ALLUVIAL VALLEYS AND ALLUVIAL SEQUENCES: TOWARDS A GEOMORPHIC ASSESSMENT

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Abstract: Criteria for identifying alluvial-valley fills in the geological record have commonly been derived from coastal areas, where high-magnitude glacioeustatic fluctuations generate predictable systems tracts. In contrast, inland alluvial valleys formed in response to climatic, tectonic, and intrinsic events of varied magnitude and duration. Sequence boundaries and architecture reflect a variety of causes, typically mediated through changes in the river's equilibrium profile and equilibrium floodplain height. We evaluate valley and sequence models using Quaternary examples from southern Asia and Australia. For these areas, proxy records are well established for climate and sea level, but the scarcity of records for tectonic activity and intrinsic channel changes hamper an interpretation of stratigraphic events.

On the large alluvial plains of northern India and central Australia, climatic changes have radically affected sediment and water discharge on timescales as short as 10^3 to 10^4 years. Periods of incision and aggradation generate discontinuity-bounded sequences (aggradational–degradational rhythms), and reaches may vary between valley and channel morphology over short periods and distances. Across Asia, changes in monsoonal precipitation have caused near-synchronous incision and aggradation in varied tectonic settings. However, mature interfluve paleosols correlative with valley bases may be local or absent on these large plains, where small interfluve channels, eolian dunes, and lakes aggrade while mainstem valleys incise. Gullied floodplains, adjacent to valleys and tributaries, and terrace deposits are useful indicators of incised systems. Climatic effects appear to be underrepresented in interpretations of ancient alluvial sequences in general.

Angular unconformities, channel diversion, and incised and tilted fans near major faults reflect tectonic controls on architecture, and soft-sediment deformation and rare surface ruptures testify to earthquake events. In smaller basins such as the Rio Grande Rift of southwestern USA, alluvial architecture reflects both tectonic and climatic controls. Channel-body amalgamation may not be a good proxy for tectonically induced subsidence, especially for megafans at upland exits where a low degree of amalgamation may reflect rapid accumulation rather than rapid subsidence and accommodation creation.

Multistory valleys and extensive multistory and single-story sheets are present in inland and coastal alluvial areas. However, below the Australian continental shelf, seismic profiles identify entrenched channels and channel belts rather than the valley fills that are commonly assumed to form under such conditions. This example shows that sea-level fall and river extensions need not generate deeply incised fluvial valleys in coastal settings.

Key words: alluvial valleys, sequences, systems tracts, interfluves, aggradation, incision, climate, monsoon, tectonics

INTRODUCTION

Since the late 1970s, ancient valley fills have received considerable attention because sand-prone valley fills constitute hydrocarbon reservoirs and aquifers. A large body of research has shown that downstream coastal valleys have reasonably predictable fills because cutting and filling respond strongly to base-level transit cycles driven by rapid, high-magnitude glacioeustatic changes, at least for Quaternary systems. Numerous sequence-stratigraphic models have linked valley dynamics with sea-level fall and rise (e.g., Shanley and McCabe 1994; Catuneanu 2006), and many coastal-valley fills have been described (Boyd et al. 2006; Dalrymple 2006).

We know much less about upstream alluvial valleys beyond the range of sea-level influence, where valley cutting and filling reflects the complex interplay of tectonics, climate, sediment supply, and river drainage changes. Despite their economic potential, upstream valley fills have proved difficult to identify in the rock record because valley and extra-valley materials are similar. Additionally, even for some Quaternary systems, key forcing factors lack proxy records that would allow reliable identification of controlling factors.

In this paper, we review some ancient alluvial-valley fills (Table 1), and discuss sequence-stratigraphic models for alluvial systems (Fig. 1) and some problems of distinguishing channels and valleys in Quaternary systems. We then discuss criteria for identifying alluvial-valley fills, elaborating on criteria set out by Fielding and Gibling (2005) and Gibling (2006), and drawing in particular on our own experience of Quaternary river systems and their stratigraphic record in Asia and Australia, which are illustrated from photographs in the accompanying DVD. Finally, we compare upstream (alluvial) and downstream (coastal) valley systems, and suggest guidelines for recognizing alluvial-valley fills and applying appropriate sequence models to alluvial successions. Although many earlier researchers have reached conclusions similar to those set out here, we hope that the present paper will serve a useful purpose in applying knowledge from several well-documented geomorphic settings to the rock record.

The Asian Quaternary study areas share a monsoonal setting and lie as much as 1200 km upstream of the present tidal limit (Fig. 2A). They include tectonically active areas of the Himalayan Foreland Basin drained by the Ganga and Brahmaputra rivers, especially the Ganga Plains of northern India. Information is also included from the Sabarmati River in the Khambat Graben of northwestern India, an active extensional basin. The Australian rivers (Fig. 3) include the Burdekin, Fitzroy, and other rivers that drain eastward from the Great Dividing Range and extended during the late Quaternary across the

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TABLE 1.—Selected literature examples of alluvial valleys from the geological record (Neoproterozoic to Pleistocene). The entries for coastal alluvial tracts represent predominantly fluvial fills and are a small sample of a large literature set.

Formation & Age	Thickness	Width	Fill	Comments	Authors
Inland Alluvial Tracts					
a) Inland valleys incised into bedrock					
Sis Cgl., Eocene – Oligocene, Spain	1.4 km	6–7.5 km	Coarsening up: conglomerates, channel sandstones, overbank fines, lacustrine limestone, and coal. Fining-up large-scale cycles. Many channel bodies within complex valley fill.	Valley along a transfer zone in thrust belt, long-lived (20 m.y.). Fining-up cycles due to sediment pulses from tectonism. Marginal unconformities pass into central disconformities. Syntectonic valley development. Topography probably <120 m during active life.	Vincent & Elliott 1997; Vincent 1999, 2001
Ocejo Fm., Pennsylvanian, Spain	25–450 m	75–1200 m+	Complex fills, conglomerate abundant, sandstone, mudstone, coal. Filled sinkholes on karsted base.	Large valleys filled by screes, debris and stream flows, floodplains, lakes, and mires. Trends follow basement structures, and incision probably linked to tectonics. Valley forms tightened by deformation.	Iwaniw 1984; Alonso 1989
Chinle Fm., Triassic, SW USA	15–90 m	1–8 km	Multistory conglomerate and sandstone bodies, minor mudstone at higher levels. Stories 1–10 m thick.	Valleys on major unconformity, with steep walls. Braided and locally meandering rivers, pass up into widespread sheets as valleys filled. Storey width similar to valley width, so streams were not underfit.	Blakey & Gubitosa,1984; Dubiel 2009
Kyrock Sandstone, Pennsylvanian, E USA	66 m	5 km	Conglomerates, pebbly sandstone, mud clasts. Fining-up cycles to 6 m thick. Shales with coal above.	Valley on Miss./Penn. Unconformity, in foreland basin. Stepped, terraced margins, and braided and meandering channels. Length >83 km, dendritic tributary pattern. Top sandstones extend beyond valley.	Sedimentation Seminar 1978
b) Inland valleys incised into strata of similar age					
Miocene, Italy	60 m	2 km	Coarse massive conglomerate, with planar cross-stratified conglomerate downvalley. Sandstone at top, some fines.	Braided-river channels a few metres deep with highly concentrated flows. Stacked sequences. Cut into lake clays in extensional basin. Incision and high sediment supply linked to igneous updoming.	Pascucci et al. 2006

TABLE 1.—*Continued.*

Formation & Age	Thickness	Width	Fill	Comments	Authors
Blairmore Gp., Cretaceous, Alberta, Canada	8.5 - 100 m	220 m - 22 km	Coarse conglomerate, with basal grooves and flutes, mudstone blocks, sandstone more common above.	Braided-river channels with gravel sheets and diagonal bars; high gradient and supply, variable discharge. Cut in fines, in foreland basin. Source 400 km distant, sources shifted to yield short-lived sediment pulses.	Leckie & Krystinik 1995
Brigham Gp, Neoproterozoic, W USA	>60 m	100s m to >2 km	Conglomerates (some matrix-supported), pebbly sandstones, nested channel sets, minor siltstone.	Stream and debris flows, possible estuarine levels, overlain by fluvial/ marine beds. Linked to Varanger glacial event, but tectonic events also possible.	Levy et al. 1994
Whiteclay Gravel Beds, Miocene, USA	20 m	300 m	Stratified sandstone and coarse conglomerate. Multistory fill, with aggradational stacking and incision.	Valley margins steep to vertical, locally overhanging. Traceable for 35 km, with sharp bends. Fault-controlled fill of a slot-canyon, with fault reactivation and probable stacking. Channels were up to 4 m deep and tens of metres wide.	Fielding et al. 2007
Prasident Sandstone, Pennsylvanian, Germany	15–50 m	100s m to >35 km	Multistory sandstones, with mudstone clasts. Massive siltstone from bank collapse.	Low-sinuosity channels in foreland basin. Thickest zones (30–45 m) at margins and where bodies amalgamated.	Hampson et al. 1999
Joggins Fm., Pennsylvanian, ECanada	To 6.5 m	>350 m	Multistory sandstone / mudstone bodies, with slumps, pedogenic clasts. 3 or more stories 1.6–4.4 m thick.	Small valley fills on alluvial plain, with stepped margins. No correlative paleosols or erosional surfaces within adjacent floodplain deposits, and not apparently part of regional stratigraphic surfaces.	Rygel & Gibling 2006
Coastal Alluvial Tracts					
Dunvegan Fm., Cretaceous, W. Canada	15–40 m	1–10 km	Multistory sandstones with mudstone clasts, up to 50% mudstone in seaward locations. Stories up to 8 m thick. Topmost stories heterolithic.	Meandering rivers within valleys, traceable for 330 km downstream across delta area of 50,000 km^2 within foreland basin. Steep margins cut into marine beds downdip and non-marine beds updip. Incision due to eustasy, but rivers deflected by faults and forebulge.	Plint 2002; Plint & Wadsworth 2003, 2006

TABLE 1.—*Continued.*

Formation & Age	Thickness	Width	Fill	Comments	Authors
Pleistocene, Indonesia	To 41 m	To 5 km	Sands to clays with shell fragments above, and some floodplain deposits within valley. Data from 3D seismic.	High- and low-sinuosity and braided systems, on alluvial/coastal plain, adjacent to volcanic arc. Traceable for >200 km, channels within valleys and meander scroll-bars and terraces prominent. Small incised tributary valleys, with dendritic patterns.	Posamentier 2001
Pleistocene, Malay Basin	40 m	>11.5 km	Composition not known. Data from 3D seismic.	Valley fill has meander belt with scroll bars at base, and incised tributaries with gullied margins. Associated fluvial systems include braided rivers, small meander belts, and ribbon bodies in 57 m interval of coastal plain.	Miall 2002

continental shelf. We also discuss the Channel Country rivers that drain internally to Lake Eyre, as well as rivers of the Riverine Plain that drain westward from the Great Dividing Range.

In discussing alluvial models, there are both advantages and disadvantages in choosing Quaternary examples from India and Australia. As an advantage, we have been able to identify key areas where detailed alluvial information can be linked to the geomorphic setting. The chronology of the strata is known with sufficient certainty to test incision and alluviation events against some forcing factors. In particular, climatic and alluvial events can be compared with unusual certainty—something that is rarely possible for the older sedimentary record.

As a disadvantage, the examples represent a limited set of global tectonic and climatic settings. The Asian plains experience the formidable Southwest Indian Monsoon, and the Australian sites experience major tropical cyclonic storms. Climatic factors may be less effective in areas where extreme events are less frequent. Although the Himalayan Foreland Basin is tectonically active, some of our field sites lie near the distal margin of the foreland basin and currently experience only modest tectonic activity. The Australian inland plains are largely inactive tectonically, although neotectonic activity has been recorded locally. In order to include a more balanced set of examples, we refer to other Neogene alluvial units, several in active extensional basins, for which exceptionally good datasets exist. A broader issue, discussed briefly, is whether the Quaternary icehouse period characterized by strong glacial and interglacial rhythms is relevant to much of the rock record.

ANCIENT ALLUVIAL-VALLEY FILLS

Table 1 lists literature examples of the relatively few alluvial-valley fills in upstream settings in the literature for which detailed information is available. In addition to our Indian and Australian case studies, much literature is available for Neogene alluvial strata in inland settings beyond the range of oceanic effects. Table 2 presents a small selection of this literature, chosen to represent datasets of sufficiently high resolution to allow an assessment of controlling factors. Although the assessments generally refer to stratigraphic intervals within the basin fills, some individual alluvial events can be compared with proxy records.

Inland Alluvial Tracts

Rock units in Table 1 that represent inland alluvial tracts range in age from Neoproterozoic to Pleistocene. Several examples are valley fills on bedrock unconformities, which are relatively easy to identify (Gibling 2006), and their fills are dominated by conglomerates laid down by flood flows, hyperconcentrated flows, and debris flows. In contrast, few valley fills have been identified in alluvial-plain successions where valley fills are less distinctive and where their bases may not correspond to prominent paleosols or other floodplain surfaces (Rygel and Gibling 2006). In all examples in Table 1, valley dimensions are considerably greater than those of the component channels—commonly an order of magnitude larger and probably much more in large valley fills such as the 450-m-thick fills of the Ocejo Formation (Iwaniw 1984). However, Joggins Formation valley dimensions are little larger than those of their component channels (Rygel and Gibling 2006). Valley fills are also important components of alluvial fan and volcanoclastic apron deposits (e.g., Smith 1988).

Where the original authors discussed controls on valley incision and filling, a link to tectonic activity is commonly the preferred explanation. Many of the examples in Table 1 follow fault lines or were influenced by deformation (Vincent 2001; Fielding et al. 2007), and their fills may reflect high rates of sediment supply caused, for example, by hinterland drainage changes and igneous doming (Leckie and Krystinik 1995; Pascucci et al. 2006). For none of these examples has a clear link been demonstrated between cutting and filling and climatic changes.

Both tectonic and climatic effects are prominent in the examples of Table 2. In the Rio Grande Rift in New Mexico (Mack et al. 2006), basin-bounding and intrabasinal faults influenced alluvial architecture during a period of aggradation, whereas glacial–interglacial cycles

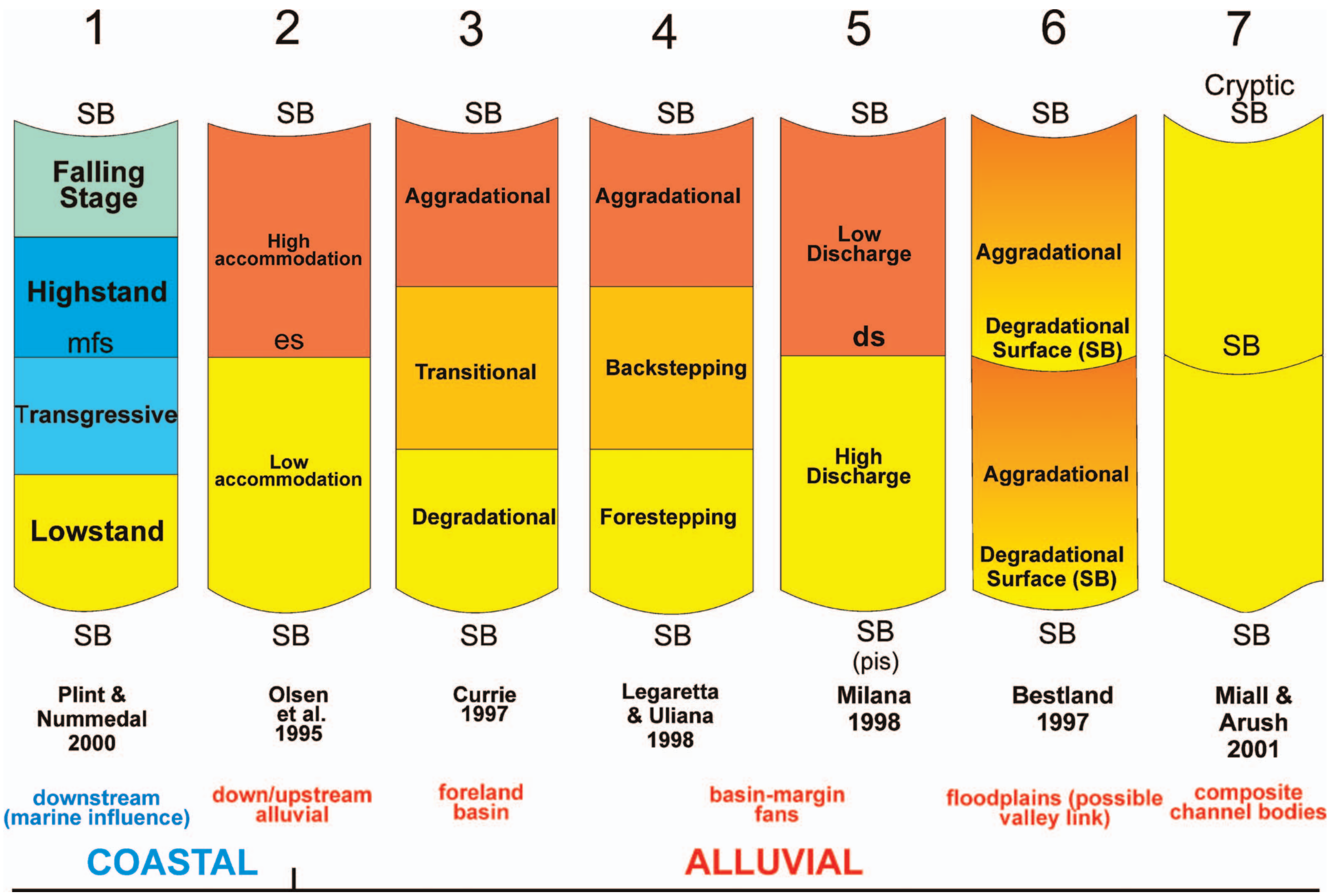

FIGURE 1.—Literature examples of sequence-stratigraphic models and systems tracts for alluvial strata. Most examples include reference to valley fills and floodplain deposits. Systems tracts in adjacent columns are not intended to be equivalent. SB = sequence boundary; mfs = maximum flooding surface; es = expansion surface; ds = downlap surface; pis = proximal incision surface. For Column 1, Wright and Marriott (1993) referred the main phase of alluvial buildup to the transgressive systems tract. For column 2, see also Martinsen et al. (1999), McCarthy et al. (1999), and Catuneanu (2006). For Column 6, see also Törnqvist et al. (2003). For Column 5, see also Weissmann et al. (2002). For Column 6, see also Bull (1991) and Gibling et al. (2005). All terms were identified as systems tracts, apart from those in Column 6.

were important during a later degradational phase when tectonic activity was reduced. Climatic effects were prominent in the St. David Formation of Arizona (Smith 1994) based on correlation between facies and paleosol stable isotope values. In the Pannonian Basin of Hungary (Nádor et al. 2003), cyclic alluvial patterns recorded by grain size and magnetic susceptibility provide a good correlation with Milankovitch effects. For all three areas, magnetostratigraphy provided age control.

