel, L.** and **Baker, V.R.** (Eds). (1996) *Global Continental Palaeohydrology*. John Wiley.

**Grootes, P.M., Stuiver, M., White, J.W.C., Johnsen, S.** and **Jouzel, J.** (1993) Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores. *Nature*, **366,** 552–554.

**Hallet, B., Hunter, L.** and **Bogen, J.** (1996) Rates of erosion and sediment evacuation by glaciers: a review of field data and their implications. *Global Planet. Change*, **12,** 213–235.

**Haq, B.U., Hardenbol, J.** and **Vail, P.R.** (1987) Chronology of fluctuating sea-levels since the Triassic. *Science*, **235,** 1156–1167.

**Haq, B.U., Hardenbol, J.** and **Vail, P.R.** (1988) Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. In: *Sea-Level Changes: an Integrated Approach* (Ed. by C. K. Wilgus, B. S. Hastings, C. G. S. C. Kendall, H. W. Posamentier, C. A. Ross and J. C. Van Wagoner), *Spec. Publ. Soc. Econ. Paleont. Miner.*, **42,** 71–108.

**Hays, J.D., Imbrie, J.** and **Shackleton, N.J.** (1976) Variations in the earth's orbit: Pacemaker of the ice ages. *Science*, **194,** 1121–1132.

**Helland-Hansen, W.** and **Gjelberg, J.G.** (1994) Conceptual basis and variability in sequence stratigraphy: a different perspective. *Sedim. Geol.*, **92,** 31–52.

**Heller, P.L.** and **Paola, C.** (1996) Downstream changes in alluvial architecture: an exploration of controls on channel-stacking patterns. *J. Sedim. Res.*, **66,** 297–306.

**Hovius, N.** (1998) Controls on sediment supply by large rivers. In: *Relative Role of Eustasy, Climate, and Tectonism in Continental Rocks* (Ed. by K. W. Shanley and P. J. McCabe), *Spec. Publ. Soc. Econ. Paleont. Miner.*, **59,** 3–16.

**Hovius, N.** (1999) Macro scale process-systems of mountain belt erosion. In: *Geomorphology and Global Tectonics* (Ed. by M. A. Summerfield), pp. 77–105. John Wiley, Chichester.

**Hovius, N.** and **Leeder, M.** (1998) Clastic sediment supply to basins. *Basin Res.*, **10,** 1–5.

**Howell, J.A.** and **Flint, S.S.** (1996) A model for high resolution sequence stratigraphy within extensional basins. In: *High Resolution Sequence Stratigraphy: Innovations and Applications* (Ed. by J. A. Howell and J. F. Aitken). *Spec. Publ. Geol. Soc.*, **104,** 129–138.

**Huggenberger, P.** (1993) Radar facies: recognition of facies patterns and heterogeneities within Pleistocene Rhine gravels, NE Switzerland. In: *Braided Rivers* (Ed. by J. L. Best and C. S. Bristow), *Spec. Publ. Geol. Soc.*, **75,** 163–176.

**Hurrell, J.W.** (1995) Decadal trends in the North Atlantic Oscillation regional temperatures and precipitation. *Science*, **269,** 676–679.

**Imbrie, J.** and **Imbrie, K.** (1979) *Ice Ages*. Harvard University Press, Cambridge, MA.

**Imbrie, J., Hays, J.D., Martinson, D.G., McIntyre, A., Mix, A.C., Moreley, J.J., Pisias, N.G., Prell, W.L.** and **Shackleton, N.J.** (1984) The orbital theory of Pleistocene climate: support from a revised chronology of the marine $\delta^{18}O$ record. In: *Milankovitch and Climate* (Ed. by A. L. Berger, J. Imbrie, J. Hays, G. Kukla and B. Saltzman), pp. 269–306. Reidel.

**Jervey, M.T.** (1988) Quantitative geological modeling of siliciclastic rock sequences and their seismic expression. In: *Sea-Level Changes: an Integrated Approach* (Ed. by C. K. Wilgus, B. S. Hastings, C. G. S. C. Kendall, H. W. Posamentier, C. A. Ross and J. C. Van Wagoner), *Spec. Publ. Soc. Econ. Paleont. Miner.*, **42,** 47–69.

**Johnsen, S.J., Clausen, H.B., Dansgaard, W., Fuhrer, K., Gundestrup, N., Hammer, C.U., Iversen, P., Jouzel, J., Stauffer, B.** and **Steffensen, J.P.** (1992) Irregular glacial interstadials recorded in a new Greenland ice core. *Nature*, **359,** 311–313.

**Kasse, K., Vandenberghe, J.** and **Bohncke, S.** (1995) Climatic change and fluvial dynamics of the Maas during the late Weichselian and early Holocene. *Palâoklimaforschung*, **14,** 123–150.

**Khan, I.A., Bridge, J.S., Kappelman, J.** and **Wilson, R.** (1997) Evolution of Miocene fluvial environments, eastern Potwar plateau, northern Pakistan. *Sedimentology*, **44,** 221–251.

**Knighton, D.** (1998) *Fluvial Forms and Processes*. Edward Arnold, London.

**Knox, J.C.** (1976) Concept of the Graded Stream. In: *Theories of Landform Development* (Ed. by W. N. Melhorn and R. C. Flemel), pp. 169–198. Publications in Geomorphology, State University of New York at Binghamton, Binghamton, NY.

**Knox, J.C.** (1983) Responses of river systems to Holocene climates. In: *Late Quaternary Environments of the United States,* Vol. 2*, the Holocene* (Ed. by H. E. Wright and S. C. Porter), pp. 26–41. University of Minnesota Press.

