

## Chapter 23

# River Landforms and Sediments: Evidence of Climatic Change

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### Introduction

Significant changes in the style of superimposed fluvial deposits have long been used by sedimentologists as an indication of broad changes in climate. Certainly, in traversing the globe from one environmental extreme to another – from humid to arid regions – it is possible to discern substantial differences in the character of rivers, both from the point of view of the forms that they adopt and the sediments that they carry (Schumm 1977; Wolman and Gerson 1978). However, rivers react to a number of large-scale stimuli, and it is often difficult to determine whether a change in character reflects tectonic or climatic influences, or both (Frostick and Reid 1989a). Attempts to attribute cause have inevitably and ingeniously simplified the setting by choosing systems in areas where most factors are presumed to have remained more-or-less constant whilst the putative controlling factor has varied monotonically. So, for example, location on a stable craton may allow an assessment of the impacts of climate change on river systems without the additional complications that arise from tectonic instability (Schumm 1968; Rust and Nanson 1986). However, while this approach may be useful in deducing the response of rivers to recent shifts in climate – say, those of the late Pleistocene and Holocene – and may be instructive in indicating the direction and magnitude of likely changes to be expected in river systems during periods of environmental change, the sedimentary legacies are often too similar to those assumed to have arisen from tectonic

influences to ascribe changes in sedimentary style confidently to either set of causes when stepping further back in time (Frostick et al. 1992).

In fact, rivers are comparatively insensitive to changes in climate unless these changes are substantial. Moreover, it is likely that there is considerable hysteresis in the relation between climate change and river metamorphosis. Intuitively, it might be argued that the rate of change in a parameter such as channel sinuosity would be greater during a shift towards aridity, with the tendency to increased flashiness in the flood regime and, therefore, greater potential erosional damage, than it would in a corresponding period of increasing humidity, when channel change might depend upon sediment accretion at a time of progressively decreasing rates of sediment yield (see, e.g., Hereford 1984, 1986).

Nanson and Tooth (1999) implied that they were surprised by the declamation (made by the author in the 1st edition of this book) that rivers are insensitive to comparatively small degrees of climate change, though, later, they conceded that the response rate might depend on local circumstances, indicating that ‘dryland rivers which are confined within bed-rock gorges, stabilised by effective riparian vegetation, or restrained by indurated or very clay-rich alluvium, are probably relatively insensitive to all but extreme environmental changes, whereas rivers within erodible silty or sandy alluvium will probably respond much more readily to even modest changes’ (Nanson et al. 2002).

The sensitivity of rivers to climate change is also conditioned, in part, by the wide range in flood magnitude that is experienced under a singular climatic regime and by the erosional or depositional legacy of large events. Baker and his colleagues (Baker 1977;

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Baker et al. 1983; Patton et al. 1982) have drawn attention to the erosional implications of very large floods having recurrence intervals in the order of  $10^3$  years in the Northern Territories of Australia and western Texas. Nanson (1986) has described what he calls flood-plain stripping in the coastal valleys of New South Wales. Here, he has deduced that substantial quantities of accumulated sediment are removed periodically during the passage of rare high-magnitude floods, leaving channel dimensions that bear little relation to the more frequent floods ordinarily thought to be channel-formative and a flood-plain topography that is difficult to interpret in the context of observed modern flows. Under a drier regime, Schumm and Lichty (1963) collated historical records to show that the Cimarron River of south-western Kansas was widened dramatically from an average of 15 to 200 m by a single high-magnitude flood in 1914. During the next 25 years, channel width increased to an average value of 365 m with the passage of other damaging floods, after which it declined progressively to 183 m over a period of 21 years, in sympathy with lower flood discharges. But the fact that at-a-point channel width can be shown to have had a 24-fold range during a period when climate did not change dramatically suggests that parameters such as these – so important as tools in palaeohydrology – may have only limited value in diagnosing climate change, at least in arid zones.

The damaging impact of large floods highlights another problem in using channel dimensional parameters as a diagnostic of climate change. Schumm and Lichty's (1963) study of the Cimarron River suggested a relaxation period (the lag between infliction of the flood damage and a return to pre-flood conditions) of much more than 50 years in this semi-arid environment. This compares with a relaxation period of less than 20 years in a temperate humid environment where flood frequency and the prospects of channel reparation are higher (Gupta and Fox 1974). Wolman and Gerson (1978) have suggested from rather more casual observations made in Sinai that the lack of sediment-trapping riparian vegetation and the extreme infrequency of floods in arid and hyper-arid zones removes almost entirely the potential for channel restoration. In this type-environment, the relaxation period is, to all intents and purposes, infinite. In these circumstances, and with the inevitability of poor or non-existent hydrological records in such drylands,

it may be difficult to judge whether or not a channel and its sediments are anachronistic. In other words, it may be difficult to establish whether they represent the prevailing climate or one that is now past, especially if the differences involve a comparatively narrow range of annual effective precipitation.

Having cautioned that diagnosing climate change from channel and sediment characteristics can be hazardous where extremes of weather inflict damage that is only slowly restored to reflect the prevailing climatic average, it has to be pointed out that rivers may not react entirely predictably to changing climate – at least as far as can be ascertained, given that shifts in climate can rarely be defined precisely in terms of the consequences for runoff. One problem is that each drainage basin is a unique permutation of all those factors that encourage or discourage runoff and sediment transfer. Factors which act as regulators of change may be more important in one basin than in another. Despite this complexity and the fact that the infrequency of runoff in deserts has deterred the collection of data relating to flood flows and sediment transport – so that understanding of fluvial processes in such environments is undernourished – certain patterns of climate-induced behavioural change have emerged.

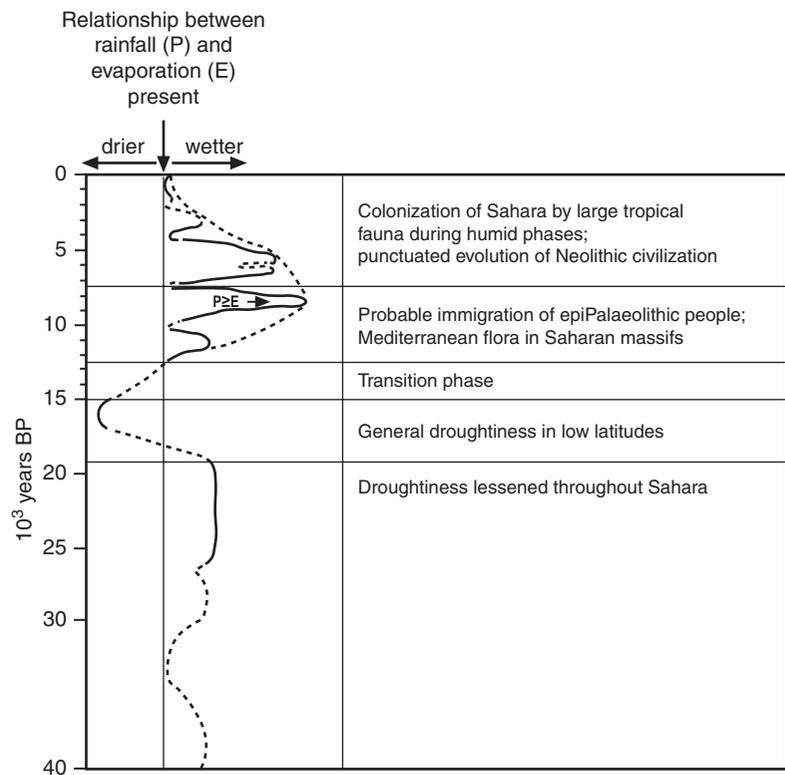
## **Quaternary Climate Change and Continental Drainage**

The changing pattern of climate in middle and low latitudes, particularly for the last 30 ka, has now been successfully documented (e.g. Street and Grove 1979; Nanson et al. 1992). Because of the equivocal nature of river responses to subtle shifts in the character of water catchments, fluvial landforms and depositional legacies have usually been used to corroborate evidence derived from other sources – principally datable, lacustrine, strand-line deposits – rather than acting as primary sources of information. However, set against evaporation, changes in river regime are, and have been, an important determinant of lake levels. Nowhere has this been more significant than in dryland lake basins such as those of the East African Rift (Butzer et al. 1972; Gasse and Street 1978), the Levant (Begin et al. 1974), Australasia (Bowler et al. 1976), western North America (Benson 1978) and, increasingly, Central Asia (Kroonenberg et al. 1997).

The water-balance curve of Lake Chad can be taken as a typical example of the changing relationship between runoff and evaporation in the period running up to and since the last glacial maximum (Fig. 23.1; Servant and Servant-Vildary 1980). Particularly noteworthy in this curve is the trend towards extreme desiccation between 20 and about 13 ka BP. This pattern was widespread throughout low and middle latitude drylands and obviously had important implications for river systems. At a comparatively local scale, low base-levels in internal drainage systems led to fluvial incision. This is not particularly well documented, if only because, although present lake levels are comparatively low, they are nevertheless higher than their late glacial minima. This means that evidence is either sub-lacustrine or buried by aggradation. So, for example, the surface of the Dead Sea is thought, on the basis of the geochemistry of evaporites, to have lain at about  $-700$  m (relative to global ocean surface), some 300 m lower than at present (Katz et al. 1977), and hydrographic surveys have shown sub-lacustrine valleys running offshore as projections of present lines of drainage (Neev and Emery 1967). A subsurface seismic examination

of small deltas on the shores of Lake Turkana in northern Kenya has revealed palaeochannels some 20 m below the present alluvial feeders. These buried palaeochannels have gradients about 1.5 times those of their modern counterparts and were given an age of about 17 ka BP, albeit on the flimsiest of arguments – that is, through an assessment of the thickness of the alluvial wedge in the context of contemporary sedimentation rates and questionable presumptions of uniformitarianism (Frostick and Reid 1986).

On a broader geographical canvas, the comparative aridity of the last glacial maximum had considerable consequence for the nature and behaviour of the so-called exotic perennial rivers that traverse the world's drylands. Perhaps best known (in circumstances where information is always sparse, either because of the poor sedimentary preservation potential of many desert environments or because information is being synthesised from a huge continental area) is that of the Nile (Adamson et al. 1980; Adamson 1982). There is inevitable controversy over the development of the integrated drainage that exists today. De Heinzelin and Paepe (1965) were of the view that the present river system is a product of the Upper Pleistocene, and that,



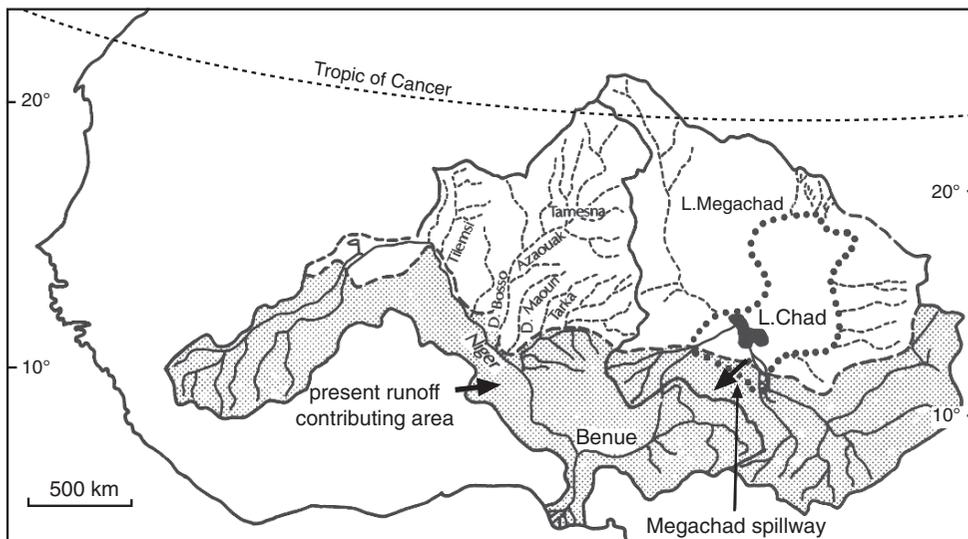
**Fig. 23.1** Climate change in the Sahel over the last 40,000 years as inferred from strand-line and other evidence in the Lake Megachad Basin (after Servant and Servant-Vildary 1980)

previously, there was a series of separate and unconnected basins. Butzer and Hansen (1968) acknowledge that the Blue Nile and other rivers rising in the highlands of Ethiopia had probably contributed to the trunk stream since the beginning of the Pleistocene, while Williams and Williams (1980) suggest that the Nile has had Ethiopian headwaters since Tertiary times. The history of the White Nile is even less certain. Kendall (1969) showed, from evidence contained in bottom sediments, that Lake Victoria had no outlet during an undefined period prior to 12 ka BP, and Williams and Adamson (1974) have speculated that the White Nile was, at best, highly seasonal if not completely ephemeral during the hyper-desiccation of the terminal Pleistocene arid phase. The picture that emerges merely reinforces a view that the Nile system is peculiar. Climate change and the ruptured tectonic setting of the White Nile headwaters give us the clues we need to understand why the present river network defies the dendritic laws of drainage that help to describe large river systems on other relatively stable cratons.

