

Riparian vegetation and the late Holocene development of an anabranching river: Magela Creek, northern Australia

Stephen Tooth[†]

Institute of Geography and Earth Sciences, University of Wales, Aberystwyth SY23 3DB, UK

John D. Jansen

Department of Geographical and Earth Sciences, University of Glasgow, Glasgow G12 8QQ, UK

Gerald C. Nanson

School of Earth and Environmental Sciences, University of Wollongong, Wollongong, NSW 2522, Australia

Tom J. Coulthard

Department of Geography, University of Hull, Hull HU6 7RX, UK

Tim Pietsch

Commonwealth Scientific and Industrial Research Organisation (CSIRO) Land and Water, Canberra, ACT 2601, Australia

ABSTRACT

Many anabranching rivers are characterized by dynamic interactions between fluvial processes and riparian vegetation, but uncertainties surround the processes and time scales of anabranch development. We use geomorphological investigations and optically stimulated luminescence (OSL) dating to determine spatial and temporal trends in the development of anabranching along a 6.5-km-long reach of Magela Creek in the seasonal tropics of northern Australia. Many trees and shrubs that survive the wet-season floods establish on the sandy beds and lower banks, such that anabranches divide and rejoin around numerous ridges and islands that are formed mainly by accretion in the lee of in-channel vegetation and, less commonly, by excision from formerly continuous island or floodplain surfaces. Once ridges and islands form, colonizing vegetation maintains their stability by increasing sediment cohesion and decreasing flow erosivity. Over the Holocene, Magela Creek has vertically aggraded and extended in length by delta progradation into Madjinbardi Billabong, resulting in a time sequence of anabranches and associated ridges and islands from older (upstream) to younger (downstream). OSL ages for islands in the upstream and middle reaches are ca. 1.6 ka and older, and the narrow, deep anabranches (width/depth [w/d] typically

~10–30) have few in-channel obstructions. Farther downstream, island OSL ages are ca. 0.7 ka and younger, anabranches tend to be wider and shallower (w/d >30) with more obstructions, and spays and locally scoured island and floodplain surfaces are more common. Based on these findings, previous flow and sediment-transport measurements, and theoretical analyses, we posit that there is a decline in anabranch efficiency from an upstream equilibrium system in mass-flux balance to a downstream disequilibrium system characterized by bed aggradation and localized island and floodplain erosion. In the downstream reaches, inefficient (high w/d and obstructed) anabranches do not persist because they either aggrade and are abandoned, or they are subdivided into more efficient (lower w/d and less obstructed) anabranches as a result of the interactions between in-channel vegetation growth and ridge and island accretion or local excision. Consequently, a more efficient anabranching system gradually develops with characteristics similar to those in the upstream reaches. This enhances downstream sediment transfer, which enables ongoing delta progradation and provides fresh sediment surfaces for vegetation to colonize and initiate new anabranches. The OSL ages from Magela Creek demonstrate that a recognizable but relatively inefficient anabranching system can develop within a few centuries, while adjustment to a more efficient system occurs over a few millennia.

Keywords: aggradation, alluvial islands, anabranching, luminescence dating, riparian vegetation.

INTRODUCTION

Over recent decades, research into the complex and subtle interactions between fluvial processes and riparian vegetation has steadily increased, and numerous publications have addressed such interactions in the context of the broader themes of hydroecology or fluvial ecogeomorphology (e.g., Osterkamp and Hupp, 1996; Thoms and Sheldon, 2000; Gurnell et al., 2000; Acreman, 2001; Dyer et al., 2002; Bennett and Simon, 2004). The influence of fluvial processes on riparian vegetation patterns has been investigated (e.g., Hupp and Osterkamp, 1996; Bendix and Hupp, 2000; Johnson, 2000), while a combination of field, experimental, and various modeling approaches has explored the influence of vegetation and associated woody debris on many aspects of river-channel process and form, including: (1) flow resistance (e.g., Darby, 1999; Kean and Smith, 2004; Heritage et al., 2004); (2) the strength and stability of channel banks, beds, bars, and islands (e.g., Ikeda and Izumi, 1990; Huang and Nanson, 1998; Abernethy and Rutherford, 1998; Gurnell et al., 2001; Brooks and Brierley, 2002; Pollen et al., 2004; van de Wiel and Darby, 2004); and (3) channel cross-section and planform adjustments (e.g., Millar, 2000; Gran and Paola, 2001; Murray and Paola, 2003; Tooth and Nanson, 2004; Tooth

[†]E-mail: set@aber.ac.uk

and McCarthy, 2004; Tal et al., 2004; Tal and Paola, 2007).

Knowledge of this vegetative influence is of interest to fluvial geomorphologists, fluvial sedimentologists, river engineers, and river managers, for it can contribute to improved understanding of past, present, and future river behavior. For instance, during the Phanerozoic Eon, the behavior of many fluvial systems changed dramatically, in large part owing to the evolution of land plants during the early Paleozoic (Schumm, 1968; Miall, 1996; Eriksson et al., 1998), and contemporary vegetated riverine settings can provide modern analogues to aid interpretation of ancient fluvial successions (e.g., Fielding and Alexander, 2001; Nakayama et al., 2002; Ward et al., 2000). Over shorter (late Quaternary and historical) time scales, many river systems have undergone dramatic changes that can in part be attributed to changing riparian vegetation assemblages, especially in catchments heavily impacted by extreme floods (e.g., Osterkamp and Costa, 1987; Friedman et al., 1996), land-use changes and flow regulation (e.g., Johnson, 1997; Merritt and Cooper, 2000; Brooks et al., 2003), and/or invasion by exotic vegetation species (e.g., Graf, 1978, 1979; Griffin et al., 1989; Rowntree, 1991). Knowledge of this vegetative influence can thus greatly inform river rehabilitation or restoration schemes (e.g., Francis, 2006) and is also a key element in ongoing efforts to anticipate and mitigate undesirable future adjustments to river systems that may result from natural or human-induced environmental change (e.g., Johnson et al., 1995; Brookes et al., 2000).