**Knox, J.C.** (1987) Climatic influence on Upper Mississippi Valley floods. In: *Flood Geomorphology* (Ed. by V. R. Baker, R. C. Kochel and P. C.Patton), pp. 279–300. John Wiley and Sons, New York.

**Knox, J.C.** (1993) Large increases in flood magnitude in response to modest changes in climate. *Nature*, **361,** 430–432.

**Knox, J.C.** (1996) Fluvial systems since 20,000 yrs BP. In: *Global Continental Palaeohydrology* (Ed. by K. J. Gregory, L. Starkel and V. R. Baker), pp. 87–108. John Wiley and Sons, New York.

**Kocurek, G.** (1998) Aeolian system response to external forcing factors – a sequence stratigraphic view of the Saharan region. In: *Quaternary Deserts and Climatic Change* (Ed. by A. S. Alsharhan, K. Glennie, G. L. Whittle and C. G. S. C. Kendall), pp. 327–337. Balkema Press.

**Kocurek, G.** and **Havholm, K.G.** (1993) Eolian sequence stratigraphy: A conceptual framework. In: *Siliciclastic Sequence Stratigraphy: Recent Developments and Applications* (Ed. by P. Weimer and H. W. Posamentier), *Am. Assoc. Petrol. Geol. Mem.*, **58,** 393–410.

**Koss, J.E., Ethridge, F.G.** and **Schumm, S.A.** (1994) An experimental study of the effects of base-level change on fluvial, coastal plain and shelf systems. *J. Sedim. Res.*, **B64,** 90–98.

**Kozarski, S.** and **Rotnicki, K.** (1977) Valley floors and changes of river channel patterns in the north Polish Plain during the late Würm and Holocene. *Quaestiones Geographicae*, **4,** 51–93.

**Kraus, M.J.** (1987) Integration of channel and floodplain suites, II. Vertical relations of alluvial paleosols. *J. Sedim. Petrol.*, **57,** 602–612.

**Kutzbach, J.E., Gallimore, R., Harrison, S.P., Behling, P., Selin, R.** and **Laarif, F.** (1997) Climate and biome simulations for the last 21,000 years. *Quat. Sci. Rev.*, **17,** 473–506.

**Lambeck, K.** (1993) Glacial rebound and sea-level change: an example of a relationship between mantle and surface processes. In: *Relationships Between Mantle Processes and Geological Processes at or Near the Earth's Surface* (Ed. by R. Wortel, U. Hansen and R. Sabadini), *Tectonophysics*, **223,** 15–37.

**Lamothe, L.** (1918) Les anciennes nappes alluviales et lignes de Rivage du bassin de la Somme et leurs rapports avec celles de la Meditarranee occidentale. *Bull. Soc. Geol., Fr.*, **18,** 3–58.

**Langbein, W.B.** and **Schumm, S.A.** (1958) Yield of sediment in relation to mean annual sediment. *Trans. Am. Geophys Union.*, **39,** 1076–1084.

**Lane, E.W.** (1955) The importance of fluvial morphology in hydraulic engineering. *Am. Soc. Civil Eng. Proc.*, **81** (745), 1–17.

**Lau, N.-C.** (1988) Variability of the observed midlatitude storm tracks in relation to low-frequency changes in the circulation pattern. *J. Atmos. Sci.*, **45,** 2718–2743.

**Leckie, D.A.** (1994) Canterbury Plains, New Zealand – Implications for sequence stratigraphic models. *Am. Assoc. Petrol. Geol. Bull.*, **78,** 1240–1252.

**Leclair, S.F., Bridge, J.S.** and **Wang, F.** (1997) Preservation of cross-strata due to migration of subaqueous dunes over aggrading and non-aggrading beds: comparison of experimental data with theory. *Geosci. Canada*, **24,** 55–66.

**Leeder, M.R.** (1975) Pedogenic carbonates and flood sediment accretion rates: a quantitative model for alluvial arid-zone lithofacies. *Geol. Mag.*, **112,** 257–270.

**Leeder, M.R.** (1978) A quantitative stratigraphic model for alluvium, with special reference to channel deposit density and interconnectedness. In: *Fluvial Sedimentology* (Ed. by A. D. Miall), *Can. Soc. Petrol. Geol. Mem.*, **5,** 587–596.

**Leeder, M.R. and Stewart, M.D.** (1996) Fluvial incision and sequence stratigraphy: alluvial responses to relative sea-level fall and their detection in the geologic record. In: *Sequence Stratigraphy in British Geology* (Ed. by S. P. Hesselbo and D. N. Parkinson), *Spec. Publ. Geol. Soc.*, **103,** 25–39.

**Leeder, M.R., Mack, G.H., Peakall, J.** and **Salyards, S.L.** (1996) First quantitative test of alluvial stratigraphic models: Southern Rio Grande rift, New Mexico. *Geology*, **24,** 87–90.

**Leeder, M.R., Harris, T.** and **Kirkby, M.J.** (1998) Sediment supply and climate change: implications for basin stratigraphy. *Basin Res.*, **10,** 7–18.

**Legarreta, L.** and **Uliana, M.A.** (1998) Anatomy of hinterland depositional sequences: Upper Cretaceous fluvial strata, Neuquen Basin, West-Central Argentina. In: *Relative Role of Eustasy, Climate, and Tectonism in Continental Rocks* (Ed. by K. W. Shanley and P. J. McCabe), *Spec. Publ. Soc. Econ. Paleont. Miner.*, **59,** 83–92.

**Leopold, L.B.** and **Bull., W.B.** (1979) Base level, aggradation, and grade. *Proc. Am. Phil. Soc.*, **123,** 168–202.