Coastal Alluvial Tracts

For ancient coastal plains, valley fills that consist of fluvial strata or contain both fluvial and marine strata have been described by many authors. Three examples are shown in Table 1. Cretaceous valley fills of the Dunvegan Formation of western Canada are especially noteworthy because drainage systems were mapped across a large delta and for more than 300 km downstream (Plint 2002). The studies by Posamentier (2001) and Miall (2002) are of particular interest because they represent valley fills documented using 3D seismic profiles from (currently) offshore areas. Both studies illustrate the heterogeneity of alluvial systems in coastal areas, as well as demonstrating high-resolution geomorphic features such as incised tributaries and underfit valleys. Other detailed bedrock examples were recorded by Willis (1997) and Garrison and van den Bergh (2006).

These fills lie in Segment 3 of incised-valley systems (Boyd et al. 2006), landward of the transgressive estuarine–marine limit and extending to the inland limit of sea-level control on fluvial systems. Measured from the average highstand shoreline, the landward limit of coastal onlap due to sea-level rise is typically less than 400 km inland, varying with hinterland sediment supply and the gradient of the alluvial surface (Blum and Törnqvist 2000).

Table 2 presents information for three Quaternary coastal tracts where controlling factors have been especially thoroughly evaluated. For the Gulf of Mexico, both glacioeustasy and climate exerted a major control on alluvial architecture (Blum and Aslan 2006). In coastal areas of northern Italy, subsidence rates varied greatly and, in concert with glacioeustasy, influenced the creation of accommodation and architectural patterns (Amorosi and Milli 2001). However, Amorosi et al. (2008) used palynological datasets to demonstrate that finer-scale alluvial architecture corresponds to changes in climatic parameters. For the Rhine–Meuse Delta and the Rhine

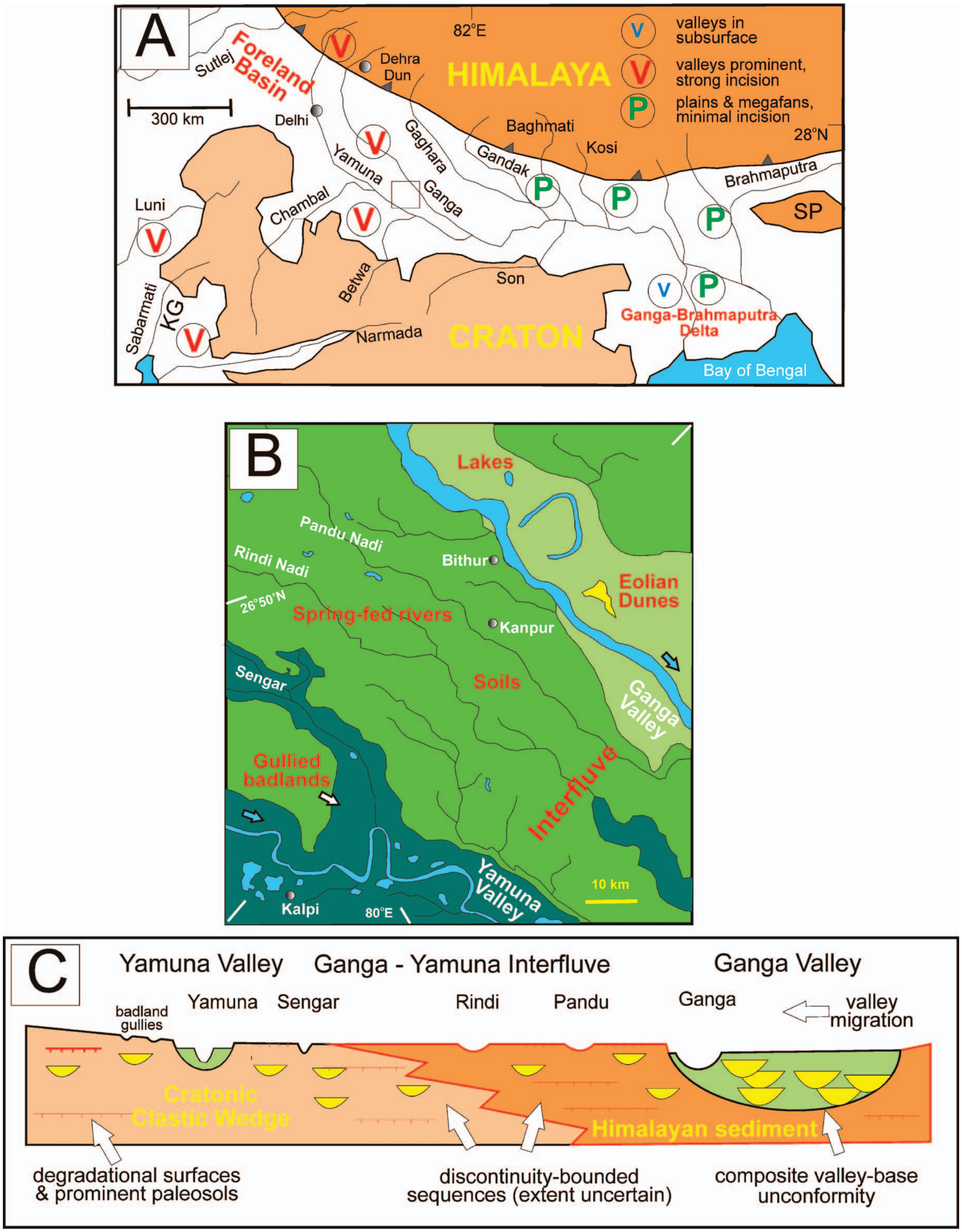

FIGURE 2.—Alluvial plains of southern Asia, for which geomorphic and Quaternary information have been drawn on in this study. A) Major rivers of the Himalayan Foreland Basin (referred to here as the Ganga Plains) and adjacent areas, to show general distribution of incised and non-incised reaches. The Yamuna, Ganga, and Gaghara rivers are separated by extensive interfluves traversed by small channels sourced on the plains by springs from monsoon rains. Some data are derived from structurally controlled depressions (duns) within the Himalayan foothills. KG = Khambat Graben, SP = Shillong Plateau. B) Landform map for Ganga–Yamuna interfluve (box in Part A), to illustrate the range of deposystems present; modified from Gibling et al. (2005). C) Schematic cross section of southern Ganga Plains (line of section shown by white lines in Part B) to show relationships of valleys, channels, and associated surfaces; modified from Sinha et al. (2009).

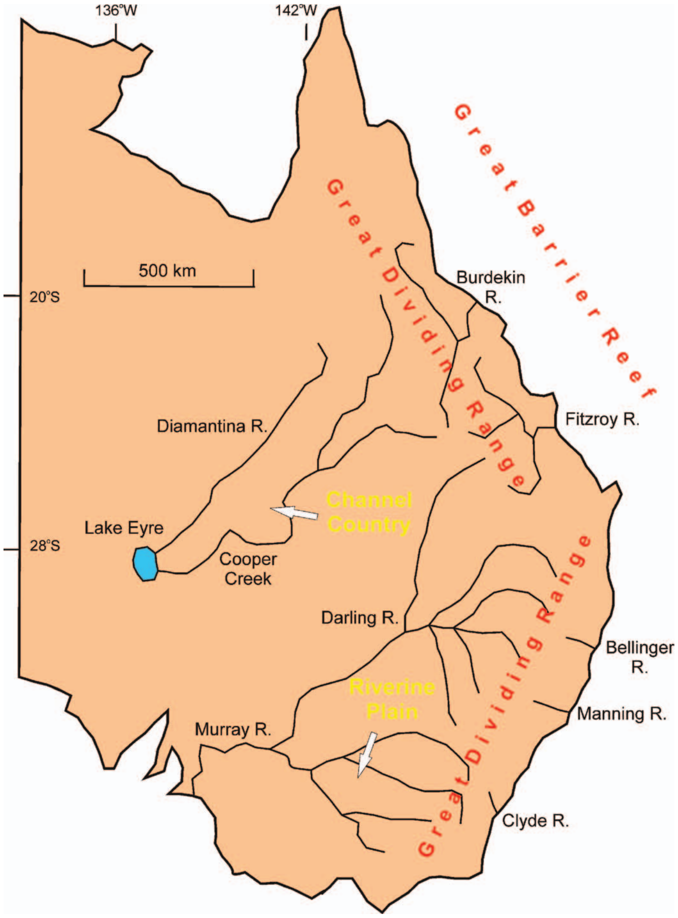

FIGURE 3.—Rivers of eastern Australia discussed in the text.

Valley, local faults and climate influenced deposition, although the overwhelming effect of glacioeustasy in coastal areas is evident (Erkens et al. 2009; Hijma et al. 2009).

ALLUVIAL VALLEYS AND SEQUENCE-STRATIGRAPHIC MODELS

Figure 1 illustrates some models that have applied sequence-stratigraphic concepts to alluvial successions, emphasizing studies that have given particular attention to inland areas. Using systems tracts identified downstream (Column 1), several studies have traced bounding surfaces into upstream alluvium based on tidal indicators, stacking patterns, and alluvial architecture (Shanley and McCabe 1991). Studies have commonly linked valley fills and multistory channel bodies to low-accommodation periods and channel bodies isolated within floodplain deposits to high-accommodation periods. In a widely used model, Wright and Marriott (1993) attributed most downstream alluvial accumulation to the transgressive systems tract. McCarthy et al. (1999) and Plint and Wadsworth (2003) identified low- and high-accommodation periods driven largely by sea level (Column 2). In their examples, valley fills and prominent paleosols (low-accommodation indicators) alternate with lacustrine, wetland, and cumulative floodplain deposits (high-accommodation indicators).

The concept of low- and high-accommodation systems tracts was extended to areas far inland by Martinsen et al. (1999). They identified expansion surfaces (Column 2) where sediments overlap valleys to cover the adjoining plain, and also recognized the balance between accommodation (A) and sediment supply (S) through an A/S ratio designed to represent stratigraphic base level. Catuneanu (2006) adopted low- and high-accommodation systems tracts as a robust framework for many alluvial systems. For a foreland basin, Currie (1997) identified degradational, transitional, and aggradational systems tracts (Column 3), with valley fills developed on degradational surfaces. Currie noted that systematic changes in systems-tract thickness imply that subsidence rates controlled accommodation. For fault-bounded basins, Gawthorpe et al. (1994) noted the importance of sediment supply and accommodation, with subsidence rates at hanging walls sufficiently high to cancel out all but the most rapid sea-level oscillations. In such settings, sequence boundaries may be poorly developed, and aggradational successions are prominent (Davies and Gibling 2003).

For basin-margin fans, two South American studies identified systems tracts that reflect alternate sediment accumulation and incision (Columns 4 and 5) and incorporate progradational and downlap stratal geometries. Legaretta and Uliana (1998) identified forestepping, backstepping and aggradational systems tracts, attributed to climate or tectonism, with valleys filled during backstepping periods. Flume experiments and field studies by Milana (1998) identified sequences generated as a result of alternate low and high discharge, without change in subsidence rate. Although they did not specify systems tracts, Weissmann et al. (2002) and Bennett et al. (2006) studied Californian fans influenced by alpine glaciation, and mapped widespread sequences ~ 15–30 m thick, bounded by valley fills and prominent paleosols. Incision took place under conditions of declining sediment:water ratio during late glacial and interglacial periods, causing loss of accumulation space, a basinward shift of deposition, and prolonged soil formation on the fan surfaces. During the main glacial periods, aggradation took place under conditions of increased sediment supply that filled the valleys and expanded over the fan surfaces with an increase in accumulation space. Long-term subsidence allowed preservation of stacked sequences. For fans in Montana, Ritter et al. (1995) identified synchronous aggradation and entrenchment of fans in varied tectonic settings, linked to climatically induced variation in discharge and sediment load.

For floodplain-dominated deposits in a variety of tectonic settings, numerous authors have recognized discontinuity-bounded sequences linked in many cases to valley fills (Column 6). The sequences represent alternate aggradation and degradation and have commonly been attributed to changes in climate and vegetation (Bull 1991; Bestland 1997; Gibling et al. 2005). Cryptic sequence boundaries (Column 7) may be recognized in stacked fluvial channel bodies or valley fills on the basis of changes in petrography and paleoflow direction (Miall and Arush 2001).

For alluvial settings, some authors have linked accommodation to "stratigraphic base level", which defines the upper limit to deposition (Shanley and McCabe 1994; Blum and Törnqvist 2000). However, as Blum and Törnqvist point out, upper limits in a fluvial regime are defined by equilibrium floodplain heights, which depend on discharge regimes and sediment supply. The strata enter preservation space (net accommodation) when they subside below the river's equilibrium profile. This profile represents the base level of erosion or maximum depth of incision, and has also been termed "geomorphic base level". Sediment accumulates in inland valleys when the equilibrium profile rises above the valley floor. Blum and Törnqvist (2000) suggested that the term "stratigraphic base level" should be abandoned because it is the same as the upper level of accommodation and does not control anything. In the Quaternary examples discussed below, lakes are mainly small and uncommon, and their local base levels do not appear to have influenced river courses.

TABLE 2.—Selected Neogene alluvial case studies for which the authors evaluated controls on alluvial accumulation and architecture. Avulsion of alluvial reaches is a prominent feature of all these case studies.

Formation, Age and Location	Tectonic Controls	Climatic Controls	Glacioeustatic Controls	References
Inland Alluvial Tracts				
Palomas and Camp Rice Fms., New Mexico, USA, Pliocene to Pleistocene (Rio Grande Rift)	Fundamental during aggradational period (5 to 0.78 Ma), linked to changes in basin symmetry and growth, and activity on basin-bounding and intrabasinal faults. Multistoreyed channel bodies border major faults, due to tectonic drawdown of axial sediment. Axial river and alluvial fan deposits intercalated, due to channel relocation. Condensed paleosols and floodplain deposits prominent away from faults. Minimal incision.	Fundamental during degradational period with reduced tectonic activity (0.78 Ma to present). Cyclic alluvial-fan deposits with calcic paleosols linked to glacial / interglacial cycles; incision prominent.	Out of range of oceanic effects.	Leeder et al. 1996; Mack and Leeder 1999; Mack and Madoff 2005; Mack et al. 2006.
St. David Fm., Arizona, USA, Pliocene to Pleistocene (extensional basin)	Period of minimal tectonic activity.	Broad correlation of sedimentation rate, channel geometry and facies abundance with climate change as deduced from pedogenic-carbonate isotope data.	Out of range of oceanic effects.	Smith 1994
Pannonian Basin, Hungary, Quaternary (two cores each nearly 500 m long)	Active subsidence regime, but sediment changes linked to tectonics do not correlate with sedimentary cycles.	General correlation of channel and floodplain (grain-size) cycles with 40 and 100 kyr Milankovitch patterns, suggesting link to glacial / interglacial cycles.	Out of range of oceanic effects.	Nádor et al. 2003
Coastal Alluvial Tracts				
Coastal plains and deltas, Italy, Quaternary (largely core data)	Rapid subsidence locally allows accumulation of thick successions; subsidence rates influence whether accommodation is created at different stages in the glacioeustatic cycles.	Glacial and interglacial changes delineated by pollen assemblages in cores, and correlate with changes in facies architecture.	Fundamental influence on architecture, controlling valley fills, lowstand paleosols, systems tracts, and stacking patterns.	Amorosi et al. 1999a, 1999b; Amorosi and Milli 2001; Amorosi et al. 2008
Coastal and alluvial plains, Gulf of Mexico, USA (Quaternary)	Steady subsidence.	Controls allostratigraphic units, terrace strata and architecture through changes in discharge regimes and sediment concentration. Interaction between climatically controlled factors and glacioeustasy results in composite, cross-cutting and superimposed valleys with adjacent mature paleosols, with fills representing 100 kyr cycles.	Controls architecture and stacking patterns within incised valley downstream from apex of alluvial plain.	Blum 1994; Blum et al. 1994; Blum and Price 1998; Blum and Aslan 2006
Rhine-Meuse Delta and Rhine Valley, Netherlands and Germany (Quaternary)	Local faults and tectonic influence on subsidence regimes, avulsion locations, deformed longitudinal profiles, and channel orientation and diversion.	Controlled terrace formation and cut-and-fill cycles in some areas and during some periods.	Fundamental control on incision during sea-level fall and on alluvial style during sea-level rise.	Cohen et al. 2002; Törnqvist et al. 2003; Stouthamer and Berendsen 2007; Erkens et al. 2009; Hijma et al. 2009

From this overview, we identify some themes that are explored below:

- Sequence boundaries have commonly been identified in upstream alluvial areas, where they are marked by valley bases, erosional floodplain surfaces, and paleosols.
- Numerous authors have linked systems tracts to tectonically created accommodation, although the interplay of climate, source-area tectonism, and basin subsidence is frequently noted (Catuneanu 2006, p. 247). The systems tracts are typically tens to hundreds of meters thick (thick enough for regional correlation), and the identification of regional thickness variations has probably encouraged researchers to link sequence architecture to tectonically generated accommodation. In other cases, however, sequences have been referred to climatic factors, and a rise in the fluvial equilibrium profile has been noted to increase accommodation space.

MODERN VALLEYS: THE ISSUE OF FLOW CONFINEMENT

Valleys are commonly understood to be landforms that are larger (typically both deeper and wider) than the channels that they contain. Following this understanding, large floods should be confined within valleys but not necessarily within the component channels. In a widely accepted definition that draws on a comparison of valley and channel sizes, Zaitlin et al. (1994) and Boyd et al. (2006) defined an incised-valley system as a “fluvially-eroded, elongate topographic low that is typically larger than a single channel form, and is characterized by an abrupt seaward shift of depositional facies across a regionally mappable sequence boundary at its base.” Flood-frequency analysis should assist in distinguishing valleys, where flow is confined to the conduit, from channels, which frequently inundate interchannel areas.

Valleys might be expected to inundate the adjacent plains less frequently than about every thirty years. For a set of gauged alluvial channels, Williams (1978) showed that the adjoining floodplains were inundated every 1.5 years on average, with recurrence intervals from 1.01 to 32 years (see also Andrews 1980). Thus, drainage systems identified as “channels” should inundate their floodplains on timescales of a year to a few decades.

However, flood frequency is difficult to apply, for several reasons. Firstly, surveyed cross sections with gauging stations are rare in large valleys and for multichannel systems, and few gauging records extend for more than a century. In an analysis based on gauging records back to 1921 for the catastrophic 1981 Laingsburg valley flood in South Africa, Zawada (1994) noted that the flow represents a 10,000 year event if the 1981 flood is excluded, but represents a 400 year event if the flood is included. Secondly, many rivers experience periods of enhanced and reduced flood magnitude and frequency over decades to millennia (Graf et al. 1991), and flood-frequency estimates may apply only to short periods. Finally, anthropogenic structures such as canals and dams have modified water and sediment discharge in many rivers.