Despite growing recognition of the key influence of vegetation on rivers, many areas of uncertainty remain. Prominent unresolved issues include: (1) the extent to which vegetative factors (e.g., type, density, age, health, bank position) and river size determine the strength of the influence; (2) the means by which indices that quantify this influence may be developed; and (3) the characteristic rates, frequency, and timing of vegetation-induced channel changes (e.g., Thorne, 1990; Abernethy and Rutherford, 1998, 2000; Millar, 2000; Simon and Collison, 2002; Micheli and Kirchner, 2002; Simon et al., 2004; van de Wiel and Darby, 2004). Australia's fluvial environments provide abundant opportunities for further research into these issues, particularly in the arid, semi-arid, and seasonal tropical regions where various tree, shrub, and grass species grow preferentially on the beds and lower banks of ephemeral or intermittent, gravel- and sand-bed river channels. Many of these riparian species are opportunistic and have evolved establishment and regeneration strategies that are dependent upon

physical disturbance and the water, sediment, and nutrients supplied during irregular flood events, while various structural modifications and growth habits enable them to survive in these highly stressed habitats. Where present in sufficient densities, these riparian species can exert a strong influence on fluvial processes and forms (Graeme and Dunkerley, 1993; Fielding et al., 1997; Tooth, 2000; Tooth and Nanson, 2000a; Sandercock, 2004), and, in many cases, they are key factors promoting the development of anabranching, whereby multiple channels divide and rejoin around semi-permanent, vegetated ridges or islands that are commonly elevated to around bankfull stage (Wende and Nanson, 1998; Taylor, 1999; Tooth and Nanson, 1999, 2000b, 2004).

Although particularly prevalent in Australia, anabranching rivers (including anastomosing as a low-energy, fine-sediment subset) occur across a spectrum of climatic and physiographic settings worldwide, and they are at least partly a response to resistant banks provided by cohesive sediment or riparian vegetation (Nanson and Knighton, 1996). Nevertheless, despite being widely described from both modern and ancient examples (Makaske, 2001), there is limited understanding of how anabranching develops over space and time because infrequent or short-lived floods commonly make it difficult to obtain lengthy time series of flow and sediment measurements, and because rates of channel and vegetation change typically are very slow relative to the length of most field monitoring programs. These uncertainties surrounding anabranching development have contributed to vigorous debate as to whether it can represent an equilibrium (i.e., stable, efficient) river pattern exhibiting sediment mass-flux balance (Nanson and Huang, 1999; Tooth and Nanson, 2000a; Jansen and Nanson, 2004), or whether it is largely or solely a disequilibrium (i.e., unstable/transitional, inefficient) pattern geared toward long-term sediment storage (Makaske, 2001; Tabata and Hickin, 2003; Abbado et al., 2005). To resolve this debate, a better understanding of the processes and time scales of the development of different anabranching rivers is necessary.

In some settings, an ergodic approach can be adopted whereby spatial (along-stream) changes in the character of the anabranches and associated vegetation are used to infer the processes that control the temporal sequence of anabranching pattern development. Magela Creek in the seasonal tropics of northern Australia (Fig. 1A) provides a good opportunity to conduct such a study because a large body of background data exists regarding its hydrology, sedimentology, and late Quaternary history, and

because previous studies have alluded to the important role of riparian vegetation in forming and maintaining its characteristic anabranching pattern (e.g., Pickup et al., 1987; Hart et al., 1987; Roberts, 1991; Wasson, 1992; Nanson et al., 1993; Nanson and Knighton, 1996; L. Erskine, 2002; Jansen and Nanson, 2004). The aims of this paper are thus threefold: (1) to document changes in anabranch morphology along Magela Creek; (2) to use these field results and optically stimulated luminescence (OSL) dating to infer the key processes and chronology of anabranch development, including the role played by vegetation; and (3) to discuss the underlying principles governing anabranch development, and the associated implications for downstream water and sediment flux. The findings presented here contribute to improved analysis of Australian anabranching rivers in particular, but also to a growing appreciation of the global diversity of anabranching rivers and channel-vegetation interactions in general.

REGIONAL SETTING

Magela Creek (catchment area of ~1565 km²) is located near Jabiru in the southeastern part of Kakadu National Park, Northern Territory (Fig. 1A). Its headwaters arise on the low-relief Arnhem Land Plateau, which consists mainly of quartzose sandstone (Kombolgie Subgroup). The creek then descends an ~200-m-high escarpment through a steep gorge before traversing the Koolpinyah Surface (Fig. 1A), a lowland complex of eroded Paleoproterozoic metasediments capped with Cenozoic alluvial, colluvial, and estuarine deposits. In the reaches below the escarpment, anabranching is extensive. Reach-average channel gradient remains roughly constant at ~0.0005–0.0006 (Fig. 1B), although there is local variability between anabranches (Jansen and Nanson, 2004). There is no evidence of a significant overall decline in gradient toward the small delta that has developed where the creek is prograding into Madjinbardi (formerly Mudginberri) Billabong, an ~1-km-long, ~90-m-wide, and ~6–8-m-deep permanent water body. Downstream of the billabong, the continuity of the creek is lost as it traverses a broad (up to 6 km), very low-gradient, ~200 km² floodplain wetland, and a defined channel only reforms near to the junction with the tidally influenced East Alligator River (Fig. 1A). This study focuses on the anabranching reaches of Magela Creek between the Ranger mine and Madjinbardi Billabong (upstream catchment area ~600 km²; Fig. 1A), which have been subject to several previous hydrological, sedimentological, and geomorphological studies, as summarized next.

Hydrology and Sedimentology

Climate in the study area is seasonal tropical with marked annual wet and dry seasons. Mean annual rainfall is ~1530 mm (80% falls during December through March), mean maximum temperature is 31–37 °C, and mean annual class A pan evaporation is ~2580 mm (Jabiru airport, 1971–2001; Jansen and Nanson, 2004). The flow regime along Magela Creek is highly variable; 80% of the annual flow occurs during January through March, and little or no flow ($<1 \text{ m}^3 \text{ s}^{-1}$) occurs during the dry season. Bankfull discharge, defined as the flow rate when stage is coincident with the uppermost level of the banks, is $\sim 40 \text{ m}^3 \text{ s}^{-1}$ for the creek as a whole, and it is exceeded ~ 10 – 12 times each wet season, with floodwaters remaining overbank on average for ~ 40 days each year. The mean annual flood ($Q_{2.3} = 525 \text{ m}^3 \text{ s}^{-1}$) is more than 13 times bankfull discharge, and the largest recorded flood (February 1980) was $1700 \text{ m}^3 \text{ s}^{-1}$ (Northern Territory Department of Lands, Planning and Infrastructure; Jansen and Nanson, 2004). Owing to the low gradient, unit stream powers remain low ($<10 \text{ W m}^{-2}$), even during large floods (Jansen and Nanson, 2004).