**Leopold, L.B.** and **Maddock, T.** (1953) The Hydraulic Geometry of Stream Channels and Some Physiographic Implications. *Prof. Pap. United States Geol. Surv.*, **252.**

**Lewin, J.** (1989) Floods in fluvial geomorphology. In: *Floods: Hydrological, Sedimentological, and Geomorphological Implications* (Ed. by K. Beven and P. Carling), pp. 265–284. John Wiley, Chichester.

**Libby, W.F.** (1952) *Radiocarbon Dating*. University of Chicago Press, Chicago.

**Lowe, J.J.** and **Walker, M.J.C.** (1997) *Reconstructing Quaternary Environments*. Addison-Wesley Longman, Harlow.

**Mack, G.H., James, W.C.** and **Monger, H.C.** (1993) Classification of paleosols. *Geol. Soc. Am. Bull.*, **105,** 129–136.

**Mackey, S.D.** and **Bridge, J.S.** (1995) Three-dimensional model of alluvial stratigraphy: theory and application. *J. Sedim. Res.*, **B65,** 7–31.

**Mackin, J.H.** (1948) Concept of the graded river. *Geol. Soc. Am. Bull.*, **59,** 463–512.

**Macklin, M.G.** and **Lewin, J.** (1993) Holocene river alluviation in Britain. *Z. Geomorph. N. F. (Suppl.)-Bd.*, **88,** 109–122.

**Makaske, B.** (1998) Anastomosing rivers. *Nederl. Geogr. Studies*, **249,** 1–287.

**Mandier, P.** (1988) *Le Relief de la Moyenne VallÈe du Rhone au Tertiaire et au Quaternaire*. Doc. du BGRM, No 151, Paris.

**Martinsen, O.J., Ryseth, A., Helland-Hansen, W., Flesche, H., Torkildsen, G.** and **Idil, S.** (1999) Stratigraphic base level and fluvial architecture. Ericson Sandstone (Campanian), Rock Springs Uplift, W. Wyoming, USA. *Sedimentology*, **46,** 235–260.

**McCarthy, P.J.** and **Plint, A.G.** (1998) Recognition of interfluve seqeunce boundaries: Integrating paleopedology and sequence stratigraphy. *Geology*, **26,** 387–390.

**McMahon, T.A., Finlayson, B.L., Haines, A.** and **Srikanthan, R.** (1987) Runoff variability: a global perspective. In: *The Influence of Climate Change and Climate Variability on the Hydrologic Regime and Water Resources* (Proceedings of the Vancouver Symposium, August 1987). *IAHS Publ.*, **168,** 3–11.

**McMahon, T.A., Finlayson, B.L., Haines, A.T.** and **Srikanthan, R.** (1992) Global Runoff. *Continental Comparisons of Annual Flows and Peak Discharges*. Catena Paperback, Catena-Verlag.

**Meade, R.H., Yuzyk, T.R.** and **Day, T.J.** (1990) Movement and storage of sediment in rivers of the United States and Canada. In: *Surface Water Hydrology* (Ed. by M. G. Wolman and H. C. Riggs) *Geological Society of America, Geology of North America Series*, **Vol. 0-1,** pp. 255–280.

**Merritts, D.** and **Ellis, M.** (1994) Introduction to special section on tectonics and topography. *J. Geophys. Res.*, **99,** 12135–12141.

**Merritts, D.J., Vincent, K.R.** and **Wohl, E.E.** (1994) Long river profiles, tectonism, and eustasy: a guide to interpreting fluvial terraces. *J. Geophys. Res.*, **99,** 14031–14050.

**Miall, A.D.** (1985) Architectural element analysis: a new method of facies analysis applied to fluvial deposits. *Earth-Sci. Rev.*, **22,** 261–308.

**Miall, A.D.** (1991) Stratigraphic sequences and their chronostratigraphic correlation. *J. Sedim. Petrol.*, **61,** 497–505.

**Miall, A.D.** (1995) Description and interpretation of fluvial deposits: a critical perspective. *Sedimentology*, **42,** 370–384.

**Miall, A.D.** (1996) *The Geology of Fluvial Deposits*. Springer, Berlin.

**Miall, A.D.** (1997) *The Geology of Stratigraphic Sequences*. Springer, Berlin.

**Milliman, J.D.** and **Syvitski, J.P.M.** (1992) Geomorphic / tectonic control on sediment discharge to the ocean: the importance of small mountainous streams. *J. Geol.*, **100,** 525–544.

**Mitchum, R.M. Jr, Vail, P.R.** and **Thompson III, S.** (1977) Seismic stratigraphy and global changes of sea-level, part 2: the depositional sequence as a basic unit for stratigraphic analysis. In: *Seismic Stratigraphy – Applications to Hydrocarbon Exploration* (Ed. by C. E. Payton), *Am. Assoc. Petrol. Geol. Mem.*, **27,** 53–62.

**Molnar, P.** and **England, P.** (1990) Late Cenozoic uplift of mountain ranges and global climate change: chicken or egg? *Nature*, **346,** 29–34.

**Molnar, P., England, P.** and **Martinod, J.** (1993) Mantle dynamics, uplift of the Tibetan Plateau, and the Indian monsoon. *Rev. Geophys.*, **31,** 357–396.

**Morton, R.A.** and **Suter, J.R.** (1996) Sequence stratigraphy and composition of Late Quaternary shelf margin deltas, northern Gulf of Mexico. *Am. Assoc. Petrol. Geol. Bull.*, **80,** 505–530.

**Muto, T.** and **Steel, R.J.** (1997) Principles of regression and transgression: the nature of the interplay between accommodation and sediment supply. *J. Sedim. Res.*, **67,** 994–1000.