The other notable element in the water-balance of drylands in the recent past was the shift towards more humid conditions during the terminal Pleistocene and early Holocene (about 12–5 ka BP; Fig. 23.1). The impact on rivers was as dramatic as was the preceding phase of desiccation, and has to be understood if only

to interpret the fluvial relics that litter the present arid landscape.

In the Sahel of West Africa, Talbot (1980) has drawn attention to the now defunct northern tributaries of the Niger, indicating that the catchment area contributing water to the trunk stream was perhaps as much as one-and-a-half times that of the present-day (Fig. 23.2). Indeed, he infers, from a broad consideration of valley configuration, that the Dallol Bosso (now largely relic) may have been the trunk stream and that the upper Niger was one of its right-bank tributaries. Further east, the catchment area contributing to Lake Chad was enormous during this humid phase of the terminal Pleistocene/early Holocene, with drainage focused on the thermally subsided Cretaceous Niger Rift, at the southern end of which now lies the shrunken rump of the present lake. In fact, Lake Megachad, spreading into the Bodele Depression, occupied an area about six times that of present Lake Victoria and not far short of the area occupied by the modern Caspian Sea (Servant and Servant-Vildary 1980; Fig. 23.2). Apart from the now relic northern feeders of Megachad that, at this time, carried seasonal discharge down from the Tibesti Massif, the other element of the regional drainage that is of considerable interest (in part because it explains patterns of sedimentation beyond the present Chad catchment and outside the area of modern



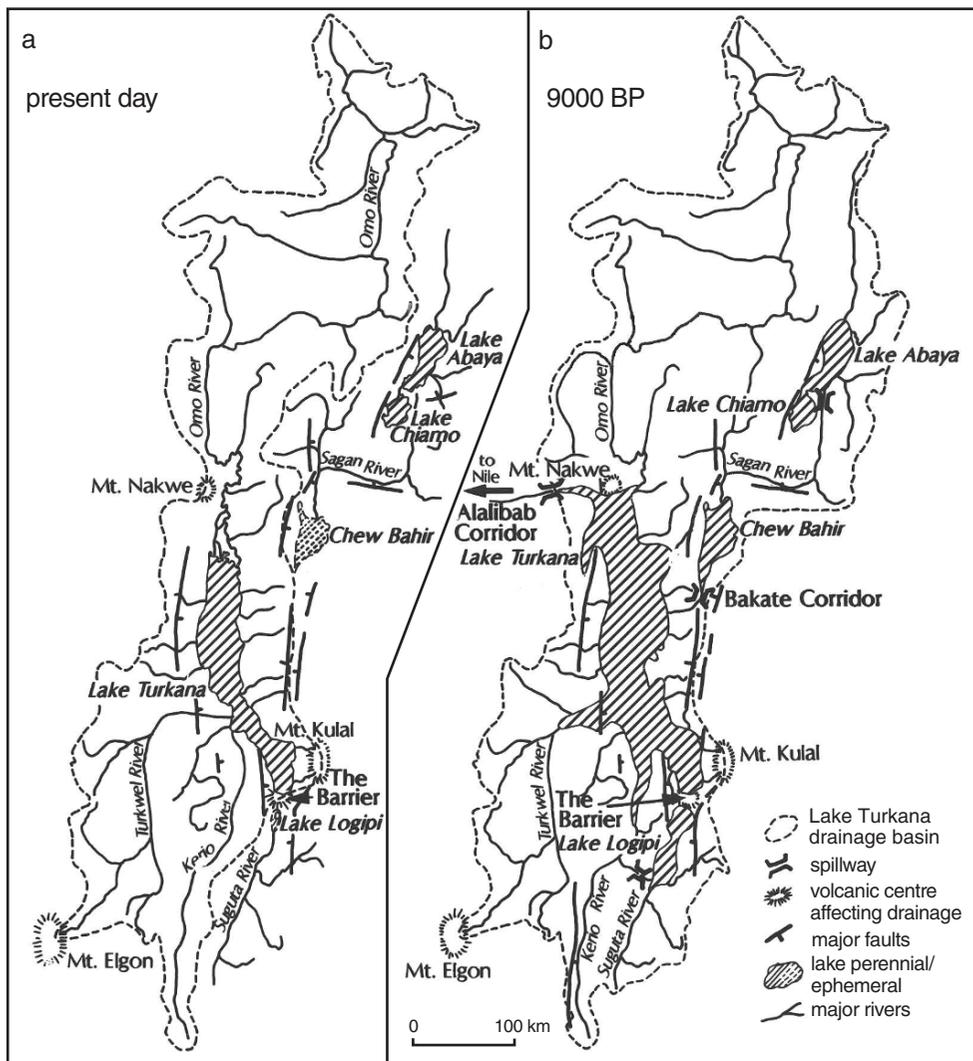
**Fig. 23.2** Water catchment of the Niger and Benue Rivers *c.* 9,000 BP and the present area contributing runoff to the Niger delta and to Lake Chad (stippled). The maximum extent of

palaeo-Lake Megachad and its early Holocene overspill to the Benue River are shown together with the largely relic drainage of the southern Sahara (after Talbot 1980)

desert) lies to the south-west of the present remnant lake. For a brief period around 9 ka BP, when the water-balance favoured rainfall over evaporation, Megachad spilled into the Benue River and, from there, waters originating in the heart of the present Sahara reached the South Atlantic via the Niger delta (Servant and Servant-Vildary 1980; Grove 1985; Figs. 23.1 and 23.2).

Neither was this the only large-scale integration of drainage on the African continent at this time. In East Africa, a change in regional water-balance led to a rise in lake-levels within closed rift basins and

in overspill from one to the other. In fact, it was at this time that the Nile catchment expanded enormously relative to its present extent, if only for a brief period. Water from Lakes Chiamo and Abaya overspilled by way of the Sagan River into Chew Bahir, which, in turn, overspilled through the Bakate Corridor to a much expanded Lake Turkana (Grove et al. 1975; Frostick and Reid 1989b; Fig. 23.3). To the south of Lake Turkana, swollen Lake Logipi spilled from the Suguta Valley westward into the Kerio River and thence to Lake Turkana (Truckle 1976), while Turkana, already collecting the seasonal rains of a portion of the



**Fig. 23.3** Water catchment of Lake Turkana in the northern section of the Gregory Rift of East Africa: (a) during the present phase of relative desiccation; and (b) during the early Holocene

humid phase about 9,000 BP, showing the swollen lakes and the connecting spillways from basin to basin and to the River Nile (after Frostick and Reid 1989b; Harvey and Grove 1982)

Ethiopian highlands through the Omo River, as it does today, spilled to the north-west through the Alalibab Corridor. From here, the waters crossed the Lotogipi Swamps to enter the Pibor River, and then the River Sobat to join the White Nile (Harvey and Grove 1982; Fig. 23.3b).

Given this temporary increase in contributing catchment, together with the overflow of Lake Victoria via the Falls at Jinja and the prevalence of relatively humid conditions across Equatoria, it is not surprising that the White Nile was three to four times the width of the present river (Adamson et al. 1982) and that Fairbridge (1963) was able to deduce a palaeodischarge three times that typical of the present-day. Williams et al. (2000) have documented the late Pleistocene/early Holocene relic meanders of the White Nile in the vicinity of El Geteina township, about 150 km upstream from Khartoum (Fig. 23.4). The interplay of the swollen sinuous river with the dunes of a large regional sand sea – legacy of the arid terminal Pleistocene – is reminiscent of the present-

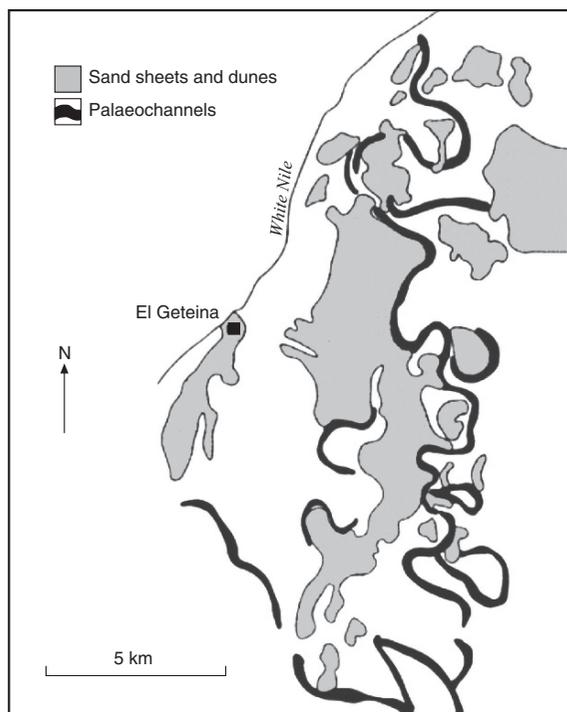
day Channel Country of central Australia (Nanson et al. 1995), although the White Nile, drawing not only on the Ethiopian highlands through the Rivers Omo and Sagan, but on the Mt Elgon massif through the Turkwel River and the drainage to and through Lake Victoria had sufficient discharge to maintain a very large, singular, meandering channel, unlike Cooper Creek.

Neither was this pattern of overflow unique to the early Holocene. For instance, Frostick and Reid (1980) have drawn attention to a previous overflow from Chew Bahir to Lake Turkana, dated tentatively as older than 100 ka. This was responsible, in part, for deepening the Bakate Corridor (re-used so conveniently in the early Holocene) and for spreading the last, coarse-grained unit of the hominid-bearing Plio-Pleistocene Koobi Fora Formation in the East Turkana Basin, the fluvio-lacustrine sediments of which have revealed so much about early human phylogeny.

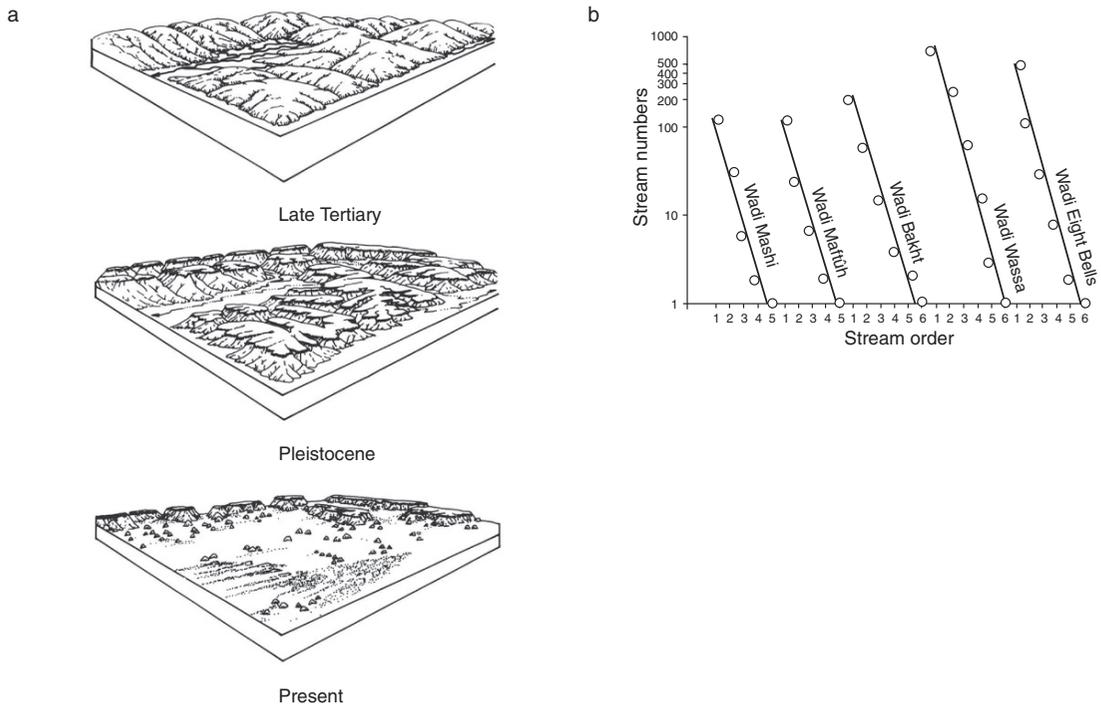
## Fluvial Landform Reconstruction

Understanding this climate-driven sequence of events has been of considerable importance in arriving at an interpretation of the underfit or relict nature of drainage in present-day drylands. It has also provided the information and confidence necessary to reconstruct large erosional and aggradational landforms even where evidence is flimsy.