Sediment load is derived mainly from weathering of the Koolpinyah Subgroup, and it consists largely of medium sand ($D_{50} = 0.42 \text{ mm}$) with minor fines. For the period 1971–1989, Roberts (1991) estimated the annual sediment yield passing gauging station 8210009 (Fig. 1A) to be 12,051 t, consisting of 43% bed material load, 45% wash load, and 12% solute load. Bed material discharge is typically $<1 \text{ kg s}^{-1}$ for flows up to around bankfull, rising up to $\sim 2 \text{ kg s}^{-1}$ in larger floods, and suspended sediment concentrations are very low, averaging 12 – 15 mg L^{-1} (Hart et al., 1987; Roberts, 1991; Jansen and Nanson, 2004). Although several small tributaries arise on the Koolpinyah Surface (Fig. 1A), they supply very little flow or sediment. Along Magela Creek, gradient, discharge, and grain size thus do not change significantly or systematically downstream, but sediment transport ends at Madjinbardi Billabong (Fig. 1A), which is progressively infilling by delta progradation (see following).

Late Quaternary Sedimentary History

During the Holocene, extensive sedimentation has occurred along the middle to lower reaches of Magela Creek in response to rising sea level and development of the estuarine floodplains of the East Alligator River (Roberts, 1991; Wasson, 1992; Nanson et al., 1993). This sedimentation has essentially infilled a trench that was excavated in the Koolpinyah Surface at

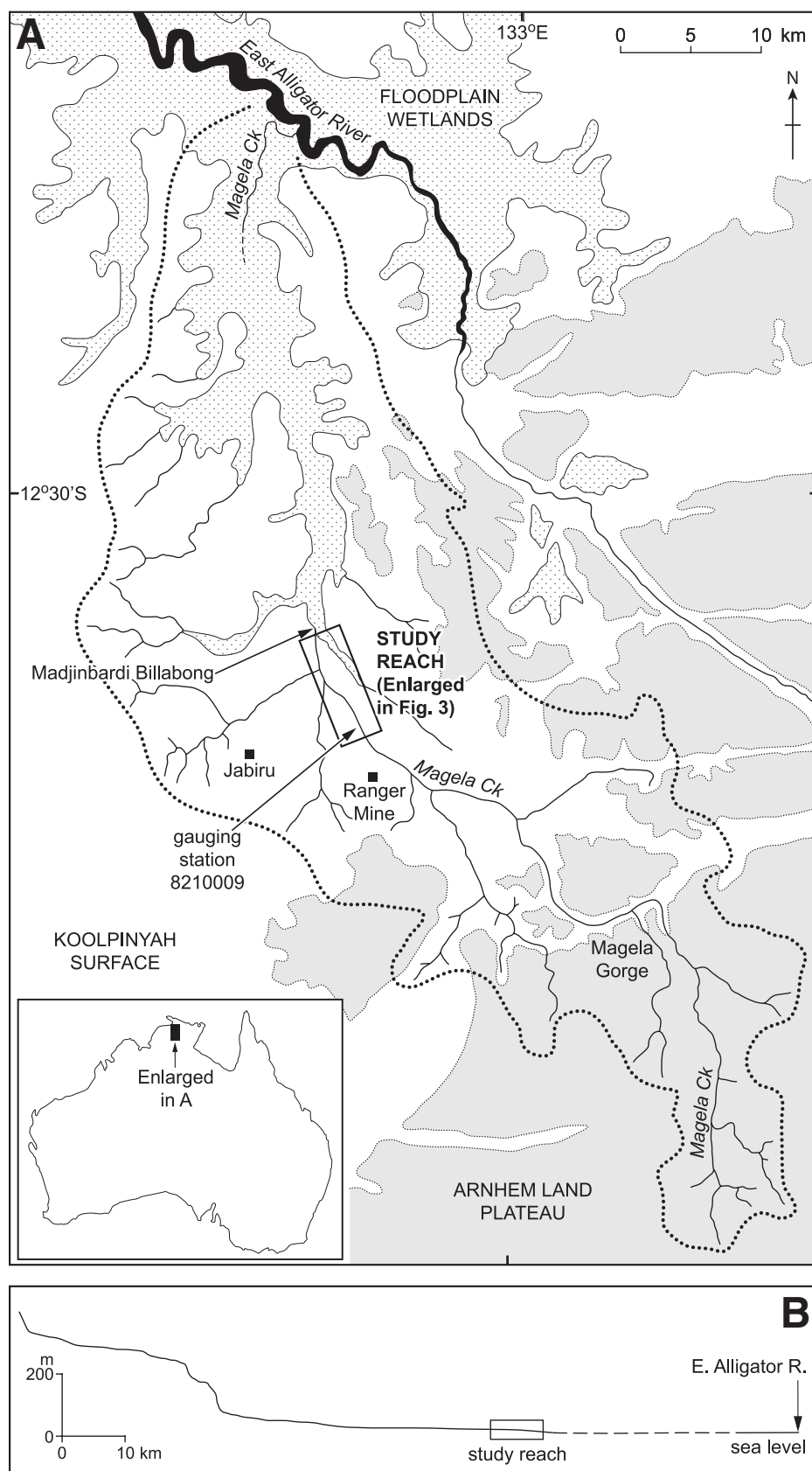


Figure 1. The Magela Creek catchment (modified after Jansen and Nanson, 2004): (A) key physiographic features and the location of the study reach; and (B) longitudinal profile.