**Nanson, G.C.** and **Croke, J.C.** (1992) A genetic classification of floodplains. *Geomorphology*, **4,** 459–486.

**Nanson, G.C.** and **Knighton, A.D.** (1996) Anabranching rivers; their cause, character and classification. *Earth Surf. Proc. Landf.*, **21,** 217–239.

**Nanson, G.C., Young, R.Y., Prices, D.M.** and **Rust, B.R.** (1988) Stratigraphy, sedimentology, and Late Quaternary chronology of the channel country of western Queensland. In: *Fluvial Geomorphology of Australia* (Ed. by R. F. Warner), pp. 151–175. Academic Press, Sydney.

**Nanson, G.C., Price, D.M.** and **Short, S.A.** (1992) Wetting and drying of Australia over the past 300 ka. *Geology*, **20,** 791–794.

**North, C.P.** (1996) The prediction and modelling of subsurface fluvial stratigraphy. In: *Advances in Fluvial Dynamics and*

*Stratigraphy* (Ed. by P. A. Carling and M. R. Dawson), pp. 395–508. John Wiley, Chichester.

**North American Commission on Stratigraphic Nomenclature.** (1983) North American Stratigraphic Code. *Am. Assoc. Petrol. Geol. Bull.*, **67,** 841–875.

**Nummedal, D., Riley, G.W.** and **Templet, P.L.** (1993) High-resolution sequence architecture: a chronostratigraphic model based on equilibrium profile studies. In: *Sequence Stratigraphy and Facies Associations* (Ed. by H. W. Posamentier, C. P. Summerhayes, B. U. Haq and G. P. Allen), *Spec. Publ. Int. Assoc. Sediment.*, **18,** 55–68.

**Nystuen, J.P.** (1998) History and development of sequence stratigraphy. In: *Sequence Stratigraphy – Concepts and Applications* (Ed. by F. M. Gradstein, K. O. Sandvik and N. J. Milton), pp. 31–116. Elsevier, Amsterdam.

**Olsen, H.** (1990) Astronomical forcing of meandering river behavior: Milankovitch cycles in Devonian of East Greenland. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **79,** 99–115.

**Olsen, H.** (1994) Orbital forcing on continental depositional systems – lacustrine and fluvial cyclicity in the Devonian of East Greenland. In: *Orbital Forcing and Cyclic Sequences* (Ed. by P. L. de Boer and D. G. Smith), *Spec. Publ. Int. Assoc. Sediment.*, **19,** 429–438.

**Olsen, H.** and **Larsen, P.H.** (1993) Structural and climatic controls on fluvial depositional systems: Devonian of East Greenland. In: *Alluvial Sedimentation* (Ed. by M. Marzo and C. Puigdefabregas), *Spec. Publ. Int. Assoc. Sediment.*, **17,** 401–423.

**Olsen, T., Steel, R.H., Høgseth, K., Skar, T.** and **Røe, S.-L.** (1995) Sequential architecture in a fluvial succession: sequence stratigraphy in the Upper Cretaceous Mesaverde Group, Price Canyon. *Utah. J. Sedim. Res.*, **B65,** 265–280.

**Orton, G.J.** and **Reading, H.G.** (1993) Variability of delatic processes in terms of sediment supply, with particular emphasis on grain size. *Sedimentology*, **40,** 475–512.

**Page, K., Nanson, G.** and **Price, D.** (1996) Chronology of Murrumbidgee River palaeochannels on the Riverine Plain, southeastern Australia. *J. Quat. Sci.*, **11,** 311–326.

**Paola, C.** (2000) Quantitative models of sedimentary basin filling. *Sedimentology*, **47** (Suppl. 1), 121–178.

**Paola, C., Heller, P.L.** and **Angevine, C.L.** (1992) The large-scale dynamics of grain size variation in alluvial basins, 1. Theory. *Basin Res.*, **4,** 73–90.

**Parrish, J.T.** (1998) *Interpreting Pre-Quaternary Climate from the Geologic Record.* Columbia University Press, New York.

**Payton, C.E.** (Ed). (1977) Seismic Stratigraphy – Applications to Hydrocarbon Exploration. *AAPG Mem.*, **27**.

**Pazzaglia, F.J., Gardner, T.W.** and **Merritts, D.J.** (1998) Bedrock fluvial incision and longitudinal profile development over geologic time scales determined by fluvial terraces. In: *Rivers Over Rock: Fluvial Processes in Bedrock Channels* (Ed. by K. J. Tinkler and E. E. Wohl), *AGU Monogr.*, **107,** 207–235.

**Peltier, W.R.** (1998) Post-glacial variations in the level of the sea: implications for climate dynamics and solid-earth geophysics. *Rev. Geophys.*, **36,** 603–689.

**Penck, A.** and **Brückner, E.** (1909) *Die Alpen im Eiszeitalter*. Tauchnitz, Leipzig.

**Perlmutter, M.A.** and **Matthews, M.D.** (1989) Global cyclostratigraphy: a model. In: *Quantitative Dynamic Straitgraphy* (Ed. by T. A. Cross), pp. 233–260. Prentice Hall, Englewood Cliffs.

**Pillans, B., Chappell, J.** and **Naish, T.R.** (1998) A review of the Milankovitch climatic beat: template for Plio-Pleistocene sea-level changes and sequence stratigraphy. *Sedim. Geol.*, **122,** 5–21.

**Pinter, N.** and **Brandon, M.T.** (1997) How erosion builds mountains. *Sci. Am.*, **276,** 74–79.

**Pirazzoli, P.A.** (1996) *Sea-Level Changes*. John Wiley, Chichester.

**Pons, L.J.** (1957) De geologie, de bodemvorming en de waterstaatkundige ontwikkeling van het Land van Maas en Waal en een gedeelte van het Rijk van Nijmegen. *Versl. Landbouwk. Onderz.*, **63-11,** 1–156.