An interesting example comes from the hyperarid core of the Sahara, a region which has been used by the US National Aeronautics and Space Administration as an Earthbound analogue of the Martian surface (El-Baz and Maxwell 1982). The Gilf Kebir plateau and surrounding area of SW Egypt – one objective of Bagnold's celebrated desert expeditions in the 1930s (Bagnold 1931) – is currently dominated by aeolian processes that form, among other features, the giant Selima Sandsheet (Breed et al. 1987). However, the area has not always been hyperarid. Peel (1939) advanced the view that the region bore the vestiges of a Tertiary landscape developed by fluvial processes, and this has been corroborated recently by surface-penetrating spaceborne imaging radar which has revealed broad alluvial valleys underlying features such as the Selima Sandsheet (McCauley et al. 1982b). Armed with this information, McCauley et al. (1982a) have recon-



**Fig. 23.4** Late Pleistocene-early Holocene relic channel meanders of the once-swollen lower White Nile east of El Geteina township, which is sited on the right-bank of the current diminutive river. The palaeochannels inter-finger with an extensive late Pleistocene sand sheet (after Williams et al. 2000)



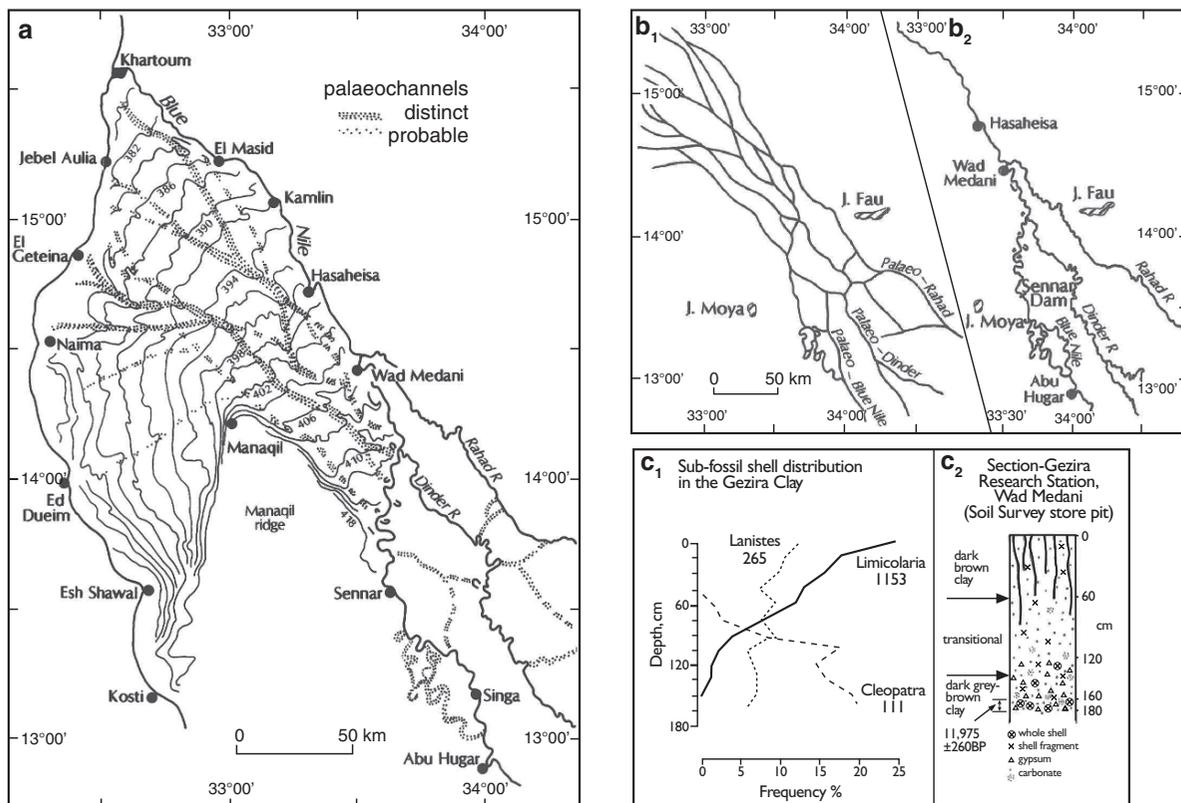
**Fig. 23.5** (a) Cartoons showing a reconstruction of the humid Tertiary, semi-arid Pleistocene and modern landscapes of the Gilf Kebir plateau, which lies in the currently hyper-arid core of the

Sahara in south-western Egypt. (b) Stream-ordering of reconstructed Tertiary drainage systems in the Gilf Kebir plateau (after McCauley et al. 1982a)

constructed the Gilf Kebir landscape (Fig. 23.5a). Using the argument that vestigial knolls littering the present landscape represent mass-wasted remnants of interfluvies, they have drawn a best approximation of the former drainage net. This reconstruction has then been 'tested' using stream-ordering rules. The regression coefficients that describe the relationship between number of streams and stream order are indistinguishable from those derived for modern drainage nets in environments less arid than those that prevail in the present-day Gilf Kebir (Fig. 23.5b).

Another case where knowledge of the climate-driven sequence of events during the late Pleistocene and early Holocene has allowed a confident interpretation of large fluvial landforms is that of the Gezira in Sudan (Williams and Adamson 1973; Adamson et al. 1982; Fig. 23.6). The Gezira is a large plain that lies between the White and Blue Niles. Superficially, it consists of clay. However, Williams and Adamson were able to establish conclusively that the plain is a relict low-angle fan of the Blue Nile, and that it is crossed by a number of defunct sand-filled distribu-

taries. It is now clear that the distributaries were a product of the terminal Pleistocene desiccation phase, when flows from the Blue Nile were probably even more seasonal and somewhat more diminutive than at present, but when a change in land-cover would have meant higher and coarser specific sediment yield from the Ethiopian hinterland. Further upstream from the fan itself, the rivers Rahad, Dinder and Blue Nile have been shown to have been elements in a complex of interconnected relatively shallow sandy channels (Fig. 23.6b<sub>1</sub>) separated only by the silty-clay of the flood-plain that accumulated from frequent overbank spills. The more humid phase of the terminal Pleistocene and early Holocene was marked by incision of the Blue Nile, an abandonment of the Gezira fan, and clarification of the drainage pattern into a trunk stream and two substantial right-bank tributaries (Fig. 23.6b<sub>2</sub>). As this occurred, silty-clay continued to accrete on the flood plain, but the change in soil-water relations brought about by fluvial incision and decreasing frequency of overbank flooding is nicely recorded by the mollusc population (Fig. 23.6c).



**Fig. 23.6** (a) Late Pleistocene low-angle alluvial fan of the Blue Nile, the Gezira, showing sandy distributary channels and contours. (b<sub>1</sub>) Reconstructed channel complex of the Blue Nile, Rahad and Dinder Rivers at the head of the Gezira fan during the arid-phase of the terminal Pleistocene. (b<sub>2</sub>) Present-day river planform, following early Holocene incision of the Nile. (c<sub>1</sub>) Changes in the abundance of three genera of molluscs with depth

in the late Pleistocene/Holocene flood-plain muds of the Blue Nile at the head of the Gezira fan. *Cleopatra* is aquatic; *Lanistes* is amphibious; *Limicolaria* is terrestrial. (c<sub>2</sub>) Soil profile on flood-plain of the Blue Nile, showing <sup>14</sup>C date derived from shell material (after Adamson et al. 1982, mollusc data originally from Tohill 1946)

Aquatic genera such as *Cleopatra*, abundant during the early Holocene humid phase, rapidly died out as flood-plain and slack-water pools became less common or non-existent; amphibious genera such as *Lanistes* were able to survive because the self-mulching properties of the crusted mud maintained a suitably moist subsoil environment for survival between successive flood inundations; terrestrial genera such as *Limicolaria* would have found conditions too wet during the early part of the Holocene humid phase, but obviously enjoyed conditions more and more as the flood-plains became drier. Adamson et al. (1982) considered that this reorganization of the Blue Nile drainage from multi-thread to single-thread stream-type had occurred somewhat before 5 ka BP.

## Climate and Channel Planform

Changes in channel planform have long been thought of as indicative of climate change, differences in the meander wavelengths of valleys and rivers that flow through them being ascribed to changes in runoff volumes during the Quaternary. However, it was Dury (e.g. 1955; 1964; 1976) who honed ideas about cause and effect, and who showed that the meander geometry of single-thread rivers is functionally related, among other things, to water discharge, at least in humid environments.

Dryland rivers tend to be wider and less sinuous than counterparts in humid regions (Schumm 1960; Wolman and Gerson 1978). Schumm (1961) ascribes

this difference, in large part, to the nature of the material deposited from the transport load: the lower the clay-silt content, the lower the bank cohesion and, consequently, the higher the width-depth ratio which, in turn, discourages the secondary currents associated with encouragement of meandering (Reid and Frostick 1997).

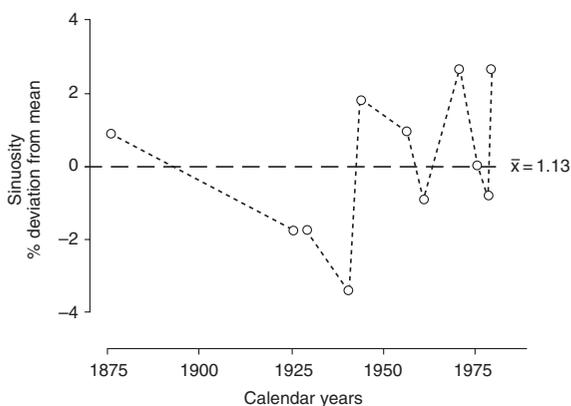
Whether subtle changes in climate that are effective over short spans of time are able to bring about channel change is open to question. Graf (1981; 1984; Fig. 23.7) provides some insight through a collation of historical records for the Gila River and its tributaries in the North American South-west. The conclusions that can be drawn from these studies is that channel shifting is a frequent occurrence but that channel sinuosity has remained largely constant throughout a period characterized by changing rainfall intensity, if not by changes in annual total rainfall (Cooke 1974). In fact, sinuosity of the Gila River deviated by no more than  $\pm 3$  percent from the mean value of 1.13 over a 104-year period of record.

Another archival study was conducted by Burkham (1972; 1976) along the same river but upstream (Fig. 23.8). Here, over the same period, a succession of large, damaging floods was shown to have led to spasmodic straightening of the channel through the erosion of floodplain bottomland. Subsequent years saw the build-up of bars and their attachment to remnants of the pre-existing flood plain so that sinuosity was eventually restored to pre-damage levels. Of incidental interest, but

having important implications for sedimentation, is the fact that the increase in flow resistance and the decrease in channel gradient that accompanied the restoration process reduced the celerity of flood waves by about 60% as sinuosity increased from 1 to 1.2.

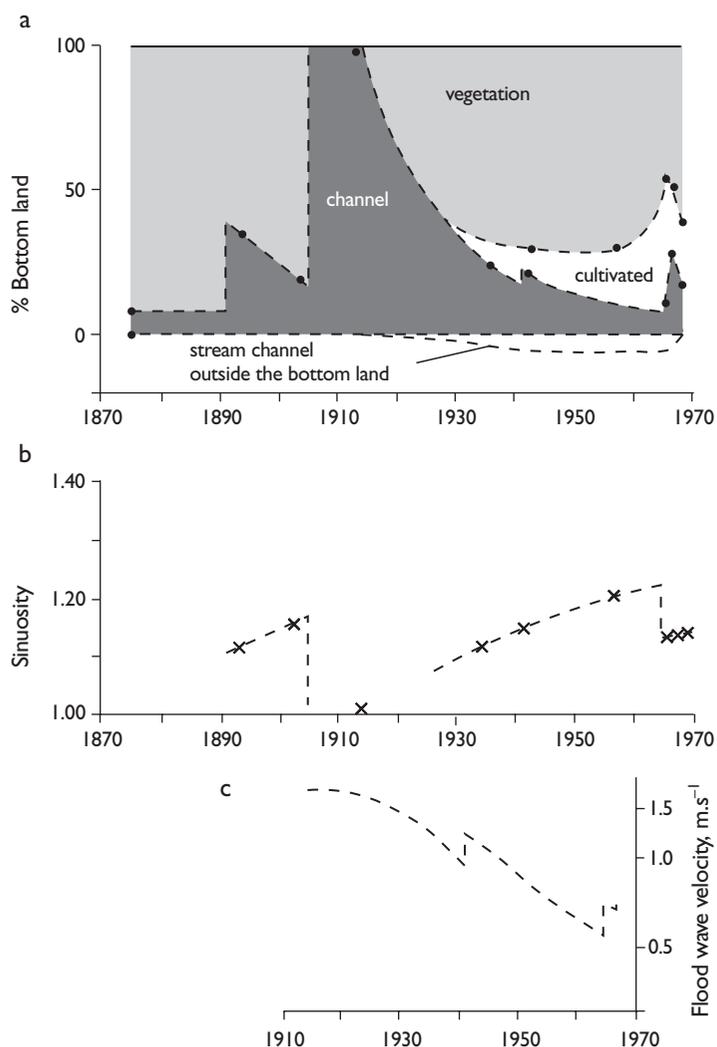
The lesson to be learnt from these two studies is that channels within a single semi-arid province (here, even the same river) can experience quite different planform changes over the same period. Burkham's study illustrates (as does Schumm and Lichty's study of channel width on the Cimarron River mentioned above) that any changes which might result from climatic alteration have to be viewed in the context of the dramatic changes brought about by individual high-magnitude floods. This suggests that rivers are comparatively insensitive as indicators of more subtle shifts in climate, responding too readily in arid environments to unusual weather, as much as reflecting the longer-term weather patterns that form an average condition – that is, climate.

