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Anabranching rivers on the Northern Plains of arid central Australia

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Abstract

Anabranching rivers are a widespread feature of the Northern Plains in the Alice Springs region of central Australia but their unusual characteristics previously have not been described. On the Northern Plains, anabranching occurs on rivers transporting bedloads of coarse sand and gravel and is characterised by channels of variable size and shape which occur within a broader, typically well-defined, *channel-train*. Channels are separated by *channel-train ridges*—narrow, flow-aligned, vegetated features—or by wider *islands*. Ridges and islands are either depositional features (formed in situ by accretionary processes) or erosional features (formed by excision from once-continuous areas of floodplain). Vegetation plays a key role in the initiation, survival and growth of depositional forms through its influence on flow, sediment transport and ridge and island stability. Anabranching is also related to the influence of tributaries, for some large rivers alternate from single-thread to anabranching along their length in response to tributary inputs of water and sediment. Tributary inputs occur during flow events that are either independent from, or in concert with, floods in the trunk channel. Ridges and islands form in association with tributaries as a result of various hydrological, depositional and erosional processes, including irrigation of enhanced numbers of in-channel trees and resulting lee-side sediment accretion, floodplain scour, and the formation and maintenance of deferred-junction tributaries. The change from single-thread to anabranching downstream of tributary junctions occurs in the absence of any significant change in channel gradient or degree of channel confinement. On the Northern Plains, anabranching appears to be a stable river pattern that helps to maintain the throughput of relatively coarse sediment in low-gradient (typically 0.0005–0.002) channels characterised by an abundance of within-channel vegetation and subject to declining downstream discharges. © 1999 Elsevier Science B.V. All rights reserved.

Keywords: anabranching; alluvial islands; arid channels; floodplain scour; ridges; riparian vegetation; river pattern; sediment transport; tributaries

1. Introduction

River pattern is a term which describes the plan-form geometry and implies the processes operating within a reach of a river (Nanson and Knighton, 1996). It represents one means whereby an alluvial

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channel can adjust its morphology to prevailing flow and sediment conditions. Although river patterns show a continuous variation of form, following the classic work of Leopold and Wolman (1957) they have traditionally been classified into straight, meandering and braided. However, more recent classifications have incorporated anabranching (including anastomosing) as a recognisable pattern (e.g., Mollard, 1973; Rust, 1978; Schumm, 1981, 1985; Brice, 1984; Knighton and Nanson, 1993; Nanson and Knighton, 1996). A central theme in many of these classifications is that natural river patterns form a continuum controlled by interactions amongst a set of continuously varying factors, such as discharge, slope, bank strength and sediment load.

Along this continuum of river pattern, many authors (e.g., Slatyer and Mabbutt, 1964; Mabbutt, 1977; Graf, 1988) consider braided channels to be particularly characteristic of ephemeral rivers as a response to common catchment conditions of abundant coarse bedloads, highly variable discharges, and readily erodible banks. Although these conditions also apply to many catchments in the Alice Springs region of arid central Australia, reaches that conform to traditional descriptions of braided channels are rare. In this region, rivers tend either to be relatively low sinuosity, single-thread channels, or to consist of multiple channels that occur within a broader, sometimes sinuous, channel tract. A preliminary description of the multiple channel reaches (Nanson and Knighton, 1996) defined them as ‘sand-dominated, ridge-forming (Type 4)’ anabranching channels. However, some reaches of channels in central Australia also display other forms of anabranching previously not described.

This paper has three main aims: first, to provide a comprehensive description of the morphological, hydraulic and sedimentological characteristics of anabranching rivers in the Alice Springs region; second, to illustrate factors contributing to the formation and maintenance of anabranching river patterns; and third, to consider the implications of anabranching for flow and sediment discharge.

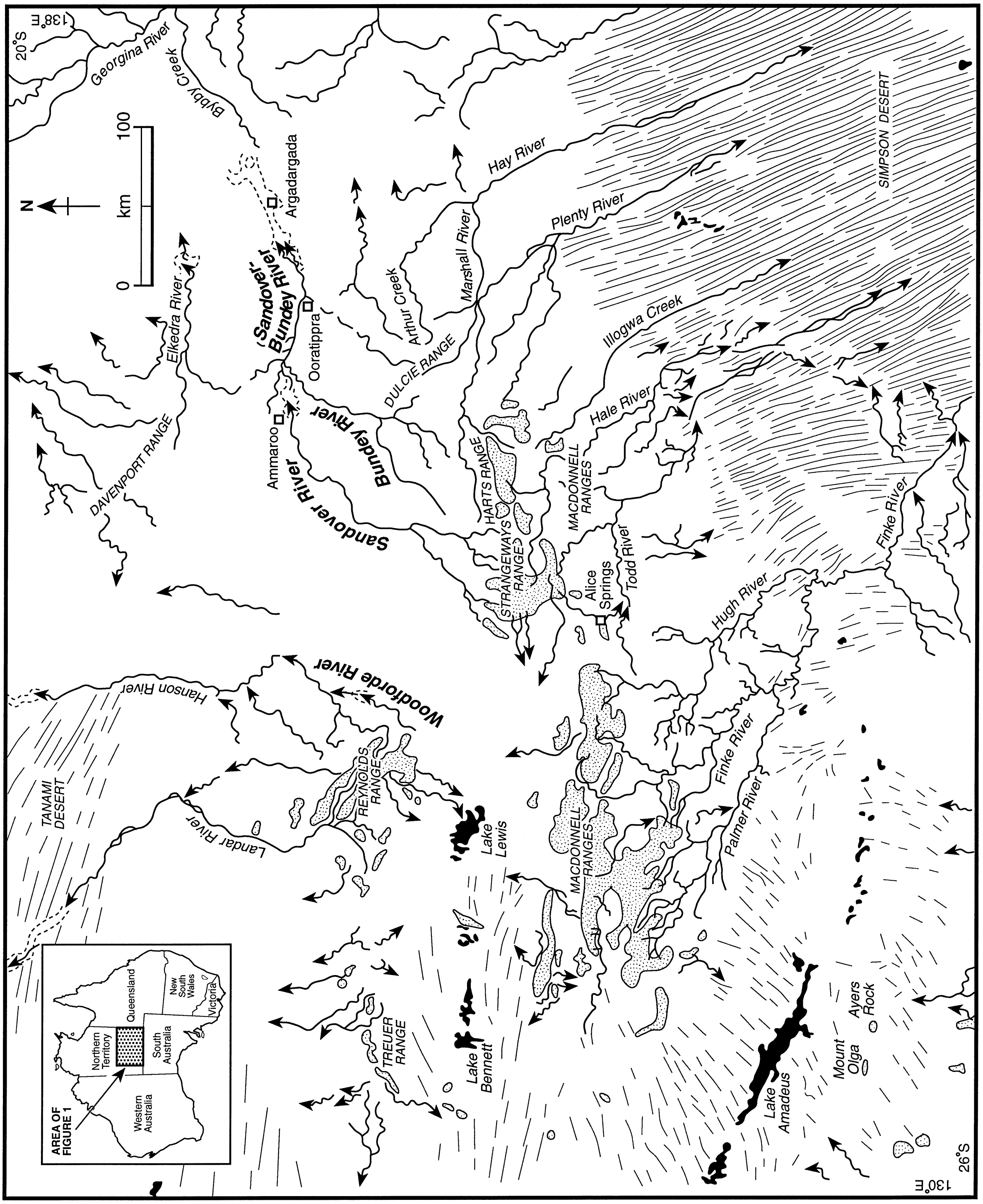
2. Regional setting

The ‘Alice Springs area’ (Stewart and Perry, 1962) is an arid region in the centre of the Australian continent (Fig. 1). It is dominated by the central ranges, a west–east trending belt of Proterozoic and Palaeozoic crystalline and sedimentary rocks which cuts across the middle of the region. The central ranges are broken by intermontane lowlands and are flanked by the extensive Northern Plains and Southern Desert Basins (Mabbutt, 1962), where uplands are restricted in extent (Fig. 1).

The findings presented here are drawn from study of rivers on the Northern Plains. Particular attention is focused on the Sandover, Bundey, Woodforde, Marshall and Plenty Rivers (Fig. 1). Although the Bundey supplies the vast majority of flow and sediment downstream of its confluence with the Sandover, the channel continues as the Sandover River. Here, it is referred to as the Sandover–Bundey River in order to avoid confusion with the Sandover River upstream of Ammaroo station (Fig. 1). Rainfall across the Northern Plains is highly variable but averages ~ 300 mm/year, and pan evaporation is high (~ 3000 mm/year). As a result, rivers remain dry for much of the year and only occasionally flow throughout their length. However, large floods can follow occasional heavy rainfalls (> 100 mm/24 h) that result from incursions of monsoonal depressions and cyclones from the north, or from the easterly passage of frontal weather systems. There are no rated gauging stations on rivers on the Northern Plains, but the last few decades have included some of the largest floods in the 100–110 years of European settlement in the region (Williams, 1970a; Baker et al., 1983; Pickup et al., 1988; Pickup, 1991).

In the upper reaches of river catchments on the Northern Plains, small, rocky channels transporting

Fig. 1. Ephemeral drainage systems in the Alice Springs region of central Australia, highlighting the main rivers referred to in this paper. Stippled areas represent land over 750 m in elevation, with these ranges generally rising 100–150 m above the surrounding plains. The Northern Plains is the extensive area north of the central belt of ranges.