**Porter, S.C.** (1989) Some geological implications of average Quaternary glacial conditions. *Quat. Res.*, **32,** 245–262.

**Posamentier, H.W.** and **Allen, G.P.** (1993) Siliclastic sequence stratigraphic patterns in foreland ramp-type basins. *Geology*, **21,** 455–458.

**Posamentier, H.W.** and **Vail, P.R.** (1988) Eustatic controls on clastic deposition II – Sequence and systems tract models. In: *Sea-Level Changes: an Integrated Approach* (Ed. by C. K. Wilgus, B. S. Hastings, C. G. S. C. Kendall, H. W. Posamentier, C. A. Ross and J. C. Van Wagoner), *Spec. Publ. Soc. Econ. Paleont. Miner.*, **42,** 125–154.

**Posamentier, H.W.** and **Weimer, P.** (1993) Siliciclastic sequence stratigraphy and petroleum geology ñ Where to from here? *Am. Assoc. Petrol. Geol. Bull.*, **77,** 731–742.

**Posamentier, H.W., Jervey, M.T.** and **Vail, P.R.** (1988) Eustatic controls on clastic deposition I – Conceptual frameworks. In: *Sea-Level Changes: an Integrated Approach* (Ed. by C. K. Wilgus, B. S. Hastings, C. G. S. C. Kendall, H. W. Posamentier, C. A. Ross and J. C. Van Wagoner), *Spec. Publ. Soc. Econ. Paleont. Miner.*, **42,** 109–124.

**Posamentier, H.W., Allen, G.P., James, D.P.** and **Tesson, M.** (1992) Forced regressions in a sequence stratigraphic framework: Concepts, examples, and exploration significance. *Am. Assoc. Petrol. Geol. Bull.*, **76,** 1687–1709.

**Potter, P.E.** (1978) Significance and origin of big rivers. *J. Geol.*, **86,** 13–33.

**Powell, J.W.** (1875) *Exploration of the Colorado River of the West and its Tributaries*. Government Printing Office. Washington, DC.

**Probst, J.-L.** (1989) Hydroclimatic fluctuations of some European Rivers since 1800. In: *Historical Changes of Large Alluvial Rivers, Western Europe* (Ed. by G. E. Petts), pp. 41–55. John Wiley and Sons, New York.

**Retallack, G.J.** (1986) Fossil soils as grounds for interpreting long-term controls on ancient rivers. *J. Sedim. Petrol.*, **56,** 1–18.

**Retallack, G.J.** (1990) *Soils of the Past – An Introduction to Palaeopedology*. Unwin Hyman, Boston.

**Richards, K.** (1982) *Rivers*. Methuen, London.

**Rogers, J.C.** (1997) North Atlantic storm track variability and its association to the North Atlantic Oscillation and climate variability of Northern Europe. *J. Clim.*, **10,** 1635–1647.

**Rotnicki, K.** (1991) Retrodiction of palaeodischarges of meandering and sinuous alluvial rivers and its palaeohydroclimatic implications. In: *Temperate Palaeohydrology* (Ed. by L. Starkel, K. J. Gregory and J. B. Thornes), pp. 431–471. John Wiley, Chichester.

**Salter, T.** (1993) Fluvial scour and incision: models for their influence on the development of realistic reservoir geometries. In: *Characterization of Fluvial and Aeolian Reservoirs* (Ed. by C. P. North and D. J. Prosser), *Spec. Publ. Geol. Soc.*, **73,** 33–51.

**Saucier, R.T.** (1994) *Geomorphology and Quaternary Geologic History of the Lower Mississippi Valley*. Mississippi River Commission, Vicksburg.

**Saucier, R.T.** (1996) A contemporary appraisal of some key Fiskian concepts with emphasis on Holocene meander belt formation and morphology. *Engineering Geol.*, **45,** 67–86.

**Schirmer, W.** (1995) Valley bottoms in the late Quaternary. *Z. Geomorph. N. F. (Suppl.)-Bd.*, **100,** 27–51.

**Schumm, S.A.** (1965) Quaternary palaeohydrology. In: *The Quaternary of the United States* (Ed. by H. E. Wright and D. G. Frey), pp. 783–794. Princeton University Press.

**Schumm, S.A.** (1968a) River Adjustment to Altered Hydrologic Regimen: the Murrumbidgee River and Palaeochannels, Australia. *Prof. Pap. United States Geol. Surv.*, **598**.

**Schumm, S.A.** (1968b) Speculations concerning palaeohydrologic controls of terrestrial sedimentation. *Geol. Soc. Am. Bull.*, **79,** 1573–1588.

**Schumm, S.A.** (1985) Explanation and extrapolation in geomorphology: seven reasons for geologic uncertainty. *Trans. Jap Geomorphol. Union.*, **6,** 1–18.

**Schumm, S.A.** (1977) *The Fluvial System*. John Wiley, New York.

**Schumm, S.A.** (1991) *To Interpret the Earth. Ten Ways to Be Wrong.* Cambridge University Press. Cambridge.

**Schumm, S.A.** (1993) River response to baselevel change: Implications for sequence stratigraphy. *J. Geol.*, **101,** 279–294.

**Schumm, S.A.** and **Brakenridge, G.R.** (1987) River responses. In: *North America and Adjacent Oceans During the Last Deglaciation* (Ed. by W. F. Ruddiman and H. E. Wright), The Geology of North America. K-3, pp. 221–240. Geological Society of America.

**Shackleton, N.J.** (1987) Oxygen isotopes, ice volume and sea-level. *Quat. Sci. Rev.*, **6,** 183–190.

**Shackleton, N.J.** and **Opdyke, N.D.** (1973) Oxygen isotope and palaeomagnetic stratigraphy of equatorial Pacific core V28–238: oxygen isotope temperatures and ice volumes on a $10^5$ and $10^6$ year scale. *Quat. Res.*, **3,** 39–55.