Having noted this, for the same dryland province and for the same historical period, Hereford (1984, 1986) has provided evidence that climate change can encourage a shift in river sedimentation and channel cross-sectional dimensions through a change in flood behaviour. He obtained rainfall, tree-ring (a surrogate for rainfall) and runoff records of the period from the 1920s through 1981 for the Little Colorado and Paria Rivers, left- and right-bank tributaries of the Colorado River that drain catchments lying in northern Arizona and southern Utah. He was able to show that the discharge record of a sub-period up to 1940 was punctuated with floods of comparatively high magnitude (Fig. 23.9). These had swept the incised valleys, widening and deepening the channels and, in places, reaching bedrock. Historical photographs revealed broad, sandy channels, free of vegetation and with steep cut-banks. From the 1940s onward, a reduction in storm rainfall intensities produced a change in runoff and a commensurate shift in flood peak discharges. This change appears to have encouraged alluviation, the development of a flood plain and consequent narrowing of the active low-flow channels by about one-third. Hereford (1986) used the spread of salt cedar (*Tamarisk chinensis* Lour.) to date floodplain development, examining growth rings to establish the age of trees that had colonized the floodplain. From this evidence, he identified a sub-horizontal substrate



**Fig. 23.7** Percentage deviation of channel sinuosity from the 1868–1980 period mean for the Gila River between Monument Hill and Powers Butte, near Phoenix, Arizona. (Data from Graf 1981)

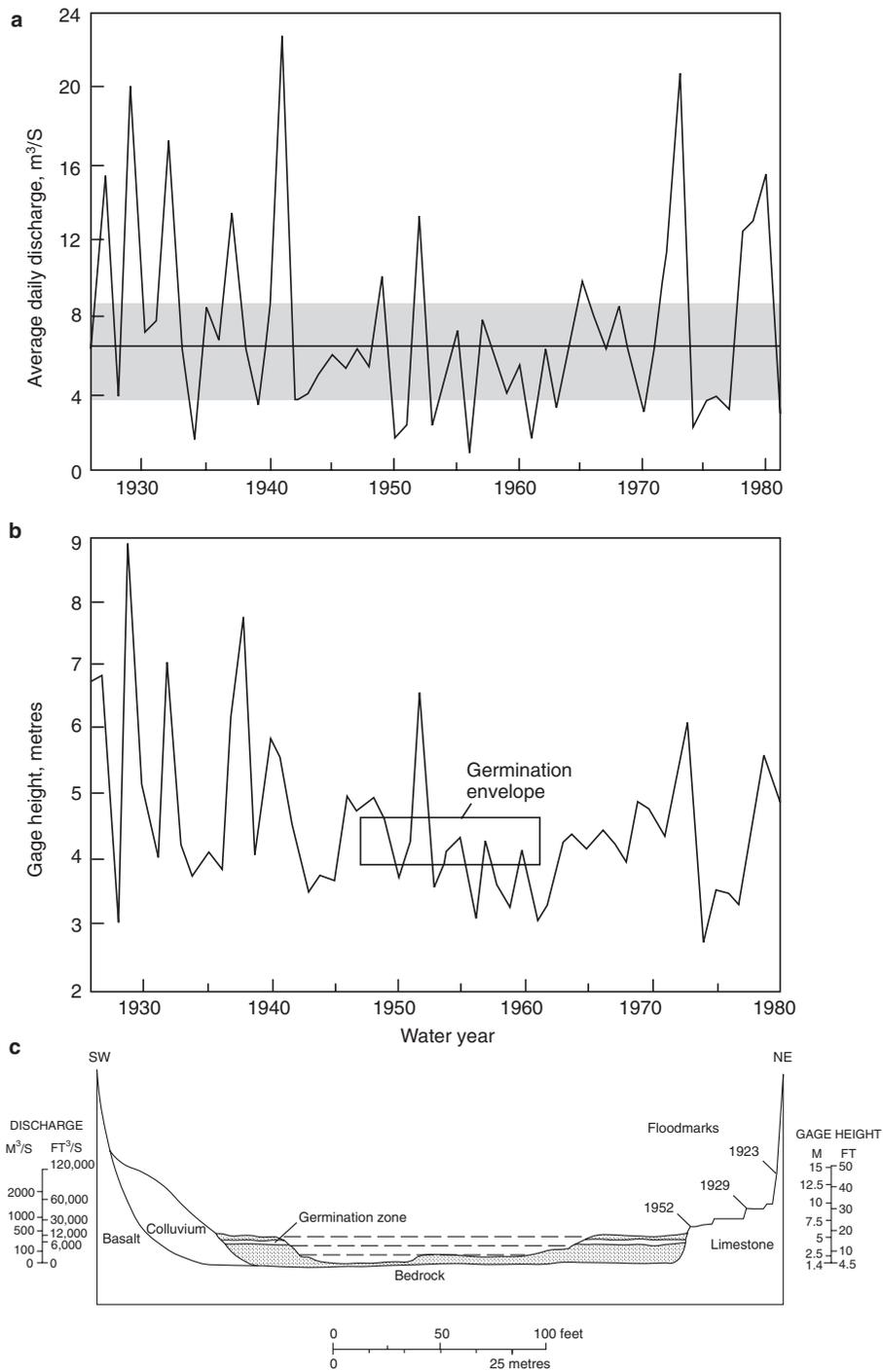
**Fig. 23.8** (a) Historical changes in the bottomland of the Gila River in Safford Valley, Arizona as a result of high magnitude floods in 1891, 1905–17, 1941 and 1967. (b) Changes in Gila River channel sinuosity in Safford Valley following flood-plain change and channel straightening by successive large flood events. (c) Changes in the average celerity of Gila River flood waves ranging in peak discharge between 283 and 566 m<sup>3</sup> s<sup>-1</sup> due to changes in channel sinuosity and, hence, flow resistance. (a and b after Burkham 1972, c after Burkham 1976)



in the alluvial microstratigraphy (the 'germination zone' in Fig. 23.9), so confirming that the progressive confinement of the channels by floodplain building was coincident with the period of reduced flood flows. The reaches studied by Hereford are confined and, because of this, the rivers had limited scope to reflect the changes in discharge and sedimentation by changes in planform. However, these case studies show that alluvial architecture and channel dimensions can indeed respond fairly rapidly to changes in the nature of storm rainfall and the non-linear response of runoff.

These comments form a backcloth against which to judge the climatic implications of those studies that have revealed systematic changes in channel form over much longer periods.

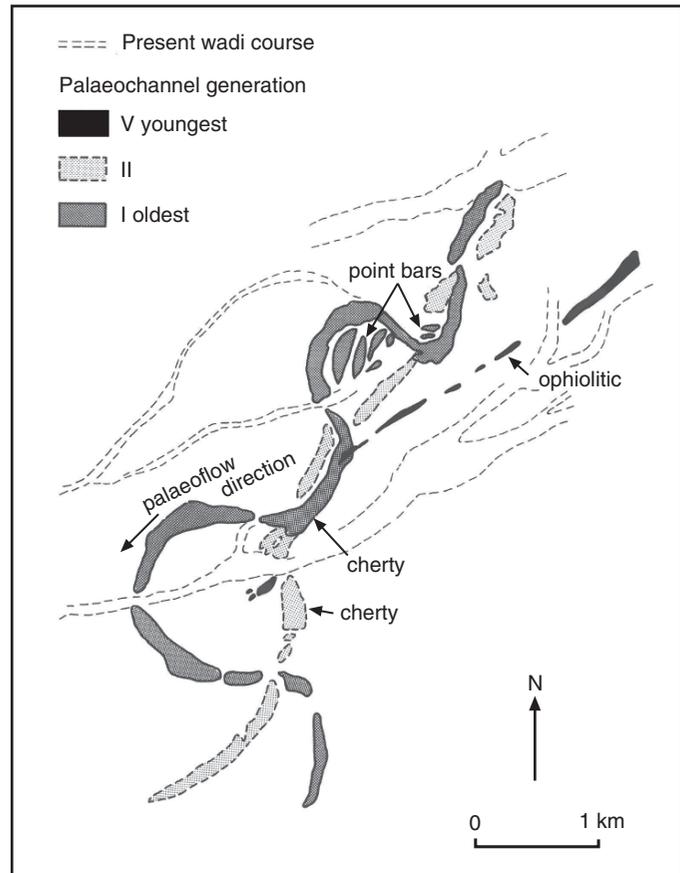
Maizels (1987) provided an interesting example from the western Sharqiya of Oman (Fig. 23.10). The palaeochannels that she described hold added fascination because preferential cementation of the coarse-grained channel sediments has allowed them to resist the erosion and ablation that has affected the surrounding non-channel sediments. As a result, the channels lie perched above the deflated plain by up to 30 m. In the most widespread sedimentary unit that was laid down in front of the Eastern Oman Mountains, Fan 1, Maizels identified as many as five generations of palaeochannels. The oldest are most sinuous, with index values that are highly variable but generally exceed 1.5. The youngest are almost straight with a typical sinuosity index of 1.03. As for



**Fig. 23.9** Time-series of flow and a cross-section of the Little Colorado River, Arizona. **(a)** Annual average daily discharge 1926–81, showing the effects of greater flood magnitudes up to the early 1940s and reduced flood magnitudes especially in the period 1942–1963. Horizontal line is the median and the stipple encloses the inter-quartile range. **(b)** River stage of the annual flood at Grand Falls gauging station 1926–80. The ‘Germination

envelope’ includes the root bowl elevations and ages of the colonial salt cedars. **(c)** Cross-section 200 m below the Grand Falls gauging station showing progressive decline in elevation of identified flood marks, the scoured pre-1940s channel, and the post-1943 flood plain growth with tell-tale salt cedar ‘germination zone’ (after Hereford 1984)

**Fig. 23.10** Plio-Pleistocene gravel-bed channel remnants of western Sharqiya, Oman, exhumed and left as bas-relief by erosion and deflation of the surrounding non-channel sediments. Sinuosity and average width decreases progressively from the oldest to the youngest generation of channels. Reproduced by permission of the Geological Society of London from 'Plio-Pleistocene raised channel systems of the western Sharqiya (Wahiba), Oman' by J.K. Maizels in *Geological Society of London Special Publication 35*, 1987



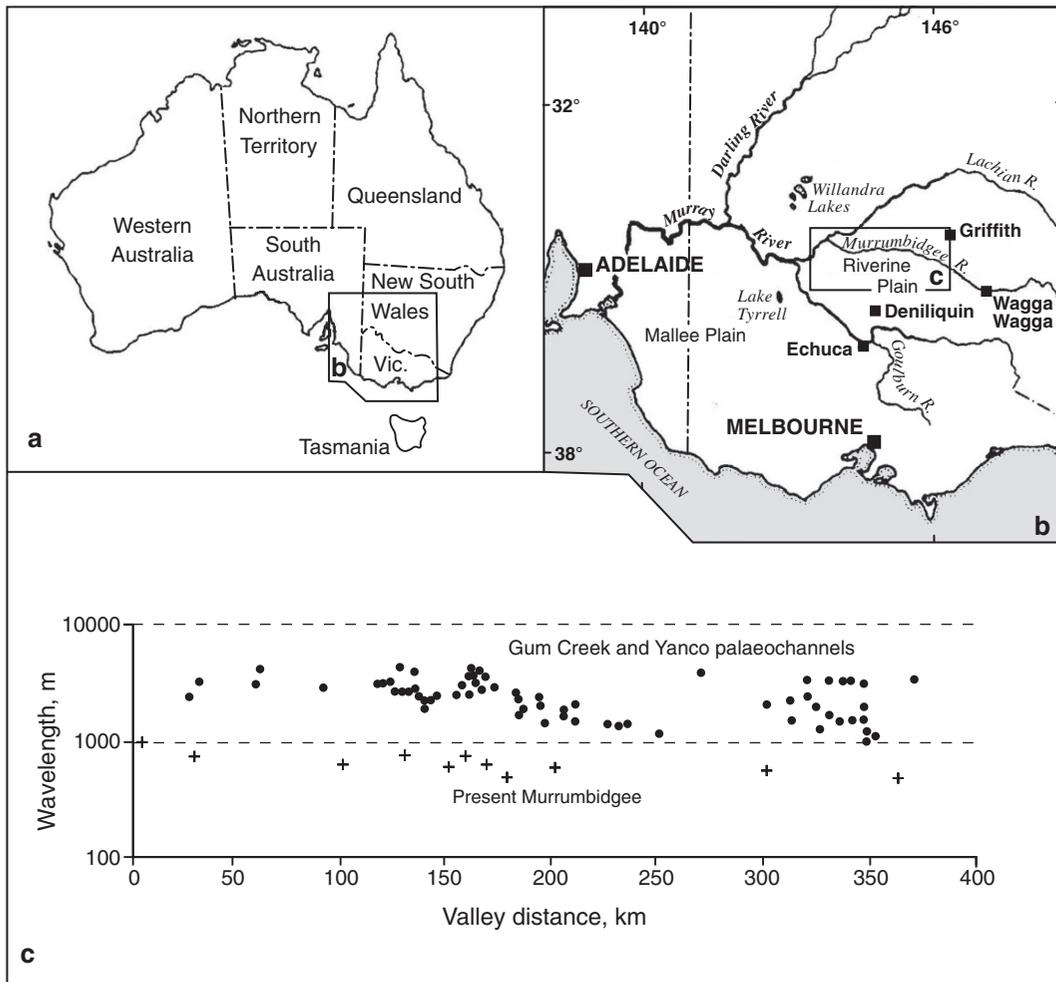
channel width, again, there appears to be a progressive decrease with age from greater than 100 m to about 50 m. These changes may reflect a change in flow regime as much as a change in peak flood flows, since Maizels' exhaustive palaeohydraulic calculations show insignificant differences in peak channel discharge between the oldest and youngest generations of channels. She rationalizes that the most sinuous channels would need at least seasonal flows to establish an equilibrium meandering form, which implies that the almost straight, youngest channels were formed under flashier, (?) ephemeral hydrographs.