In monsoonal areas that experience strongly seasonal flow, assessments of valley prominence may be misleading. Rivers may appear to be small entities within large valleys at low-flow stage. However, they may fill or overtop the conduit margins during high-stage flow, rising to levels that a casual visitor can scarcely envisage.

Satellite imagery offers a means of testing whether fluvial conduits are acting (over short timescales) as valleys that routinely confine floods or as channels that frequently inundate their surroundings. For the Ganga Plains, flood maps created by the Dartmouth Flood Observatory, New Hampshire, USA, provide an exceptional view of areas covered by floodwaters from 1985 onwards. These maps can be viewed on the observatory website at http://www.dartmouth.edu/~floods/ where they can be accessed from the Master Index of DFO Rapid Response Inundation Maps (as file DFO 2007–115, FL-2007–000096-IND; summary sheets E70N30, E80N30, and E90N30). Coupled with field observations, satellite images for the Ganga Plains allow researchers to delineate areas with strong or minimal incision (Fig. 2A). On the western Ganga Plains near to and downstream from Delhi (Fig. 2A), the Ganga and Yamuna rivers are considered to occupy valleys in most reaches. They are almost entirely restricted to narrow courses, while spring-fed monsoonal rivers cause minor floods across the extensive plain (interfluve) between them. These observations accord well with anecdotal evidence from villagers that floods do not cover interfluves along parts of the Yamuna River (Tandon et al. 2006). The Gaghara and Rapti rivers and spring-fed rivers on the Ganga–Gaghara interfluve are also largely confined but flood more extensively in places.Because these Himalayan-sourced rivers are largely restricted to their valleys, the spring-fed interfluve channels may behave as independent systems, largely detached from the big rivers.

In contrast, on the eastern Ganga Plains (Fig. 2A), the Gandak, Baghmati, and Kosi rivers show extreme flooding, inundating enormous areas for prolonged periods (Jain and Sinha 2003, 2005). The braided Brahmaputra River has flooded much of the ground between bedrock areas of the Himalayan Foothills and the Shillong Plateau (Fig. 2A).

Beyond a purely morphological assessment, trends of greater or lesser flow confinement and valley prominence on the Ganga Plains appear to correlate with trends in precipitation and unit stream power of the rivers (Sinha et al. 2005; Tandon et al. 2006). Precipitation decreases systematically westward on the plains as a result of monsoonal airflows moving inland and westward up the foreland basin from the Bay of Bengal (Bookhagen and Burbank 2006). Closer to the Bay of Bengal, rivers such as the Gandak and Kosi have low slopes, lie within a zone of high rainfall, and show large water and sediment discharges, yielding low estimates of stream power (6.4–20 W/m^2). They occupy an aggradational zone where channels show minimal incision and inundate broad floodplains every year. Farther from the Bay of Bengal, rivers such as the Ganga and Yamuna have relatively high slopes, lie within a zone of modest rainfall, and show modest discharges of both sediment and water, yielding high estimates of stream power (up to 43 W/m^2). They occupy deeply incised valleys over long reaches. The Brahmaputra responds to very high precipitation and sediment yield from the Shillong Plateau and the eastern Himalayan syntaxis, and constitutes a braidbelt within a broad, tectonically controlled bedrock valley.

These observations suggest that large basins are likely to show more varied expressions of fluvial style than small basins. Although these northern Indian rivers occupy the same alluvial plain, the area is so vast that regional differences in precipitation, slope, and tectonics may cause substantial differences in fluvial behavior and, particularly, in the degree of incision and prominence of valleys. Smaller basins would be expected to show less regional variation in this respect.

CRITERIA FOR IDENTIFYING ALLUVIAL VALLEYS

In a major review of estuarine and incised-valley systems, Boyd et al. (2006) set out 14 criteria applicable to estuarine and, potentially, alluvial valleys. Table 3 lists these criteria and provides an assessment of their application to alluvial valleys in inland areas. We discuss some of these criteria in more detail below, in the light of Indian and Australian Quaternary systems, and illustrate sequence architecture for southern Asian alluvium in Figure 4.

EROSIONAL PALEOTOPOGRAPHY (CRITERION 1A OF TABLE 3)

Some, but not all, inland alluvial valleys show prominent paleotopography.

TABLE 3.—Applicability of criteria for estuarine and incised valley systems (Boyd et al. 2006) to inland alluvial valleys. Comments are based on the modern alluvial areas discussed in the text, principally in southern Asia and Australia, and on documented case studies in the ancient record (Table 1). See text for further discussion.

Criteria for Estuarine and Incised Valley Systems (Boyd et al. 2006)	Application to Inland Alluvial Valleys
1a. Erosional paleotopographic feature, base truncates underlying strata.	Erosional, base truncates strata.
1b. Erosional relief commonly >10 m.	Size is variable, and valleys with erosional relief of only a few metres are common. Some coastal and inland valleys show minimal erosional relief, whereas confluence scours may show deep incision.
2. Base and walls constitute sequence boundary, with correlative interfluve soils.	Base and walls constitute sequence boundary. Interfluve soils may border valleys, but may not be widespread. Key surfaces may not be traceable across broad interfluves, where small rivers, lakes and dunes may aggrade as largely independent systems.
3. Incised tributary valleys	Common. Large areas of gullied floodplains (badlands) with alluvial and colluvial gully fills may border valleys.
4. Base marks basinward facies shift, with proximal facies over distal. Filled mainly during base-level rise or (in fluvial systems) due to change from low to high accommodation style.	No basinward facies shift, as valley filled largely with alluvial sediment similar to associated strata. Filled mainly when sediment supply exceeds transport capacity (balance of discharge of water and sediment changes), as a result of tectonic or climatic causes. Results in local or regional rise of equilibrium profile (temporary base level of erosion, but not base level related to standing-water bodies). Valley filling not usually related to tectonically induced changes in accommodation; however, thickness changes of large-scale sediment packages may indicate accommodation effects. Temporary sediment buildup related to equilibrium floodplain heights and megafan topography. Landslides may promote filling in bedrock areas.
5. Fill onlaps base and walls due to filling on rising base level.	Sediment buildup may onlap margins, but usually due to change in sediment/water discharge (see #4). Fill may be promoted by base-level rise where valleys impeded by tributary inputs.
6. Associated with major sequence stratigraphic surfaces, including sequence boundary, maximum flooding surface, and ravinement surfaces.	Basal erosion surface, adjacent paleosols, and floodplain erosion surfaces fit criteria for sequence boundaries; stacked fills may contain cryptic sequence boundaries. Maximum flooding and ravinement surfaces not present. Systems tracts may be applicable in some circumstances (Columns 2–5 of Figure 1), but systems tracts of Column 1 inappropriate.
7a. Component channels much smaller than valley.	As for left-hand column.
7b. Floodplain and terrace surfaces may be present.	Terraces may be difficult to identify in ancient record.
8.-13. Criteria concerning estuarine facies.	Not applicable.
14. Valleys tend to follow downwarped areas, avoid upwarped zones.	Some valleys profoundly affected by tectonic activity: incision along fault lines, erosion through upwarped and tilted strata, diversion and avulsion due to tectonic elevation changes. Floodplains uplifted by earthquakes may be abandoned.

Below many modern coastal and shelf areas worldwide, valley fills with strong erosional paleotopography are prominent, and have been cut and filled largely as a consequence of glacioeustasy linked to the abundance of supplied sediment, which may vary considerably by catchment (Blum and Aslan 2006). Although there is much local variation, the timing and duration of cutting and filling correlates in general terms with glacial and interglacial chronology. For example, below the Ganga–Brahmaputra Delta, where modern channels are not incised (Fig. 2A), buried valleys extend for at least 350 km inland from the modern shoreline, filled with some 90 m of sandy sediment (Goodbred and Kuehl 2000a). The valleys filled during the lowstand of Marine Isotope Stage (MIS) 2 and the succeeding transgression, as sea-level rise promoted accommodation increase and backfilling under conditions of high sediment supply, eventually generating an even delta plain (Umitsu 1993).

In contrast, incision in the Indian alluvial plains far inland reflects multiple causes, and the history and duration of valley cutting and filling is much less predictable. Over timescales of thousands to a few tens of thousands of years, individual drainages have varied in their degree of incision, and may in some cases have alternated between "channels" and "valleys" over relatively short timescales. To illustrate the contrast with downstream glacioeustatic controls, we discuss below evidence for incision induced by climatic and tectonic factors in different parts of the Indian plains, as well as an example from inland Australia.

Climatic Controls

There is abundant evidence that climate is a major driver of valley dynamics in southern Asia. Comparison of dated sections with modeled and proxy precipitation records (Gibling et al. 2005; Bookhagen et al. 2006) suggests that fluvial activity has responded strongly to variations in the Southwest Indian Monsoon, the intensity of which reflects insolation and, to a lesser degree, glacial boundary

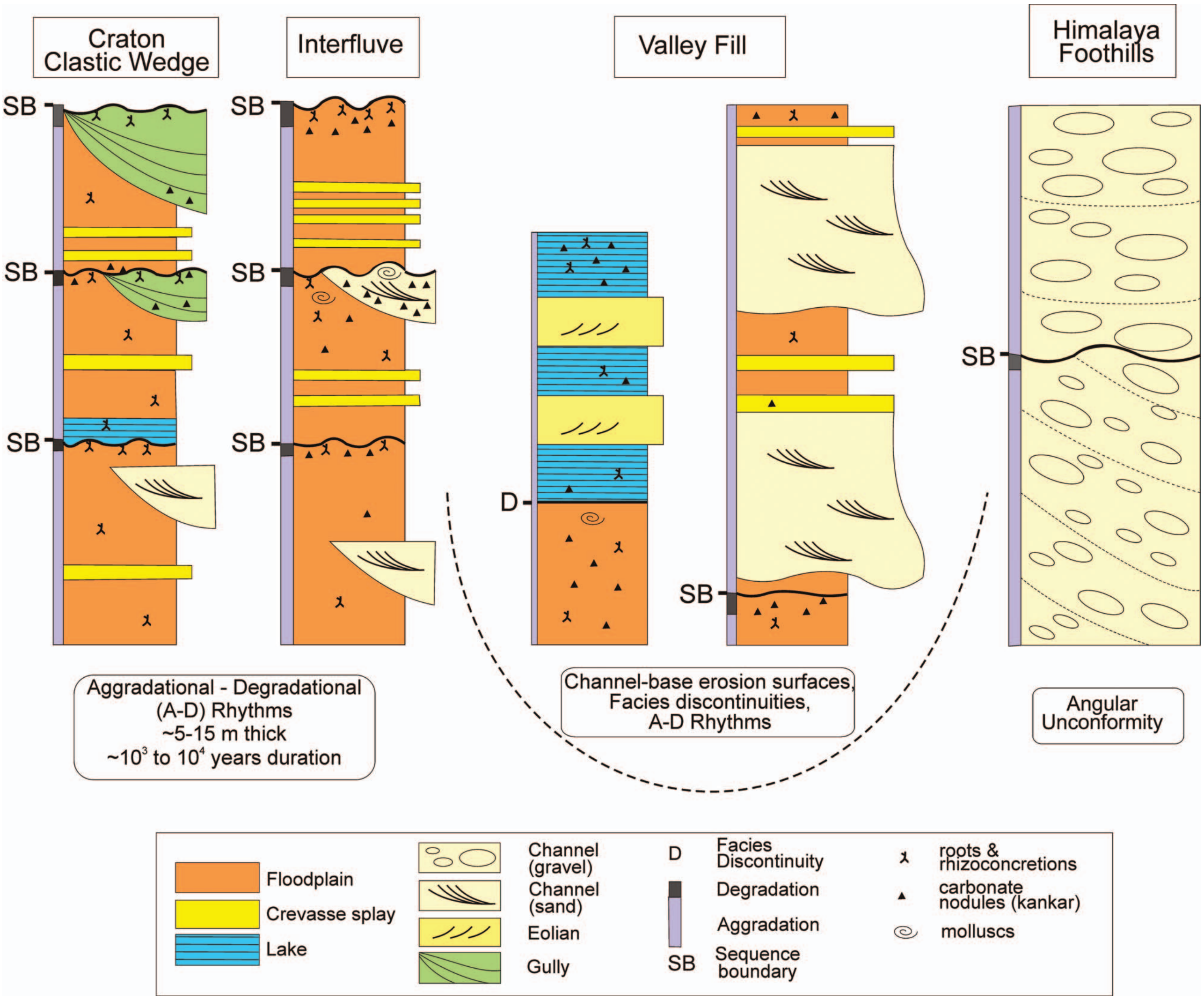

FIGURE 4.—Alluvial sequence patterns suggested by research to date in the western Ganga Plains and Himalayan Foothills. Based on information in Gibling et al. (2005), Sinha et al. (2007), Roy et al. (2007), Sinha et al. (2009), and unpublished data. No columns are shown for large megafans and river tracts in the eastern Ganga Plains (Gandak, Baghmati, and Kosi rivers) because few exposures, subsurface information, and age dates are available: see text for some details.

conditions in the North Atlantic (Prell and Kutzbach 1987; Tandon et al., 2006, Fig. 2). Discharge variations have probably crossed thresholds for fluvial geomorphic response and have caused rapid, widespread incision and aggradation.

Rivers across southern Asia incised when monsoon precipitation and river discharge intensified following the Last Glacial Maximum (LGM) of MIS 2 (see Tandon et al. 2006, Table 1, for evidence that supports this). Because incision is observed from mountain valleys, from rivers in the foreland basin, and from rivers in the Khambat Graben (Srivastava et al. 2001; Pratt-Sitaula et al. 2004; Tandon et al. 2006), this incision cannot be attributed to local tectonic activity. During peak monsoon intensity between 11 and 7 ka, large sediment volumes swept through drainage systems to accumulate in the Ganga–Brahmaputra Delta (Goodbred and Kuehl 2000a, 2000b; Goodbred 2003). Many inland valleys aggraded after ~7 ka when reduced discharge decreased erosive capacity and promoted deposition.

Rapid incision and aggradation is well illustrated by the Sabarmati River of NW India (Fig. 5), where 40 m cliffs cut through late Quaternary strata (Srivastava et al. 2001). Dating of the topmost cliff strata and the oldest alluvium trenched in the adjacent valley brackets incision between about 14 and 3.5 ka, spanning the period of post-LGM monsoon intensification. Sediment has been accumulating within the valley since 3.5 ka. Although the Sabarmati follows a tectonic lineament, the evidence suggests that incision primarily reflects enhanced monsoonal discharge.

It remains unclear whether the Sabarmati and other valleys will persist or will fill completely under the current regime of reduced discharge. However, many valleys may fill over unusually short periods. The huge sediment loads of many Asian rivers (Hovius 1998) reflect rapid weathering and denudation in humid tropical uplands, and earthquake activity releases enormous sediment volumes virtually instantaneously: the 1950 Assam earthquake released 47 billion m^3 of sediment and caused rapid aggradation of thick channel fills (Goswami 1985).

FIGURE 5.—Incised valley of the Sabarmati River near Mahudi in northwest India (Fig. 2A). The cliffs are about 40 m high, and topmost strata have been dated at 12 ± 2 ka, with a date of 4.5 ± 1 ka from a trench in the sand bar at right, suggesting incision between about 14 and 3.5 ka (Srivastava et al. 2001).

As noted above, the Gandak, Baghmati, and Kosi rivers of the eastern Ganga Plains are not presently incised (DVD 1–3). Due to a paucity of cliff exposures and drill cores, their history is poorly known, and it is not clear whether valley fills form part of these successions. However, aspects of the successions may reflect climatic events in the hinterland, especially the availability of glacial materials (Singh et al. 1993). Below the Kosi Megafan, undated borehole cuttings show the presence of a lower gravel and sand unit $>$ 60 m thick, which fines distally and probably represents glacier-fed detritus. Above, an 8–10 m upper unit of sand and mud with fining-up channel units represents the recent westward sweep of the Kosi River across the megafan, along with the deposits of spring-fed channels (Singh et al. 1993). Similarly, for the Baghmati River (Sinha et al. 2005), undated borehole cuttings indicate the presence of a lower sand sheet, with an upper sheet of sand and mud laid down by anastomosing channels similar to those of the modern river.

Tectonic Controls

Tectonic effects on alluvium are also prominent locally. In the Himalayan Foothills, piedmont alluvial fans border strands of the Main Boundary Thrust in an intermontane depocentre or "dun" (Mukerji 1990). At Pinjaur Dun in the Sutlej River catchment (Fig. 2A, DVD 4), the fans are dissected by narrow valleys up to 40 m deep, and have been steepened and tilted below the thrust, suggesting that upwarping led to incision (Tandon et al. 2006; Singh and Tandon 2007). The topmost fan strata are dated at 24 ± 4.5 ka, and later monsoon intensification may have played a part in the incision. Tectonic activity also promoted incision of alluvial terraces in Nepal (Lavé and Avouac 2000). At Dehra Dun (Fig. 2A), piedmont pebble and cobble gravels rest with angular unconformity on underlying gravels (Fig. 4), indicating that tectonic tilting promoted degradation and generated sequence boundaries.

On the main alluvial plains south of the Himalaya, there is little evidence that frequent tectonic events have caused incision. In north Bihar, earthquakes (such as the 1934 event of 8.4 magnitude) take place along faults that do not break the surface, and digital elevation models show that the Baghmati River has responded to tectonic tilting without incision (Jain and Sinha 2005). The 2001 Bhuj earthquake of northwest India (magnitude 7.7), located on a contractional structure west of the Sabarmati River (Fig. 2A), did not produce ground-surface rupture but produced liquefaction in the form of sand blows, sand-blow craters, and lateral spreading over a 400 km radius, as well as causing local subsidence and uplift (Hengesh and Lettis 2002). An 1819 earthquake (magnitude $\sim$ 8) on a fault north of Bhuj , however, did produce surface rupture, and diverted the Indus River, producing a lake on the downthrown side of the fault (Hengesh and Lettis 2002).

Although commonly linked to faults by some researchers, cliffed reaches on the Ganga Plains do not necessarily correlate with fault lines. The Ganga River forms a prominent cliff line along its southern margin (Fig. 2B, DVD 5 and 6), and lies within a strongly asymmetric valley with a less distinctive northern margin. There is no indication that the cliff line is fault-controlled, and the asymmetry may best be explained by the progressive southward migration of the channel in response to thrusting and deformation at the Himalayan Front to the north (Tandon et al. 2006).

Soft-sediment deformation is prominent locally. On the Ganga Plains near Kalpi (Fig. 2B), sediment dikes terminate at an erosional discontinuity in floodplain strata with dewatered sands, and calcite veins are prominent elsewhere (DVD 7 and 8). These features are indicative of earthquake activity, which may have caused uplift or river diversion and created the discontinuity (Gibling et al. 2005), in a manner perhaps analogous to the effects of earthquakes in northwest India.