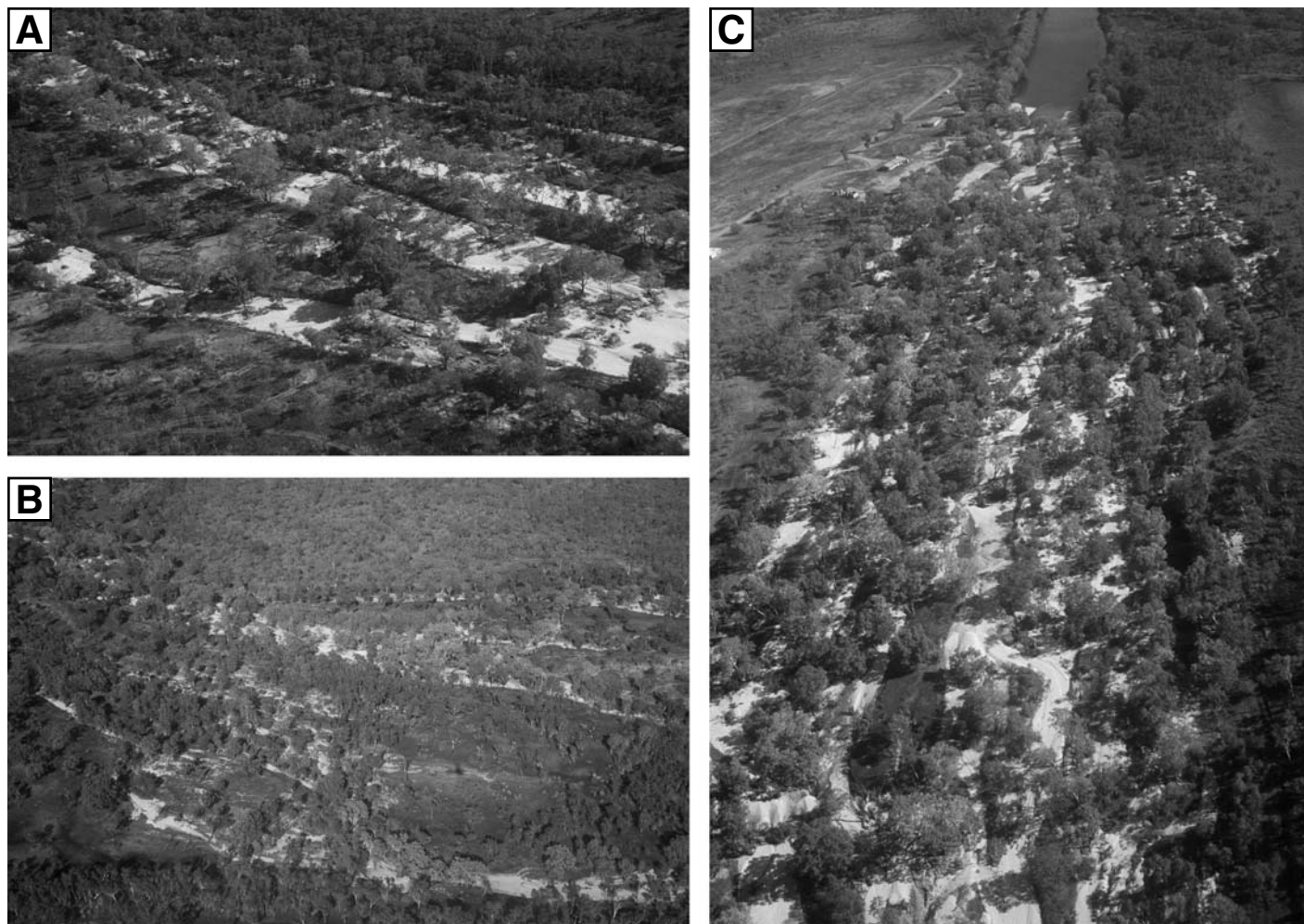


Figure 2. Oblique aerial photographs of different parts of the study reach illustrating: (A) anabranches with few in-channel trees dividing around moderate-size ridges and islands (upstream reaches, flow from left to right); (B) anabranches with variable numbers of in-channel trees dividing around a mixture of large islands and small ridges (middle reaches, flow from left to right); and (C) anabranches with abundant in-channel trees dividing around numerous small ridges (downstream reaches near Madjinbardi Billabong, flow from bottom to top).

times of lower sea level during the late Quaternary, and it has pushed the tidal limit ~40 km downstream from a position near the upstream end of the study reach at ca. 6 ka (Nanson et al., 1993) to its present position near the East Alligator River. A detailed sediment budget, supported by thermoluminescence (TL) and radiocarbon (^{14}C) dates from the alluvial valley fill, demonstrates that vertical aggradation ($\sim 1\text{--}2\text{ mm yr}^{-1}$) has prevailed along Magela Creek during most of the Holocene but suggests that, at present, the creek is roughly in mass-flux balance with much lower vertical aggradation rates (Roberts, 1991; Nanson et al., 1993). The middle to lower reaches above Madjinbardi Billabong are now essentially unconfined along the eastern margin so that aggradation can also occur laterally, but channel-belt width does not increase systematically downstream, and gradual growth of the

delta into the billabong demonstrates that most contemporary sedimentation is occurring in the downstream direction. Aerial photographs and repeat cross-section surveys show that very few morphological changes have occurred in the study reach over the last 50–60 yr, with the exception of the delta front that has advanced ~190 m between 1950 and 2002 (Jansen and Nanson, 2003, 2004).

Channel Morphology and Riparian Vegetation

Upstream of Madjinbardi Billabong, Magela Creek is characterized by numerous anabranching channels that divide and rejoin around stable, vegetated ridges and islands up to several kilometers long (Fig. 2). Ridges tend to be narrow relative to their length (length/width >10) and

islands are broader (length/width <10), but this distinction is somewhat arbitrary, and a range of intermediate forms also occurs. Riparian vegetation assemblages are complex (L. Erskine, 2002); the anabranch beds host variable but generally low numbers of trees (e.g., *Melaleuca argentea*, *M. leucadendra*, *Pandanus aquaticus*, *P. spiralis*), while banks, ridges, and islands are typically more densely colonized by trees and shrubs (e.g., *M. viridiflora*, *M. leucadendra*), and an understory of grasses (e.g., *Sorghum* spp.) (Fig. 2). At the upstream end of the study reach, a few islands support dense stands of large, mature rain forest species (e.g., *Lophopetalum arnhemicum*, *Syzygium forte* ssp. *potamophilium*, *Carralia brachiata*). Marginal floodplains support a more open, savannah-like tree cover (e.g., *Acacia* spp., *Pandanus* spp., *Corymbia porrecta*) (Fig. 2). Tree sizes and spacings

along the channel bank lines are variable but are typically one tree (trunk diameter >0.5 m) spaced every 2–7 m. Owing to the absence of clearly defined annual growth rings in many tree species in the Australian tropics (Ogden, 1978, 1981), dendrochronology is not suitable for estimating ages, but based on observations over several decades of monitoring, some of the larger trees (diameters >1 m) are probably hundreds of years old.