20°S
138°E
Georgina River
Bybby Creek
N
0
100
km
Argadargada
Hay River
Plenty River
SIMPSON DESERT
Marshall River
Arthur Creek
Sandover-Bundey River
Ooratippra
DULCIE RANGE
Elkedra River
Illogwa Creek
Hale River
Ammaroo
Bundey River
Sandover River
DAVENPORT RANGE
HARTS RANGE
MACDONNELL RANGES
STRANGEWAYS RANGE
Alice Springs
Todd River
Finke River
Hugh River
Woodforde River
Hanson River
TANAMI DESERT
REYNOLDS RANGE
Landar River
Lake Lewis
MACDONNELL RANGES
Finke River
Palmer River
Ayers Rock
Mount Olga
Lake Amadeus
Lake Bennett
TREUER RANGE
AREA OF FIGURE 1
Queensland
Northern Territory
South Australia
Western Australia
New South Wales
Victoria
26°S
130°E

sand and gravel converge on the piedmont to give rise to well-defined channels flanked by higher alluvial surfaces, bedrock or aeolian sandplain. In the middle reaches, bankfull channel capacities generally decrease downstream due to declining discharges resulting from flow transmission losses and floodwave attenuation. Channels remain well-defined for much of their length but, in the lower reaches, channels eventually disappear and bedload transport ceases, although occasional large floods continue across broad, low-gradient, alluvial surfaces known in Australia as 'floodouts' (Tooth, 1999). The principal concerns of this paper are channel forms and processes in the middle reaches.

3. Anabranching river patterns on the Northern Plains

For some rivers on the Northern Plains, such as the Bundey (Sandover–Bundey), Woodforde and Marshall, anabranching is the dominant pattern in the middle reaches. Anabranching is characteristic both of large rivers such as the Bundey (Sandover–Bundey), which anabranches for ~70 km, and

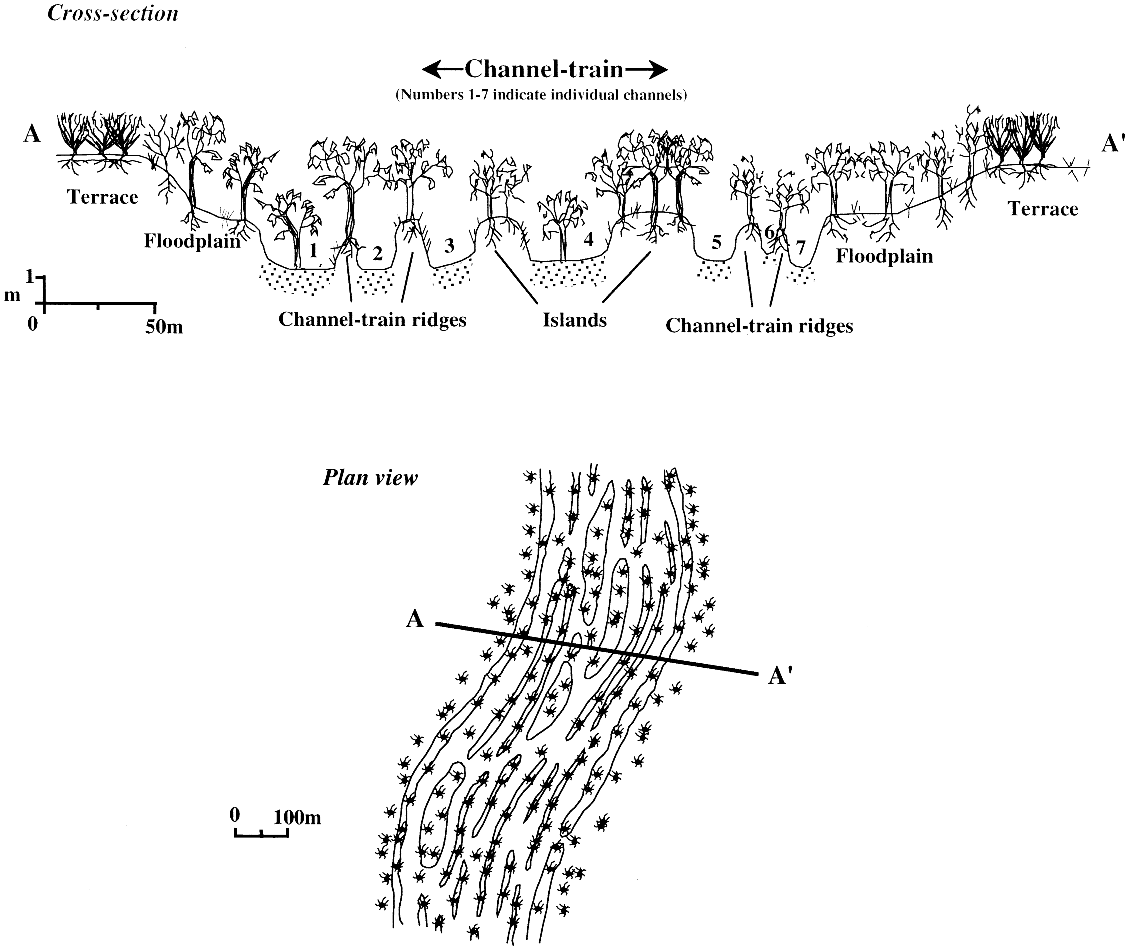


Fig. 2. Schematic illustrations of the typical characteristics of anabranching reaches. Individual channels within the channel-train are separated either by narrow ridges or broader islands. Definition of individual channels is partly stage-dependent for many ridges or islands separating channels at low flows may be drowned during higher flows.

smaller rivers such as the Woodforde, which anabranches for ~ 8 km.

Fig. 2 schematically illustrates typical characteristics of anabranching channels on the Northern Plains. The *channel-train* is the entire complex of channels in the cross-section (Fig. 2) and is typically relatively straight, although it sometimes displays a series of low-amplitude curves. The margins of the channel-train are laterally stable and are usually formed by older, indurated alluvial terraces, often in association with substantial aeolian sands.

The number of channels within the broader channel-train (Fig. 2) varies from reach to reach. In piedmont reaches there are typically between 2 and 4 channels but further downstream there may be as many as 15 channels. Channels are separated either by *channel-train ridges*, which are relatively narrow in relation to their length (length to width ratio > 10) or by *islands*, which are relatively broad in relation to their length (length to width ratio < 10) (Figs. 2 and 3). This distinction between ridges and islands is arbitrary, however, and a range of intermediate forms occurs. Shapes of ridges and islands vary widely in plan view but are typically elongate (width remains roughly constant along their length) or tear-shaped (broader at their upstream end and tapering downstream) with long axes aligned parallel to the direction of flow (Figs. 2 and 3). Ridges and islands are generally steep sided (bank angles $> 40°$) and composed of sand and mud with a vegetation cover of trees (principally river red gums, *Eucalyptus camaldulensis*), shrubs and grasses. While the tops of islands generally approximate or exceed bankfull level of the channel-train, ridges occur at a wide range of elevations up to bankfull (bankfull being defined by the elevation of the floodplains at the margins of the channel-train) (Fig. 4). Islands can persist for up to several kilometres downstream but individual ridges are usually not more than a few hundred metres long. Hence, individual channels follow roughly parallel courses for varying distances. Where ridges have been breached, flow and sediment transport are often diverted from one channel to another.

Individual channels within the channel-train vary widely in morphology, both within a given reach and between different reaches, and have width–depth ratios that vary between 10 and 200 and bankfull capacities that vary from 1 to 200 m^2. Many larger channels (such as those that have a width–depth ratio > 50 or exceed 60 m^2 in capacity) typically possess a number of small, poorly developed ridges (Fig. 4b). However, in reaches where anabranching is well-developed, channel width–depth ratios generally range between 20 and 40 and bankfull capacities are less variable. In many channels, bedrock outcrops and growth of *E. camaldulensis* are common. Bed elevations and bed slopes of adjacent channels often vary widely such that, where channels of different elevation merge at the downstream end of a dividing ridge or island, bars of sand and gravel with avalanche faces up to 2 m high are present. Hydraulic calculations for anabranching channel reaches are difficult because variable elevation of the ridges and islands makes definition of bankfull problematic and because large numbers of in-channel and riparian trees create uncertainties in estimation of roughness coefficients. However, although variable, unit stream powers typically range between 5 and 30 W/m^2.

On the Northern Plains, anabranching usually occurs over reaches several kilometres in length before it becomes less well-defined and the rivers revert to largely single-thread patterns. On short rivers such as the Woodforde, reversion to a single-thread form occurs in the middle to lower reaches, but larger rivers such as the Bundey (Sandover–Bundey) and Marshall typically alternate from anabranching to single-thread at several points through their middle reaches. For all the anabranching rivers on the Northern Plains, a comparison of 1950s aerial photographs with those taken in the 1980s shows that there has been essentially little channel change in anabranching reaches during this time, despite a series of large floods. Changes have probably occurred to individual channels or to intervening ridges or islands but at a scale finer than can be detected on aerial photographs. As a whole, therefore, anabranching here appears to be a stable channel form.

Anabranching patterns similar to those of the Bundey, Marshall and Woodforde Rivers are widespread on the Northern Plains but, surprisingly, there has been little mention of the unusual characteristics of these channels in the literature. Many authors (e.g., Mabbutt, 1962, 1967, 1977, 1986; Stidolph et al., 1988; Pickup, 1991) generally refer