**Shanley, K.W.** and **McCabe, P.J.** (1991) Predicting facies architecture through sequence stratigraphy: an example from the Kaiparowits Plateau. *Utah. Geology*, **19,** 742–745.

**Shanley, K.W.** and **McCabe, P.J.** (1993) Alluvial architecture in a sequence stratigraphic framework: a case study from the Upper Cretaceous of southern Utah, U.S.A. In: *Quantitative Modelling of Clastic Hydrocarbon Reservoirs and Outcrop Analogs* (Ed. by S. S. Flint and I. D. Bryant), *Spec. Publ. Int. Assoc. Sediment.*, **15,** 21–55.

**Shanley, K.W.** and **McCabe, P.J.** (1994) Perspectives on the sequence stratigraphy of continental strata: report of a working group at the 1991 NUNA Conference on High Resolution Sequence Stratigraphy. *Am. Assoc. Petrol. Geol. Bull.*, **74,** 544–568.

**Slingerland, R.L.** and **Snow, R.S.** (1988) Stability analysis of a rejuvenated fluvial system. *Z. Geomorph. N. F. (Suppl.)-Bd.*, **67,** 93–102.

**Sloss, L.L.** (1962) Stratigraphic models in exploration. *Am. Assoc. Petrol. Geol. Bull.*, **46,** 1050–1057.

**Sloss, L.L.** (1963) Sequences in the cratonic interior of North America. *Geol. Soc. Am. Bull.*, **74,** 93–113.

**Smith, G.A.** (1994) Climatic influences on continental deposition during late-stage filling of an extensional basin, southeastern Arizona. *Geol. Soc. Am. Bull.*, **106,** 1212–1228.

**Smith, N.D., Cross, T.A., Dufficy, J.P.** and **Clough, S.R.** (1989) Anatomy of an avulsion. *Sedimentology*, **36,** 1–23.

**Stanley, D.J. Warne, A.G.** (1993) Nile Delta: recent geological evolution and human impact. *Science*, **260,** 628–634.

**Starkel, L.** (1987) The evolution of European rivers – a complex response. In: *Palaeohydrology in Practice* (Ed. by K. J. Gregory, J. Lewin and J. B. Thornes), pp. 333–339. John Wiley, Chichester.

**Starkel, L.** (1991) Long-distance correlation of fluvial events in the temperate zone. In: *Temperate Palaeohydrology* (Ed. by L. Starkel, K. J. Gregory and J. B. Thornes), pp. 473–495. John Wiley, Chichester.

**Starkel, L., Gregory, K.J.** and **Thornes, J.B.** (Eds). (1991) *Temperate Palaeohydrology*. John Wiley, Chichester.

**Straffin, E.C., Blum, M.D., Colls, A.** and **Stokes, S.** (2000) Alluvial stratigraphy of the Loire and Arroux Rivers, Burgundy, France. *Quaternaire*, **10,** 271–282.

**Summerfield, M.A.** (1985) Plate tectonics and landscape development on the African continent. In: *Tectonic Geomorphology* (Ed. by M. Morisawa and J. Hack), pp. 27–51. Allen and Unwin, Boston.

**Suter, J.R.** and **Berryhill, H.L. Jr** (1985) Late Quaternary shelf-margin deltas, northwest Gulf of Mexico. *Am. Assoc. Petrol. Geol. Bull.*, **69,** 77–91.

**Talling, P.J.** (1998) How and where do incised valleys form if sea-level remains above the shelf edge? *Geology*, **26,** 87–90.

**Tebbens, L.A., Veldkamp, A., Westerhoff, W.** and **Kroonenberg, S.B.** (1999) Fluvial incision and channel downcutting as a response to Lateglacial and Early Holocene climate change: the River Meuse lower reach. *J. Quat. Sci.*, **14,** 59–75.

**Tesson, M., Allen, G.P.** and **Ravenne, C.** (1993) Late Pleistocene shelf-perched lowstand wedges on the Rhone continental shelf. In: *Sequence Stratigraphy and Facies Associations* (Ed. by H. W.Posamentier, C. P. Summerhayes, B. U. Haq and G. P. Allen), *Spec. Publ. Int. Assoc. Sediment.*, **18,** 183–196.

**Tesson, M.** and **Gensous, B.** (1998) Líenregistrement des cycles climatiques et eustatiques quaternaires de marges recentes du bassin Nord-Mediterraneen. *C. R. Academie des Sciences, Paris, Sciences de la Terre Des Planetes*, **326,** 121–127.

**Toomey, R.S., Blum, M.D.** and **Valastro, S. Jr.** (1993) Late Quaternary climates and environments of the Edwards Plateau, Texas. *Glob. Plan. Change*, **7,** 299–320.

**Törnqvist, T.E.** (1993) Holocene alternation of meandering and anastomosing fluvial systems in the Rhine-Meuse Delta (central Netherlands) controlled by sea-level rise and subsoil erodibility. *J. Sedim. Petrol.*, **63,** 683–693.

**Törnqvist, T.E.** (1994) Middle and late Holocene avulsion history of the River Rhine (Rhine-Meuse delta, Netherlands). *Geology*, **22,** 711–714.

**Törnqvist, T.E.** (1995) Discussion: alluvial architecture of the Quaternary Rhine–Meuse river system in the Netherlands. *Geol. Mijnb.*, **74,** 183–186.

**Törnqvist, T.E.** (1998) Longitudinal profile evolution of the Rhine–Meuse system during the last deglaciation: interplay of climate change and glacio-eustasy? *Terra Nova*, **10,** 11–15.