Downstream Channel Changes

In their study of Magela Creek, Nanson et al. (1993) noted how well-defined anabranches upstream tended to give way to more “braided” channels downstream. Jansen and Nanson (2004) also highlighted downstream trends and, in particular, observed that the numbers and widths of anabranches, and the amount of colonizing vegetation, tend to increase downstream, trends that they linked with delta progradation into Madjinbardi Billabong. In this paper, we extend this work by using detailed field surveys and OSL dating to infer key processes and time scales of anabranching development along the creek.

METHODS

The 6.5 km study reach incorporates the lowest 2.5 km of the reach studied in detail by Jansen and Nanson (2004), starting just upstream of gauging station 8210009 and extending downstream to Madjinbardi Billabong (Fig. 1A).

Field Surveys

Owing to dense vegetation canopies that obscure many of the smaller anabranches (Fig. 2), aerial photographs were unsuitable for mapping downstream changes in anabranching planform, so differential global positioning system (DGPS) surveys were used instead (Fig. 3). Using one fixed receiver and one strapped to a rider on an all-terrain vehicle (quad bike), positions were recorded along the anabranch centerlines and at every anabranch bifurcation or junction. The limited numbers of channels that were too small (<3 m wide) to drive down, or that divided around minor bars (<5 m long and <1 m high), were not mapped.

To complement the DGPS surveys, 15 cross sections were surveyed at ~0.5 km intervals downstream (Fig. 3). Each survey incorporated all the anabranches present and extended onto the marginal floodplains and/or valley sides. Following approaches developed for analysis of other anabranching rivers (Tooth, 2000; Tooth and Nanson, 2004), “bankfull” levels for individual anabranches across each surveyed sec-

tion were defined relative to the elevation of a typically clear break in slope between the bank face and bank top (banks being represented by the sides of ridges, islands, or marginal floodplains), and the lower level was adopted in instances where elevations were different on opposing banks. This morphological definition of bankfull corresponds closely to those obtained by alternative methods, such as minimum width/depth (w/d) ratio (Williams, 1978; Knighton, 1998; Tooth, 2000), and it provides the only clear and consistent reference level for comparing downstream changes in anabranch morphology. Alternative definitions of bankfull (e.g., by reference to a common flow frequency) are not appropriate in this setting, since they would vary between different-size anabranches (Jansen and Nanson, 2004).

At each surveyed cross section, counts were made of the number of obstacles to flow on individual anabranch beds within 25 m upstream and 25 m downstream of the survey line. “Obstacles” included live trees and shrubs (>90% of all obstacles), dead or fallen trees/shrubs, and major accumulations of coarse woody debris, any of which could significantly influence flow and sediment movement. Closely spaced (<0.2 m) trees and shrubs, or multiple trunks growing from a common rootstock, were counted as one obstacle. Very small seedlings and saplings (diameters <0.05 m) that had a limited influence on flow and sediment movement were not included. For each anabranch, the number of obstacles was divided by anabranch bed area (bed width multiplied by 50 m) to estimate obstacle density.

OSL Dating

To investigate the ages of ridges and islands (for simplicity, hereafter referred to generally as “islands” except when a distinction is relevant), samples for OSL dating were collected at five locations that were spaced at roughly equal distances downstream (Fig. 3). At each location, samples were collected from the largest island where its formation clearly could be attributed to alluvial deposition between anabranches (depositional islands; see following). This sampling strategy was expected to provide an approximation to the maximum age of island development at each location and ensured consistency in island selection by minimizing the risk of preferentially selecting either small (presumably young) depositional islands, or the localized islands originating as a result of scour and incision into older alluvium (erosional islands; see following).

From each selected island, two samples, ~10–60 m apart, were collected from the island core by augering through sand and minor silt

to a depth of 1–2 m. A 20-cm-long metal tube was attached to the auger head, pushed into the bottom of the auger hole until full, and withdrawn without exposing the sample to light. Both ends of the metal tube were packed and sealed with thick black plastic to prevent moisture loss and to ensure that no mixing occurred within the sample.

OSL dating was undertaken using methods and instrumentation described in detail in Olley et al. (2004a). Samples were prepared using standard procedures (e.g., Aitken, 1998) designed to isolate pure extracts of 180–212 μ m light-safe quartz grains. Single-grain OSL measurements were made using a Risø TL/OSL DA-15 instrument (described in Bøtter-Jensen et al., 2000) and by applying the modified single-aliquot regenerative-dose protocol of Olley et al. (2004a), which incorporates an infrared wash prior to each OSL readout. The “central age model” of Galbraith et al. (1999) was used to verify that all samples had equivalent natural dose (D_n) distributions consistent with a single population and to calculate burial doses (D_b). Lithogenic radionuclide activity concentrations in the OSL samples were determined using high-resolution gamma spectrometry (Murray et al., 1987), and dose rates were calculated using the conversion factors of Stokes et al. (2003). The β -attenuation factors were taken from Mejdahl (1979), and cosmic dose rates were calculated from Prescott and Hutton (1994). In this seasonally dry, sandy setting, a long-term average water content of $10\% \pm 5\%$ was used for all samples.

RESULTS

Figures 2 through 7 illustrate the characteristics of anabranching along the study reach. The number of anabranches generally varies between two and eight (Figs. 4–5), except in two short (<100 m) sections that are divided only by bars and small ridges (Fig. 3, XS2 and XS5). These latter sections were termed “single channels” by Jansen and Nanson (2004) because they effectively function as one cross section during flows near or at bankfull. Subtle downstream changes in the character of the anabranching pattern occur, enabling the study reach to be divided into three broad zones (Figs. 2–6): the upstream reaches (XS1–XS5), the transitional middle reaches (XS6–XS9), and the downstream reaches (XS10–XS15).