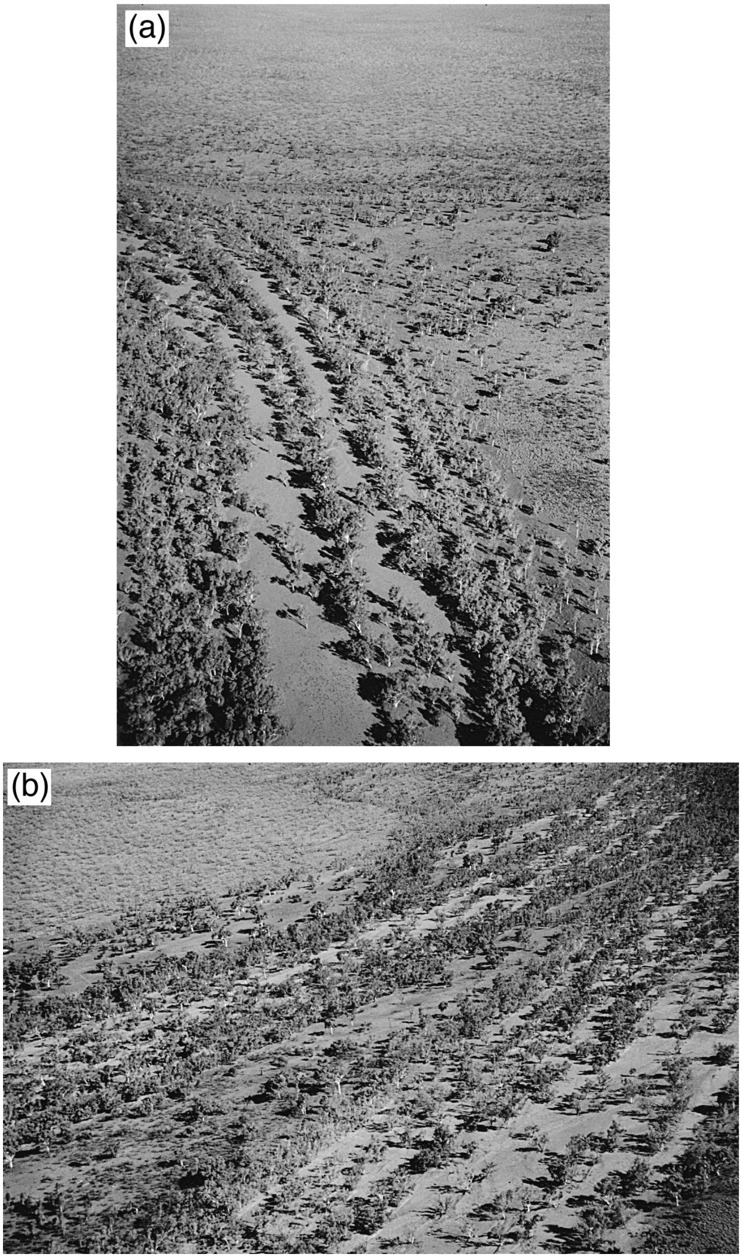
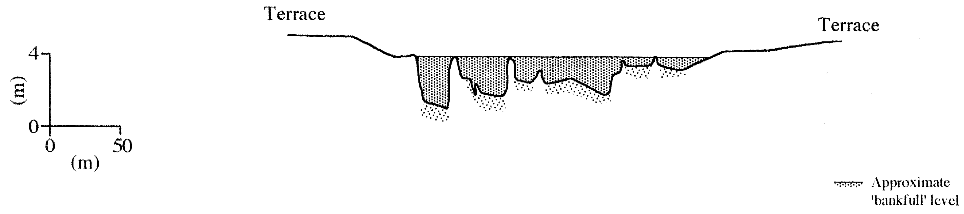


Fig. 3. Oblique aerial views, illustrating the different styles of anabranching channel on the Northern Plains: (a) Sandover–Bundey River, showing ridge-form anabranching where channels are separated by linear, vegetated ridges (flow direction is from bottom right to top left); (b) Bundey River, showing island-form anabranching where channels are separated by broad islands (flow direction is from top right to bottom left).

only to ‘braided’ rivers in their commentaries on the fluvial geomorphology of the Alice Springs region and, indeed, the Woodforde River has even been cited as ‘a good example’ of a braided river (Evans, 1972, p. 5). However, while braided rivers are characterised by flow which is separated by bars within


a) Ridge-form anabranching

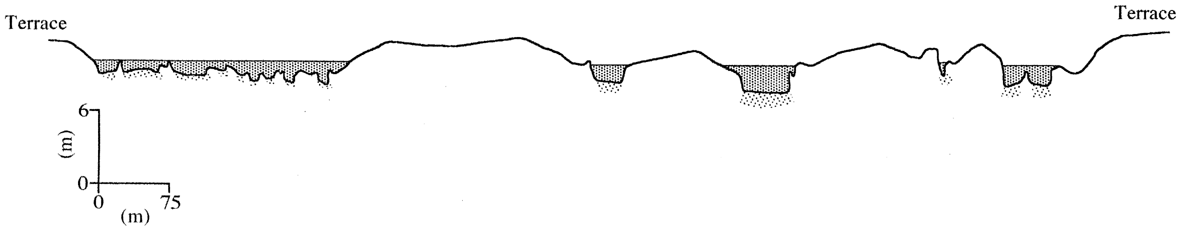

b) Island-form anabranching

Fig. 4. Examples of surveyed cross-sections from anabranching reaches of rivers on the Northern Plains showing (a) ridge-form anabranching (Sandover–Bundey River) and (b) island-form anabranching (Bundey River). The sections correspond to anabranching Types 4 and 2, respectively (Nanson and Knighton, 1996) and have a different scale but the same vertical exaggeration (12.5).

the channel, braid bars are generally poorly vegetated, and diamond-, rhomboid- or lozenge-shaped in plan. These characteristics provide stark contrast with the well-vegetated, very elongate or tear-shaped ridges and islands of the Bundey, Marshall and Woodforde Rivers. In addition, while braid bars are usually submerged at bankfull stage and are frequently reworked, ridges and islands are often elevated to bankfull level (Fig. 2) and are very stable. Hence, these rivers cannot be accurately termed 'braided'. Nevertheless, where channel-train ridges are not well developed (such as in piedmont reaches of the Woodforde River), reaches sometimes appear closer to braiding with broad, low-elevation, mid-channel bars dividing the channel, but such reaches are relatively uncommon.

Similar anabranching patterns to those on the Northern Plains have also been observed in the Kimberley region of Western Australia (Wende and Nanson, 1998). In their classification of anabranching rivers, Nanson and Knighton (1996) include the central Australian and Kimberley examples in their 'sand-dominated, ridge-forming (Type 4)' category. They suggest that the distinguishing characteristics of this style of anabranching are stable, narrow, steep-sided, vegetated, sandy ridges that divide the channel-train into a series of relatively straight or gently curving, subparallel, narrow and deep channels (Figs. 3a and 4a). For ease of discussion, this is referred to here as 'ridge-form anabranching'.

On the Northern Plains, in addition to ridge-form anabranching, some reaches also display other forms of anabranching. For instance, a 25 km reach of the Bundey River downstream of the confluence of its three main piedmont tributaries (upper Bundey River, Frazer and Alkara Creeks) is characterised by a broad belt of channels flowing in a south–north direction. Between three and five major channels up to 350 m in width can be identified and are separated by large islands up to several kilometres long (Figs. 3b and 4b). This pattern corresponds more closely to the 'sand-dominated, island-forming (Type 2)' category of anabranching rivers (Nanson and Knighton, 1996), referred to here as 'island-form anabranching'.

The only Type 2 anabranching river studied to date is Magela Creek, northern Australia, where channels are separated by wide, well-vegetated islands and follow subparallel courses with intermittent, relatively wide and sometimes braided reaches. However, although the Bundey River has some similarities with Magela Creek, on the Bundey there are also numerous smaller, often poorly defined channels separated by low ridges or smaller islands. These occur both *within* and *adjacent* to many major channels (Fig. 4b). Hence, the major channels are themselves characterised by ridge-form anabranching. Overall, therefore, this reach of the Bundey River displays two *coexisting* styles of anabranching.

The coexistence of two styles of anabranching (Types 2 and 4 of Nanson and Knighton, 1996) is also present to a lesser degree in piedmont reaches of the Bundey, where ridges sometimes occur within larger channels separated by wide islands. In addition, many reaches of the Marshall River display characteristics very similar to those of the Bundey. Although the preliminary classification of anabranching channels (Nanson and Knighton, 1996) suggested that the apparently higher stream powers (15–35 W/m^2) of Type 4 rivers differentiates them from lower energy (4–8 W/m^2) Type 2 rivers, data from the Bundey indicate greater overlap in the stream powers of these two anabranching styles than previously has been acknowledged. For example, on the Bundey, both Type 2 and Type 4 anabranching occur with bankfull unit stream powers in individual channels ranging between 1–30 W/m^2. As knowledge of anabranching channels expands, the preliminary classification of Nanson and Knighton (1996) will undoubtedly be further modified.

4. Factors contributing to anabranching on the Northern Plains

River patterns on the Northern Plains vary widely between adjacent catchments. The anabranching patterns of the Bundey and Woodforde Rivers provide stark contrast with the neighbouring single-thread Sandover River and while anabranching is characteristic of many reaches of the Marshall, the adjacent Plenty River is largely single-thread. These contrasting river patterns are not related to differences in channel gradients, for bed slopes along all these rivers are very similar, typically declining from around 0.002 in the piedmont to around 0.001 or less through the middle reaches. However, the calibre of transported bed material varies widely due to differences in catchment lithology, tributary gradients and the proportion of tributary-derived drainage. For the anabranching Bundey, Woodforde and Marshall Rivers, which drain catchments comprised mainly of coarse-grained crystalline rocks and receive additional sediment supplies from moderate- to high-gradient tributaries in their middle reaches, bed material mainly consists of coarse sand to granule gravel, with median grain size typically 0.5 to −0.5 phi (0.71 to 1.4 mm) (Fig. 5). For the single-thread Sandover and Plenty Rivers, which drain catchments with finer-grained crystalline rocks and receive very limited sediment supplies from tributaries in their middle reaches, bed material is finer and mainly consists of medium to coarse sand, with median grain size typically 2 to 0.5 phi (0.25 to 0.71 mm) (Fig. 5). This difference in bed material calibre appears to be a key factor contributing to the contrast in river patterns on the Northern Plains, with anabranching characteristic of rivers transporting relatively coarse bedloads.

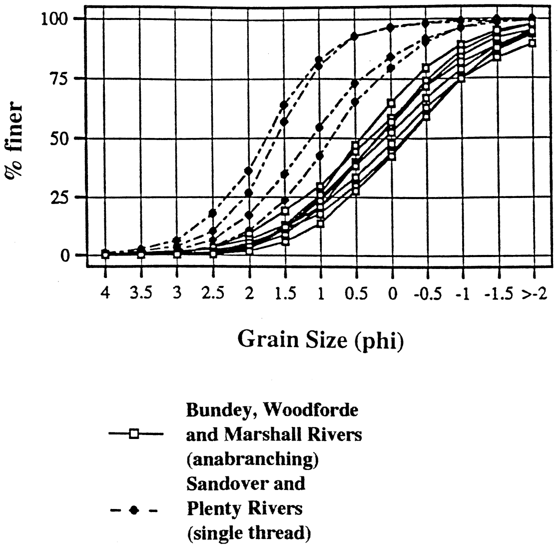


Fig. 5. Grain size curves for bed material from rivers on the Northern Plains. Anabranching patterns are characteristic of those rivers transporting bedloads of coarse sand and gravel. Each curve is the average of three samples.