**Törnqvist, T.E., Wallinga, J., Murray, A.S., De Wolf, H., Cleveringa, P.** and **De Gans, W.** (2000) Response of the Rhine-Meuse system (west-central Netherlands) to the last Quaternary glacio-eustatic cycles: a first assessment. *Global Planet. Change*, in press.

**Torres, W.F.J.** and **Jain, S.C.** (1984) *Aggradation and Degradation of Alluvial Channel Beds*. Iowa Institute for Hydraulic Research Report 274, University of Iowa, Iowa City.

**Tushingham, A.M.** and **Peltier, W.R.** (1992) Validation of the ICE-3G model of Würm-Wisconsin deglaciation using a global database of relative sea-level histories. *J. Geophys. Res.*, **97,** 3285–3304.

**Vail, P.R., Mitchum, R.M.** and **Thompson III, S.** (1977) Seismic stratigraphy and global changes of sea-level, part 4: global cycles of relative changes of sea-level. In: *Seismic Stratigraphy – Applications to Hydrocarbon Exploration* (Ed. by C. E. Payton), *Am. Assoc. Petrol. Geol. Mem.*, **26,** 83–97.

**Van den Berg, J.H.** (1995) Prediction of alluvial channel pattern of perennial rivers. *Geomorphology*, **12,** 259–279.

**Vandenberghe, J.** (1995) Postglacial river activity and climate: state of the art and future prospects. *Palâoklimaforschung*, **14,** 1–9.

**Van de Plassche, O.** (1982) Sea-level change and water-level movements in the Netherlands during the Holocene. *Meded. Rijks Geol. Dienst*, **36,** 1–93.

**Van der Woude, J.D.** (1984) The fluviolagoonal palaeoenvironment in the Rhine/Meuse deltaic plain. *Sedimentology*, **31,** 395–400.

**Van Dijk, G.J., Berendsen, H.J.A.** and **Roeleveld, W.** (1991) Holocene water level development in The Netherlands' river area; implications for sea-level reconstruction. *Geol. Mijnb.*, **70,** 311–326.

**Van Wagoner, J.C.** (1995a) Overview of sequence stratigraphy of foreland basin deposits: Terminology, summary of papers, and glossary of sequence stratigraphy. In: *Sequence Stratigraphy of Foreland Basin Deposits* (Ed. by J. C. Van Wagoner and G. T. Bertram), *Am. Assoc. Petrol. Geol. Mem.*, **64,** ix–xxi.

**Van Wagoner, J.C.** (1995b) Sequence stratigraphy and marine to nonmarine facies architecture of foreland basin strata, Book Cliffs, Utah, U.S.A. In: *Sequence Stratigraphy of Foreland Basin Deposits* (Ed. by J. C. Van Wagoner and G. T. Bertram), *Am. Assoc. Petrol. Geol. Mem.*, **64,** 137–223.

**Van Wagoner, J.C.** (1998) Sequence stratigraphy and marine to nonmarine facies architecture of foreland basin strata, Book Cliffs, Utah, U.S.A.: Reply. *Am. Assoc. Petrol. Geol. Bull.*, **82,** 1607–1618.

**Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S.** and **Hardenbol, J.** (1988) An overview of the fundamentals of sequence stratigraphy and some key definitions. In: *Sea-Level Changes: an Integrated Approach* (Ed. by C. K. Wilgus, B. S. Hastings, C. G. S. C. Kendall, H. W. Posamentier, C. A. Ross and J. C. Van Wagoner), *Spec. Publ. Soc. Econ. Paleont. Miner.*, **42,** 39–45.

**Van Wagoner, J.C., Mitchum, R.M., Campion, K.M.** and **Rahmanian, V.D.** (1990) *Siliciclastic Sequence Stratigraphy in Well Logs, Cores, and Outcrops: Concepts for High-Resolution Correlation of Time and Facies: AAPG Methods in Exploration 7*. AAPG, Tulsa.

**Veldkamp, A.** and **Van den Berg, M.W.** (1993) Three-dimensional modelling of Quaternary fluvial dynamics in a climo-tectonic dependent system. A case study of the Maas record (Maastricht, The Netherlands). *Global Planet. Change*, **8,** 203–218.

**Veldkamp, A.** and **Van Dijke, J.J.** (1998) Modelling long-term erosion and sedimentation processes in fluvial systems: A case study for the Allier/Loire system. In: *Palaeohydrology and Environmental Change* (Ed. by G. Benito, V. R. Baker and K. J. Gregory), pp. 53–66. John Wiley, Chichester.

**Walker, R.G.** (1990) Facies modeling and sequence stratigraphy. *J. Sedim. Petrol.*, **60,** 777–786.

**Walker, R.G.** (1992) Facies, facies models and modern stratigraphic concepts. In: *Facies Models* (Ed. by R. G. Walker and N. P. James), pp. 1–14. Geological Association of Canada, St. John's.

**Walling, D.E.** (1983) The sediment delivery problem. *J. Hydrol.*, **65,** 209–237.

**Walling, D.E.** and **Webb, B.W.** (1983) Patterns of sediment yield. In: *Background to Palaeohydrology* (Ed. by K. J. Gregory), pp. 69–100. John Wiley, Chichester.

**Walling, D.E.** and **Webb, B.W.** (1996) Erosion and sediment yield: a global overview. In: *Erosion and Sediment Yield: Global and Regional Perspectives* (Ed. by D. E. Walling and B. W. Webb), *Int. Assoc. Hydrol. Sci. Publ.*, **236,** 3–20.

**Wanless, H.R.** and **Weller, J.M.** (1932) Correlation and extent of Pennsylvanian cyclothems. *Geol. Soc. Am. Bull.*, **43,** 1003–1016.