In fact, Wolman and Gerson's (1978) compilation of data that compares flows in arid and humid regions may offer corroboration for the apparent contradiction between undifferentiated values of calculated peak flow and the very obvious change in channel planform. They have shown that flood peak discharges are indistinguishable from one environment to another, at least where water catchments range in area up to 100 km<sup>2</sup>, even though the exponent relating total annual runoff to

catchment area in humid environments is almost double its arid zone equivalent.

There are no dates attached to the Sharqiya palaeochannels, though they may be of Pliocene to Early Pleistocene age. In any case, there are no other independent lines of evidence for climate change, so the channels and their sediments become a valuable, if imprecise, guide to changing climate, as they do in even older desert settings (e.g. the reconstruction of Triassic landscape in a rift basin of the North Sea; Frostick et al. 1992).

The importance of dating sediments in order to provide a framework for palaeoenvironmental interpretation of channel form is nowhere more self-evident than on the Riverine Plain of south-eastern Australia (Fig. 23.11). Schumm (1968) had offered a skilfully argued interpretation of channel adjustments to climate change. Three generations of channels had previously been identified: the oldest had been called the Prior Streams by Butler (1950), while another group of palaeochannels, younger than the Prior Streams, had



**Fig. 23.11** (a) Map of Australia showing the location of the Riverine Plain. (b) Modern rivers of the Riverine Plain of south-east Australia. (c) Meander wave-lengths of the Gum Creek

(35–25 ka) and Yanco (20–13 ka) palaeochannels and of the modern Murrumbidgee River (after Page et al. 1996)

been designated as the Ancestral Rivers (Pels 1964); both of these had been superseded by the modern channels, amongst which, the Murrumbidgee River was selected by Schumm for comparison with its predecessors. The present-day Murrumbidgee is fairly sinuous, values of the sinuosity index lying in the region of two, and it was deemed to be a suspended-load type channel. This is matched more or less by the Ancestral Rivers, although they had channel widths typically double those of the Murrumbidgee and estimated bankfull discharges that were some five times those of the modern river. The Prior Streams were deemed by Schumm to have had a completely different planform,

with a sinuosity index generally lying just above unity and channel widths as much as eight times that of the Murrumbidgee.

Schumm (1968) drew on his previous analysis of channel form on the Great Plains of N America (Schumm 1963) to point to the important role of sediment in part-determining channel character. Schumm (1960) had originally speculated that the inverse relation between channel width-depth ratio and the silt-clay fraction of the channel perimeter reflected the cohesion of clays and the ability of clay-rich deposits to maintain near-vertical sidewalls. In his 1968 paper, he also acknowledged the need to take account

of the calibre of sediment presented to the river by hillslope processes, and the adjustment of river form needed to maintain a measure of transport efficiency and avoid choking. In effect, he proposed that a shift in sediment transport towards bedload (represented by the sand that was thought to dominate the bed material of the Prior Streams) had been accommodated by a straightening and, hence, steepening of the channel and by channel widening. The widening was facilitated by the lack of shear strength inherent in the sand that now formed a large fraction of the channel deposits. It was postulated that the Prior Streams were a response to aridification and the increased mobilization of coarse-grained sediment.

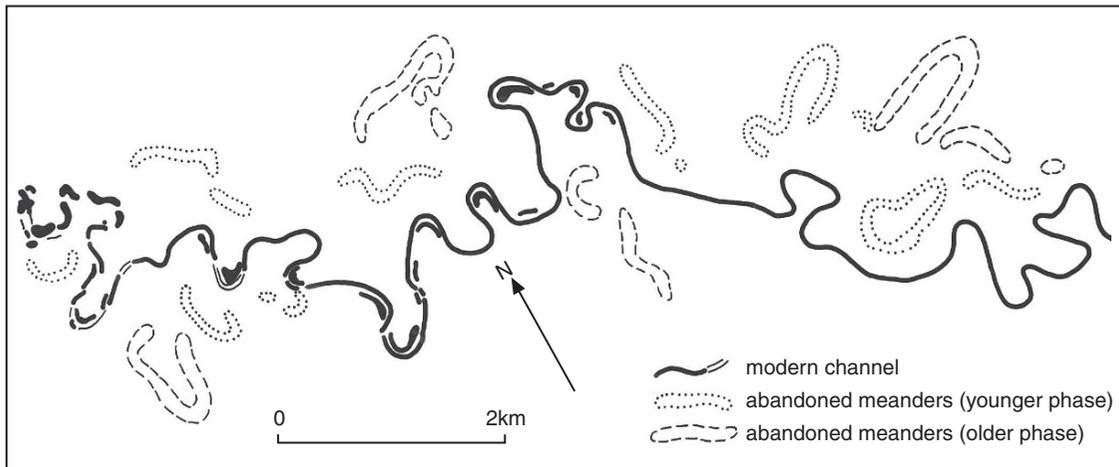
This interpretation was questioned by Bowler (1978), but it has been overturned by Page et al. (1996) who had the advantage of further field analyses of channel sediments and dimensions and, more significantly, a series of thermoluminescence dates to determine channel ages. They had also the advantages of the rapid increase in understanding of late Quaternary climate change that marked the last third of the 20th century, to which they themselves were contributing much in the context of drylands. Page et al. were able to identify four generations of palaeochannel: (1) the Coleambally system, dating from 100 to 80 ka and corresponding with some of Schumm's Prior Streams, represents a high degree of fluvial activity; Schumm had speculated that the channels were much younger and formed under arid conditions during the last glacial maximum; (2) the Kerarbury system, dating between 55 and 35 ka and corresponding to Schumm's northern Prior Streams, was active during what is now regarded as a sub-pluvial phase in inland and southern Australia; (3) the Gum Creek system, dating from 35 to 25 ka and corresponding with Schumm's Ancestral Rivers, reflects enhanced fluvial activity; and (4) the Yanco system, dating from 20 to 13 ka and grouped by Schumm with the Ancestral Rivers, is characterized by large lateral accretion features such as scroll bars and ox-bows. Significantly, there is a dearth of palaeochannels dated between 80 and 55 ka. Page et al. have drawn attention to this as an interval that includes Oxygen Isotope Stage 4, a period known to be characterized by widespread aridity.

The four palaeochannel systems indicate substantially larger discharges than occur in the modern Murrumbidgee River. This is reflected in the channel

geometry (Fig. 23.11c). For example, the Gum Creek and Yanco systems have channel widths averaging 225 m and meander wavelengths averaging 3000 m, compared with the modern Murrumbidgee, where equivalents are 60 and 550 m. Page et al. have suggested a cooler climate with reduced evaporation and an increase in seasonal snow-pack melt in the south-eastern highlands that form the headwaters as being responsible for the episodic increase in river discharge during the late Pleistocene. They further suggest that sediment availability was governed by reductions in vegetation and an increase in periglacial activity and that this change contributed to the coarsening of river sediment character. The amelioration of climate during the Holocene led to disappearance of the headwater glaciers, an altitudinal rise in the tree-line and a lessening of coarse sediment supply. The river response to a reduction in both water discharge and sediment flux is seen in the high sinuosity and modest width of the modern Murrumbidgee.

Some corroboration of this Holocene trend in channel planform comes from the Gran Chaco of northern Argentina, where channel widths have decreased in response to a reduction in runoff volume even though meander geometry has remained essentially unchanged (Baker 1978; Fig. 23.12). However, the unfolding story of fluvial form and sediments on the Riverine Plain indicates that caution is required in using rivers as diagnostic indicators of climatic aridification and humidification.

Another study from the Australian continent prompts geomorphologists to be circumspect about the use of channel form and sediments as an indicator of climate change. The sand-bed, anastomosing channels of Cooper Creek, a major feeder of the endorheic Lake Eyre Basin, appear to be incised in a braid-plain which had previously been interpreted as a relic of a former flow regime. Nanson et al. (1986) have argued, albeit on the self-confessed basis of a paucity of hydrological records, that the braid-plain is a contemporary feature and that it is utilized as a floodway for very high discharges. The incised, anastomosed channels are there to accommodate the flows of more moderate floods. The braids and braid bars are unusual in that they consist of sand-sized clay-rich aggregates. However, the contemporaneity of two distinct channel types over such a large area and the suggestion that neither is anachronistic counsels the need for caution



**Fig. 23.12** *Osage-type* underfit modern channels and remnants of wider precursors on the Gran Chaco of Argentina (after Baker 1978)

in making climatic inferences from apparent changes in channel form and deposits both elsewhere and for earlier times.

This fascinating confusion is compounded further by another example of juxtaposed, contemporary, but contrasting channel types, in this case from the Northern Plains of central Australia. Tooth and Nanson (2004) have examined two ephemeral channels that, for several tens of kilometres, run sub-parallel courses within a few kilometres of each other along the same topographical depression. The longitudinal slopes of the two channels do not differ measurably, but the Plenty River has a bed of medium to coarse sand and has few tributaries, while the Marshall River transports coarse sand and granules and has several tributaries. The Plenty River has a single-thread channel, contrasting surprisingly with the Marshall River, which consists of numerous narrow anabranching channels (Fig. 23.13). Tooth and Nanson explain the juxtaposition of contrasting channel types by the frequency of tributary flows and the provision of perched groundwater that has encouraged tree growth in the Marshall River and the consequent establishment of mid-channel bars and islands as sediment has accumulated in the lee of the trunks. Maintenance of sediment-transporting competence has required adjustment of flow resistance by streamlining the islands to form elongate ridges that now separate the sub-parallel anabranching channels. Regardless of whether this analysis is correct, there remains the intriguing fact that two completely

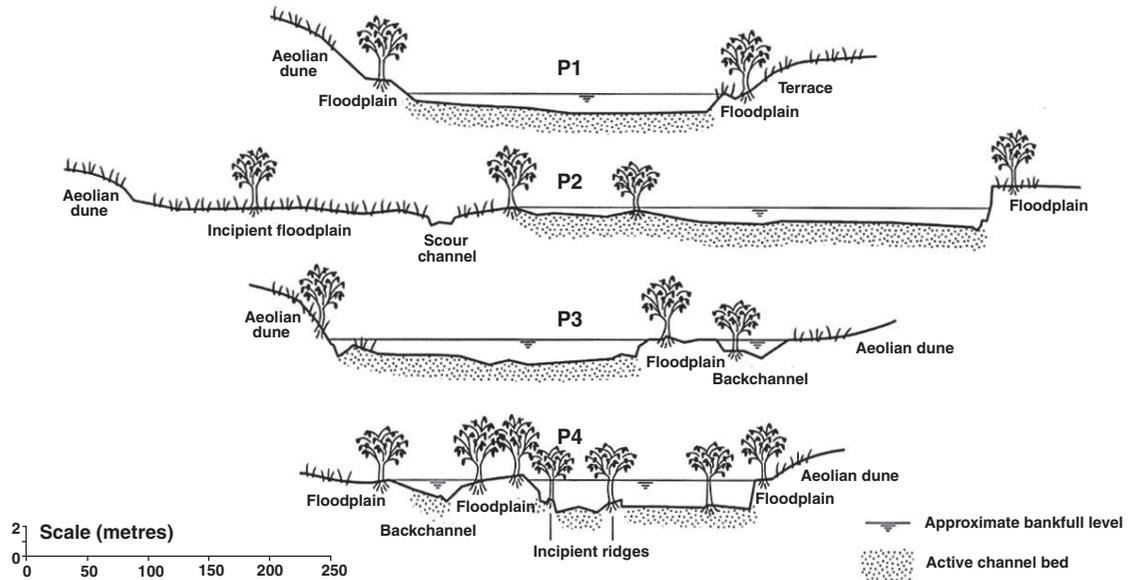
contrasting channel-types lie alongside each other. Yet, there are no differences in climate between the two catchments, suggesting that a change in channel form from one to the other could not be used to indicate unequivocally climate change in a stratigraphic sequence.