Anabranching can also be directly related to patterns of tributary drainage, for both the Bundey (Sandover–Bundey) and Marshall Rivers alternate from single-thread to anabranching along their length in response to tributary inflows. This occurs either where one small tributary joins the river or where several tributaries join the river within a short reach. Fig. 6 illustrates the relationship between tributary inflows and anabranching in the middle reaches of the Sandover–Bundey, clearly showing how the number of channels increases for short distances below tributary junctions before the channel reverts to a largely single-thread form. This increase in the number of channels downstream of tributary junctions occurs in the absence of any significant change in channel gradient or degree of channel confinement.

In the catchments of the Bundey, Woodforde and Marshall Rivers, tributaries vary in character from those transporting coarse sand and gravel as bedload to those transporting mainly suspended load, yet ridge- or island-form anabranching can result across this range. Hence, the processes responsible for the formation of channel-train ridges and islands may be tributary-related, evidence for which comes from the sedimentology of ridges and islands.

5. Sedimentology of ridges and islands

Examples of excavated sections from typical ridges and islands are presented in Fig. 7. In all instances, basal coarse sand and granule/pebble gravel is overlain by a finer overburden varying from coarse sand through to mud. The top of the basal sand and gravel is generally elevated above the surface of the adjacent channel bed. For many islands and floodplains, as well as for a smaller number of ridges, the finer overburden shows little textural differentiation or preserved sedimentary structures. For many other ridges, however, the overburden consists of separate sedimentary units, although the number, texture and thickness of units vary both from ridge to ridge and even along the same ridge (Fig. 7). Boundaries between units are usually indistinct with textural changes gradational but in rarer instances erosional contacts can be identified. Lenses consisting of partially-decayed leaves and twigs are

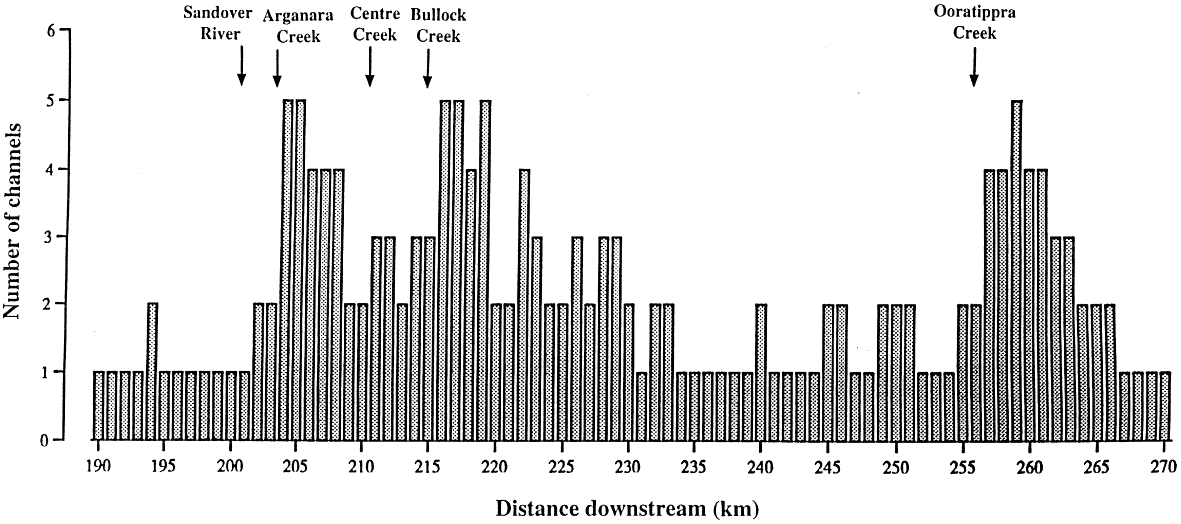
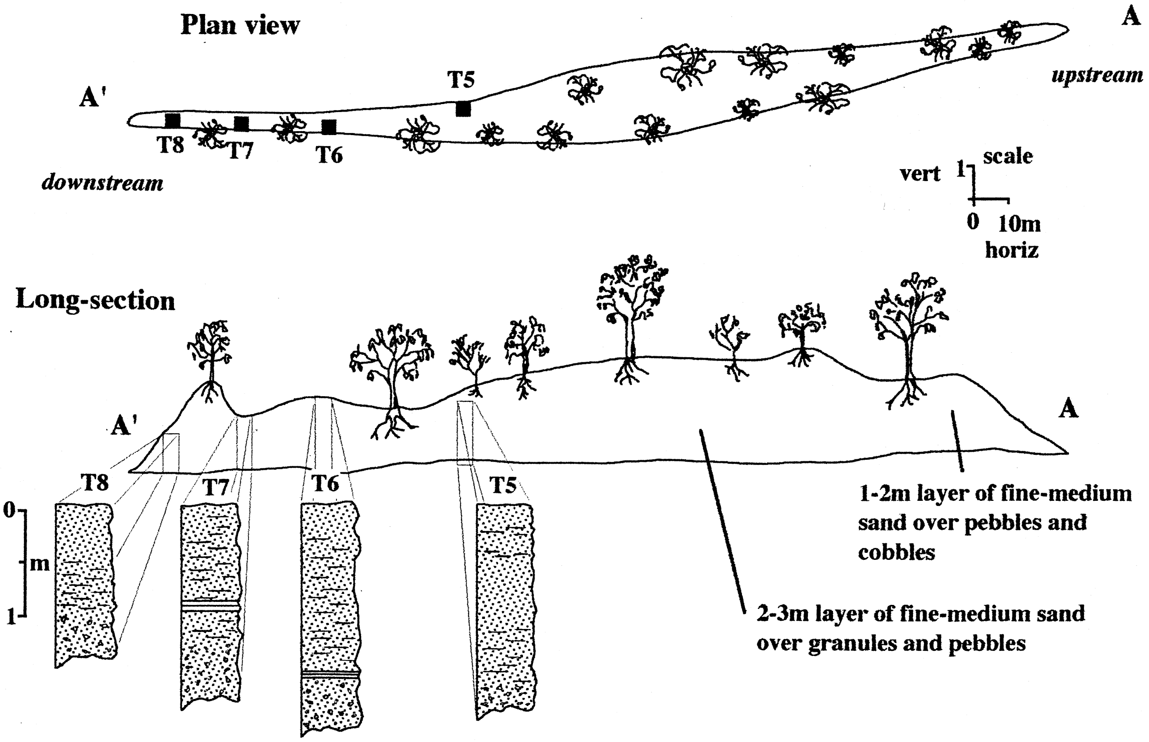


Fig. 6. Relationship between tributary inflows and anabranching in the middle reaches of the Sandover–Bundey River, based on assessment of the number of channels at 1 km intervals (determined from field surveys and aerial photographs). Although defining the number of channels across a given section involves a degree of subjectivity, the data nevertheless demonstrate how the number of channels increases for a short distance downstream of the tributary junctions, resulting in ridge-form anabranching, before the river reverts to a largely single-thread channel with only occasional ridges and islands.

a) Channel-train ridge, Sandover-Bundey River



b) Small island,Woodforde River

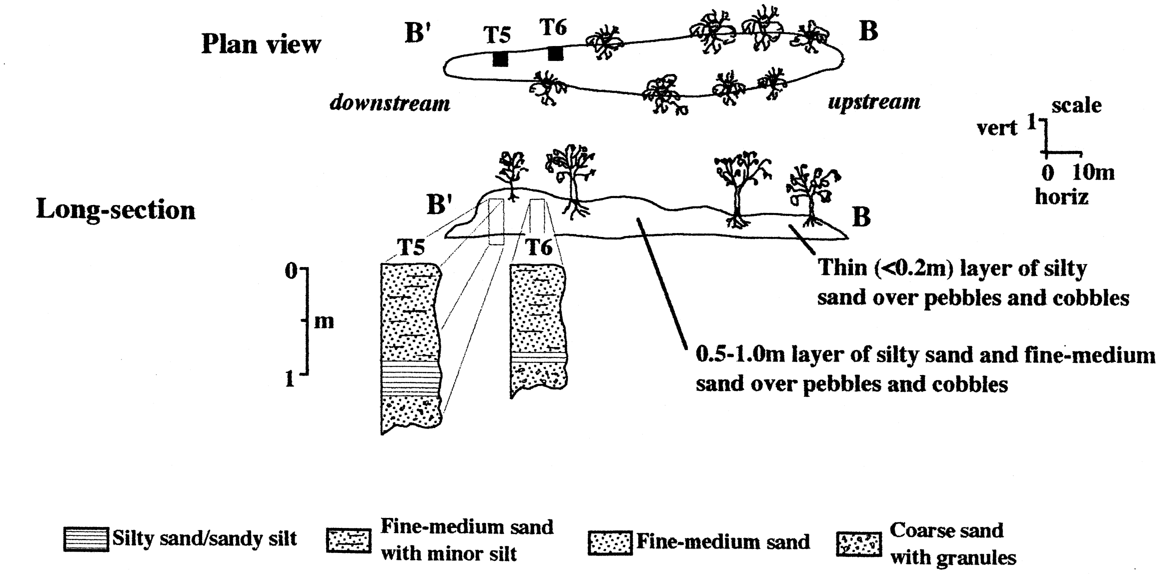


Fig. 7. Excavated sections illustrating the typical morphology and sedimentology of ridges and islands. Trenches were excavated perpendicular to the downstream direction and sediments were described from the face parallel to flow.

often found high in the successions but, given rapid rates of organic decay in the region, these organics are thought to be too young to be usefully dated by radiocarbon techniques.