**Waylen, P.R.** (1996) Global hydrology in relation to palaeohydrological change. In: *Global Continental Palaeohydrology* (Ed. by K. J. Gregory, L. Starkel and V. R. Baker), pp. 61–86. John Wiley, Chichester.

**Wescott, W.A.** (1993) Geomorphic thresholds and complex response of fluvial systems – some implications for sequence stratigraphy. *Am. Assoc. Petrol. Geol. Bull.*, **77,** 1208–1218.

**Wheeler, H.E.** (1964) Baselevel, lithostratigraphic surface, and time stratigraphy. *Geol. Soc. Am. Bull.*, **75,** 599–610.

**Wilgus, C.K., Hastings, B.S., Kendall, C.G.S.C., Posamentier, H.W., Ross, C.A.** and **Van Wagoner, J.C.** (Eds) (1988) Sea-Level Changes. An Integrated Approach. *Spec. Publ. Soc. Econ. Paleont. Miner.*, **42,** 1–407.

**Williams, G.P.** (1978) Bankfull discharge of rivers. *Water Res. Res.*, **14,** 1141–1154.

**Williams, G.P.** (1987) Palaeofluvial estimates from dimensions of former channels and meanders. In. *Flood Geomorphology* (Ed. by V. R. Baker, R. C. Kochel, and P. C. Patton), pp. 321–334. John Wiley and Sons.

**Willis, B.** (1993a) Ancient river systems in the Himalayan foredeep, Chinji village area, northern Pakistan. *Sedim. Geol.*, **88,** 1–76.

**Willis, B.** (1993b) Evolution of Miocene fluvial systems in the Himalayan foredeep through a two kilometer thick succession in northern Pakistan. *Sedim. Geol.*, **88,** 77–122.

**Willis, B.J.** and **Behrensmeyer, A.K.** (1994) Architecture of Miocene overbank deposits in northern Pakistan. *J. Sedim. Res.*, **B64,** 60–67.

**Wohl, E.E.** and **Enzel, Y.** (1996) Data for palaeohydrology. In: *Global Continental Palaeohydrology* (Ed. by K. J. Gregory, L. Starkel and V. R. Baker), pp. 23–60. John Wiley, Chichester.

**Wood, L.J., Ethridge, F.G.** and **Schumm, S.A.** (1993) The effects of rate of base-level fluctuation on coastal-plain, shelf and slope depositional systems: an experimental approach. In: *Sequence Stratigraphy and Facies Associations* (Ed. by H. W. Posamentier, C. P. Summerhayes, B. U. Haq and G. P. Allen), *Spec. Publ. Int. Assoc. Sediment.*, **18,** 43–53.

**Wood, L.J., Ethridge, F.G.** and **Schumm, S.A.** (1994) An experimental study of the influence of subaqueous shelf angles on coastal plain and shelf deposits. In: *Siliciclastic Sequence Stratigraphy. Recent Developments and Applications* (Ed. by P. Weimer and H. W. Posamentier), *Am. Ass. Petrol. Geol. Mem.*, **58,** 381–391.

**Wright, H.E. Jr** (1987) Synthesis: Land south of the ice sheets. In: *North America and Adjacent Oceans During the Last Deglaciation* (Ed. by W. F.Ruddiman and H. E. Wright), GSA Geology of North America, Vol. K-3, pp. 479–488.

**Wright, H.E., Jr, Kutzbach, J.E., Webb, T., Ruddiman, W.F.,**

**Street-Perrott, F.A.** and **Bartlein, P.J.** (Eds). (1993) *Global Climates Since the Last Glacial Maximum*. University of Minnesota Press, Minneapolis.

**Wright, V.P.** (Ed). (1986) *Paleosols*. Princeton University Press, Princeton.

**Wright, V.P.** and **Marriott, S.B.** (1993) The sequence stratigraphy of fluvial depositional systems: the role of floodplain sediment storage. *Sedim. Geol.*, **86,** 203–210.

**Wyroll, K.-H.** (1988) Determining the causes of Pleistocene stream aggradation in the central coastal areas of western Australia. *Catena*, **15,** 39–51.

**Yang, C.-S.** and **Nio, S.-D.** (1993) Application of high resolution sequence stratigraphy to the Upper Rotliegend in the offshore. In: *Siliciclastic Sequence Stratigraphy* (Ed. by P. Weimer and H. W. Posamentier), *Am. Assoc. Petrol. Geol. Mem.*, **58,** 285–316.

**Yoshida, S., Miall, A.D.** and **Willis, A.** (1998) Sequence stratigraphy and marine to nonmarine facies architecture of foreland basin strata, Book Cliffs, Utah, U.S.A. *Am. Assoc. Petrol. Geol. Bull.*, **82,** 1596–1606.

**Zaitlin, B.A., Dalrymple, R.W.** and **Boyd, R.** (1994) The stratigraphic organization of incised-valley systems associated with relative sea-level change. In: *Incised-Valley Systems: Origin and Sedimentary Sequences* (Ed. by R. W. Dalrymple, R. Boyd and B. A. Zaitlin), *Spec. Publ. Soc. Econ. Paleont. Miner.*, **51,** 45–60.

**Zaleha, M.J.** (1997) Fluvial and lacustrine palaeoenvironments of the Miocene Siwalik Group, Khaur area, northern Pakistan. *Sedimentology*, **44,** 349–368.

**Zhang, Z., Sun, K.** and **Yin, J.** (1997) Sedimentology and sequence stratigraphy of the Shanxi Formation (Lower Permian) in the northwestern Ordos Basin, China: an alternative sequence model for fluvial strata. *Sedim. Geol.*, **112,** 123–136.