Downstream Changes in Anabranch Morphology and Obstacle Density

The DGPS survey (Fig. 3) illustrates that, in the upstream reaches, anabranches are relatively

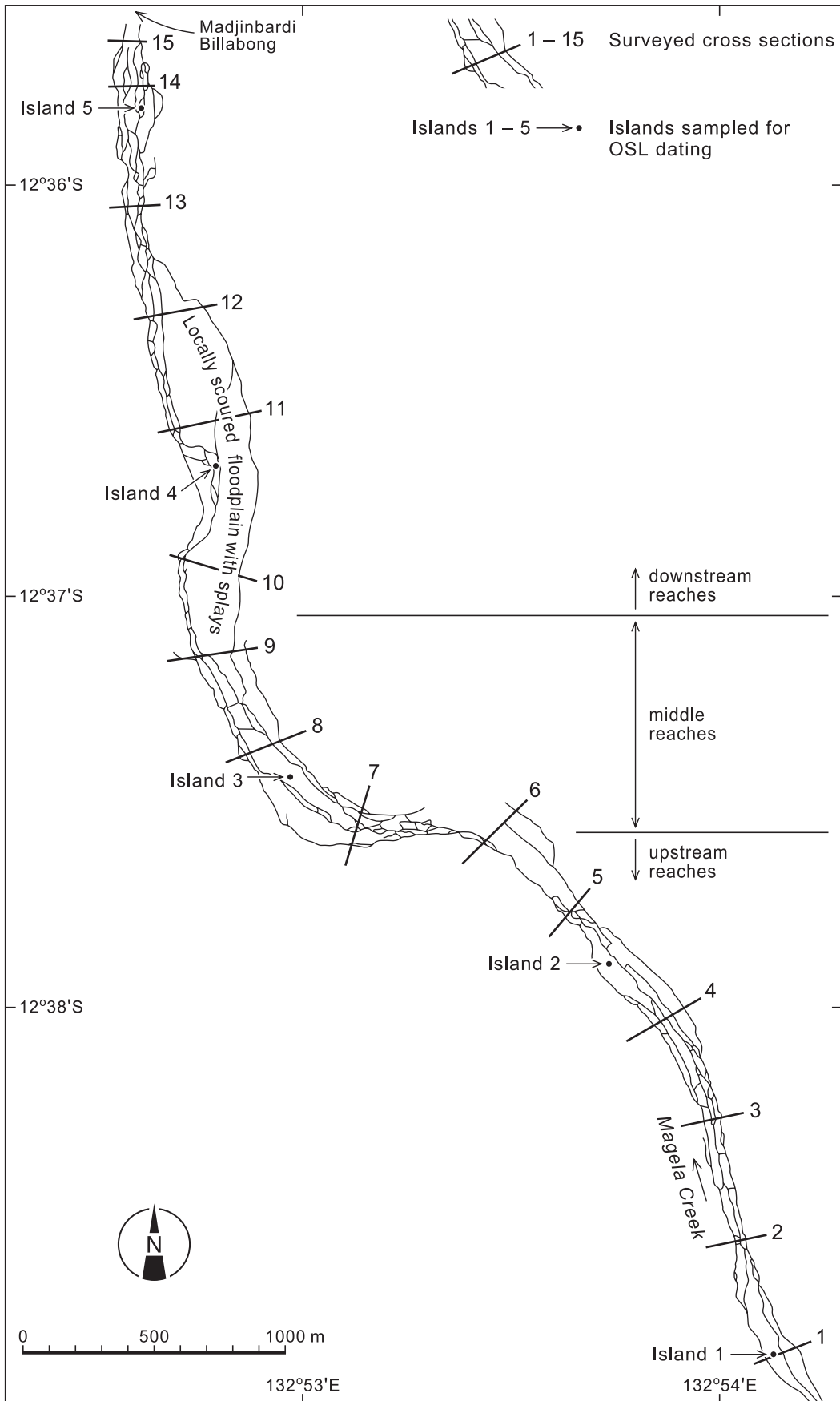


Figure 3. Plan view map of the anabranching pattern in the study reach, as determined using differential global positioning system (DGPS) during the dry season, and the locations of surveyed cross sections and optically stimulated luminescence (OSL) samples. The boundaries between the three zones are approximate only, and gauging station 8210009 (Fig. 1A) is located on the left-bank of XS2. As stage increases, some of the minor ridges are drowned so that some cross sections that appear divided during zero or low flows effectively function as a single cross section at higher flow (e.g., XS2 and XS5). Note that the lines represent the anabranch centerlines (not anabranch bed widths), and therefore the ridge and island widths between anabranches are slightly exaggerated.