Sedimentary units typically dip from the centre of ridges towards adjacent channel beds, with the angle of dip generally between 30° and 60° (Fig. 8). In such instances, ridges are composed of a central core of coarse sand and granule/pebble gravel which decreases in thickness towards the ridge margins, with overlying units generally following the same pattern. Cross-cutting by overlying units can occasionally be identified, sometimes with textural reversals. Due to bioturbation resulting from growth of colonising trees, shrubs and grasses, sedimentary structures are rare but, where preserved, fine-medium sand shows either weakly developed trough cross-beds or opposed planar cross-beds with the foresets generally meeting at the ridge centre (Fig. 8).

In some instances, sedimentary units in ridges dip below the levels of adjacent channel beds and can be traced up to 1 m away from the ridge margins to

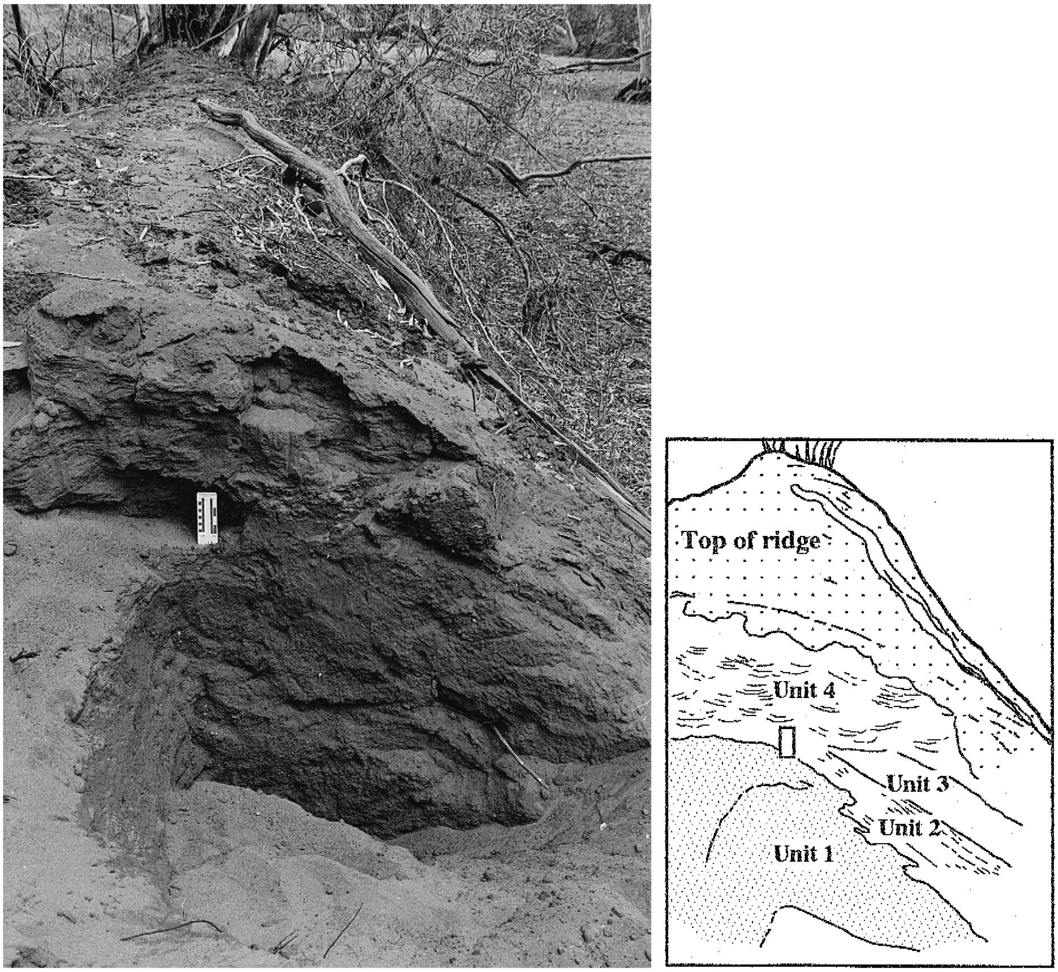


Fig. 8. Photograph and interpretative sketch illustrating the sedimentology of a typical channel-train ridge on the Sandover–Bundey River (view into centre of ridge, flow direction towards camera). A central core of structureless coarse sand and granule/pebble gravel (unit 1) is overlain by fine to medium sand with planar cross-beds (unit 2), structureless silty sand (unit 3) and fine to medium sand with trough cross-beds (unit 4). Units dip towards the ridge margins, with clear signs of interfingering between units 1 and 2. Contacts between units are both gradational and erosional. The left-hand side of the scale is marked in centimetres and the right-hand side in inches.

depths of around 15–20 cm below the bed surfaces. Interfingering between the silt and sand of ridges and adjacent channel sand and gravel can sometimes be found. For ridges and islands showing little internal textural differentiation, however, ridge silt and sand appears to underlie channel sand and gravel and to join with neighbouring ridges or floodplains.

Although details of the sedimentology vary even within any one ridge or island, some general conclusions can be drawn. The complex sedimentology of many ridges and islands strongly indicates that they have mainly formed in situ by accretionary processes (i.e., they are depositional features). For instance, interbedded fine–medium sand and silty sand identified in some ridges (Fig. 7) may represent depositional couplets resulting from separate flood events or from pulses on an individual flood wave. However, where ridges and islands show little internal textural differentiation or where their sedimentology and roughly horizontal sedimentary units differ little from that of adjacent floodplains, indications are that they have been cut from areas of formerly continuous floodplain (i.e., they are erosional features). The external morphologies of depositional and erosional ridges and islands are similar and are not readily distinguishable. Both depositional and erosional types can occur within a given reach and across a given section, suggesting that anabranching patterns as a whole result from a number of depositional and erosional processes.

While the depositional or erosional origins of relatively narrow ridges and smaller islands can be established from their sedimentology, the origins of larger islands found in some anabranching reaches are more difficult to ascertain. Due to limited stratigraphic exposures of larger islands, it is unclear whether they are primarily depositional or erosional in origin. Anabranching (including anastomosing) has usually been defined with reference to islands excised from floodplains (e.g., Knighton and Nanson, 1993) but recent acknowledgement has been given to the possibility of islands formed by within-channel deposition (Nanson and Knighton, 1996; see also Sarkar and Basumallick, 1968). In many cases, it is hard to establish the origins of islands characterising certain anabranching channels (Nanson and Knighton, 1996) but, as the following discussion indicates, it is likely that examples of both large depositional and large erosional islands can be found in anabranching channels on the Northern Plains.

6. Formative processes of ridges and islands

The broad distinction between primarily depositional and primarily erosional forms provides a useful basis for a discussion of the formative processes of ridges and islands comprising anabranching river patterns.

6.1. Depositional forms

A number of studies in various fluvial contexts have documented how flow separation induced by obstacles such as bridge piers, stranded ice blocks, boulders and riparian vegetation can result in a variety of depositional and erosional features collectively termed ‘obstacle marks’ (Dzulynski and Walton, 1965; see Allen, 1982, for a summary). Depositional features are generally known as ‘current shadows’ and erosional features as ‘current crescents’ (Allen, 1982).

Along channels in the Alice Springs region, growth of in-channel trees, such as *E. camaldulensis*, is characteristic of many reaches. These trees act as substantial obstacles and influence local patterns of flow and sediment transport. Hence, for anabranching rivers on the Northern Plains, many depositional ridges and smaller islands (width < 10 m) probably originate as current shadows on the downstream side of in-channel trees. Indeed, the morphological and sedimentological characteristics of depositional ridges and islands (Figs. 7 and 8) are consistent with current shadow formation in two main respects. First, ridges and islands range in size from low, short and narrow up to elevated, lengthy and wide forms. The sedimentology of different size depositional ridges and islands shows no consistent differences, suggesting that small ridges can grow in size to become larger ridges or islands. Second, where preserved, internal sedimentary structures are similar to small current shadows previously described in the literature (e.g., Karcz, 1968; Williams, 1970b; Picard and High, 1973; Sneh, 1983), sometimes containing opposed foresets of fine–medium sand.