Example from Inland Australia

Climatic fluctuations are implicated in the behavior of many inland Australian systems. In Quaternary deposits of the Channel Country (Fig. 3), where rivers drain internally to Lake Eyre, muddy topstratum deposits are associated with the modern anastomosing rivers. At shallow depth, widespread sand and gravel sheets extend to $>$ 40 m depth (DVD 9), and their upper parts show paleochannels scaled to much larger discharge than at present, with meander-belt scroll bars (DVD 10) and lateral-accretion sets. These coarse-grained deposits represent aggressive sediment transport during periods of elevated precipitation and discharge, especially during MIS 7, 5, and 3, which were pluvially enhanced in Australia (Nanson et al. 1992; Gibling et al. 1998; Nanson et al. 2008). Although Lake Eyre was a perennial lake up to 25 m deep during early MIS 5, subsequent perennial periods were less effective and alternated with prolonged ephemeral periods (Magee et al. 1995). There is no evidence that Lake Eyre highstands affected events upstream in the Channel Country some hundreds of kilometers upstream. A similar link to precipitation and discharge phases is also evident for the Riverine Plain (Fig. 3), part of the Murray River catchment in southeastern Australia (Page et al. 2009).

Very low subsidence rates in this cratonic setting have generally resulted in amalgamated coarse-grained sheets that may represent much of the later Pleistocene and probably contain cryptic sequence boundaries of climatic origin. Neotectonic activity has influenced fluvial courses in several inland areas, for example in association with the Innamincka Dome of the Lake Eyre basin and the Cadell Block of the Riverine Plain (Nanson et al. 2008; Page et al. 2009).

In summary, the southern Asian and Australian examples indicate that:

- Alluvial systems show rapid alternation between incision and aggradation, especially under monsoonal forcing, and drainage systems may alternate between valley and channel states, or at least between deeply and modestly incised states.
- Many alluvial events correlate well with monsoonal proxy records. Some climatic events of exceptionally high magnitude, such as post-

LGM monsoon intensification and later decline, generated continent-wide incision and aggradation.

- Tectonic activity has generated valleys and sequences close to thrust fronts, and locally causes sediment disruption and upwarping on the open plains. However, few proxy records exist for fault movement and tectonically induced subsidence, and it is difficult in most cases to evaluate the degree to which tectonic events caused stratigraphic events.

SCALE OF BASAL RELIEF (CRITERION 1B)

Valley models typically draw on evidence for deep incision that created prominent sequence boundaries. Our observations indicate that some, but not all, inland and coastal valleys show deep scour and prominent erosional relief. Because incision characterizes virtually all fluvial conduits (Salter 1993), erosional margins alone are not diagnostic of valleys, especially because their prominence may reflect the most recent major flood (Wolman and Miller 1960; Schumm and Lichty 1963; Nash 1994). Furthermore, some important fluvial surfaces may show only modest incision. As discussed later, flume-tank models of Strong and Paola (2008) suggest that the final valley form need not correspond to any particular surface generated during incision, and that valleys may not be characterized by prominent incised boundaries. We highlight here case studies from Australian and Asian coastal systems and inland Australian examples that illustrate these two caveats.

Some Key Fluvial Surfaces Have Minimal Incision

Channels with minimal incision have been imaged on seismic profiles below Australian continental shelves, and may routinely have flooded the adjacent plains during lowstand periods. Several large rivers crossed the low-gradient shelf of the Great Barrier Reef of northeastern Australia during sea-level lowstands. The subsea extension of the Burdekin River has conduits up to 2500 m wide and 20 m deep, with anabranches where the gradient was especially low and with more notable incision in distal areas (Fielding et al. 2003, 2005). In seismic profiles, the conduits show a simple cross-sectional geometry, with lateral-accretion deposits formed in meandering channels. The fluvial bodies show only modest degrees of incision, being essentially a single story thick although wider than a typical story (Fig. 6). Similar features are also observed in the subsea extension of the Fitzroy River (Ryan et al. 2007), where conduits are up to 1600 m wide and 20 m deep, with high-sinuosity reaches and lateral-accretion deposits. Incision is most pronounced in inshore and distal areas, with a modestly incised mid-shelf zone.

In southern Australia, the subsea extension of the Murray River has conduits up to 1000 m wide and 20 m deep (Hill et al. 2009). Point-bar deposits indicate that some reaches were meandering, and composite channel bodies represent amalgamation of deposits generated during multiple sea-level cycles. Onshore, the lower Murray River was influenced by fault lines and neotectonic activity, and channels are incised up to 130 m below the adjacent plain. The downstream reduction in width and depth reflects the low shelf gradient, less neotectonic activity, and relatively short periods of subaerial exposure and fluvial activity through the glacial cycle.

For all three of these river systems, flow was not always confined to the conduits, potentially allowing the river to avulse and relocate within a channel belt. Thus, interfluves are likely to have experienced flooding, militating against the formation of well developed paleosols. Fielding et al. (2003) and Ryan et al. (2007) considered these conduits to be "entrenched" rather than "incised", denoting a degree of basal erosion consistent with "channels" rather than "valleys".

These observations contrast with Gulf of Mexico systems. In this setting, incision below highstand shorelines tended to fix the river positions, resulting in "stratigraphic partitioning" between the conduits and interfluves (Blum and Aslan 2006). Flow appears to have been confined largely to the conduits, allowing the development of prominent paleosols on interfluves.

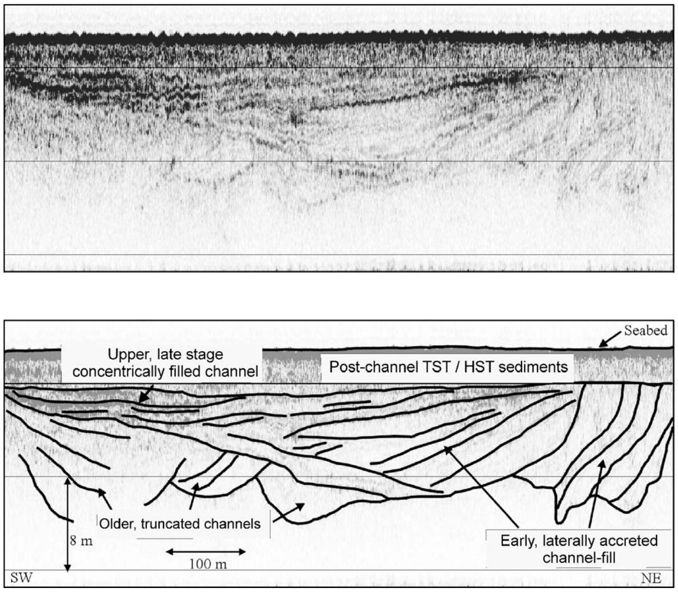

FIGURE 6.—Seismic profile (uninterpreted above, and interpreted below) for subsea channel fills of the Burdekin River, northeast Australia. Note that the bulk of the fill comprises a single set of lateral-accretion deposits.

The modest degree of incision of some rivers in their mid-shelf reaches may reflect long periods of falling sea level as glacial ice built up. Consequently, coastal rivers tend to be graded to a mid-shelf position, rather than to the lowest sea levels at times of maximum ice buildup where proximity to the shelf break would have promoted incision (Blum and Aslan 2006; Hill et al. 2009). Gulf of Mexico rivers were probably graded for much of their later existence to a level 40 to 85 m below present sea level (Blum and Aslan 2006, their Fig. 4B). Additionally, situations in which the gradient of the alluvial system exceeds that of the shelf may result in alluvial aggradation without prominent incision, as well as detachment of the alluvial system from the shoreline (Petter and Muto 2008).

Incision was also modest for lowstand alluvial systems below the broad, low-gradient shelf of the East China Sea. Here, an extensive fluvial sheet averages 30 m thick and is $>$ 330 km wide, and rests on an erosional surface (Wellner and Bartek 2003). Wellner and Bartek (2003) emphasized the importance of two factors in creating this sheet-like fluvial body: a) shelf physiography, where a low-gradient shelf damped down incision and promoted lateral migration of channels, and b) high-frequency variation in precipitation and discharge, especially reduced discharge later in MIS 2, which reduced the energy of the system and limited incision.

Similar wide fluvial sheets with only modest incision have been noted in the ancient record of coastal fluvial systems. Holbrook (2001) recorded a Cretaceous composite valley fill 28 m thick and more than 87 km wide in the southwestern USA, with less than 15 m of basal relief. In Queensland, Australia, Allen and Fielding (2007) documented Permian sequence boundaries covered by braided-fluvial sheets with minimal basal incision. The strata were laid down in a slowly subsiding cratonic basin subject to glacioeustasy, where the low gradients of the alluvial plain and shelf damped down incision and led to alluvial sheets in which any valleys would have been very shallow. Low rates of relative sea-level fall may also generate sheet-like bodies (Strong and Paola 2008).

Some Channel Confluences Show Exceptionally Deep Incision

Channel confluences may be sites of deep scour. In the Brahmaputra River, depth soundings show that scours at the confluences of anabranches and of tributary and main channels may be as much as five times the mean channel depth (Best and Ashworth 1997). This contrasts strongly with surveyed cross sections of modern rivers and experimental studies, for which maximum channel depth is commonly less than twice the mean depth (Gibling 2006, his Table 9). In the Brahmaputra example, deep incision is an intrinsic effect and does not denote a sequence boundary. Similarly large confluence scours have been identified in the Triassic Hawkesbury Sandstone of Australia (Miall and Jones 2003) and the Morrison Formation of the southwest USA (Cowan 1991).

CORRELATIVE SURFACES ON ALLUVIAL PLAINS (CRITERION 2)

Interfluve paleosols that correlate with episodes of incision are common in coastal plains and in some smaller alluvial basins. However, they may be absent or present only locally in large alluvial basins such as the Ganga Plains. Interfluves between valleys on large alluvial plains are complex geomorphic areas, and the time available for soil development is locally variable.

For coastal plains, deep valley incision driven by large, prolonged sea-level falls commonly results in reduced overbank flooding and prolonged periods of minimal sedimentation on adjacent interfluves. Depending on climatic factors, prominent soils may form on these lowstand surfaces, correlative with sequence-bounding valley bases. Quaternary lowstand paleosols are prominent on the coastal plains of Italy (Amorosi et al. 1999a; Amorosi et al. 2008) and the Gulf of Mexico (Blum and Price 1998; Blum and Aslan 2006). Tandon and Gibling (1997), Feldman et al. (2005), and Fischbein et al. (2009) documented Pennsylvanian bedrock examples, from an icehouse period similar to the late Quaternary.

In contrast, on the Ganga Plains, the Yamuna, Ganga, and Gaghara rivers pass through Himalayan exits with a quasi-regular spacing (Hovius 1996), so that the rivers are separated by low-relief interfluves tens to more than 100 km wide and hundreds of kilometers in extent downslope (Fig. 2A, B). Despite their apparent simplicity, these broad alluvial surfaces are complex entities formed by amalgamation of alluvium from different sources. For the Ganga–Yamuna Interfluve (Fig. 2C), petrographic studies show that the interfluve represents an amalgamation of: a) a clastic wedge sourced from the cratonic Chambal and Betwa rivers, either a transversely directed megafan or the product of cratonic axial rivers at the basin margin (Sinha et al. 2009), and b) Himalayan alluvium that onlaps the cratonic wedge.

Interfluves between the major rivers exhibit a complex mosaic of landforms. It is unlikely that a single correlative surface could be traced across an interfluve or correlated between adjacent interfluves and clastic wedges. The interfluves are traversed by small channels (Sengar, Rindi Nadi and Pandu Nadi in Fig. 2B) that arise on the interfluves from springs replenished by monsoon rains. Source-bordering eolian dunes are also present locally on the plains (DVD 11 to 15), with extensive sandhills east of Delhi (Tandon et al. 2006). Lakes are minor components of this interfluve, but large lakes or tals (DVD 16) and many small oxbow lakes are common elsewhere, recording more than 20,000 years of lake history (Sharma et al. 2004; Sinha et al. 2005).

Aggradational–degradational rhythms are commonly prominent below the interfluves. Although these rhythms may correspond to incisional events in the mainstem Ganga and Yamuna valleys, they more probably record migration or avulsion of small plains-fed channels, climatic and vegetational effects, or possibly local tectonic events. Such rhythms are prominent architectural features below the Ganga–Yamuna Interfluve, as indicated from cliffs more than 30 m high and drill cores up to 50 m long. In large cliffs at Kalpi dated at ~ 119 to 34 ka, aggradational–degradational rhythms are ~ 15 m thick, and consist largely of floodplain deposits with immature paleosols and small channel bodies deposited by spring-fed rivers. These deposits are interrupted by erosional discontinuities marked by groundwater and pedogenic carbonates, carbonate gravel, and gully fills (Figs. 4, 7, and DVD 17 and 18; Gibling et al. 2005; Sinha et al. 2006). Some floodplain deposits are capped by prominent, red paleosols rich in carbonate nodules that record periods of minimal sedimentation or erosion (Fig. 4; Sinha et al. 2007). It is not known how far individual discontinuities and paleosols extend at any of these locations, but we suspect that most are of local extent. Adjacent to the Ganga and Sengar rivers, carbonate-rich paleosols cap some cliff successions (Gibling et al. 2005), and may correlate with the adjacent valley margins. Thick calcretes are present on alluvial surfaces in the Thar Desert of northwestern India (Dhir et al. 2004; DVD 19 and 20).

Too little is known about the subsurface stratigraphy of megafans and interfluves in the eastern Ganga Plains to determine whether similar rhythmic successions are present. On the Gandak megafan (Mohindra et al. 1992), calcareous paleosols are common in the topmost strata, and could be present at depth, and zones rich in carbonate nodules are present at depth below the Baghmati plains (Sinha et al. 2005).

In contrast to the situation on large alluvial plains, small alluvial basins may show important paleosol units that correlate with incision along major drainage axes. In the Plio-Pleistocene successions of the Rio Grande Rift, stacked petrocalcic paleosols form condensed sections that record prolonged periods of minimal sedimentation, allowing the formation of mature paleosols (Mack and Leeder 1999; Mack et al. 2006). These authors linked the paleosol units to several causes in different parts of the basin and at different times: a) basin tilting along bounding faults which draws drainages to the more rapidly subsiding areas; b) movement of rivers into other basin strands, leaving floodplains inactive; c) incision on alluvial fans, and d) a period of prolonged degradation and floodplain stasis as tectonic activity waned.

FIGURE 7.—Cliff 33 m high at Kalpi on the Yamuna River, India (Fig. 2B). Arrows denote prominent, carbonate-cemented erosional surfaces that divide floodplain and channel deposits into aggradational–degradational rhythms (sequences) from water's edge to cliff top. Person is circled.

In summary,

- Sequences with thicknesses of 5–15 m and short durations (~ 10^3 to 10^4 years) appear to characterize floodplain deposits in the Ganga–Yamuna regions of the Ganga Plains; they may have multiple causes and need not be related to trunk-valley incision.
- Valley-bordering paleosols are present on floodplain surfaces locally but, because valley incision and aggradation may be short-lived, prolonged soil formation may be unusual.
- Interfluve channels, lakes, and eolian dunes may aggrade during periods of trunk-system incision. Thus, models that invoke prolonged, widespread stasis of interfluve surfaces appear unrealistic for large alluvial plains.
- Wide interfluves may constitute an alluvial system that operates independently of the major rivers. Thus, events in the two systems need not correspond, although both systems could be affected simultaneously by climatic or tectonic events.
- In view of the complex geomorphic patterns of large alluvial plains, it is unlikely that key surfaces will be basinwide. In contrast, mature paleosols may be widespread in smaller basins, especially where tectonic effects are important.

INCISED TRIBUTARIES AND GULLIES (CRITERION 3)

Our observations agree with the view of Posamentier (2001) and Miall (2002) that incised tributaries constitute good evidence for the presence of incised valleys, implying that the valleys are not flooding across their margins. Using seismic time slices, these authors observed good examples in Miocene fluvial strata offshore Indonesia and in the Malay Basin (Table 1).

The Ganga Plains show excellent examples of incised tributaries and zones of floodplain degradation bordering valleys. The Yamuna Valley is flanked for some 250 km by gullied badlands (DVD 21) that also extend northwards along the tributary Sengar River, which is incised near the valley (Figs. 2B, 7). Small gullied areas flank the southern margin of the Ganga Valley but are too small to be shown in Figure 2B. Along the Chambal and Betwa rivers to the south, badlands cover large areas, including a 5,000 km^2 tract along the Chambal River, where some gullies are > 10 m deep (Haigh 1984; DVD 22). Badland gully fills of alluvial and colluvial material, up to 10 m thick, are present in outcrops (Fig. 4, DVD 18; Gibling et al. 2005), and gullied zones may be correlative with some incised valleys. However, gullying has been variously attributed to climate change, local uplift, and human activity, although gullied tracts predate the late medieval Mughal period and are not caused solely by recent agricultural practices (Haigh 1984).

Triassic and Cenozoic formations in the western USA contain excellent ancient analogues for these gullied and badland landscapes (Retallack 1986; Kraus and Middleton 1987; Bestland 1997; Bestland et al. 1997), linked in some cases to incised rivers. In these examples, extensive floodplain erosional surfaces (some of them terraced) are marked by prominent paleosols and covered by alluvial and colluvial material with weakly developed paleosols. Retallack (1986) linked some paleosols and erosional surfaces to deeply incised channels, and some erosional surfaces border channel bodies that supplied sediment to cover and "heal" the landscape surfaces (Kraus and Middleton 1987). Bestland (1997) noted that the Cenozoic successions represent aggradational pulses separated by degradational events, and inferred alternate landscape stabilization and destabilization in response to climatic instability and vegetational change. Kraus and Middleton (1987) inferred periods of upwarping to explain the erosional surfaces.

Incised tributary valleys are well represented in Pennsylvanian strata in midcontinental USA (Feldman et al. 1995; Kvale and Archer 2007; Fischbein et al. 2009). They form part of mappable drainage networks and feed into much larger trunk fluvial systems, typically with thick, coarse-grained alluvial fills.

DIMENSIONS OF VALLEYS AND COMPONENT CHANNELS (CRITERION 7A)

Our observations concur with those of Schumm and Ethridge (1994), who noted that many paleovalley fills are an order of magnitude larger than average modern coastal-plain channels. Ancient valley fills commonly record this contrast (Table 1), as do coastal valleys (Plink-Bjørklund and Steel 2006). Blakey and Gubitosa (1984) noted that, within relatively narrow Triassic valleys, channels were much shallower than the host valleys but channel and valley widths matched and the channels were not underfit.

On bedrock unconformities, it is clear that valleys were incised prior to deposition of the existing fill, and that their original and present dimensions were similar. In contrast, Blum and Price (1998) and Blum and Aslan (2006) described "composite valley-fill unconformities" (Fig. 8) below the Gulf of Mexico coastal plain, formed by the amalgamation of numerous smaller valleys as a result of avulsion. Numerous ancient examples are known (Willis 1997; Holbrook 2001). The dimensions of a composite valley fill are much greater than the instantaneous dimensions of the valley, and a failure to appreciate this may lead to erroneous assumptions about incision processes and (paleo)flow volumes.