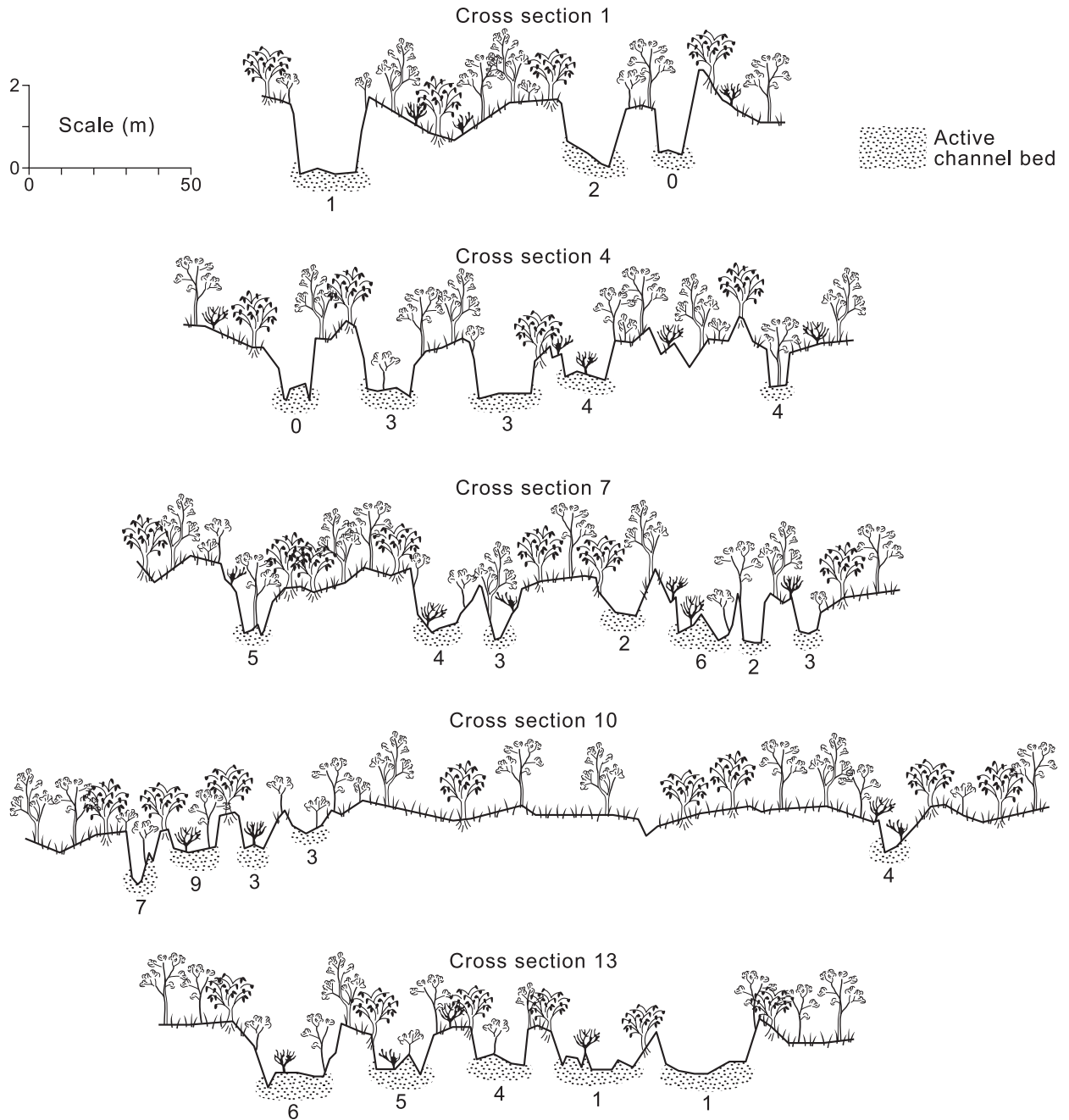


Figure 4. Examples of surveyed cross sections from various points along the study reach (see Fig. 3 for locations). The distribution of trees is schematic only. The number of obstructions within each anabranch is indicated (see text for further explanation).

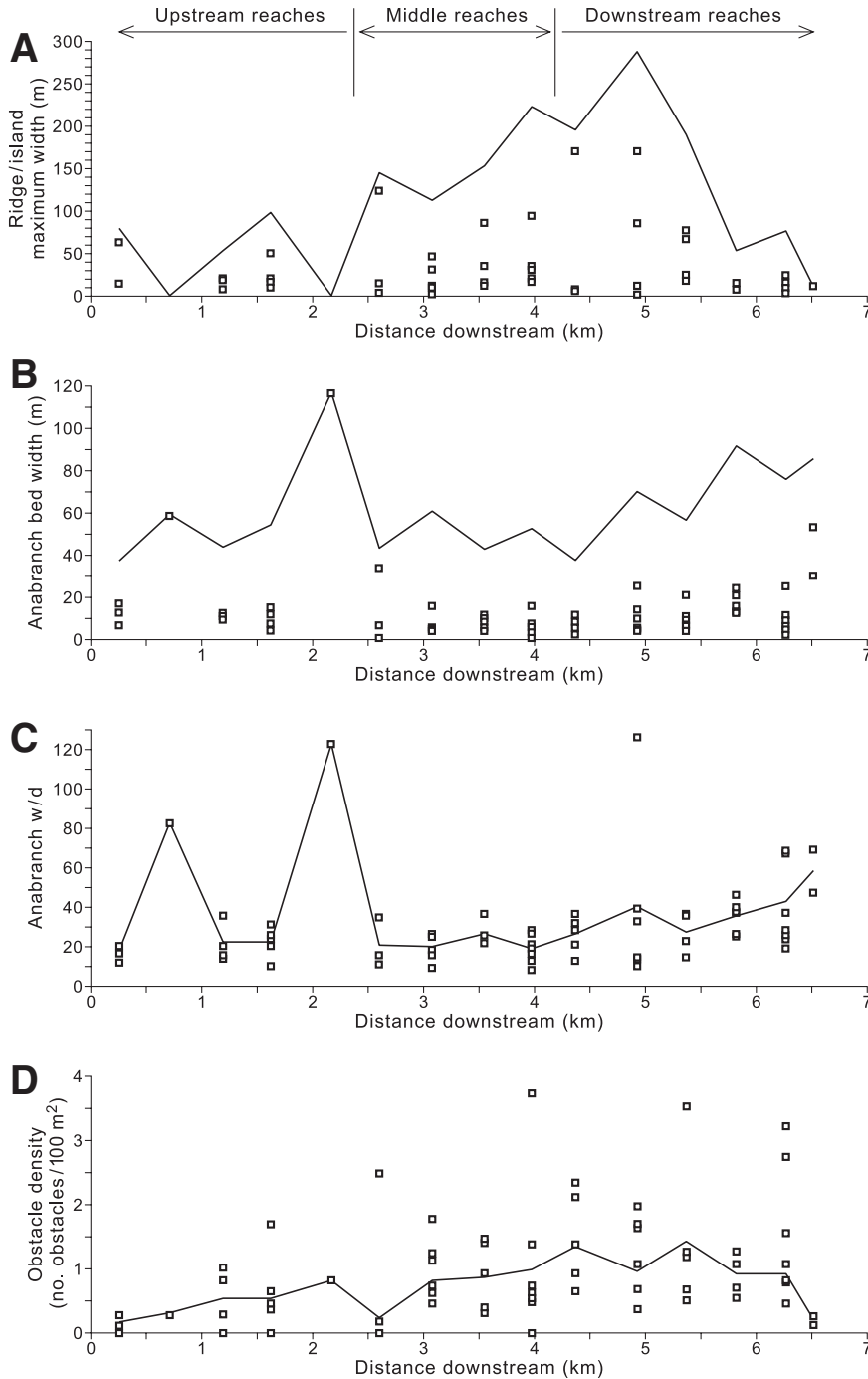


Figure 5. Graphs showing downstream trends in selected parameters along Magela Creek. Distance downstream is determined from an arbitrary starting point at the head of the study reach. The approximate boundaries between the upstream and middle reaches, and between the middle and downstream reaches, are indicated (see also Fig. 3). The values of the parameters for individual anabranches or ridges and islands at the 15 surveyed cross sections are represented by open squares. The total or mean values of the selected parameters have been calculated for each cross section and joined by solid lines to indicate the overall downstream trends: (A) individual ridge or island widths (open squares) and total ridge or island width summed across each cross section (solid line); (B) individual anabranch bed widths (open squares) and total bed width summed across each cross section (solid line); (C) individual anabranch w/d (open squares) and mean w/d ratio calculated for each cross section (solid line); and (D) obstacle densities in individual anabranches (open squares) and mean obstacle density calculated for each cross section (solid line).

long, and the distances between points of bifurcation and confluence are typically >200 m. Short, narrow ridges are present, but there are many moderate-size islands up to 500 m long and 70 m wide (Figs. 3, 5A, and 7B). In the transitional middle reaches, anabranch lengths are more variable, and a few anabranches become shallower downstream before terminating as sandy splays that form minor (<1.5 m) topographic highs on island or floodplain surfaces (Figs. 3 and 7C). Numerous small ridges are present, but there is an increased number of large islands up to 600 m long and 130 m wide (Figs. 3 and 5A). Large islands are also found in the downstream reaches, where many island and floodplain surfaces are marked by splays or by shallow (<1.5 m), discontinuous scours (e.g., Figs. 3 and 7D). In the last 1 km above the billabong, anabranches are typically relatively short with numerous bifurcations and confluences, corresponding to a decrease in the number of large islands and a marked increase in the number of small ridges (Fig. 5A and 7A).