### The Arroyo Problem

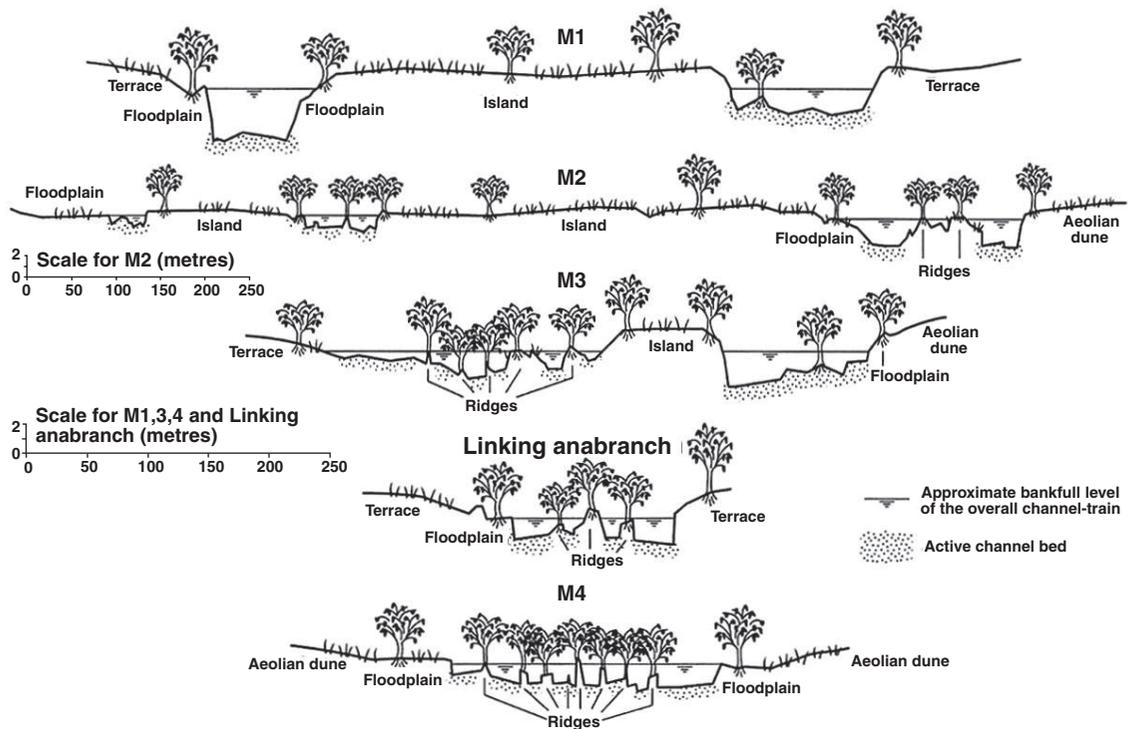
Having examined the possibilities and problems of matching changes in the fluvial system to climate change and *vice versa* on the grand scale, the moment has come to turn the spotlight on the intense debate that surrounded, and still surrounds, arroyo development in the American South-west.

Briefly, the end of the 19th century witnessed an apparently sudden, geographically widespread, progressive and deep incision of previously flat-floored alluvial bottomland. A comprehensive account is given by Cooke and Reeves (1976) who indicate that while the exact timing of initial incision may vary, most of the trenching was accomplished between 1865 and 1915. Today, there is some suggestion that the process has been reversed and that net aggradation is occurring (Leopold 1976), despite reports that individual arroyos continue to grow by head-cutting (Malde and Scott 1977). In fact, rates of aggradation will be much lower than rates of incision, and Leopold et al. (1966) have advised that long-term monitoring of processes

## a - Plenty River



## b - Marshall River



**Fig. 23.13** Cross sections of two ephemeral channels that run sub-parallel courses less than 2.5 km apart on the Northern Plains of central Australia. (a) The Plenty River, which is a single-thread channel, largely devoid of trees, with a bed material com-

posed of sand. (b) The Marshall River, which has multiple narrow anabranches separated by tree-induced ridges and islands and a bed material of coarse sand and granules (after Tooth and Nanson 2004)

will be needed in order to achieve an understanding of the current direction that arroyo development is taking.

The controversy surrounding the initiation of arroyos was fuelled by the fact that not only were there some shifts in climate that might indirectly have brought about trenching, but that, simultaneously, land-use of the area was fairly abruptly changed through the introduction of cattle by colonial non-indigenes. Whatever the cause, it is generally agreed that runoff was encouraged through a depletion of vegetative ground cover. Bailey (1935), among others, blamed overgrazing and rejected the case for climate change. Devevan (1967) sat on the fulcrum and argued that higher intensity summer storms had fallen on drought-weakened and overgrazed vegetation. Bryan (1941), in reviewing a longer period of time leading up to the events of the late 19th century and including the period of Pueblo Culture, was inclined to argue for increased runoff as a product of climate change and a loss of vegetation. Leopold (1951) approached the changing climate problem from a more subtle point of view. He was able to show that the number of light raindays (thought to be vital to sustaining the herb and grass community as a partial ground cover) had been significantly lower in the last part of the 19th century (Fig. 23.14), and speculated that this reduction allowed the less frequent but higher magnitude runoff events to ravage valley bottomlands, so carving out the arroyos. His analyses of rainfall in New Mexico were later corroborated by Cooke's (1974) collation and analyses of records obtained at stations in Arizona and the suggested implications for runoff were supported by Hereford's (1984, 1986) assessment of flood flows up to and including the early 1940s in the Paria and Little Colorado Rivers (Fig. 23.9).

Leopold's rainfall analysis suggests a mid 20th century trend in storm intensity that would bring a return of rainfall patterns that characterized the period of arroyo cutting. In this circumstance, it should be possible to see signs of another epicycle of erosion. However, other factors have come to bear that complicate the picture. Graf (1978; Fig. 23.15a,b) has traced the spread of riparian tamarisk in the Colorado Plateau since its introduction from Europe in the late 19th century. In addition, he has drawn attention to the role of both riparian and channel vegetation in increasing flow resistance, showing that the amount of biomass on the floodway distinguishes entrenched and unentrenched channels, at least in upland Colorado

(Graf 1979; Fig. 23.15c). These and other factors have complicated landform response to what are, after all, subtle changes in climatic variables, so that the cause of arroyo initiation still remains elusive.

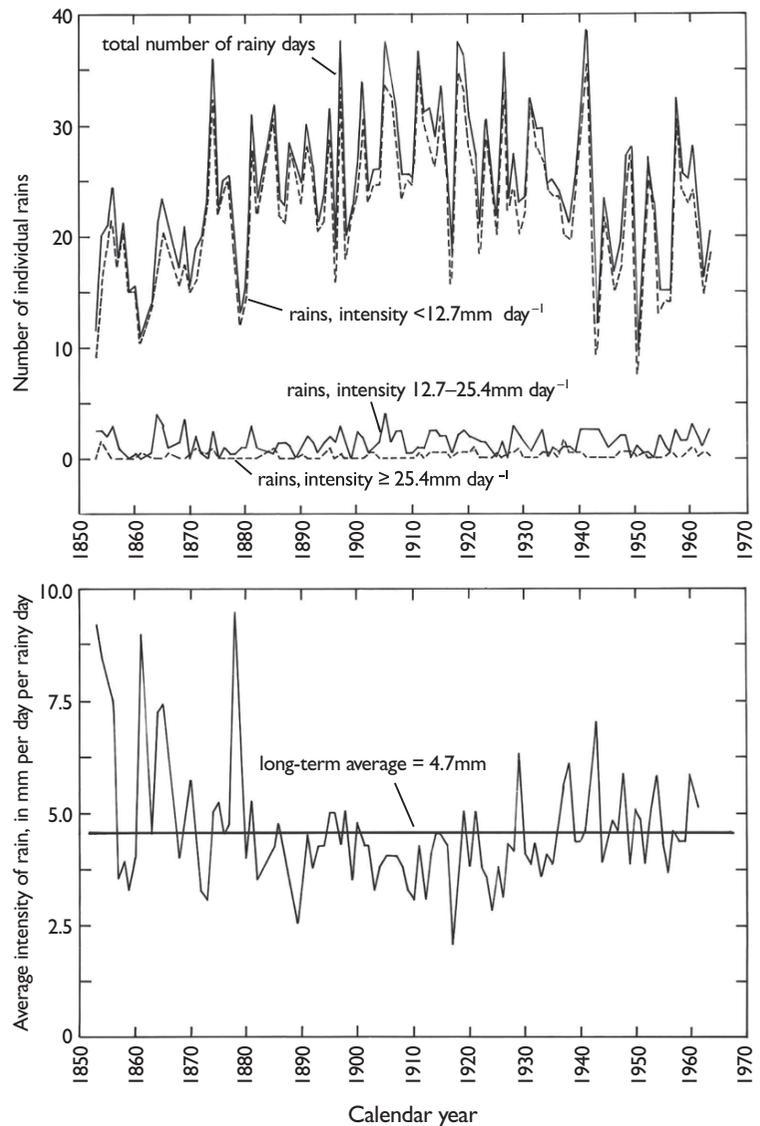
Indeed, some believe that climate change is unnecessary as an explanation for arroyo initiation (Patton and Schumm 1981). Schumm and Hadley (1957; Fig. 23.16) have proposed a cycle of trenching and alluviation that they suggest accounts for the discontinuous nature of many arroyos. Transmission losses during flash flooding are thought to be responsible for encouraging localised deposition along a channel, which in turn, produces equally localised steepening of the channel gradient and eventually encourages incision and knickpoint recession. The reduction of gradient downstream of the knick, together with erosional displacement of material from the knickpoint brings about alluviation of the previously entrenched lower reaches, while arroyo development progresses upstream. In the fullness of time, renewed incision occurs at steeper sections in the alluvium that has been deposited in the trunk stream and a new knick moves progressively upstream in a new cycle.

A great deal of scientific enquiry has gone into the arroyo problem, yet the results remain equivocal. Perhaps as important an upshot of what at one time seemed a pressing problem in need of a solution has been the investment in obtaining a general understanding of fluvial processes, especially those of the world's drylands.

## Dryland River Deposits

Dryland ephemeral rivers differ from perennial counterparts in the rate at which they convey sediment and, to some degree, in the character of their deposits (Reid and Frostick 1987, 1997). The reasons for such differences lie as much outside as within the river channel and are associated with differences in the degree of protection of the ground by vegetation, the relative (in)stability of topsoil structure, presence/absence of biopore control of soil hydraulic conductivity and the incidence of surface ponding and overland flow, and so on – that is, all those factors that influence the availability and transfer of material from hillslopes. Within the river, the hydraulic feedback that is associated with the type and quantity of material with which it is presented leads not only to differences in channel plan and

**Fig. 23.14** Frequency of non-summer (Oct.–June) rainfalls by storm size and the average rainfall per rainy day at Santa Fe, New Mexico, covering the major period of arroyo incision (1865–1915) and subsequent developments (after Leopold et al. 1966)

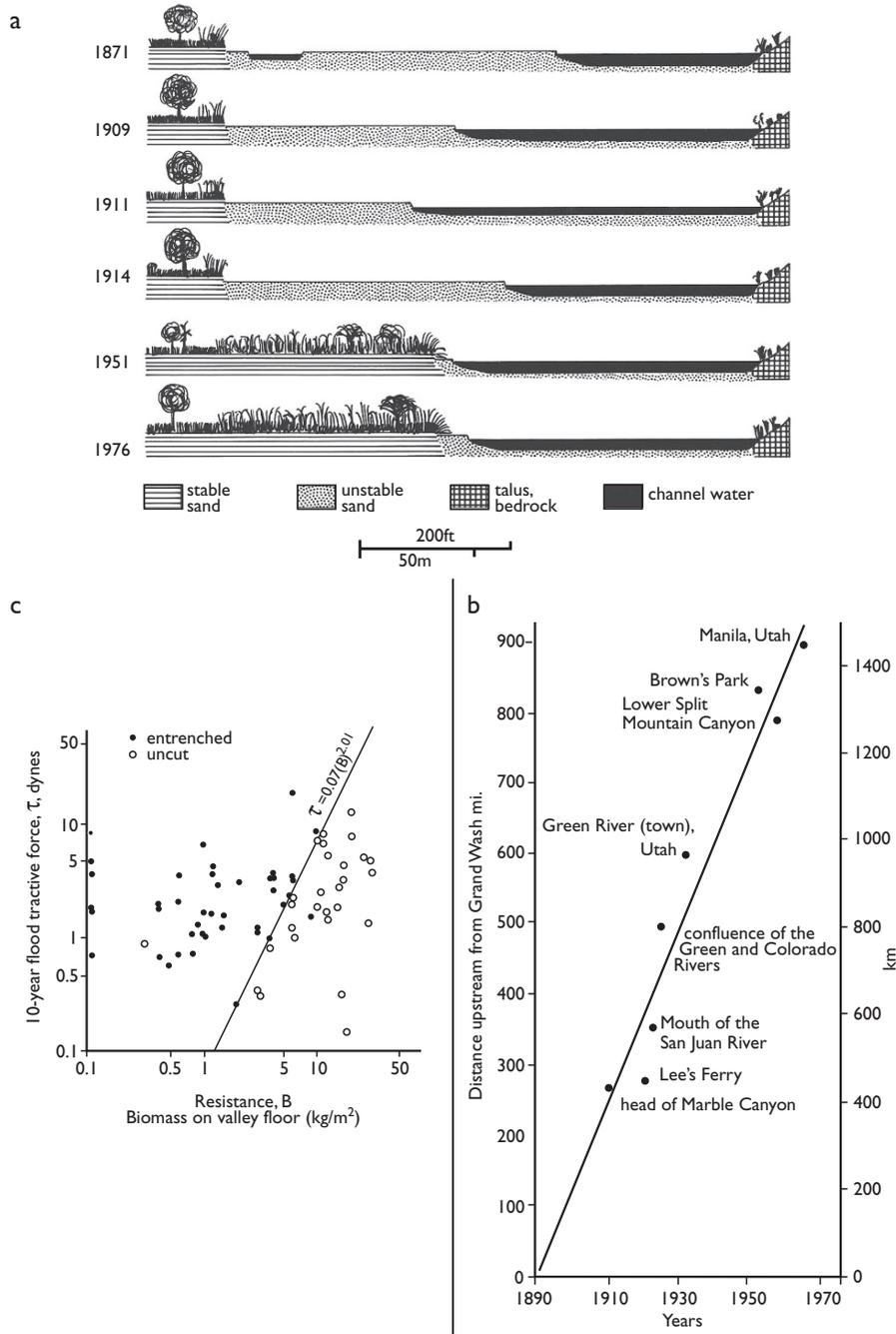


cross-sectional form, as discussed above, but also in the architecture of the alluvium.