Analogue experiments have demonstrated the creation of composite valley fills. Strong and Paola (2008) conducted tank experiments on valley cutting and filling, modeling a passive-margin setting where subsidence increases basinward and using a constant sediment and water supply to isolate the effects of coastal base-level change. They observed that erosional surfaces are diachronous and amalgamated, and that valley-base unconformities form over a period so prolonged that some deposits above the unconformity are older than some deposits below. Although the stratigraphic form of the deposit resembles a valley with a prominent basal surface, this surface did not exist as a topographic valley form at any given time. Strong and Paola (2008) distinguished stratigraphic valleys (the valley-form erosional surface preserved in the stratigraphic record) from topographic valleys (the topography at an instant in time).

The Ganga Valley upstream from Kanpur (Fig. 2B) is a stratigraphic valley that contains smaller channel bodies and has a probable composite unconformity at its base. Numerous smaller channel bodies penetrated during drilling lie within floodplain and eolian deposits and

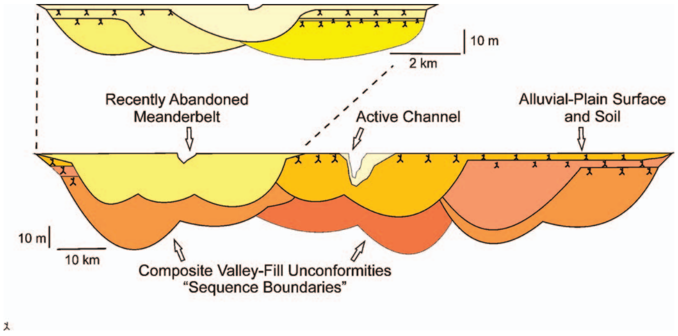

FIGURE 8.—Composite valley fills, based on Texas coastal plain bordering the Gulf of Mexico; modified from Blum and Price (1998).

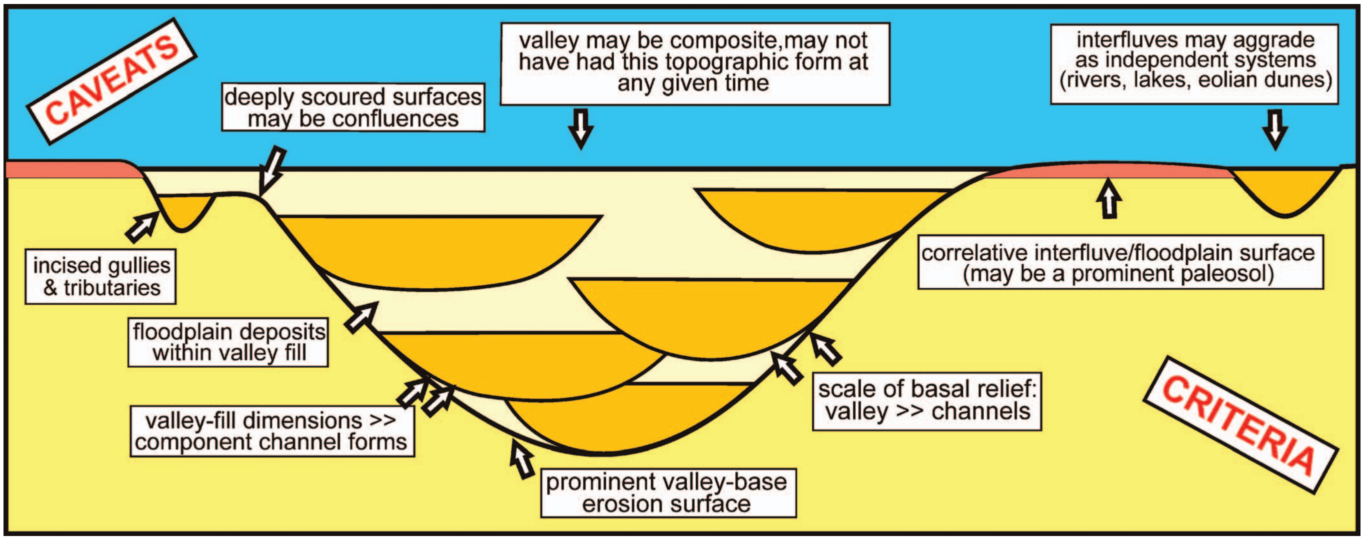

FIGURE 9.—Guidelines for identifying alluvial valley fills in the geological record. Text in the lower part of the diagram shows criteria that have been shown to be valid in certain areas, whereas text in the upper part lists caveats that may influence the decision to identify a valley fill. See Table 3 and text for details.

date back to ~60 ka (Fig. 4; Gibling et al. 2005; Roy et al. 2007; Sinha et al. 2007). Prominent paleosols with carbonate nodules in the cores mark discontinuities. Cliff exposures near Bithur consist of floodplain deposits capped by lacustrine and eolian strata dated at 27.5 to 25.2 ka (Fig. 4). These facies suggest that Ganga Valley channels became underfit and floodplains were replaced by shallow lakes and eolian dunes during the Last Glacial Maximum, when proxy records suggest reduced monsoonal precipitation. The top of the floodplain unit is not a degradational surface but marks a prominent facies discontinuity. Just below the valley near Bithur, partially amalgamated channel bodies dated at < 10 ka record renewed Ganga discharge and Holocene aggradation.

Similar evidence for reduced discharge is also seen along some reaches of the Yamuna Valley, where floodplain deposits are capped by a prominent lacustrine unit (DVD 23 and 24). The unit has been dated at 15.5 ka radiocarbon years (Williams and Clarke 1995; Tandon et al. 2006), indicating reduced discharge in MIS 2.

Age dates suggest that channel bodies below the northern part of the Ganga Valley are older, supporting a progressive southward migration of the Ganga River, suggested also by the river's location at the southern valley margin. Thus, the Ganga valley has migrated southward, creating a composite, diachronous valley fill with dimensions that greatly exceed the instantaneous topography. The valley fill contains internal sequence boundaries (carbonate-rich paleosols) and facies discontinuities (Fig. 4).

Many alluvial valleys in the rock record follow tectonic lineaments that may have been sufficiently long-lived to generate large stratigraphic valleys that contain smaller channels. The Cenozoic Sis Conglomerate of the Spanish Pyrenees is a remarkable sediment body 1.4 km thick and 7.5 km wide, formed along a transverse fault during thrusting (Table 1; Vincent 2001). The sediment body includes tilted stratal sets and angular unconformities. The valley fill evolved for some 25 million years, generating a thick stratal package that includes floodplain fines, lakes, and coal, but the topography at any given time did not exceed 120 m (S. Vincent, written communication, 2005). The base of the Sis Conglomerate thus represents a stratigraphic valley but not a topographic valley.

TERRACES (CRITERION 7B)

We concur with the view that terraces provide important evidence for valley recognition. In modern valleys such as those across much of northwest Europe, flights of terraces commonly result from repeated incision and aggradation superimposed on long-term downcutting (Bridgland, 2000; Bridgland et al., 2006). The Somme Valley of France was generated by incision over about a million years as a result of prolonged uplift, during which aggradational periods generated widespread terraces that probably represent climatic variations (Antoine et al. 2003). Terraces are infrequently identified in the older record (Holbrook 2009). Quaternary subsea examples have been imaged in seismic profiles (Thomas and Anderson 1994; Simms et al. 2006), and strath terraces cut into the substrate were identified off Brittany by Menier et al. (2006). Although difficult to identify in the ancient record, older examples include the studies of Sedimentation Seminar (1978), Bestland (1997), and Posamentier (2001).

In southern Asia, terraces constitute an important facies component in upland and lowland valleys (Lavé and Avouac 2000; Monecke et al. 2001; Tandon et al. 2006; Gibling et al. 2008), and are especially prominent in deep valleys draining the Himalaya (DVD 25 to 28). In some cases, episodes of accumulation and incision have been linked to variations in monsoonal strength (Bookhagen et al. 2006). Terraces along an alluvial reach are commonly assumed to represent a system-wide alluviation episode. However, terraces along the Belan River in northern India (DVD 29 to 31) and the Bellinger River in Australia may have similar elevations but different ages, and thus represent local intra-system variation (Cohen and Nanson 2008; Gibling et al. 2008). For the Clyde and Manning Rivers of coastal Australia, strong precipitation and discharge events can cause catastrophic stripping of floodplain deposits (Nanson 1986), which contributes to local variation in terrace preservation (DVD 32 and 33).

EVALUATION OF GUIDELINES FOR RECOGNIZING ALLUVIAL-VALLEY FILLS

It is apparent from the above discussion that alluvial and coastal valleys show points of similarity and difference (Table 3; Fig. 9). The differences primarily reflect the huge influence of sea level on downstream systems, which forces incision, mediates valley filling, and generates a predictable set of systems tracts related to base-level transit cycles that operate in the Milankovitch band. (However, the architecture of the fills largely reflects sediment delivery from upstream: Blum and Aslan 2006).

In contrast, upstream alluvial systems are subject to multiple influences over varied and commonly short timescales. These influences include a) precipitation and, in some settings, meltwater availability, b) tectonics, including regional subsidence and fault motions, and c) intrinsic drainage changes such as avulsion, river capture, and channel and valley migration. Away from coastal areas, the recognition of sequence boundaries may be problematic because allocyclic and autocyclic events do not necessarily generate recognizable signals (Neal and Abreu 2009). Monsoonal precipitation changes are somewhat predictable because they respond to insolation and glacial effects, but tectonic and intrinsic events have a low level of predictability. As with coastal valleys, fills may be composite and may contain sequence boundaries and major discontinuities.

ARCHITECTURE AND GEOMETRY OF ALLUVIAL-VALLEY FILLS

In an important definition paper, Holbrook (2001) divided valley fills into those with a valley-form (concave-up) basal unconformity and those with a smooth to nearly smooth basal unconformity (Table 4). In the latter group, relief on the basal surface was similar to or less than the thickness of larger overlying channel-fill elements. In essence, Holbrook's system recognizes lensoid and sheet-like valley fills, although scales and aspect ratios of the two groups were not set out. Holbrook divided each group into four types (Table 4), based on the presence or absence of nested valley fills with the alluvial body (whether aggradation was interrupted by episodes of local or regional incision), as well as by stacking patterns (lateral or vertical amalgamation of valley fills).

Our evaluation of Quaternary valley fills includes information about their architecture that, in some cases, allows comparison with Holbrook's classification. Good information is available from Quaternary fluvial systems such as the Burdekin River, where fluvial conduits are filled and for which seismic profiles are available. However, insufficient information is available for many inland areas of the Indian and Australian plains, where valleys are still evolving and for which cores and cliff outcrop allow only a limited evaluation of valley architecture.

For well-documented Asian and Australian examples, we identify multistory valleys, multistory sheets, and single-story sheets, which correspond with three of Holbrook's types (Fig. 10; Table 4). We use more general terms than those of Holbrook because it is not always possible to be certain if incision surfaces were local or regional—a key aspect of his classification. However, high-resolution age dating indicates that monsoon intensification following the Last Glacial Maximum led to fluvial incision in many Asian rivers. The Ganga Valley record contains sequence boundaries that probably represent other regional climatic events, suggesting that it is a compound–complex valley in Holbrook's system. Fluvial deposits below and bordering the Gulf of Mexico constitute a stacked multivalley complex, and those below the East China Sea constitute a channel sheet formed during and since the LGM. The subsurface sand sheets of the Australian Channel Country include components that date back to nearly 750 ka (Nanson et al. 2008) and are probably stacked multivalley complexes.

Additionally, we identify entrenched channels and channel belts typified by former river reaches below continental shelves in Australia (Fig. 10). These are not technically valley fills because they scale with individual channels in the system (Fig. 6). Fluvial deposits of this type appear to be common below some offshore areas, related to numerous factors that include shelf slope and the depth of the shelf edge. They show that valleys with prominent incision were not universally generated during periods of lowered sea level.

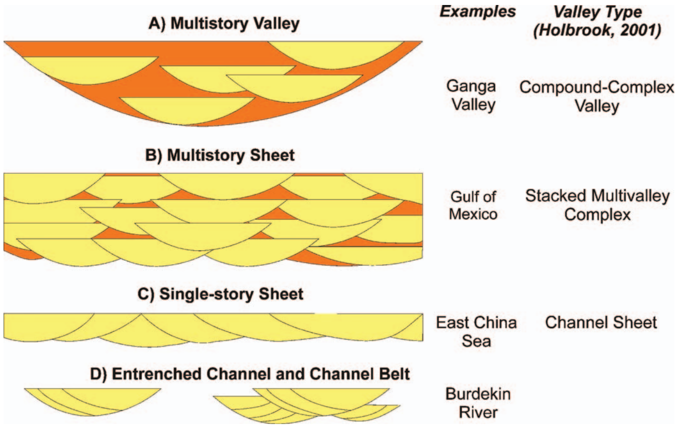

FIGURE 10.—Schematic diagram to illustrate Quaternary valley fills and incised channel bodies discussed in the text. See Table 4 for references to Quaternary examples. Note that nested valley forms may be present in some examples but are not shown in the diagram.

For rapidly subsiding basins with a high sediment supply, Holbrook (2001) suggested that incisional periods would have been few and allomembers may not be present. Although subsurface data are sparse, current information suggests that megafan deposits of the Himalayan Foreland Basin consist largely of aggradational channel and interchannel successions, in accord with examples from the ancient record (Davies and Gibling 2003).

ALLUVIAL SEQUENCE MODELS: UNDERSTANDING ACCOMMODATION

For large alluvial plains, especially in foreland basins, we follow Blum and Törnqvist (2000) in suggesting that accommodation terminology should be applied with caution. Sequences with low- and high-accommodation systems tracts have been widely regarded as the prime form of stratal packaging in inland alluvial systems (Column 2 of Fig. 1; Catuneanu 2006), and have commonly been linked to tectonism acting through subsidence (e.g., Currie 1997). Although this may be true in some cases, we suggest that many fine-scale aspects of stratigraphic architecture in these deposits may reflect climatic effects.

Researchers have tended to favor tectonically driven accommodation scenarios to explain alluvial successions for several reasons: 1) accommodation models are familiar to many of us because of their evident application to coastal valleys influenced by sea-level change, 2) some alluvial basins experience active tectonism, and 3) accommodation can readily be explored by mapping stratal thickness variation. Regional subsidence, uplift and subsidence associated with individual faults, and forebulge dynamics may greatly influence the development of foreland and other basins (Catuneanu et al. 1997; Plint and Wadsworth 2006). However, decrease and increase in space for sediment accumulation has also been interpreted to reflect changing balance of water and sediment discharge (Columns 4 and 5 of Fig. 1; Weissmann et al. 2002). If the terms "accommodation" and "base level" are used in alluvial studies, it needs to be clear whether subsidence or change in the "fluvial equilibrium profile" is being invoked to explain accommodation.

We do not mean to minimize tectonic controls, the importance of which is evident in many parts of Asia and Australia and in other areas (Table 2). However, it is by no means clear that the many prominent

TABLE 4.—Valley types identified by Holbrook (2001), with Quaternary examples identified in the present study (see Fig. 10). Entrenched Channels and Channel Belts are not technically valley fills, and were not part of Holbrook's (2001) system.

Valley Types	Definition	Quaternary Examples Identified in Present Study
Valley-form Basal Unconformity		
Simple	Single valley scour, fill represents consistent aggradation	
Complex	Valley fill interrupted by local incision	
Compound	Valley fill interrupted by regionally significant incision	
Compound-Complex	Valley fill interrupted by local and regionally significant incision	**Ganga Valley, India** (Tandon et al. 2006; Sinha et al. 2007): Valley fill contains numerous channel fills; incision during monsoon intensification (~20 ka B.P. to present) was a regional event in Asia; sequence boundaries within valley fill may reflect earlier regional incision events; valley form migrates laterally due to advancing Himalayan thrust front.
Smooth to Near-smooth Basal Unconformity		
Channel Sheet	Rests on regional erosion surface, fill lacks valley-scale surfaces; aggradation may cause stacking of channel belts	**East China Sea** (Wellner & Bartek 2003): Multi-storey fluvial sheet >330 km wide and 30 m average thickness (maximum 53 m). Formed since last glacial cycle (~20 ka B.P. to present). Fed by Changjiang (Yangtze) and Huanghe (Yellow) rivers. Interaction of glacioeustasy and climatic factors on a low-gradient shelf. Contains local autocyclic incisions and possible regional incision / aggradation phases due to high-frequency climatic events. Valley underfilled, with capping marine beds.
Stacked Channel Sheet	Two or more superimposed channel sheets with no intervening open-marine strata	
Multivalley Complex	Laterally amalgamated valley fills	
Stacked Multivalley Complex	Vertically amalgamated valley fills with no intervening open-marine strata	**Gulf of Mexico, Texas Coastal Plain** (Blum & Aslan 2006): Vertically and laterally amalgamated valley complexes, representing succession of 100 kyr valley fills. Interaction of glacioeustasy and climatic factors.
Additional Responses to Glacioeustatic Events (not included by Holbrook 2001)		
Entrenched Channels and Channel Belts	Channel body or belt with evidence for some incision, relatively narrow and not amalgamated into sheet	**Burdekin River, Australia** (Fielding et al. 2003): Individual channel body or a few amalgamated channel bodies. Not technically a valley fill because accretion surfaces accord with channel dimensions. Represents lowstand extension across shelf.

surfaces visible in alluvial successions in the rock record represent tectonic effects. The Asian Quaternary case studies cited above, as well as studies elsewhere (Bull 1991; Ritter et al. 1995; Bestland 1997; Weissmann et al. 2002), indicate that climatic effects have been generally undervalued in interpreting the stratigraphic record, as suggested by Blum (1994).

On alluvial plains under the strong driving force of the monsoon, many key alluvial surfaces and packages show a first-order correlation with patterns of precipitation and discharge, and some (such as post-LGM incision caused by monsoon intensification) may be of continental extent. Effects intrinsic to channel systems are also very important. Wells and Dorr (1987) noted that the Kosi River can rise 9 m in a day, and annual floods are commonly large enough to shift channels (Jain and Sinha 2003). We believe that, together, climatic and intrinsic effects are capable of generating a fine-scale architecture that may dominate interfluves and clastic wedges (Fig. 4), perhaps including some megafans.

Given the many uncertainties in assigning sequences to particular causes, it may be best to recognize aggradational–degradational rhythms as a "ruling motif" (Column 7, Fig. 1), considering their correlation to valley fills where such can be identified. This nongenetic terminology allows for varied explanations without prejudging the causes. Despite the short duration and low thickness of many such rhythms, they can legitimately be described as "sequences" because they have erosional boundaries. As discussed by Schlager (2004) and Neal and Abreu (2009), sequences are scale-independent and fractal in nature, and their duration and thickness should not be used to erect sequence hierarchies.