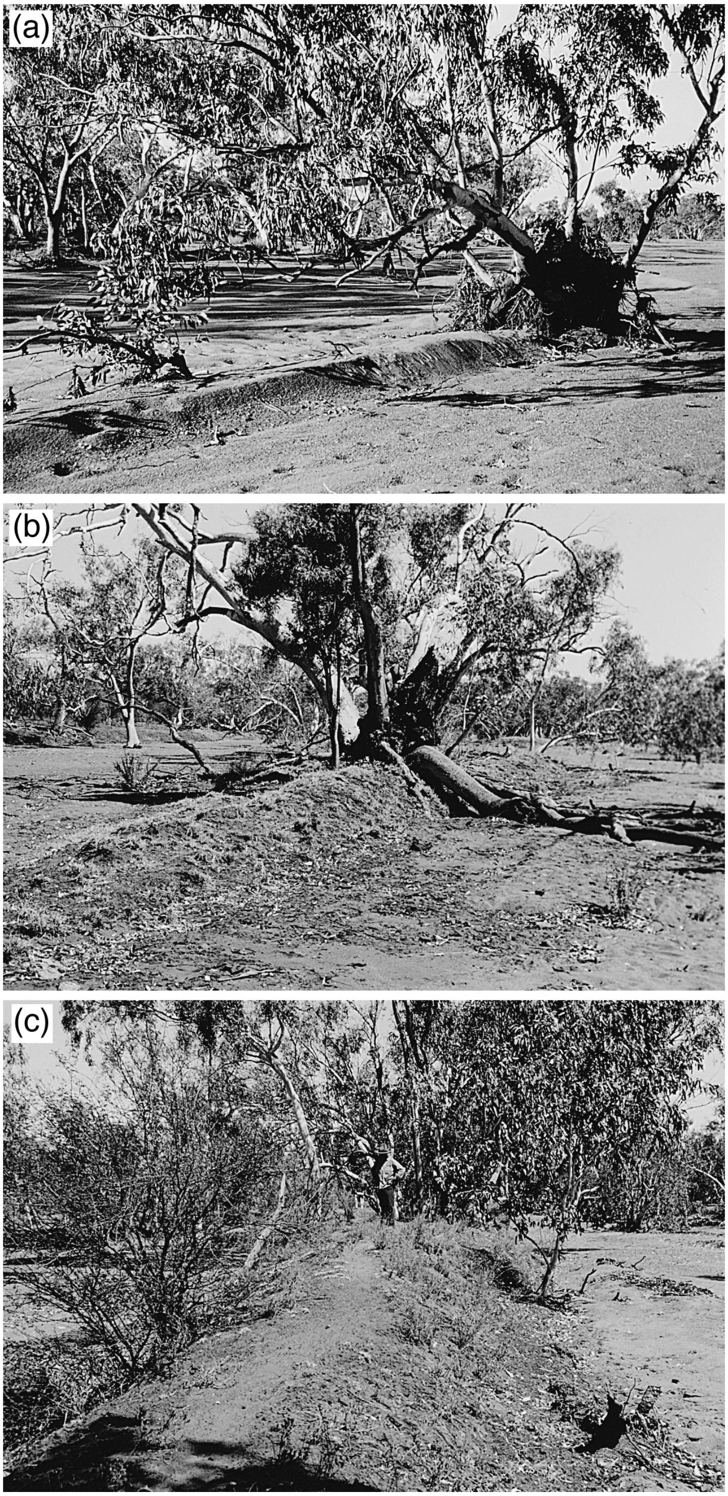
Although ridges and islands may be initiated as current shadows, the great length (>100 m) and height (>2 m) of many depositional ridges and islands suggest that other factors are important in their continued growth and maintenance, particularly subsequent colonisation by vegetation, such as grasses or young saplings. The contribution of in-channel and riparian vegetation to the stabilisation and subsequent growth of fluvial deposits has been widely reported in a number of contexts (e.g., Hadley, 1961; Mabbutt, 1977; Graf, 1978, 1979; Woodyer et al., 1979; Osterkamp and Costa, 1987; Pickup et al., 1988; Thorne, 1990; Graeme and Dunkerley, 1993; Brooks and Brierley, 1997), where its influence appears to be twofold: first, the binding influence of roots on freshly deposited sediments provides protection from scour during later floods; and second, by increasing roughness and reducing flow velocities, sediment deposition is induced.

On the Northern Plains, although extensive root networks of colonising trees and shrubs on ridges and islands are likely to provide considerable local protection from scour, more extensive protection is provided by growth of grasses such as Silky Browntop (*Eulalia fulva*), Desert Bluegrass (*Bothriochloa ewartiana*), Queensland Bluegrass (*Bothriochloa eurantiara*), and Mitchell grass (*Astreleba pectinata*). Many of these species are tough, stout perennials, forming dense tussocks and sometimes providing thick root mats. Hence, they are likely to provide considerable cohesion for the predominantly sandy deposits forming ridges and islands. Grass densities on ridges and islands vary considerably in response to drought and grazing pressure but, following the method of Dunaway et al. (1994), the volume of roots in the top 4 cm of bank sediment for six samples from the well-grassed Woodforde River and Frazer Creek (a piedmont tributary of the Bundey River) ranged from 10–30%. These values are comparable to the volume of grass roots in bank sediment reported for other fluvial systems (Smith, 1976; Dunaway et al., 1994) where grasses have been shown to significantly reduce bank erosion.

The sedimentology of depositional ridges and islands (Figs. 7 and 8) and the influence of the colonising vegetation suggest that ridges and islands grow as a result of three main contemporaneous processes: downstream progradation, vertical accretion and lateral accretion. Oblique accretion (Nanson and Croke, 1992) plays a more limited role in their growth. The initial deposit is typically a small ridge of sand and granule/pebble gravel, usually on the downstream side of a tree (Fig. 9a). Subsequent colonisation by young saplings encourages deposition of finer sand and silty sand, representing high saltation or suspended load. Continued growth of the saplings and possible colonisation by grasses encourages further longitudinal, vertical and lateral growth (Fig. 9b) of the ridge or incipient island. Where the cover of saplings or grasses is sparser, silty sand or mud deposited during waning flood stages may provide some protection from the erosive effects of subsequent flood flows. These finer-grained deposits, sometimes containing up to 60% silt and clay, occur either as individual laminae or coupled with bands of fine to medium sand (Fig. 7). The end result of these processes is a ridge or small island (Fig. 9c) consisting of a core of sand and gravel enveloped by an assemblage of finer-grained strata.

In addition to the growth of individual ridges and islands, flood flow interaction with the whole complex of ridges and islands has to be considered. As a series of ridges and islands grows, it is possible that those in favourable locations in the channel (such as in the lee of other ridges and islands) may survive and grow, while those in less favourable locations (such as between already well-developed ridges) are more likely to be eroded. It is also possible that once a series of islands and ridges is developing, then helical secondary flows in the channels may encourage further growth by scouring intervening channel floors and transporting sediment onto neighbouring ridges or islands, in the manner suggested by flume experiments (e.g., Nezu et al., 1985; Nezu and Nakagawa, 1989; Tsujimoto, 1989), and field descriptions of the formation of scroll bars (Nanson, 1980, 1981) and sandy channel-train ridges in monsoonal northern Australia (Wende and Nanson, 1998). However, as flow structures during floods in the anabranching channels are unknown at present, this suggestion can remain only speculative.

Growth rates of ridges and islands are largely unknown. In the ridges and islands examined there was little organic material suitable for dating by radiocarbon techniques. Nevertheless, the occasional presence of thick (~ 0.5 m) cosets of sedimentary


(a)
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structures such as trough and planar cross-bedding in some ridges and islands (Fig. 8) suggests sometimes fast rates of vertical and lateral growth during flood events. However, while growth of many smaller ridges clearly can be related to colonisation by present-day vegetation, the distribution of trees growing on top of many larger ridges and islands suggests that initial formation considerably pre-dates the present colonising vegetation. For instance, on larger ridges and islands, there is often little evidence of any down-ridge succession in the age or size of trees, as might occur if the present vegetation had established in association with growth of the features (cf. Osterkamp and Costa, 1987). As the age of many ridges and islands may exceed the maximum life-span of trees such as *E. camaldulensis* (~ 400 years, Ogden, 1978), trees initiating the features have probably died and been replaced by younger trees.

6.2. Erosional forms

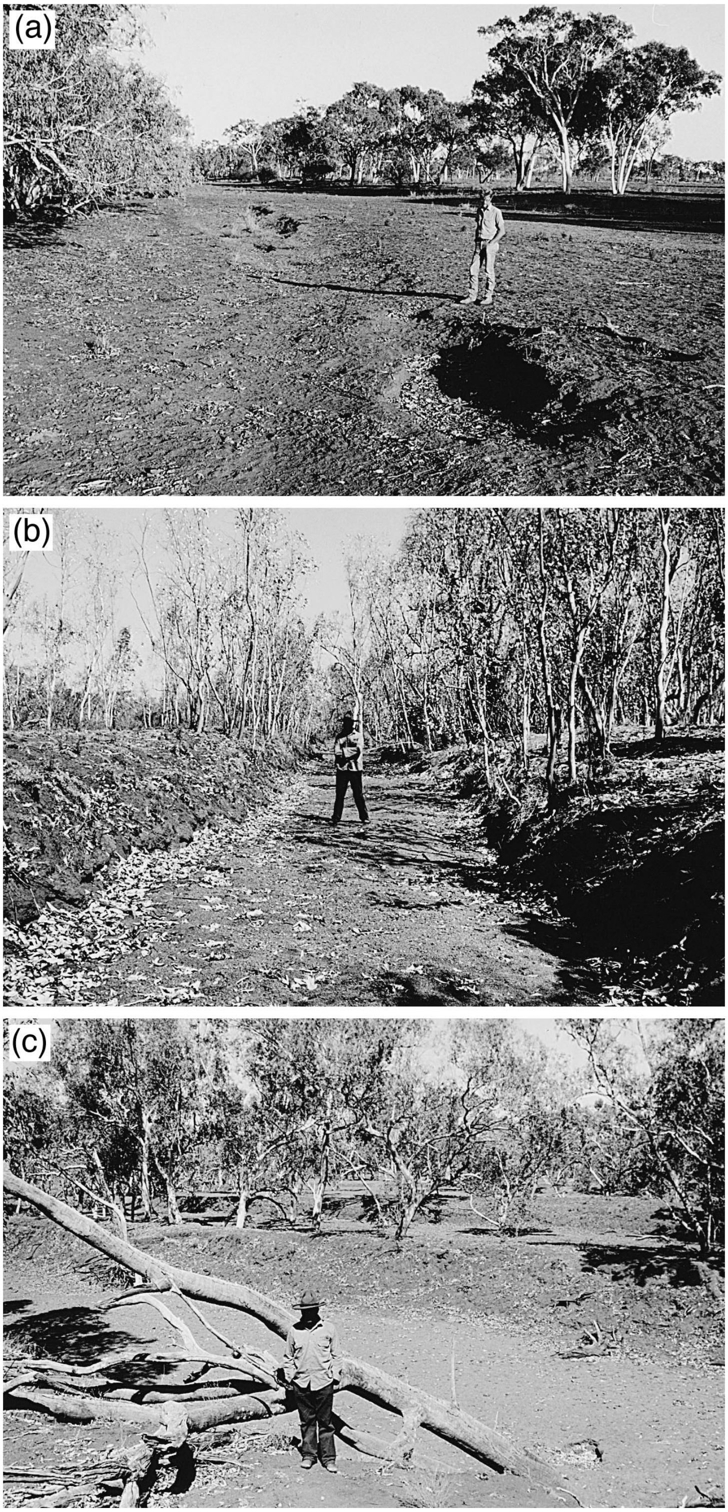
For ridges and islands excised from once-continuous areas of floodplain, explanation of formative processes lies in a consideration of causes and processes of channel avulsion. A number of studies have shown how channel avulsion is a key factor in the formation and maintenance of anabranching and anastomosing river patterns, with channel cutting involving crevasse splay evolution or processes of floodplain scour (e.g., Fisk, 1952; Popov, 1962; Smith and Smith, 1980; Schumann, 1989; Smith et al., 1989; Brizga and Finlayson, 1990; McCarthy et al., 1992; Schumm et al., 1996).