Alexandrov et al. (2007) have used the fact that the northern Negev enjoys (or suffers) from seasonal differences in the nature of storm rainfall. This not only highlights the reasons for high specific annual yields of suspended sediment in drylands, but shows how a single variable – storm type – impacts on sediment delivery in the same catchment, so removing the complication of comparing different catchments, each with its peculiar, even if similar, lithological, soil and landuse characteristics. In autumn and spring, convectively-enhanced cellular storms deliver high intensity rainfall

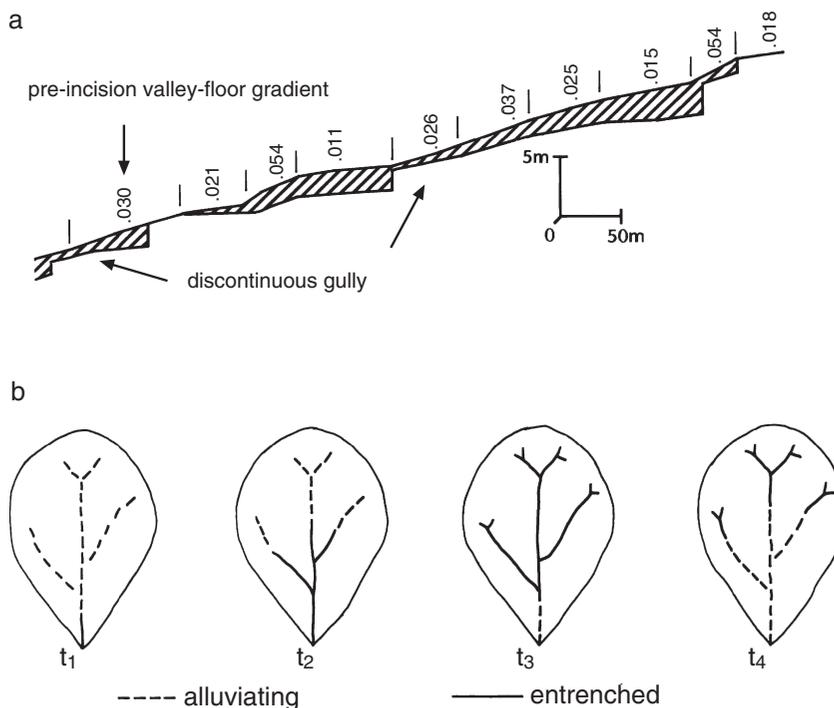
whereas in winter, storms are frontal in origin and deliver ubiquitous rainfall of low intensity. Over a 10-year period, cellular convective storms produced 21% of the runoff but yielded 56% of the suspended sediment, while frontal storms contributed 79% and yielded 44%, respectively. This study helps point to what consequences there might be for fine-grained sedimentation in response to subtle shifts in rainfall intensity as climate changes.

For coarser-grained sediment, Laronne and Reid (1993) have demonstrated that bedload flux in ephemeral gravel-bed channels is several orders of magnitude higher than in perennial channels at similar



**Fig. 23.15** (a) Sketches of Green River cross-section at Bowknot Bend, Utah, derived from historical photographs and field survey before and after the arrival of tamarisk (salt cedar) in the 1930s, showing the dramatic stabilization of alluvium, constriction of the low-water channel and increased flow resistance of the floodway. (b) Spread of tamarisk up the Colorado and Green Rivers – a rate of colonization averaging  $20 \text{ km a}^{-1}$  – af-

ter its introduction to North America from Europe in the 1880s. (c) Separation of entrenched and un-entrenched valley bottomlands in upland Colorado as a function of biomass-induced flow resistance, allowing for the estimated average tractive force of the local 10-year flood at peak discharge. The line is a fitted discriminator and not a line derived by regression analysis (a and b after Graf 1978; c after Graf 1979)



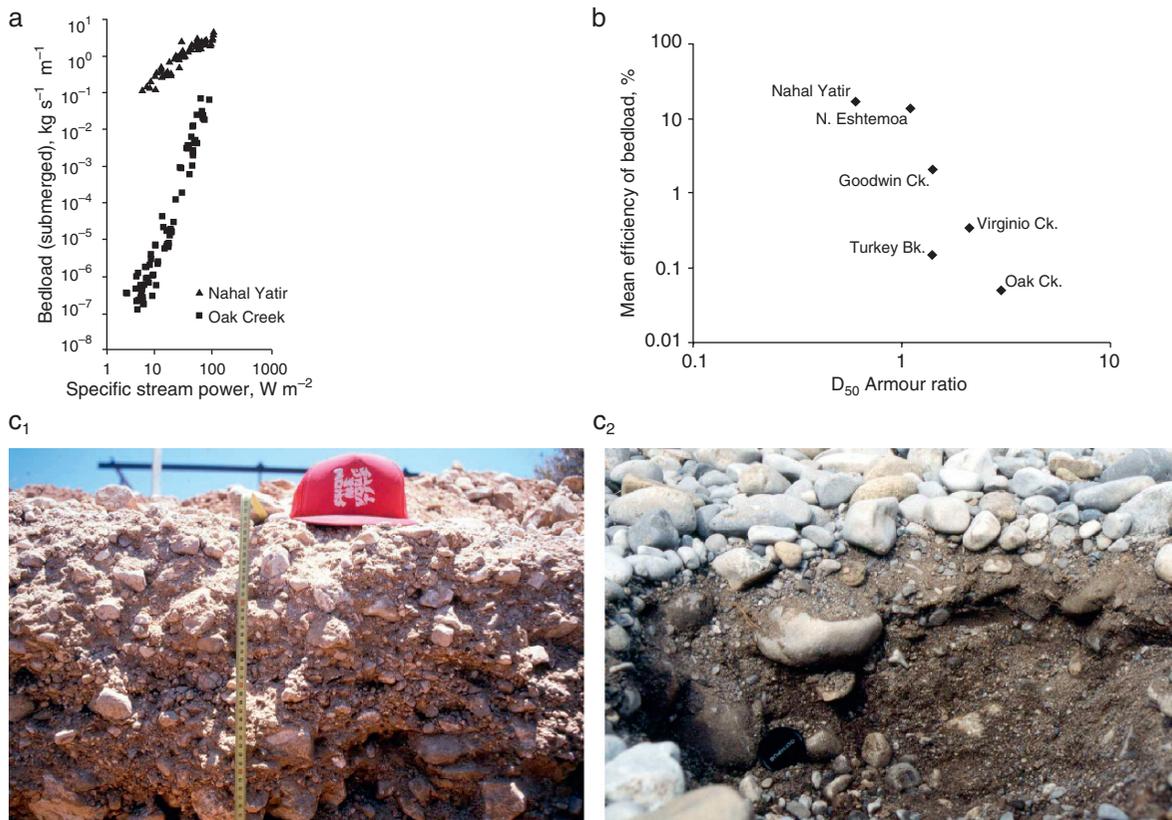
**Fig. 23.16** (a) Discontinuous gullies in Dam 17 Wash, near Cuba, New Mexico, showing knick-points that have moved up-channel from over-steepened sections of the pre-incision

alluvium. (b) Cycle of trenching and alluviation in semi-arid drainage basins (after Schumm and Hadley 1957)

levels of boundary shear stress or unit stream power (Fig. 23.17). The essential reason for the differences has been shown to relate to the lack of armour layer development in ephemeral channels. This has been related functionally to the abundant supply of sediment in drylands, with their poorly vegetated slopes, and the ready replacement of smaller grain-sizes that are selectively removed from the channel bed by flood flows. Reid et al. (1999) have used the differences in bedload flux between perennial and ephemeral rivers to speculate on what effects a major change in climate might have on coarse-grained sediment yield. They have shown that the efficiency of bedload transport (effectively the percentage of stream power used in transport) is inversely related to the channel-bed armour ratio (the relation between a parameter of the grain-size distributions of the surface and sub-surface layers). One ephemeral stream is shown to be, on average, 345 times more efficient than the most armoured perennial stream for which there is comparable data. They also show that the specific bedload

sediment yield of one upland ephemeral channel is about 18 times that of an equivalent perennial channel having a wooded catchment of about the same size.

How does this information about sedimentary processes become useful in understanding sedimentary sequences? Talbot (1980) has given a schematic and regionally generalized sequence of river sediments that has arisen from shifts in climate in the western Sahel during the terminal Pleistocene and Holocene (Fig. 23.18). The sediment column is dominated by sand (which is derived in part from the reworking of southward driven Saharan dunes), but the period of maximum regional humidity that centres on 9 ka BP is characterized by a change towards suspended-load type systems and indicates greater vegetation cover and soil development. These comparatively large changes in sediment calibre reflect what, for this region, have been end-members of the climatic spectrum. However, curiously, there is no suggestion that the more subtle shifts in climate that are reflected in contemporaneous



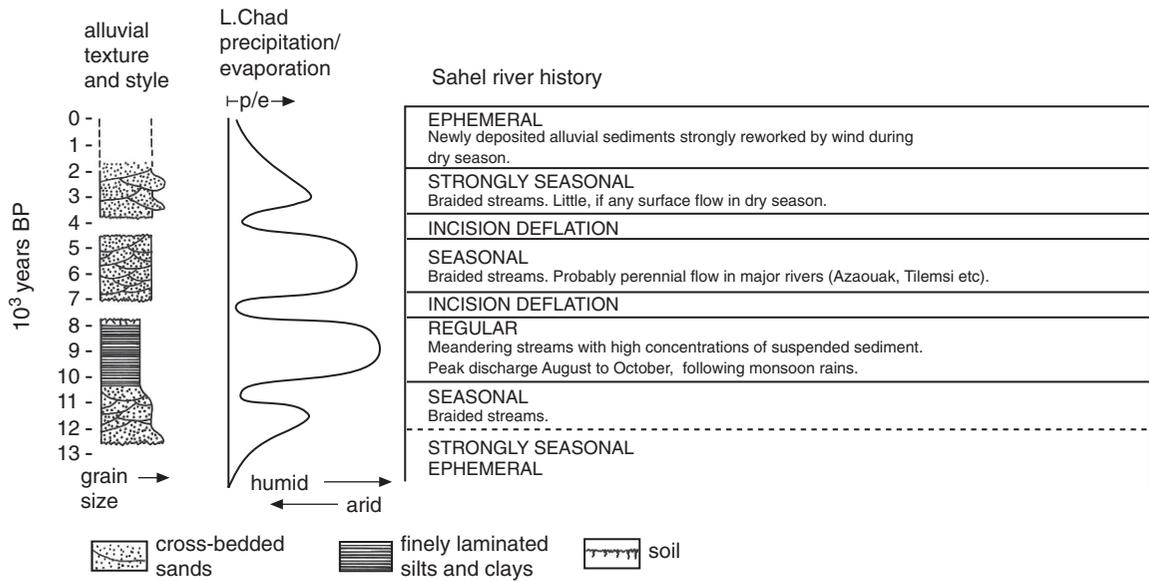
**Fig. 23.17** (a) Bedload sediment flux as a function of unit stream power in the unarmoured ephemeral gravel-bed Nahal Yatir, Israel, and the armoured perennial gravel-bed Oak Creek, Oregon, showing the much higher transports rates in the Yatir as a function of the environmentally-controlled absence of armour development. (b) Bagnold's (1973) index of percentage bedload transport efficiency,  $E = 100i_b/(\omega/\tan\alpha)$ , where  $i_b$  is the bedload flux (submerged weight) per unit channel width,  $\omega$  is specific stream power, and  $\tan\alpha$  is assumed constant at 0.63, as a function of the armour ratio of the channel bed sediments

expressed as the dividend of the median grain sizes of the surface and subsurface layers in two ephemeral (Nahal Yatir, Nahal Eshtemoa), one seasonal (Goodwin Creek) and three perennial (Virginio Creek, Turkey Brook, Oak Creek) gravel-bed channels where bedload was established with bed-slot samplers. (c) Sections through the gravel beds of the unarmoured ephemeral Nahal Yatir ( $c_1$ ), the hat resting on the channel-bed surface, and the armoured perennial River Wharfe, England ( $c_2$ ) (a after Laronne and Reid 1993, b after Reid et al. 1999)

lesser risings of palaeo-Lake Chad are translated into deposit character.