Although not necessarily inappropriate, the use of systems-tract terminology to alluvial successions may be problematic. The concept of systems tracts originated in marine basins where stratal bodies can be linked to global sea-level change (although local modifications have been widely noted, e.g., Martinsen and Helland-Hansen 1995). Where seismic records are available, observable features such as progradation, aggradation, and retrogradation should be applied in describing "accommodation successions", rather than "highstand" and "lowstand", which imply a linkage to base-level transit cycles (Neal and Abreu 2009).

The identification of systems tracts in an alluvial basin tends to imply a basinwide effect, whether the authors intended this or not. However, alluvial regions such as the Ganga Plains are huge areas with many geomorphic elements (orogenic and cratonic sources; megafans, interfluves and axial drainage systems) and large precipitation gradients. In basins of this scale, basinwide bounding surfaces will be a rarity, and most prominent surfaces may be of local extent. Additionally, systems tracts were initially designed to record parallel responses to forcing factors through a range of depositional systems (alluvial, coastal, deep sea), rather than for one system (alluvial). In these respects, "nonmarine" sequence stratigraphy may need to throw off some of the shackles of a marine-based framework.

There are also dangers in inferring accommodation from the degree of amalgamation of channel bodies in the bedrock record. Amalgamated bodies are commonly used to infer a low-accommodation setting or period, whereas bodies isolated in floodplain deposits are used to infer a high-accommodation setting or period. The link is relevant to many coastal valleys (Blum and Törnqvist 2000), and is also valid in some alluvial contexts such as cratonic settings with slow subsidence rates (Leckie and Cheel 1997; White and Leckie 1999; Allen and Fielding 2007). However, several studies have noted that alluvial aggradation rates may vary without change in base-level or upstream controls, with potential implication for channel-stacking patterns (Holbrook et al. 2006; Petter and Muto 2008).

Linkage between amalgamation and accommodation may be misleading or incorrect in other cases. Such a linkage may be particularly misleading in the case of megafans (distributive fluvial systems) which are dominant in many inland basins (Weissmann et al. 2010). Megafans originate where sediment-charged rivers at mountain exits deposit mud and sand as flow spreads out and decelerates, and their deposits typically exhibit channel bodies isolated in mudstone and rarely amalgamated (Nichols 1987; Hirst 1991). Not all megafans are located in rapidly subsiding settings with high accommodation. For example, the Kosi and Gandak megafans lie in a zone of rapid subsidence near the Himalayan Front (Fig. 2A), but a cratonic clastic wedge (probable megafan) at the southern fringe of the foreland basin (Fig. 2C) was laid down in a slowly subsiding region. Thus, the low degree of amalgamation in megafan deposits may typically reflect rapid sand and mud deposition, rather than tectonically driven accommodation. Additionally, tough floodplain muds and paleosols in seasonal climates may prevent channel enlargement, generating fixed channel bodies through local geomorphic controls (Gibling 2006).

To avoid inappropriate inferences of accommodation, Patterson (2009) recommended the use of the nongenetic terms amalgamated, semi-amalgamated, and non-amalgamated channel complexes to characterize channel-body architecture.

APPLICATION OF QUATERNARY OBSERVATIONS TO DEEP TIME

We have drawn on Quaternary systems in evaluating models for alluvial-valley fills. However, insights from these systems may be less applicable or even inappropriate when applied to other parts of the geological record.

The current icehouse period with its high-magnitude and high-frequency changes in sea level and climate differs considerably from earlier greenhouse periods, with considerable effects on marine and coastal systems (Dalrymple 2006; Sømme et al. 2009). A few studies have discussed how these changes would affect fluvial systems. Willis (1997) suggested that, under greenhouse conditions with modest sea-level changes, valley fills would tend to be dominated by coarser fluvial input. The prominence of valleys in coastal areas may reflect in part the magnitude of relative sea-level change (Rygel et al. 2008). Gibling (2006) noted that Jurassic and Cretaceous valley fills, formed during a greenhouse period with little or no glacial ice, were in general smaller than those of the Carboniferous and Permian, when the buildup and melting of glacial ice caused high-magnitude changes in sea level.

Precambrian and Cambrian to Silurian fluvial systems, which predated the advent of a widespread cover of vascular plants, show substantial differences from modern systems (Davies and Gibling, 2010a, 2010b; Long, this volume). Among many differences in sediment transport and storage, a prime contrast lies in the enhanced strength of river banks colonized by vegetation, leading to contrasts in alluvial architecture. The deposits of pre-vegetational river channels typically comprise broad sheets with little evidence of channel margins and limited floodplain material. Meandering rivers with systematic point-bar migration and stable floodplains appear to have been rare prior to the advent of riparian vegetation, but increased greatly in abundance once terrestrial surfaces had been colonized (Cotter, 1978; Davies and Gibling, 2010a). Valleys are likely to be difficult to identify in pre-vegetational deposits, and pre-vegetational river systems may have responded very differently than Quaternary systems to forcing factors.

CONCLUSIONS

The discipline of sequence stratigraphy was initially designed to analyze coastal and shallow marine strata, and many concepts appropriate to these settings have been applied to updip alluvial systems, including criteria for identifying alluvial-valley fills. However, there are considerable differences in the factors that govern architecture in alluvial and coastal-marine settings. In the coastal realm, high-magnitude glacioeustatic fluctuations, on a 10^4 to 10^5 year timescale in the late Quaternary, result in sequences with coastal valleys, correlative interfluve paleosols, and a predictable succession of systems tracts. In contrast, a combination of climatic, tectonic, and intrinsic factors of varied magnitude and duration generate inland alluvial valleys. Where precipitation shows strong secular variation, as in the monsoonal setting of southern Asia, climate is a strong forcing factor that, over short timescales of 10^3 to 10^4 years, may be the dominant factor in creating the alluvial architecture.

As a result of these differing controls, criteria for the recognition of valley fills in coastal settings are not always applicable in updip alluvial settings. Although both coastal and alluvial valleys are commonly deeply incised, the degree of incision varies in space and time across inland tracts due to short-term episodes of incision (sequence-boundary formation) and aggradation that are linked to changes in the river's equilibrium profile and equilibrium floodplain height. These events generate aggradational–degradational rhythms—a nongenetic term that may be useful in inland settings. Mature paleosols commonly cover the areas between coastal valleys but, across wide alluvial plains, eolian, lacustrine, and channel facies may build up while mainstem valleys incise. Thus, traceable sequence boundaries may be restricted to local areas in large basins, although they may be areally important in small basins. Useful criteria for confirming incision include the presence of gullied surfaces, which are prominent adjacent to many valleys and their tributaries, and terraces, although these may be difficult to recognize in the ancient record.

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REFERENCES

Allen, J.P., and Fielding, C.R., 2007, Sequence architecture within a low-accommodation setting: An example from the Permian of the Galilee and Bowen basins, Queensland, Australia: American Assocation of Petroleum Geologists, Bulletin, v. 91, p. 1503–1539.

Alonso, J.L., 1989, Fold reactivation involving angular unconformable sequences: theoretical analysis and natural examples from the Cantabrian Zone (Northwest Spain): Tectonophysics, v. 170, p. 57–77.

Amorosi, A., and Milli, S., 2001, Late Quaternary depositional architecture of Po and Tevere river deltas (Italy) and worldwide comparison with coeval deltaic successions: Sedimentary Geology, v. 144, p. 357–375.

Amorosi, A., Colalongo, M.L., Pasini, G., and Preti, D., 1999a, Sedimentary response to Late Quaterary sea-level changes in the Romagna coastal plain (northern Italy): Sedimentology, v. 46, p. 99–121.

Amorosi, A., Colalongo, M.L., Fusco, F., Pasini, G., and Fiorini, F., 1999b, Glacio-eustatic control of continental-shallow marine cyclicity from Late Quaterary deposits of the southeastern Po Plain, Northern Italy: Quaternary Research, v. 52, p. 1–13.

Amorosi, A., Pavesi, M., Ricci Lucchi, M., Sarti, G., and Piccin, A., 2008, Climatic signature of cyclic fluvial architecture from the Quaternary of the central Po Plain, Italy: Sedimentary Geology, v. 209, p. 58–68.

Andrews, E.D., 1980, Effective and bankfull discharges of streams in the Yampa River basin, Colorado and Wyoming: Journal of Hydrology, v. 46, p. 311–330.

Antoine, P., Munaut, A.-V., Limondin-Lozouet, N., Ponel, P., Duperon, J., and Duperon, M., 2003, Response of the Selle River to climatic modifications during the Lateglacial and Early Holocene (Somme Basin—Northern France): Quaternary Science Reviews, v. 22, p. 2061–2076.

Bennett, V.G.L., Weissmann, G.S., Baker, G.S., and Hyndman, D.W., 2006, Regional-scale assessment of a sequence-bounding paleosol on fluvial fans using ground-penetrating radar, eastern San Joaquin Valley, California: Geological Society of America Bulletin, v. 118, p. 724–732.

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

Bestland, E.A., 1997, Alluvial terraces and paleosols as indicators of Early Oligocene climate change (John Day Formation, Oregon): Journal of Sedimentary Research, v. 67, p. 840–855.

Bestland, E.A., Retallack, G.J., and Swisher C.C., III, 1997, Stepwise climate change recorded in Eocene–Oligocene paleosol sequences from central Oregon: Journal of Geology, v. 105, p. 153–172.

Blakey, R.C., and Gubitosa, R., 1984, Controls of sandstone body geometry and architecture in the Chinle Formation (Upper Triassic), Colorado Plateau: Sedimentary Geology, v. 38, p. 51–86.

Blum, M.D., 1994, Genesis and architecture of incised valley fill sequences: A late Quaternary example from the Colorado River, Gulf Coastal Plain of Texas, in Weimer, P., and Posamentier, H.W., eds., Siliciclastic Sequence Stratigraphy: Recent Developments and Applications: American Association of Petroleum Geologists, Memoir 58, p. 259–283.

Blum, M.D. and Aslan, A., 2006, Signatures of climate vs. sea-level change within incised valley-fill successions: Quaternary examples from the Texas Gulf Coast: Sedimentary Geology, v. 190, p. 177–211.

Blum, M.D., and Price, D.M., 1998, Quaternary alluvial plain construction in response to glacio-eustatic and climatic controls, Texas Gulf coastal plain, in Shanley, K.W., and McCabe, P.J., eds., Relative Role of Eustasy, Climate, and Tectonism in Continental Rocks: SEPM, Special Publication 59, p. 31–48.

Blum, M.D., and Törnqvist, T.E., 2000, Fluvial responses to climate and sea-level change: a review and look forward: Sedimentology, v. 47, p. 2–48.

Blum, M.D., Toomey, R.S., III, and Valastro, S., Jr., 1994, Fluvial response to Late Quaternary climatic and environmental change, Edwards Plateau, Texas: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 108, p. 1–21.

Bookhagen, B., and Burbank, D.W., 2006, Topography, relief, and TRMM-derived rainfall variations along the Himalaya: Journal of Geophysical Research, v. 33, L08405, doi:10.1029/2006GL026037, p. 1–5.

Bookhagen, B., Fleitmann, D., Nishiizumi, K., Strecker, M.R., and Thiede, R.C., 2006, Holocene monsoonal dynamics and fluvial terrace formation in the northwest Himalaya, India: Geology, v. 34, p. 601–604.

Boyd, R., Dalrymple, R.W., and Zaitlin, B.A., 2006, Estuarine and incised-valley facies models, in Posamentier, H.W., and Walker, R.G., eds., Facies Models Revisited: SEPM, Special Publication 84, p. 171–236.

Bridgland, D.R., 2000, River terrace systems in north-west Europe: an archive of environmental change, uplift and early human occupation: Quaternary Science Reviews, v. 19, p. 1293–1303.

Bridgland, D.R., Antoine, P., Limondin-Lozouet, N., Santisteban, J.K., Westaway, R., and White, M.J., 2006, The Palaeolithic occupation of Europe as revealed by evidence from the rivers: data from IGCP 449: Journal of Quaternary Science, v. 21, p. 437–455.

Bull, W.B., 1991, Geomorphic Responses to Climate Change: Oxford, U.K., Oxford University Press, 326 p.

Catuneanu, O., 2006, Principles of Sequence Stratigraphy: Amsterdam, Elsevier, 375 p.

Catuneanu, O., Sweet, A.R., and Miall, A.D., 1997, Reciprocal architecture of Bearpaw T-R sequences, uppermost Cretaceous, Western Canada Sedimentary Basin: Bulletin of Canadian Petroleum Geology, v. 45, p. 75–94.

Cohen, K.M., Stouthamer, E., and Berendsen, H.J.A., 2002, Fluvial deposits as a record for Late Quaternary neotectonic activity in the Rhine–Meuse delta, The Netherlands: Netherlands Journal of Geosciences, v. 81, p. 389–405.

Cohen, T.J., and Nanson, G.C., 2008, Topographically associated but chronologically disjunct late Quaternary floodplains and terraces in a partly confined valley, south-eastern Australia: Earth Surface Processes and Landforms, v. 33, p. 424–443.

Cotter, E., 1978, The evolution of fluvial style, with special reference to the Central Appalachian Paleozoic, in Miall, A.D., ed., Fluvial Sedimentology: Canadian Society of Petroleum Geologists Memoir 5, p. 361–383.

Cowan, E.J., 1991, The large-scale architecture of the fluvial Westwater Canyon Member, Morrison Formation (Upper Jurassic), San Juan Basin, New Mexico, in Miall, A.D., and Tyler, N., eds., The Three-Dimensional Facies Architecture of Terrigenous Clastic Sediments and its Implications for Hydrocarbon Discovery and Recovery: SEPM, Concepts in Sedimentology and Paleontology, p. 80–93.

Currie, B.S., 1997, Sequence stratigraphy of nonmarine Jurassic–Cretaceous rocks, central Cordilleran foreland-basin system: Geological Society of America, Bulletin, v. 109, p. 1206–1222.

Dalrymple, R.W., 2006, Incised valleys in time and space: an introduction to the volume and an examination of the controls on valley formation and filling, in Dalrymple, R.W., Leckie, D.A., and Tillman, R.W., eds., Incised Valleys in Time and Space: SEPM, Special Publication 85, p. 5–12.

Davies, S.J., and Gibling, M.R., 2003, Architecture of coastal and alluvial deposits in an extensional basin: the Carboniferous Joggins Formation of eastern Canada: Sedimentology, v. 50, p. 415–439.

Davies, N.S., and Gibling, M.R., 2010a, Cambrian to Devonian evolution of alluvial systems: The sedimentological impact of the earliest land plants: Earth-Science Reviews, v. 98, p. 171–200.

Davies, N.S., and Gibling, M.R., 2010b, Paleozoic vegetation and the Siluro-Devonian rise of fluvial lateral accretion sets: Geology, v. 38, p. 51–54.

Dhir, R.P., Tandon, S.K., Sareen, B.K., Ramesh, R., Rao, T.K.G., Kailath, A.J., and Sharma, N., 2004, Calcretes in the Thar Desert: genesis, chronology and paleoenvironment: Indian Academy of Science, Proceedings (Earth and Planetary Science), v. 113, p. 473–515.

Erkens, G., Dambeck, R., Volleberg, K.P., Bouman, M.T.I.J., Bos, J.A.A., Cohen, K.M., Wallinga, J., and Hoek, W.Z., 2009, Fluvial terrace formation in the northern Upper Rhine Graben during the last 20 000 years as a result of allogenic controls and autogenic evolution: Geomorphology, v. 103, p. 476–495.

Feldman, H.R., Gibling, M.R., Archer, A.W., Wightman, W.G., and Lanier, W.P., 1995, Stratigraphic architecture of the Tonganoxie Paleovalley Fill (Lower Virgilian) in northeastern Kansas: American Association of Petroleum Geologists, Bulletin, v. 79, p. 1019–1043.

Feldman, H.R., Franseen, E.K., Joeckel, R.M., and Heckel, P.H., 2005, Impact of longer-term modest climate shifts on architecture of high-frequency sequences (cyclothems), Pennsylvanian of mid-continent U.S.A.: Journal of Sedimentary Research, v. 75, p. 350–368.

Fielding, C.R., and Gibling, M.R., 2005, Distinguishing between channel and valley fills: definitions, diagnostic criteria and dimensional data (abstract): 8th International Conference on Fluvial Sedimentology, Delft, Netherlands, Abstracts, p. 101.

Fielding, C.R., Trueman, J.D., Dickens, G.R., and Page, M., 2003, Anatomy of the buried Burdekin River channel across the Great Barrier Reef shelf: how does a major river operate on a tropical mixed siliciclastic/carbonate margin during sea level lowstand?: Sedimentary Geology, v. 157, p. 291–301.

Fielding, C.R., Trueman, J.D., Dickens, G.R., and Page, M., 2005, Geomorphology and internal architecture of the ancestral Burdekin River across the Great Barrier Reef shelf, northeast Australia, in Blum, M.D., Marriott, S.B., and Leclair, S.F., eds., Fluvial Sedimentology VII, International Association of Sedimentologists, Special Publication 35, p. 321–347.

Fielding, C.R., LaGarry, H.E., LaGarry, L.A., Bailey, B.E., and Swinehart, J.B., 2007, Sedimentology of the Whiteclay Gravel Beds (Ogallala Group) in northwestern Nebraska, USA: structurally controlled drainage promoted by Early Miocene uplift of the Black Hills Dome: Sedimentary Geology, v. 202, p. 58–71.

Fischbein, S.A., Joeckel, R.M., and Fielding, C.R., 2009, Fluvial–estuarine reinterpretation of large, isolated sandstone bodies in epicontinental cyclothems, Upper Pennsylvanian, northern Midcontinent, USA, and their significance for understanding late Paleozoic sea-level fluctuations: Sedimentary Geology, v. 216, p. 15–28.

Garrison, J.R., Jr., and van den Bergh, T.C.V., 2006, Effects of sedimentation rate, rate of relative rise in sea level, and duration of sea-level cycle on the filling of incised valleys: examples of filled and "overfilled" incised valleys from the upper Ferron Sandstone, Last Chance Delta, east-central Utah, U.S.A., in Dalrymple, R.W., Leckie, D.A., and Tillman, R.W., eds., Incised Valleys in Time and Space: SEPM, Special Publication 85, p. 239–279.

Gawthorpe, R.L., Fraser, A.J., and Collier, R.E.L., 1994, Sequence stratigraphy in active extensional basins: implications for the interpretation of ancient basin-fills: Marine and Petroleum Geology, v. 11, p. 642–658.

Gibling, M.R., 2006, Width and thickness of fluvial channel bodies and valley fills in the geological record: A literature compilation and classification: Journal of Sedimentary Research, v. 76, p. 731–770.

Gibling, M.R., Nanson, G.G., and Maroulis, J.C., 1998, Anastomosing river sedimentation in the Channel Country of central Australia: Sedimentology, v. 45, p. 595–619.