For anabranching channels on the Northern Plains, it is difficult to determine the exact erosional processes by which any one ridge or island has been excised from floodplain, as the evidence remaining after excision usually does not include clues as to the origin of the episode. Nevertheless, field observations provide little evidence of channel cutting by progressive splay development. Along anabranching reaches, there are few examples of breaches in channel banks or ‘blind anabranching channels’ (Harwood and Brown, 1993) that would occur if splays or channels were progressively extending through floodplains. Well-vegetated banklines, general lack of levees and lateral confinement of channels and floodplains by alluvial terraces or aeolian sands all limit the potential for splay development.

In contrast, numerous examples of floodplain scour can be found in anabranching reaches. Scours are initiated by overbank flows which result either from exceedance of bankfull level or by damming and local ponding of tributary floodwaters by flows in the trunk channel. Scours generally occur some 5–10 m from channel margins behind prominent stands of bankline trees and form small (0.1–0.2 m deep), elliptical pits or elongate depressions incised on floodplain surfaces and oriented downstream (Fig. 10a). Field observations suggest that these scours represent the early stages of channel formation with subsequent channel cutting proceeding by a process termed *linear dissection* of floodplains. Linear dissection involves selective floodplain erosion along a preferred line of scour leading to excavation of an elongate furrow. Continued deepening and extension of the furrow in the upstream and downstream directions eventually results in channel cutting (Fig. 10b). Subsequent routing of flow and bedload sediment through this newly excavated channel incorporates it into the broader anabranching system. Hence, extensive channel cutting by this process results in anabranching channels separated by relatively narrow, elongate, ridges or islands composed of former floodplain (Fig. 10c).

There are three main factors promoting linear dissection of floodplains along anabranching reaches: first, well-vegetated banklines which protect banks from laterally extensive stripping and preserve that part of the floodplain as a ridge or island; second, confinement of overbank flows over the floodplain by adjacent alluvial terraces or aeolian sands; and third, the tendency for floodplain sediments to readily disaggregate in the presence of water. Using the Emerson (1967) Aggregate Test, field assessments of the structural stability of soil aggregates (3–5 mm)

Fig. 9. Series of photographs illustrating growth of depositional ridges and islands: a) small current shadow of sand and granules in the lee of a river red gum (flow direction is from top right to bottom left); b) small, elongate ridge colonised by grasses (flow direction is from top right to bottom left); c) well-developed ridge colonised by large river red gums and shrubs (flow direction is towards camera).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showed that in all cases floodplain sediments are characterised by slaking: aggregates collapsed upon immersion in water and the water remained clear after 15 min (Chan and Abbott, 1993). The tendency for floodplain sediments to readily slake in water results from the relatively low percentage of silt and clay (typically $< 40\%$) which means that unvegetated, or sparsely vegetated, sediments have little cohesion.

Once a preferred line of floodplain scour is initiated, erosion may proceed relatively rapidly, for scours provide semi-channelised pathways for subsequent overbank flows. In some reaches, where shallow scours on floodplain surfaces intersect deeper scours or anabranches, knickpoints up to 30 cm high are sometimes found at the junction. Hence, an explanation similar to that of Schumann (1989) may apply in these instances, with further channel cutting resulting from knickpoint migration along the line of the scour.

7. The role of tributaries in contributing to anabranching

Earlier discussion indicated how anabranching on the Northern Plains is related to patterns of tributary drainage. Given the different styles of anabranching (ridge- and island-form), the different character of tributary channels (varying from those transporting relatively coarse bedload to those transporting mainly suspended load) and the different depositional and erosional processes involved in ridge and island formation, there is probably a range of mechanisms whereby tributaries contribute to the formation of anabranching river patterns. However, field investigations and anecdotal accounts of local pastoralists indicate that the tributary influence operates under two main sets of circumstances: first, through inputs of water and sediment to a dry trunk channel either prior to, or in the absence of, flows originating further upstream (‘asynchronous tributary flow’, Thornes, 1977); and second, through inputs of water and sediment to a wet trunk channel during periods of flood flow generated further upstream (‘fully integrated flow’, Thornes, 1977). In either circumstance, depositional and erosional ridges and islands can form as a result of the processes outlined above.

7.1. Asynchronous tributary flow

Although there are no gauged data from which to assess the frequency or timing of flows in tributaries in relation to those in trunk channels, the anecdotal evidence suggests that flows emanating from tributaries often result in trunk channels flowing downstream of the junctions, while reaches further upstream remain dry. Bankfull capacities of discharges for tributary channels are usually only minor in comparison to trunk channel capacities and thus tributary inflows only result in low flow (sub-bankfull) events in trunk channels. Nevertheless, it is possible that the more frequent supply of moisture to sections of channel immediately downstream of tributary junctions (‘channel-bed irrigation’) encourages denser growth or greater numbers of in-channel trees which, by acting as obstacles to flow, initiate depositional ridges as current shadows (Fig. 9a). However, the influence of channel-bed irrigation on densities or numbers of in-channel trees is difficult to ascertain, for although aerial photographs show that many anabranching reaches are characterised by greater numbers of trees than single channel reaches, this is partly a result of large numbers of trees growing on top of ridges and islands.

Regardless of the influence of moisture supply on numbers of in-channel trees, once depositional ridges and islands are initiated, their growth depends on survival during subsequent flood events. The more frequent, low-magnitude flows experienced by channel reaches downstream of tributary junctions may enable continued growth of ridges through processes of downstream progradation and vertical and lateral accretion (Fig. 9b–c). Furthermore, sediment supply

Fig. 10. Series of photographs illustrating channel formation and excision of ridges and islands by linear dissection of floodplains: (a) elongate scours on a sparsely-vegetated floodplain surface (flow direction is away from camera); (b) small, shallow channel excavated in once-continuous floodplain (flow direction is away from camera); (c) series of channels and ridges excavated from floodplain (flow direction is from right to left). The tops of the ridges are accordant and their sedimentology is indistinguishable from that of the adjacent floodplain.

may also be an important factor in the survival and growth of ridges and islands, especially if tributaries supply predominantly fine-grained suspended material (Fig. 11a). For instance, during low flows emanating from these tributaries, a veneer of silt and mud may be deposited on the small, developing

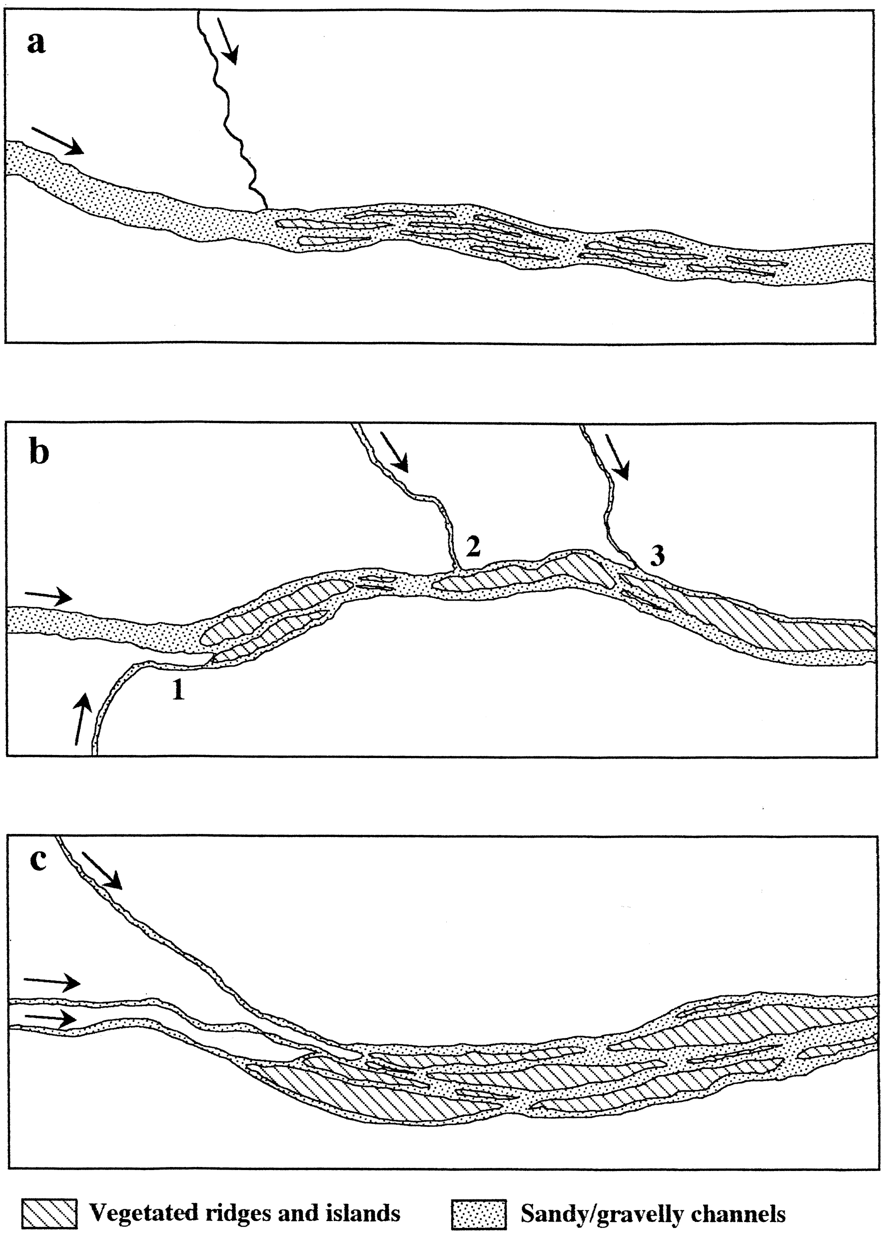

Fig. 11. Schematic diagrams illustrating typical situations in which anabranching develops in association with tributary junctions: (a) formation of ridges and islands by accretion in the lee of in-channel trees; (b) formation of ridges and islands as a result of deferred-junctions where small tributaries attempt to enter a larger trunk stream; (c) formation of ridges and islands as a result of deferred-junctions at the confluence of two or more similar-size tributaries. In (a) tributaries usually supply fine-grained suspended loads but in (b) and (c) tributaries supply bedloads of sand and gravel.

ridges, thus providing a cohesive coating that protects them from erosion during subsequent larger flood events generated upstream. However, water and fine sediment supplied by tributaries are limited and are gradually exhausted downstream of tributary junctions. Here, ridges no longer have the cohesion to survive larger flood events and the channel reverts to a single-thread form (Fig. 11a).