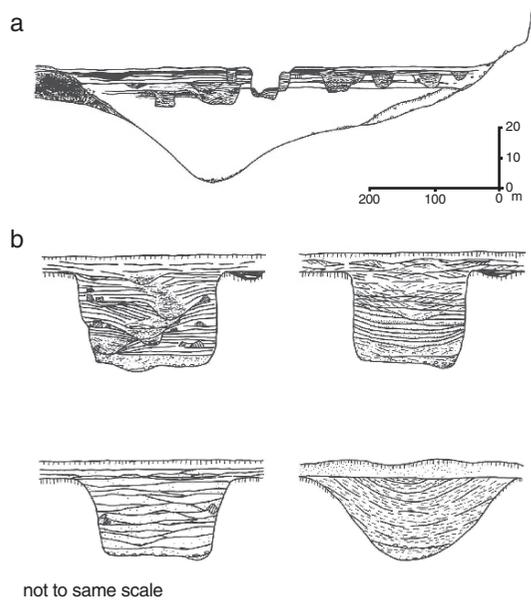
Indeed, Love (1982) points to the equivocal relations between fluvial deposition and climate using the mid and late Holocene channel-fills that are exposed by present-day incision within Chaco Canyon, New Mexico (Fig. 23.19). These palaeochannels range in size, and, therefore, in their probable role and importance as part of the contemporary drainage system. But they also range widely in the calibre and style of sedimentation and include palaeochannels typical of ephemeral, flash-flood, 'bedload-type' streams (Fig. 23.19b, lower

left), those of 'mixed-load type' (upper left) as well as those of 'suspended-load type' (lower right). Yet, tree-ring and other sources of data show no dramatic shifts in climate during the period covering this episode of canyon filling. On the other hand, there are indications of phases of greater-than and less-than normal rainfall that may be reminiscent of the pattern established for the period of arroyo incision and possible refilling during the late-19th/20th century. Although Love remains sceptical that these climatic wobbles can be used to explain differences in channel and channel-fill character, it suggests that a thorough examination of present-day



**Fig. 23.18** Schematic generalized sequence of sedimentation by West Sahel rivers during the terminal Pleistocene and Holocene

set against the palaeoclimate curve derived from strand-line and other evidence in the Lake Chad Basin (after Talbot 1980)

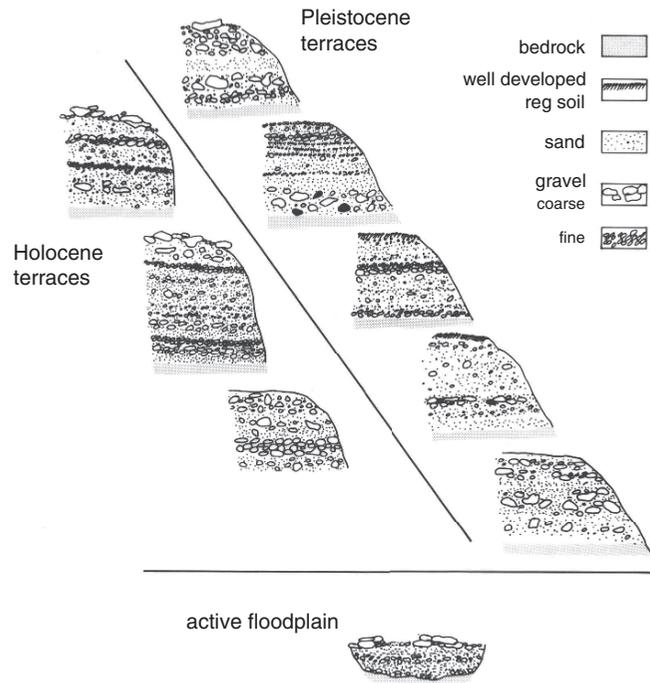


**Fig. 23.19** Styles of late Holocene channel-fills exposed in section by present-day arroyo development in Chaco Canyon, New Mexico (after Love 1982)

arroyo fills might be useful in at least indicating the range of alluvial architecture that might be expected following known, subtle shifts in climate.

Having issued a cautionary note, it is possible to state that desert stream sediments may well carry tell-tale signs of relatively small changes in climate. Grossman and Gerson (1987) have drawn a distinction between Pleistocene and Holocene river terraces in the southern Negev (Fig. 23.20). The older deposits are built partly by debris flows and display a commensurately disorganized fabric, a wide range of clast size (up to 1.5 m), and a poor degree of stratification. The younger terrace deposits are fluvial in origin, displaying a high degree of stratification, an ordered fabric, and so on. There are also differences in the reg soils that developed on the two sets of terraces. Those of Pleistocene origin show greater illuvial horizonation and a deeper profile. The inference is that the older terraces reflect a moderately arid to semi-arid climate in which rainfall was occasionally sufficient to encourage mass-wasting of talus slopes in headwater reaches and so provide material of the right consistency for debris flows. At the same time, the rainfall regime, while not generous, nevertheless encouraged soil development. The Holocene terraces reflect the onset of the extreme aridity that characterizes the region at present. Debris flows were not a feature of the sediment transfer system and soil development was inhibited by the infrequency of rainfall.

**Fig. 23.20** Differentiation of the largely fluvial sediments of the Holocene terraces of the Timna Valley, southern Negev, laid down by flash floods that punctuated extremely arid conditions and those terrace sediments of Pleistocene age which consist, in part, of debris-flow deposits and indicate a slightly ameliorated climate that produced moderately arid to semi-arid conditions. Reproduced by permission of the Geological Society of London from 'Fluvial deposits and morphology of alluvial surfaces as indicators of Quaternary environmental changes in the southern Negev, Israel' by S. Grossman and R. Gerson in *Geological Society of London Special Publication 35*, 1987

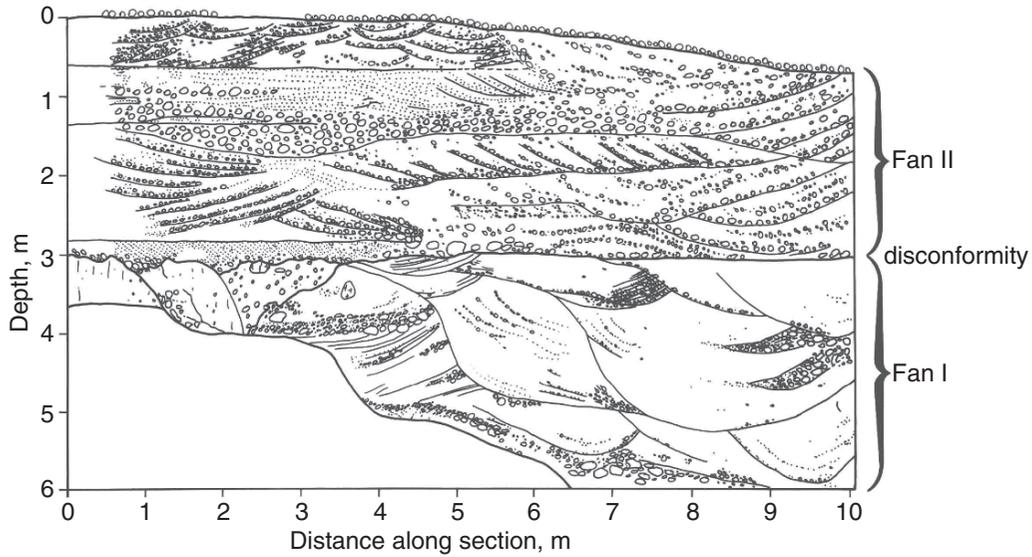


Maizels (1987; Fig. 23.21) offers another glimpse of the sedimentary legacy of changes in climate, albeit that it is the sediments and not independent lines of evidence that provide the clues, so that there is always the danger of circular argument. Notwithstanding this problem, the lowest unit of the Wadi Andam Fan complex (Fan I) exhibits a cut-and-fill structure that matches the meandering nature of the channels that drained from the Eastern Oman Mountains during the wetter conditions of the early Pleistocene. The beds of Fan II are, in contrast, thinner and more tabular, reflecting the flashier flood regime of the braided streams that developed in the region during arid phases of the mid to late Pleistocene.

The examples discussed so far are, by and large, headwater or upper catchment deposits of small to moderate-sized drainage systems. However, the deposits of larger rivers also reflect shifts in climate. The patterns of change are not dissimilar to those already described except that the character of the sediment is governed by processes of comminution and selective entrainment that operate over the long transport distances that are involved. Adamson's (1982; Fig. 23.22) compilation of hydrological and sedimentological

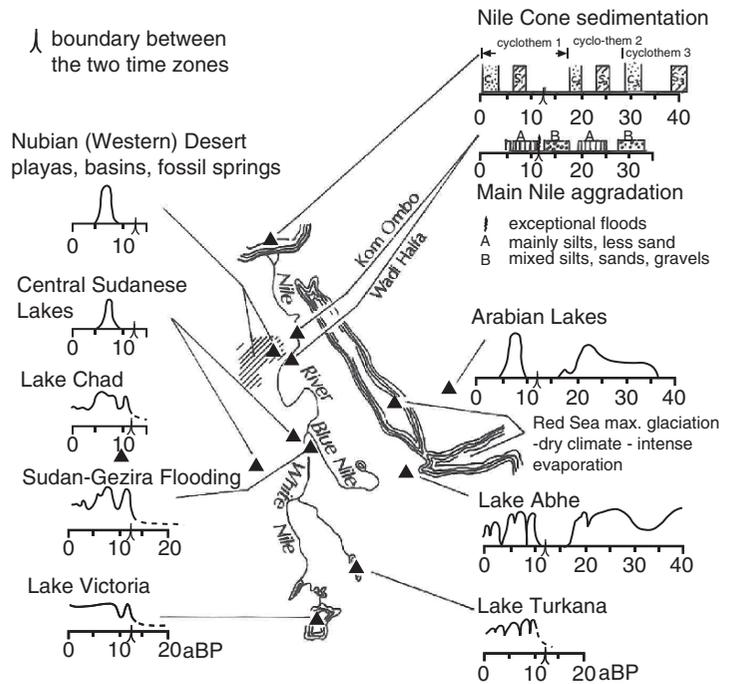
information for the expanded Nile basin and adjacent areas provides a thoroughly researched example. In particular, the fine sediments deposited along the main Nile and in its delta are equated with the ameliorated climate of the period that preceded the last glacial maximum and of the early Holocene, while coarser sands are a product of the terminal Pleistocene and late Holocene arid phases. A similar pattern of events is drawn from analyses of the sediments of the Niger Delta (Pastouret et al. 1978) and those of the deep-sea fan that lies off the mouth of the Amazon (Damuth and Fairbridge 1970).

In the Channel Country of central Australia, Rust and Nanson (1986) found a regionally extensive sand sheet underlying the mud-pellet braid-plain of the modern Cooper Creek, which they date tentatively as between 200 and 50 ka. They relate the sand to high-sinuosity meandering channels visible on air photography where the mud-pellet braid plain is undeveloped and infer a wetter climate and more sustained flow regime. There is no explanation for the switch in sediment character to the peculiar clay-pellet clasts of the modern braid plain, but it is taken to signify aridification of the catchment.



**Fig. 23.21** Deposits of the Plio-Pleistocene Wadi Andam Fan Complex of western Sharqiya, Oman. Fan I was laid down by sinuous streams that probably had at least a seasonal discharge regime and indicate a wetter climate than Fan II, which was a braid-plain built by ephemeral flash floods. Reproduced by

permission of the Geological Society of London from 'Plio-Pleistocene raised channel systems of the western Sharqiya (Wahiba), Oman' by J.K. Maizels in *Geological Society of London Special Publication 35*, 1987



**Fig. 23.22** Summary of hydrological and sedimentological data for the greater Nile Basin and adjacent areas during the late Pleistocene and Holocene (after Adamson 1982)

## Conclusions

Desert rivers undoubtedly respond to those gross changes in climate that bring a shift in environment from arid to semi-arid or even sub-humid conditions and *vice versa*. Perhaps this is not surprising given that Langbein and Schumm's (1958) celebrated (if contentious) curve relating present-day specific sediment yield to effective rainfall is at its steepest for the world's drylands. At finer resolution, it is still debatable whether river response reflects lesser changes in climate, if only because the alterations which occur in ground cover and soil that affect the runoff process are stepped in character and do not vary continuously with increasing or decreasing rainfall. In any case, several studies in drylands suggest that storm type and rainfall intensity rather than rainfall amounts are as important in determining runoff response and, hence, sediment transport. Besides this, the impact of occasional large floods undoubtedly tends to mask the gradual alteration of channel form that might be expected to accompany diminutive changes in climate.

There are well-documented examples where both river planform and sedimentary deposits suggest that considerable uncertainty lies in attempting to interpret them in terms of climate change. As a consequence, considerable circumspection is required and other lines of evidence should be sought as corroboration. However, despite the difficulties that are experienced in calibrating the fluvial measuring-stick in terms of climate, river character is a valuable, and sometimes singular, guide to climate-induced environmental change, especially in deserts where biogenic evidence is often absent.

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