Gibling, M.R., Tandon, S.K., Sinha, R., and Jain, M., 2005, Discontinuity-bounded alluvial sequences of the southern Gangetic Plains, India: aggradation and degradation in response to monsoonal strength: Journal of Sedimentary Research, v. 75, p. 369–385.

Gibling, M.R., Sinha, R., Roy, N.G., Tandon, S.K., and Jain, M., 2008, Quaternary fluvial and eolian deposits on the Belan River, India: paleoclimatic setting of Paleolithic to Neolithic archeological sites over the past 85,000 years: Quaternary Science Reviews, v. 27, p. 391–410.

Goodbred, S.L., Jr., 2003, Response of the Ganges dispersal system to climate change: a source-to-sink view since the last interstade: Sedimentary Geology, v. 162, p. 83–104.

Goodbred, S.L., Jr., and Kuehl, S.A., 2000a, The significance of large sediment supply, active tectonism, and eustasy on margin sequence development: Late Quaternary stratigraphy and evolution of the Ganges–Brahmaputra delta: Sedimentary Geology, v. 133, p. 227–248.

Goodbred, S.L., Jr., and Kuehl, S.A., 2000b, Enormous Ganges–Brahmaputra sediment discharge during strengthened early Holocene monsoon: Geology, v. 28, p. 1083–1086.

Goswami, D.C., 1985, Brahmaputra River, Assam, India: Physiography, basin denudation, and channel aggradation: Water Resources Research, v. 21, p. 959–978.

Graf, J.B., Webb, R.H., and Hereford, R., 1991, Relation of sediment load and flood-plain formation to climatic variability, Paria River drainage basin, Utah and Arizona: Geological Society of America, Bulletin, v. 103, p. 1405–1415.

Haigh, M.J., 1984, Ravine erosion and reclamation in India: Geoforum, v. 15, p. 543–561.

Hampson, G., Stollhofen, H., and Flint, S., 1999, A sequence stratigraphic model for the Lower Coal Measures (Upper Carboniferous) of the Ruhr district, north-west Germany: Sedimentology, v. 46, p. 1199–1231.

Hengesh, J.V., and Lettis, W.R., 2002, Geologic and tectonic setting, in Jain, S.K., Lettis, W.R., Murty, C.V.R., and Bardet, J.-P., eds., Bhuj, India Earthquake of January 26, 2001 Reconnaissance Report: Earthquake Spectra, Supplement A to v. 18, p. 7–22.

Hijma, M.P., Cohen, K.M., Hoffmann, G., van der Spek, A.J.F., and Stouthamer, E., 2009, From river valley to estuary: the evolution of the Rhine mouth in the early to middle Holocene (western Netherlands, Rhine–Meuse delta): Netherlands Journal of Geosciences, v. 88, p. 13–53.

Hill, P.J., De Deckker, P., Von Der Borch, C., and Murray-Wallace, C.V., 2009, Ancestral Murray River on the Lacepede Shelf, southern Australia: Late Quaternary migrations of a major river outlet and strandline development: Australian Journal of Earth Sciences, v. 56, p. 135–157.

Hirst, J.P.P., 1991, Variations in alluvial architecture across the Oligo-Miocene Huesca fluvial system, Ebro Basin, Spain, in Miall, A.D., and Tyler, N., eds., The Three-Dimensional Facies Architecture of Terrigenous Clastic Sediments and its Implications for Hydrocarbon Discovery and Recovery: SEPM, Concepts in Sedimentology and Paleontology, p. 111–121.

Holbrook, J., 2001, Origin, genetic interrelationships, and stratigraphy over the continuum of fluvial channel-form bounding surfaces: an illustration from middle Cretaceous strata, southeastern Colorado: Sedimentary Geology, v. 144, p. 179–222.

Holbrook, J., 2009, A persisting preference for progressive piling: Rock vs. river biases in the medium-term processes and architectural complexity of channel-belt stacking: From River to Rock Record, Programme and Abstracts, Aberdeen, U.K.

Holbrook, J., Scott, R.W., and Oboh-Ikuenobe, F.E., 2006, Base-level buffers and buttresses: a model for upstream versus downstream control of fluvial geometry and architecture within sequences: Journal of Sedimentary Research, v. 76, p. 162–174.

Hovius, N., 1996, Regular spacing of drainage outlets from linear mountain belts: Basin Research, v. 8, p. 29–44.

Hovius, N., 1998, Controls on sediment supply by large rivers, in Shanley, K.W., and McCabe, P.J., eds., Relative Role of Eustasy, Climate, and Tectonism in Continental Rocks: SEPM, Special Publication 59, p. 3–16.

Iwaniw, E., 1984, Lower Cantabrian basin margin deposits in NE Leon, Spain—a model for valley-fill sedimentation in a tectonically active, humid climatic setting: Sedimentology, v. 31, p. 91–110.

Jain, V., and Sinha, R., 2003, Hyperavulsive-anabranching Baghmati river system, north Bihar plains, eastern India: Zeitschrift für Geomorphologie, v. 47, p. 101–116.

Jain, V., and Sinha, R., 2005, Response of active tectonics on the alluvial Baghmati River, Himalayan foreland basin, eastern India: Geomorphology, v. 70, p. 339–356.

Kraus, M.J., and Middleton, L.T., 1987, Dissected paleotopography and base-level changes in a Triassic fluvial sequence: Geology, v. 15, p. 18–21.

Kvale, E.P., and Archer, A.W., 2007, Paleovalley fills: Trunk vs. tributary: American Assocation of Petroleum Geologists, Bulletin, v. 91, p. 809–821.

Lavé, J., and Avouac, P., 2000, Active folding of fluvial terraces across the Siwaliks Hills, Himalayas of central Nepal: Journal of Geophysical Research, v. 105, p. 5735–5770.

Leckie, D.A. and Cheel, R.J., 1997, Sedimentology and depositional history of Lower Cretaceous coarse-grained clastics, southwest Alberta and southeast British Columbia: Bulletin of Canadian Petroleum Geology, v. 45, p. 1–24.

Leckie, D.A., and Krystinik, L.F., 1995, Cretaceous igneous-clast conglomerate in the Blairmore Group, Rocky Mountain Foothills and adjacent subsurface (Bow Island Formation), Alberta, Canada: Bulletin of Canadian Petroleum Geology, v. 43, p. 320–342.

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, v. 24, p. 87–90.

Legarreta, L., and Uliana, M.A., 1998, Anatomy of hinterland depositional sequences: Upper Cretaceous fluvial strata, Neuquen Basin, west-central Argentina, in Shanley, K.W., and McCabe, P.J., eds., Relative Role of Eustasy, Climate, and Tectonism in Continental Rocks: SEPM, Special Publication 59, p. 83–92.

Levy, M., Christie-Blick, N., and Link, P.K., 1994, Neoproterozoic incised valleys of the eastern Great Basin, Utah and Idaho: fluvial response to changes in depositional base level, in Dalrymple, R.W., Boyd, R., and Zaitlin, B.A., eds., Incised-Valley Systems: Origin and Sedimentary Sequences: SEPM, Special Publication 51, p. 369–382.

Mack, G.H., and Leeder, M.R., 1999, Climatic and tectonic controls on alluvial-fan and axial-fluvial sedimentation in the Plio-Pleistocene Palomas Half Graben, southern Rio Grande Rift: Journal of Sedimentary Research, v. 69, p. 635–652.

Mack, G.H., and Madoff, R.D., 2005, A test of models of fluvial architecture and palaeosol development: Camp Rice Formation (Upper Pliocene–Lower Pleistocene), southern Rio Grande rift, New Mexico, USA: Sedimentology, v. 52, p. 191–211.

Mack, G.H., Seager, W.R., Leeder, M.R., Pérez-Arlucea, M., and Salyards, S.L., 2006, Pliocene and Quaternary history of the Rio Grande, the axial river of the southern Rio Grande rift, New Mexico, USA: Earth-Science Reviews, v. 79, p. 141–162.

Magee, J.W., Bowler, J.M., Miller, G.H., and Williams, D.L.G., 1995, Stratigraphy, sedimentology, chronology and palaeohydrology of Quaternary lacustrine deposits at Madigan Gulf, Lake Eyre, South Australia: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 113, p. 3–42.

Martinsen, O.J., and Helland-Hansen, W., 1995, Strike variability of clastic depositional systems: Does it matter for sequence-stratigraphic analysis?: Geology, v. 23, p. 439–442.

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, SW Wyoming, USA: Sedimentology, v. 46, p. 235–259.

McCarthy, P.J., Faccini, U.F., and Plint, A.G., 1999, Evolution of an ancient coastal plain: palaeosols, interfluves and alluvial architecture in a sequence stratigraphic framework, Cenomanian Dunvegan Formation, NE British Columbia, Canada: Sedimentology, v. 46, p. 861–891.

Menier, D., Reynaud, J.-Y., Proust, J.-N., Guillocheau, F., Guennoc, P., Bonnet, S., Tessier, B., and Goubert, E., 2006, Basement control on shaping and infilling of valleys incised at the southern coast of Brittany, France, in Dalrymple, R.W., Leckie, D.A., and Tillman, R.W., eds., Incised Valleys in Time and Space: SEPM, Special Publication 85, p. 37–55.

Miall, A.D., 2002, Architecture and sequence stratigraphy of Pleistocene fluvial systems in the Malay Basin, based on seismic time-slice analysis: American Association of Petroleum Geologists, Bulletin, v. 86, p. 1201–1216.

Miall, A.D., and Arush, M., 2001, Cryptic sequence boundaries in braided fluvial successions: Sedimentology, v. 48, p. 971–985.

Miall, A.D., and Jones, B.G., 2003, Fluvial architecture of the Hawkesbury Sandstone (Triassic), near Sydney, Australia: Journal of Sedimentary Research, v. 73, p. 531–545.

Milana, J.P., 1998, Sequence stratigraphy in alluvial settings: A flume-based model with applications to outcrop and seismic data: American Association of Petroleum Geologists, Bulletin, v. 82, p. 1736–1753.

Mohindra, R., Parkash, B., and Prasad, J., 1992, Historical geomorphology and pedology of the Gandak Megafan, Middle Gangetic Plains, India: Earth Surface Processes and Landforms, v. 17, p. 643–662.

Monecke, K., Winsemann, J., and Hanisch, J., 2001, Climatic response of Quaternary alluvial deposits in the upper Kali Gandaki valley (West Nepal): Global and Planetary Change, v. 28, p. 293–302.

Mukerji, A.B., 1990, The Chandigarh Dun alluvial fans: An analysis of the process–form relationship, in Rachocki, A.H., and Church, M., eds., Alluvial Fans: A Field Approach: New York, Wiley, p. 131–149.

Nádor, A., Lantos, M., Toth-Makk, A., and Thamo-Bozso, E., 2003, Milankovitch-scale multi-proxy records from fluvial sediments of the last 2.6 Ma, Pannonian Basin, Hungary: Quaternary Science Reviews, v. 22, p. 2157–2175.

Nanson, G.C., 1986, Episodes of vertical accretion and catastrophic stripping: A model of disequilibrium flood-plain development: Geological Society of America, Bulletin, v. 97, p. 1467–1475.

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

Nanson, G.C., Price, D.M., Jones, B.G., Maroulis, J.C., Coleman, M., Bowman, H., Cohen, T.J., Pietsch, T.J., and Larsen, J.R., 2008, Alluvial evidence for major climate and flow regime changes during the middle and late Quaternary in eastern central Australia: Geomorphology, v. 101, p. 109–129.

Nash, D.B., 1994, Effective sediment-transporting discharge from magnitude-frequency analysis: Journal of Geology, v. 102, p. 79–95.

Neal, J., and Abreu, V., 2009, Sequence stratigraphy hierarchy and the accommodation succession method: Geology, v. 37, p. 779–782.

Nichols, G.J., 1987, Structural controls on fluvial distributary systems—the Luna System, northern Spain, in Ethridge, F.G., Flores, R.M., and Harvey, M.D., eds., Recent Developments in Fluvial Sedimentology: SEPM, Special Publication 39, p. 269–277.

Olsen, T., Steel, R., Hogseth, 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: Journal of Sedimentary Research, v. B65, p. 265–280.

Overpeck, J., Anderson, D., Trumbore, S., and Prell, W., 1996, The southwest Indian monsoon over the last 18000 years: Climate Dynamics, v. 12, p. 213–225.

Page, K.J., Kemp, J., and Nanson, G.C., 2009, Late Quaternary evolution of Riverine Plain paleochannels, southeastern Australia: Australian Journal of Earth Sciences, v. 56, p. S19-S33.

Pascucci, V., Gibling, M.R., and Sandrelli, F., 2006, Valley formation and filling in response to Neogene magmatic doming of Elba Island, Tuscany, Italy, in Dalrymple, R.W., Leckie, D.A., and Tillman, R.W., eds., Incised Valleys in Time and Space: SEPM, Special Publication 85, p. 327–343.

Patterson, P.E., 2009, Alluvial hierarchy: description of alluvial strata in the rock record: From River to Rock Record, Aberdeen, Scotland, U.K., Abstract.

Petter, A.L., and Muto, T., 2008, Sustained alluvial aggradation and autogenic detachment of the alluvial river from the shoreline in response to steady fall of relative sea level: Journal of Sedimentary Research, v. 78, p. 98–111.

Plink-Bjørklund, P., and Steel, R.J., 2006, Incised valleys on an Eocene coastal plain and shelf, Spitsbergen—part of a linked shelf-slope system, in Dalrymple, R.W., Leckie, D.A., and Tillman, R.W., eds., Incised Valleys in Time and Space: SEPM, Special Publication 85, p. 281–307.

Plint, A.G., 2002, Paleo-valley systems in the Upper Cretaceous Dunvegan Formation, Alberta and British Columbia: Bulletin of Canadian Petroleum Geology, v. 50, p. 277–296.

Plint, A.G., and Nummedal, D., 2000, The falling stage systems tract: recognition and importance in sequence stratigraphic analysis, in Hunt, D.R., and Gawthorpe, R.L., eds., Sedimentary Responses to Forced Regressions: Geological Society of London, Special Publication 172, p. 1–17.

Plint, A.G., and Wadsworth, J.A., 2003, Sedimentology and palaeogeomorphology of four large valley systems incising delta plains, western Canada Foreland Basin: implications for mid-Cretaceous sea-level changes: Sedimentology, v. 50, p. 1147–1186.

Plint, A.G., and Wadsworth, J.A., 2006, Delta-plain paleodrainage patterns reflect small-scale fault movement and subtle forebulge uplift: Upper Cretaceous Dunvegan Formation, Western Canada Foreland Basin, in Dalrymple, R.W., Leckie, D.A., and Tillman, R.W., eds., Incised Valleys in Time and Space: SEPM, Special Publication 85, p. 219–237.

Posamentier, H.W., 2001, Lowstand alluvial bypass systems: Incised vs. unincised: American Association of Petroleum Geologists, Bulletin, v. 85, p. 1771–1793.

Pratt-Sitaula, B., Burbank, D.W., Heimsath, A., and Ojha, T., 2004, Landscape disequilibrium on 1000–10,000 year scales, Marsyandi River, Nepal, central Himalaya: Geomorphology, v. 58, p. 223–241.

Prell, W.L., and Kutzbach, J.E., 1987, Monsoon variability over the past 150,000 years: Journal of Geophysical Research, v. 92, p. 8411–8425.

Retallack, G.J., 1986, Fossil soils as grounds for interpreting long-term controls on ancient rivers: Journal of Sedimentary Petrology, v. 56, p. 1–18.

Ritter, J.B., Miller, J.R., Enzel, Y., and Wells, S.G., 1995, Reconciling the roles of tectonism and climate in Quaternary alluvial fan evolution: Geology, v. 23, p. 245–248.

Roy, N.G., Sinha, R., Gibling, M.R., Jain, M., and Murray, A.S., 2007, Valley-fill stratigraphy in the southern Ganga basin: southward migration and monsoonal forcing: Quaternary International, v. 167–168 Supplement, p. 388–389.

Rust, B.R., and Nanson, G.C., 1986, Contemporary and palaeo channel patterns and the late Quaternary stratigraphy of Cooper Creek, southwest Queensland, Australia: Earth Surface Processes and Landforms, v. 11, p. 581–590.

Ryan, D.A., Bostock, H.C., Brooke, B.P., and Marshall, J.F., 2007, Bathymetric expression of the Fitzroy River palaeochannel, northeast Australia: Response of a major river to sea-level change on a semi-rimmed, mixed siliciclastic–carbonate shelf: Sedimentary Geology, v. 201, p. 196–211.

Rygel, M.C., and Gibling, M.R., 2006, Natural geomorphic variability recorded in a high-accommodation setting: fluvial architecture of the Pennsylvanian Joggins Formation of Atlantic Canada: Journal of Sedimentary Petrology, v. 76, p. 1230–1251.

Rygel, M.C., Fielding, C.R., Frank, T.D., and Birgenheier, L.P., 2008, The magnitude of Late Paleozoic glacioeustatic fluctuations: A synthesis: Journal of Sedimentary Research, v. 78, p. 500–511.

Salter, T., 1993, Fluvial scour and incision: models for the development of realistic reservoir geometries, in North, C.P., and Prosser, D.J., eds., Characterization of Fluvial and Aeolian Reservoirs: Geological Society of London, Special Publication 73, p. 33–51.

Schlager, W., 2004, Fractal nature of stratigraphic sequences: Geology v. 32, p. 85–188.

Schumm, S.A., and Ethridge, F.G., 1994, Origin, evolution and morphology of fluvial valleys, in Dalrymple, R.W., Boyd, R., and Zaitlin, B.A., eds., Incised-Valley Systems: Origin and Sedimentary Sequences: SEPM, Special Publication 51, p. 11–27.

Schumm, S.A., and Lichty, R.W., 1963, Channel widening and flood-plain construction along Cimarron River in Southwestern Kansas: U.S. Geological Survey, Professional Paper 352-D, p. 71–88.

Sedimentation Seminar, 1978, Sedimentology of the Kyrock Sandstones (Pennsylvanian) in the Brownsville Paleovalley, Edmonson and Hart counties, Kentucky: Lexington, Kentucky, Kentucky Geological Survey, Series X, p. 24.

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

Shanley, K.W., and McCabe, P.J., 1994, Perspectives on the sequence stratigraphy of continent strata: American Association of Petroleum Geologists, Bulletin, v. 78, p. 544–568.

Sharma, S., Joachimski, M., Sharma, M., Tobschall, H.J., Singh, I.B., Sharma, C., Chauhan, M.S., and Morgenroth, G., 2004, Lateglacial and Holocene environmental changes in Ganga plain, Northern India: Quaternary Science Reviews, v. 23, p. 145–159.

Simms, A., Anderson, J.B., Taha, Z.P., and Rodriguez, A.B., 2006, Overfilled versus underfilled incised valleys: examples from the Quaternary Gulf of Mexico, in Dalrymple, R.W., Leckie, D.A., and Tillman, R.W., eds., Incised Valleys in Time and Space: SEPM, Special Publication 85, p. 117–139.