7.2. Fully integrated flow

The main process of anabranch formation during periods of overbank flow is cutting of erosional ridges and islands by linear dissection of floodplains (Fig. 10a–c). This often occurs where high flows in the trunk channel cause local ponding of tributary floodwaters (‘hydrologic damming’) which results in aggressive periods of flow on floodplains adjacent to the trunk channel. Linear dissection of floodplains leads to excision of ridges and islands from floodplain, resulting in either ridge- or island-form anabranching.

In other instances, frequent damming of tributary inflows by high flows in the trunk channel over time deflects the mouth of the tributary channel several hundred metres downstream. As such, many anabranches take the form of deferred-junction tributaries, separated from the trunk channel by large islands excised from floodplain or developed by within-channel deposition. Deferred-junction tributaries are commonplace along many anabranching rivers on the Northern Plains, and usually occur where a small tributary attempts to join with a larger trunk channel. They have some similarities with the examples described by Nanson et al. (1993) from Magela Creek in northern Australia, but do not result from differential aggradation of tributary and trunk channels. The vast majority of tributary channels on the Northern Plains are graded to the level of the trunk channels. Typical examples of deferred-junction tributaries are illustrated in Fig. 11b. They commonly occur where the attempted junction angle of tributary and trunk channel is close to a right-angle, resulting in pronounced downvalley deflection of the lower section of the tributary (Fig. 11b, location 1). In other instances, the tributary joins an anabranch of the trunk channel dividing around a large island, with the head of the island lying *upstream* of the tributary mouth (Fig. 11b, locations 2 and 3). Explanations for this may involve migration or avulsion of the tributary mouth from an original position upstream of the island head or alternatively, that by acting as an obstacle to flow, continued deposition at the island head results in upstream growth to leave the tributary connected to an anabranch.

In addition to formation of deferred-junction tributaries, anabranches can also develop downstream of the confluence of similar-size channels (Fig. 11c). A prime example is found on the middle Bundey River, where the upper Bundey River, Frazer Creek and Alkara Creek converge at a break in a sandstone range. Despite acute junction angles between the three channels, beyond the range they do not merge as one single channel but instead follow subparallel courses as a broad belt of anabranching channels dividing around large islands (Figs. 3b and 4b), before eventually merging into a single channel ~ 25 km downstream. As in the case of deferred-junction tributaries, frequent ponding of floodwaters by high flows in neighbouring channels over time might result in deferral of this type of channel junction. The origins of the large islands separating the channels is uncertain but they may form either by excision from floodplain or by within-channel deposition.

Earlier discussion demonstrated how anabranching is characteristic of channels transporting relatively coarse-grained bedload, such as the Bundey, Woodforde and Marshall Rivers. This is supported by the fact that deferred junctions of both dissimilar- and similar-size channels are uniquely associated with channels transporting bedloads of coarse sand and gravel. Hence, as for tributaries supplying suspended loads to the trunk channel (Fig. 11a), bedload sediment supply may also be an important explanatory factor in anabranch development. Possible explanations for this may be found by considering the implications of anabranching for flow and sediment discharge.

8. Implications of anabranching for flow and sediment discharge

The close association between anabranching river patterns and coarse bedloads on the Northern Plains invites three related questions. First, what are the implications of anabranching for flow and bedload discharge in these low-gradient catchments ? Second, do anabranching channels possess any advantages over other channel forms for the conveyance of flow and bedload ? Third, if so, how do these advantages help to explain the maintenance of anabranching channels on the Northern Plains?

For rivers on the Northern Plains, decreasing downvalley flow volumes, flood peaks and channel gradients mean that sediment transport capacity must also decline downstream. As a result, sediment discharge is transport-limited rather than supply-limited. Recently, Nanson and Knighton (1996) have argued that a fundamental advantage that anabranching channels possess over single channels is that, in situations where it is not possible to increase channel gradient, division of a single-thread channel into two or more anabranches concentrates flow and increases velocity and bed shear stress, which enables the system to transport water and sediment more efficiently. Through analysis of some basic hydraulic relationships for alluvial channels which include flow continuity, roughness and several sediment transport functions, Nanson and Huang (1999) have extended this argument further. They demonstrate quantitatively that conversion from a single to an anabranching channel through the formation of ridges or islands results in a reduction of total flow width and an increase in flow depth, mean flow velocity, and bed shear in each anabranch to levels sufficient to maintain or enhance water and sediment throughput without increasing gradient.

The hydraulic and sedimentary advantages that anabranching appears to confer over single-thread channels helps to explain anabranching on the Northern Plains. In these rivers, there are limited opportunities for increasing gradient in order to maintain or increase downstream sediment flux, as a result of several factors. Channels are generally already of very low sinuosity, thus reducing the possibility of increasing gradient by further reducing sinuosity. Furthermore, many channel beds are positioned just above bedrock and they transport water and sediment towards stable or gradually aggrading basins, factors which reduce the possibility of increasing gradient by downcutting. For rivers such as the Sandover and Plenty, which transport relatively fine-grained bedload (Fig. 5), wide and shallow, single-thread channels are sufficient to transport the supplied bedload at a rate necessary to maintain stable bed levels. However, for rivers such as the Bundey, Marshall and Woodforde, which transport relatively coarse bedload (Fig. 5), a similar channel form appears to be insufficient to transport bedload at the rate required over time to maintain stable bed levels. This is especially likely to be the case where tributaries provide a supply of water that encourages growth of obstructing in-channel trees, or where they introduce additional supplies of coarse sand and gravel (Fig. 11a–c). However, if a system of ridges and islands becomes established downstream of tributary junctions, this provides both a temporary store for sediment and enables flow and bedload to be routed through a system of relatively narrow and deep anabranching channels. As a result, total flow width is reduced (commonly by up to 20%) and velocity, bed shear stress and rates of bedload transport in anabranches may be increased to levels sufficient to ensure onward transport of sediment and maintenance of bed levels.

Adjustments to the flow system which enable the maintenance of bedload transport will be subtle, for as Nanson and Huang (1999) concede, hydraulic adjustments more complex than those proposed in their simple model probably restrain the capacity of the channels to move significant additional sediment. A major factor influencing this restraint is likely to be the extra roughness generated by large numbers of trees lining the ridges and islands in anabranching reaches, which would limit predicted increases in flow velocity and sediment discharge. For rivers on the Northern Plains, a lack of flow gauging data and difficulties in assessing roughness in heavily-treed channels (Graeme and Dunkerley, 1993) means that changes in roughness through anabranching reaches are largely unknown at present. Similarly, whilst a lack of bedload transport measurements makes it impossible to test these assertions using field data, the model results of Nanson and Huang (1999) provide a logical, possible explanation for anabranching on the Northern Plains.

9. Conclusion

River patterns on the Northern Plains of the Alice Springs region range from single-thread to anabranching due to contrasts in bed material calibre and patterns of tributary drainage. On the Sandover and Plenty Rivers, which transport bedloads of medium to coarse sand, channels are typically single-thread and relatively wide and shallow. On the Bundey, Woodforde and Marshall Rivers, which transport bedloads of coarse sand to granules, many reaches are characterised by anabranching channels occurring within a broader channel-train. The individual anabranches are relatively deep and narrow and are separated by channel-train ridges—narrow, flow-aligned, vegetated features—or by wider islands. Ridges and islands are either depositional features (formed in situ by accretionary processes) or erosional features (formed by excision from once-continuous areas of floodplain). Vegetation plays a key role in the initiation, survival and growth of depositional forms through its influence on flow and sediment transport. As such, these distinctive fluvial landforms contribute to the growing body of knowledge termed ‘biogeomorphology’ (Viles, 1988; Hupp et al., 1995).

Anabranching is also related to the influence of tributaries, for both the Bundey and Marshall Rivers alternate from single-thread to anabranching along their length in response to tributary inputs of water and sediment. Tributary inflows occur either independently from, or in concert with, flows in trunk channels. Ridges and islands form downstream of tributary junctions as a result of various hydrological, depositional and erosional processes, including irrigation of enhanced numbers of in-channel trees and resulting lee-side sediment accretion, linear dissection of floodplains, and by formation and maintenance of deferred-junction tributaries. Through their influence on river patterns, tributary inflows on many rivers on the Northern Plains have a greater effect than has previously been described for ephemeral channels. Furthermore, the importance of sub-bankfull flows emanating from tributaries as a contributory factor to the initiation, stabilisation and growth of some ridges and islands contrasts with the often overriding dominance attributed to large floods in shaping ephemeral channel morphology. Ridges and islands forming downstream of tributary junctions provide temporary storage sites for sediment and appear to help maintain the throughput of relatively coarse sediment in these low-gradient channels, which are characterised by an abundance of within-channel vegetation and subject to declining downstream discharges. Anabranching channels are a common feature of arid Australia and thus similar tributary-related mechanisms may contribute to anabranching in other low-gradient, arid catchments.

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