Singh, H., Parkash, B., and Gohain, K., 1993, Facies analysis of the Kosi megafan deposits: Sedimentary Geology, v. 85, p. 87–113.

Singh, V., and Tandon, S.K., 2007, Evidence and consequences of tilting of two alluvial fans in the Pinjaur dun, Northwestern Himalayan Foothills: Quaternary International, v. 159, p. 21–31.

Sinha, R., Gibling, M.R., Jain, V., and Tandon, S.K., 2005, Sedimentology and avulsion patterns of the anabranching Baghmati River in the Himalayan foreland basin, India, in Blum, M.D., and Marriott, S.B., eds., Fluvial Sedimentology VII: International Association of Sedimentologists, Special Publication 35, p. 181–196.

Sinha, R., Tandon, S.K., Sanyal, P., Gibling, M.R., Stuben, D., Berner, Z., and Ghazanfari, P., 2006, Calcretes from a Late Quaternary interfluve in the Ganga Plains, India: Carbonate types and isotopic systems in a monsoonal setting: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 242, p. 214–239.

Sinha, R., Bhattacharjee, P.S., Sangode, S.J., Gibling, M.R., Tandon, S.K., Jain, M., and Godfrey-Smith, D., 2007, Valley and interfluve sediments in the Southern Ganga plains, India: Exploring facies and magnetic signatures: Sedimentary Geology, v. 201, p. 386–411.

Sinha, R., Kettanah, Y., Gibling, M.R., Tandon, S.K., Jain, M., Bhattacharjee, P.S., Dasgupta, A.S., and Ghazanfari, P., 2009, Craton-derived alluvium as a major sediment source in the Himalayan Foreland Basin of India: Geological Society of America, Bulletin, v. 121, p. 1596–1610.

Smith, G.A., 1988, Sedimentology of proximal to distal volcaniclastics dispersed across an actic foldbelt: Ellensburg Formation (late Miocene), central Washington: Sedimentology, v. 35, p. 953–977.

Smith, G.A., 1994, Climatic influences on continental deposition during late-stage filling of an extensional basin, southeastern Arizona: Geological Society of America, Bulletin, v. 106, p. 1212–1228.

Sømme, T.O., Helland-Hansen, W., and Granjeon, D., 2009, Impact of eustatic amplitude variations on shelf morphology, sediment dispersal, and sequence stratigraphic interpretation: Icehouse versus greenhouse systems: Geology, v. 37, p. 587–590.

Srivastava, P., Shukla, U.K., Mishra, P., Sharma, M., Sharma, S., Singh, I.B., and Singhvi, A.K., 2000, Luminescence chronology and facies development of Bhur sands in the interfluve region of Central Ganga Plain, India: Current Science, v. 78, p. 498–503.

Srivastava, P., Juyal, N., Singhvi, A.K., Wasson, R.J., and Bateman, M.D., 2001, Luminescence chronology of river adjustment and incision of Quaternary sediments in the alluvial plain of the Sabarmati River, north Gujarat, India: Geomorphology, v. 36, p. 217–229.

Stouthamer, E., and Berendsen, H.J.A., 2007, Avulsion: The relative roles of autogenic and allogenic processes: Sedimentary Geology, v. 198, p. 309–325.

Strong, N., and Paola, C., 2008, Valleys that never were: time surfaces versus stratigraphic surfaces: Journal of Sedimentary Research, v. 78, p. 579–593.

Tandon, S.K., and Gibling, M.R., 1997, Calcretes at sequence boundaries in Upper Carboniferous cyclothems of the Sydney Basin, Atlantic Canada: Sedimentary Geology, v. 112, p. 43–67.

Tandon, S.K., Gibling, M.R., Sinha, R., Singh, V., Ghazanfari, P., Dasgupta, A.S., Jain, M., and Jain, V., 2006, Alluvial valleys of the Gangetic Plains, India: Timing and causes of incision, in Dalrymple, R.W., Leckie, D.A., and Tillman, R.W., eds., Incised Valleys in Time and Space: SEPM, Special Publication 85, p. 15–35.

Thomas, M.A., and Anderson, J.B., 1994, Sea-level controls on the facies architecture of the Trinity–Sabine incised-valley system, Texas continental shelf, in Dalrymple, R.W., Boyd, R., and Zaitlin, B.A., eds., Incised-Valley Systems: Origin and Sedimentary Sequences: SEPM, Special Publication 51, p. 63–82.

Törnqvist, T.E., Wallinga, J., and Busschers, F.S., 2003, Timing of the last sequence boundary in a fluvial setting near the highstand shoreline—Insights from optical dating: Geology, v. 31, p. 279–282.

Umitsu, M., 1993, Late Quaternary sedimentary environments and landforms in the Ganges delta: Sedimentary Geology, v. 83, p. 177–186.

Vincent, S.J., 2001, The Sis palaeovalley: a record of proximal fluvial sedimentation and drainage basin development in response to Pyrenean mountain building: Sedimentology, v. 48, p. 1235–1276.

Waelbroeck, C., Labeyrie, L., Michel, E., Duplessy, J.C., McManus, J.F., Lambeck, K., Balbon, E., and Labracherie, M., 2002, Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records: Quaternary Science Reviews, v. 21, p. 295–305.

Weissmann, G.S., Mount, J.F., and Fogg, G.E., 2002, Glacially-driven cycles in accumulation space and sequence stratigraphy of a stream-dominated alluvial fan, San Joaquin Valley, California, U.S.A.: Journal of Sedimentary Research, v. 72, p. 240–251.

Weissmann, G.S., Hartley, A.J., Nichols, G.J., Scuderi, L.A., Olson, M., Buehler, H., and Banteah, R., 2010, Fluvial form in modern continental sedimentary basins: Distributive fluvial systems: Geology, v. 38, p. 39–42.

Wellner, R.W., and Bartek, L.R., 2003, The effect of sea level, climate, and shelf physiography on the development of incised-valley complexes: a modern example from the East China Sea: Journal of Sedimentary Research, v. 73, p. 926–940.

Wells, N.A., and Dorr, J.A., Jr., 1987, Shifting of the Kosi River, northern India: Geology, v. 15, p. 204–207.

White, J.M., and Leckie, D.A., 1999, Palynological age constraints on the

Cadomin and Dalhousie formations in SW Alberta: Bulletin of Canadian Petroleum Geology, v. 47, p. 199–222.

Williams, G.P., 1978, Bank-full discharge of rivers: Water Resources Research, v. 14, p. 1141–1154.

Williams, M.A.J., and Clarke, M.F., 1995, Quaternary geology and prehistoric environments in the Son and Belan valleys, north central India: Geological Society of India, Memoir 32, p. 282–308.

Williams, M.A.J., Pal, J.N., Jaiswal, M., and Singhvi, A.K., 2006, River response to Quaternary climatic fluctuations: evidence from the Son and Belan valleys, north-central India: Quaternary Science Reviews, v. 25, p. 2619–2631.

Willis, B.J., 1997, Architecture of fluvial-dominated valley-fill deposits in the Cretaceous Fall River Formation: Sedimentology, v. 44, p. 735–757.

Wolman, M.G., and Miller, J.P., 1960, Magnitude and frequency of forces in geomorphic processes: Journal of Geology, v. 68, p. 54–74.

Wright, V.P., and Marriott, S.B., 1993, The sequence stratigraphy of fluvial depositional systems: the role of floodplain sediment storage: Sedimentary Geology, v. 86, p. 203–210.

Zaitlin, B.A., Dalrymple, R.W., and Boyd, R., 1994, The stratigraphic organization of incised-valley systems associated with relative sea-level change, in Dalrymple, R.W., Boyd, R., and Zaitlin, B.A., eds., Incised-Valley Systems: Origin and Sedimentary Sequences: SEPM, Special Publication 51, p. 45–60.

Zawada, P.K., 1994, Palaeoflood hydrology of the Buffels River, Laingsburg, South Africa: was the 1981 flood the largest?: South African Journal of Geology, v. 97, p. 21–32.

DIGITAL APPENDIX

The following supplementary figures are available in electronic format either on the DVD accompanying this volume or through the digital archive on the SEPM website at http://www.sepm.org/

See Figure 2A for Asian locations and Figure 3 for Australian locations.

S1. Upstream view of the Gandak River and sand flats near Patna, India. Note the flat nature of the landscape and the minimal degree of incision of the channel into adjacent alluvium, in accord with the prolonged and widespread flooding experienced in this area. The sand bars are in use for agriculture during the dry season. Photo by M.R.Gibling.

S2. Upstream view of Baghmati River anabranch at Benibad near Muzzafarpur, India. Note the flat nature of the landscape and the minimal degree of incision of the channel into adjacent alluvium, in accord with the prolonged and widespread flooding experienced in this area. Scientists are standing on a low levee a few meters high and tens of meters wide that borders the channel. See details in Sinha et al. (2005). Photo by M.R.Gibling.

S3. Upstream view of Baghmati River anabranch near Nawada, India. Scientists are standing below a crevasse channel (at lower right), a meter-thick splay from which buried an orchard during the previous season’s flooding. This site provides field evidence for the frequent overbank flooding indicated in the flood map. See details in Sinha et al. (2005). Photo by M.R.Gibling.

S4. Alluvial fan lobe in foreground, where a temple is built on the lobe, and in the middle distance. The lobe is cut by an incised channel about 40 m deep, shallowing distally. The site lies within the Himalayan Foothills of India, in the intermontane valley of Pinjaur Dun, bounded to the north (left) by the Main Boundary Thrust and to the south (right) by the Siwalik Hills. The topmost strata of the lobe date to ~24 ka B.P., and incision post-dates this period of deposition. Fans in Pinjaur Dun are tilted, and incision was a response to uplift on the Main Boundary Fault (Tandon et al. 2006; Singh and Tandon 2007). Photo by M.R.Gibling.

S5. Cliffs about 30 m high along the southern margin of the Ganga Valley near Kannauj, northwest of Kanpur, India (Text-figure 2B). Downstream view. The cliffs are cut into late Quaternary alluvium which dates back to about 27 ka B.P. downstream at Bithur. See details in Gibling et al. (2005) and Sinha et al. (2007). Photo by M.R.Gibling.

S6. Cliffs about 20 m high along the southern margin of the Ganga Valley near Kannauj, northwest of Kanpur, India (Text-Figure 2B). Downstream view. Note the shallow gullies cutting through the cliffs, part of a narrow belt of badlands bordering the valley in this area (Sinha et al. 2007). Photo by M.R.Gibling.

S7. Clastic dikes of red clay, with some white calcite precipitates, cutting through silty alluvium in cliffs along the Yamuna Valley near Kalpi, India. The dikes terminate below a discontinuity within the Quaternary section, just above the level of the photo. Note the distorted stratification in the alluvium which, along with the dikes, suggests deformation due to earthquake activity. Measuring stick is 50 cm long. See details in Gibling et al. (2005). Photo by M.R.Gibling.

S8. Near-vertical calcite vein that transects ~5 m of alluvium in terrace cuts, at Chillahia on the Belan River, India. Hammer is 30 cm long. See details in Gibling et al. (2008). Photo by M.R.Gibling.

S9. Fluvial sand sheet exposed in bank of anabranch, Cooper Creek, Australia. The topstratum of the bank is dark mud attributed to anastomosing rivers similar to those of the present day. The pale substratum is an unusual exposure of a widespread sand sheet proven from augering, drilling and trenches across much of the Channel Country. The sand sheet dates from MIS 3 back to about 750,000 years before present, and represents periods of enhanced fluvial discharge and sediment transport linked to secular variation in precipitation (Gibling et al. 1998; Nanson et al. 2008). Undercutting of the soft sand has caused bank migration, toppled trees, and resulted in unusual amounts of sand on the adjacent point bar. Photo by M.R.Gibling.

S10. Relict meanders and point bars with scroll-bar topography on alluvial surface, Cooper Creek, Australia. White bar is 2 km long. The relict topography represents the top of a near-surface sand sheet attributed to an earlier period of enhanced fluvial activity. See Rust and Nanson (1986) for details. Aerial photo CAB 7059 Run 4 Number 141, General Manager, Australian Surveying and Land Information Group, Canberra.

S11. Source-bordering eolian mound in Ganga Valley (Gahira Bypass Section), near Unnao north of Kanpur, India. The silts were dated to early-mid Holocene by Srivastava et al. (2000). Photo by M.R.Gibling.

S12. Eolian mound in Ganga Valley, showing thick units of poorly stratified silt, with a vegetated cap and paleosol. Photo by M.R.Gibling.

S13. Close-up of yellow silt in eolian mound, Ganga Valley (DVD 12), showing poor stratification and weakly defined red layers, suggesting incipient paleosols. Trowel is 15 cm long. Photo by M.R.Gibling.

S14. Source-bordering eolian mound of weakly stratified sand and silt in the Belan Valley, India. Eolian deposits in the valley yielded dates from about 14 to 7 ka B.P., representing a period of climatic instability as the monsoon intensified following the Last Glacial Maximum (Gibling et al. 2008). Photo by M.R.Gibling.

S15. Poorly stratified sand with disseminated shell fragments in eolian mound, Belan Valley (DVD 14). Lens cap is 5 cm in diameter. Photo by M.R.Gibling.

S16. Baraila Tal (large lake), Bihar, India. Abundant pale mounds in the foreground are the “chimneys” of crustacean burrows, extending up to 15 cm above the mud surface. Mounds in the distance are piles of lake reeds collected by local farmers. See Sinha et al. (2005). Photo by M.R.Gibling.

S17. Carbonate-cemented erosional surface (discontinuity) within alluvial cliffs along Yamuna Valley near Kalpi, India. Several similar surfaces, which mark both pedogenic and groundwater carbonate accumulation, divide the cliff succession into aggradational-degradational rhythms (see text). Hammer is 30 cm long. See Gibling et al.

(2005) and Sinha et al. (2007) for a description of these rhythms. Photo by M.R.Gibling.

S18. Colluvial gully fills up to 10 m thick in cliffs along the Yamuna Valley near Kalpi, India. Strata filling a major gully dip systematically to the right across most of the illustrated cliff face, and are cut by two successive gully fills at right of the photo. Cliff is 10 m high, and the topmost cliff strata represent the cultural level of human occupation. The gully forms and fills are analogous to modern badland features that border the modern Yamuna River. See Gibling et al. (2005) for a detailed account of these gully fills, which yielded a date of 36 ka B.P. Photo by M.R.Gibling.

S19. Thick calcrete on terrace surface at Benar near Jodhpur, in the Thar Desert of northwest India (north of the Luni River in Text-figure 2A. See Dhir et al. (2004) for details. Photo by M.R.Gibling.

S20. Close-up of calcrete in DVD 19 to show closely packed nodules. Scale is 9 cm long. Photo by M.R.Gibling.

S21. Gullied badlands behind incised valley of the Yamuna River near Kalpi, India. Gullies are well vegetated and up to 15 m deep, and they dissect late Quaternary alluvium along a broad belt bordering the river. Photo by M.R.Gibling.

S22. Gullied cliff face along the Betwa River near Kotra, India (Text-figure 2A). Gullies are up to 15 m deep and form part of a wide belt bordering the river. They cut into an undated alluvial succession that contains erosional surfaces and comprises stacked aggradational and degradational rhythms. The succession contains fluvial carbonate gravels derived from erosion of floodplain deposits. Tough material in foreground is an older, well cemented alluvial unit. See description in Gibling et al. (2005). Photo by M.R.Gibling.

S23. Gullied cliff face along the Yamuna Valley at Tilauli near Allahabad, India. The main part of the cliff consists of red-brown floodplain silt and clay. At the cliff top is an indurated, well stratified yellow silt 3 m thick that is rich in gastropods and interpreted as a lacustrine unit. Shells yielded a date of 15.5 radiocarbon years B.P. (Williams and Clarke 1995), calibrated to ~18.8 ka B.P. The change from floodplain to lake deposition at the cliff top represents a period of reduced discharge on the alluvial plain. Subsequent incision by the Yamuna River post-dates the lacustrine unit, and is attributed to enhanced discharge during intensification of the Southwest Indian Monsoon following the Last Glacial Maximum (Tandon et al. 2006). Photo by M.R.Gibling.

S24. Close-up of lacustrine unit at Tilauli (DVD 23). The unit is 3 m thick, and has partly slumped down the cliff in the foreground. Note gullied landscape and Yamuna Valley in distance. Photo by M.R.Gibling.

S25. Alluvial terrace (centre-right) where the Gandak River has cut through alluvium from a tributary valley near Kalopani, Nepal Himalaya. The higher cliff at centre-left is largely cut through bedrock. Hut in fields at centre-right of photo is 5 m high. Photo by M.R.Gibling.

S26. Alluvial terrace from the tributary Miristi Khola, incised by the Gandak River north of Tatopani, Nepal Himalaya. House on terrace top is 8 m high. See Monecke et al. (2001) for a description of the alluvium. Photo by M.R.Gibling.

S27. Terraces at base of Gandak Valley south of the Main Central Thrust near Tatopani, Nepal Himalaya. The valley cuts through the Annapurna and Dhaulagiri Massifs, 8 km above sea-level, parts of which are visible in the distance. The valley is about 6.5 km deep. People on bridge in foreground for scale. Photo by M.R.Gibling.

S28. Close-up of terraces in DVD 27 to show coarse-grained alluvium and occurrence of terraces in small rock-cut embayments. People on bridge in foreground for scale. Photo by M.R.Gibling.

S29. Alluvial terraces of the Belan River, India, with Kaimur Hills of the Indian Craton visible to the south. The river at left is cut into Proterozoic quartzites, and the terrace succession at right commences with channel-base groundwater calcrete, which projects as ledges into the river. People are standing on the top of the calcrete. The alluvium in the cliff yielded dates of about 90 to 20 ka B.P. (Williams et al. 2006). Photo by M.R.Gibling.

S30. Alluvial terrace and cultivated inset terrace, Belan River, India. The alluvium at this location yielded dates back to about 13 ka B.P. (Gibling et al. 2008), a quite different spectrum of ages from the terrace succession shown in DVD 29, about 5 km upstream. Photo by M.R.Gibling.

S31. Strath (bedrock) terrace on Proterozoic quartzite, with thin alluvial cover, Chopani-Mando, Belan River, India. The terrace level on the far bank of the river was the site of Palaeolithic and Mesolithic settlements (Gibling et al. 2008). Photo by M.R.Gibling.

S32. Charity Creek on the Manning River, New South Wales, Australia, looking upstream. At the bend at the extreme left, the alluvial terrace has been partially stripped away by flood events in the 1968 to 1978 period, leaving an expanse of gravel. Site of "catastrophic stripping" described by Nanson (1986). Photo by M.R.Gibling.

S33. Close-up of Charity Creek site at river bend at extreme left in DVD 32, looking downstream. The alluvial terrace has been stripped away over a width of about 50 m, leaving an incised terrace margin and a gravel expanse. Photo by M.R.Gibling.