Cross-section surveys (Fig. 4) illustrate subtle downstream changes. With the exception of the two “single channel” sections (XS2 and XS5), the upstream and middle reaches have relatively narrow and deep anabranches, whereas the downstream reaches tend to have wider and shallower anabranches, as shown by overall downstream increases in total bed width and w/d ratio (Figs. 5B and 5C). Frequency histograms of w/d ratios clearly illustrate this trend toward wider, shallower anabranches in the downstream reaches (Fig. 6). The surveys also indicate a slight tendency toward greater variability in the relative elevations of anabranch beds across a given section in the downstream reaches, a change that corresponds to an increase in the number of large (>0.5 m high) 2-D and 3-D dunes.

These downstream changes in the character of the ridges, islands, and anabranches correspond closely to an increase in the density of obstructions in the anabranch beds. For any given surveyed cross section, obstacle density is highly variable between individual anabranches, but if the mean obstacle densities for each surveyed section are considered, there is an overall downstream increase (Fig. 5D), with the exception of the anabranches immediately above the billabong. Qualitative field observations also indicate an increase in the number of seedlings and saplings (diameters <0.05 m) growing in anabranch beds in these downstream reaches.

Downstream Changes in Island Age

The OSL analytical data (Table 1) reveal low overdispersion (σ_d) values, indicating that the

sampled sediments were uniformly bleached prior to deposition (Olley et al., 2004a, 2004b) and justifying the use of the “central age model” (Galbraith et al., 1999) to calculate burial doses. The corresponding OSL ages (Table 1; Fig. 8) demonstrate that the islands tend to become younger downstream. Islands 1 and 2 (upstream reaches) are ca. 2 ka or older, island 3 (middle reaches) is ca. 1.6 ka, and islands 4 and 5 (downstream reaches) are ca. 0.7 ka or younger.

INTERPRETATIONS

Along Magela Creek, the downstream changes in anabranch morphology, obstacle density, and island age can be used to infer the key processes and chronology of anabranch development. Riparian vegetation appears to play an important role, as explored next.

Influence of Vegetation on Anabranch Formation

Field evidence reveals that the ridges and islands dividing the anabranches along Magela Creek form in association with vegetation as a result of both depositional and erosional mechanisms. Previous TL and ^{14}C dates for the alluvial valley fill beneath the present-day creek have demonstrated that aggradation has prevailed over most of the Holocene (Roberts, 1991; Nanson et al., 1993), and indeed our field observations indicate that the ridges and islands mostly form by depositional mechanisms (Figs. 7A–7B), and that erosional mechanisms (Figs. 7C–7D) mainly play a secondary, modifying role.

Depositional mechanisms result from sediment accretion that occurs in the lee of deep-rooted trees or shrubs (e.g., *Melaleuca* spp., *Pandanus* spp.) that are able to establish on a channel bed during a dry season and survive subsequent wet-season floods. By introducing a substantial element of flow roughness and acting as obstacles to flow, these in-channel species commonly initiate ridges as small, lee-side deposits of sand (Fig. 7A). Subsequent colonization by seedlings/saplings or grasses in the intervals between floods helps these incipient ridges to stabilize and encourages further deposition of sediment during subsequent floods, so that ridges grow longitudinally, laterally, and vertically (Fig. 7B), and commonly coalesce with neighboring ridges. These depositional mechanisms eventually form extensive sub-parallel ridges or large islands that separate anabranches, as has been documented for many riparian vegetation communities in other parts of central and northwestern Australia (Wende and Nanson, 1998; Tooth and Nanson, 1999, 2000b). Along the study reach, numerous fea-

tures at various stages of this developmental sequence can be identified; in the downstream reaches, small incipient ridges representing the early stages are most common, whereas in the upstream reaches, larger ridges and well-developed islands representing the later stages are most prominent (Fig. 2).

Erosional mechanisms result from overbank flows that scour floodplain or island surfaces. The high flow variability, coupled with the variable elevation of anabranch beds relative to the elevations of the dividing islands or marginal floodplains (Fig. 4), promotes regular overbank flows. Vegetation or woody debris may provide a trigger and/or determine the location of overbank flow, especially where channels are densely obstructed. Locally, scour is initiated by deepening of minor channels within splay complexes (Fig. 7C), but, more typically, it occurs beyond the distal margins of splays to form discontinuous depressions up to 1 m deep (Fig. 7D) that commonly have prominent knickpoints at their upstream ends. Ongoing scour and knickpoint retreat ultimately form a deeper, more continuous channel that is gradually integrated into the existing anabranch pattern and starts to transport bed sediment. Along the study reach, splays and

locally scoured island and floodplain surfaces are particularly prominent in the middle and downstream reaches, especially on the eastern side of the channel belt (Fig. 3, XS6–XS13), but these processes only slightly modify an anabranching pattern essentially established by depositional mechanisms.

Influence of Vegetation on Ridge and Island Stability

Ridges and islands consist principally of fine to medium sand (silt-clay content <15%), and thus possess little intrinsic cohesion. In a creek with such a variable flow regime, and where velocities and boundary shear stresses during most flows are above the threshold for sand entrainment, how do the ridges and islands dividing narrow anabranches persist? The strong inference is that once ridges and islands form, colonizing vegetation plays a critical role in maintaining their stability by increasing sediment cohesion and decreasing flow erosivity. Currently, there is no universally accepted method for the difficult task of quantifying the vegetative contribution to bank (ridge/island) stability (e.g., Abernethy and

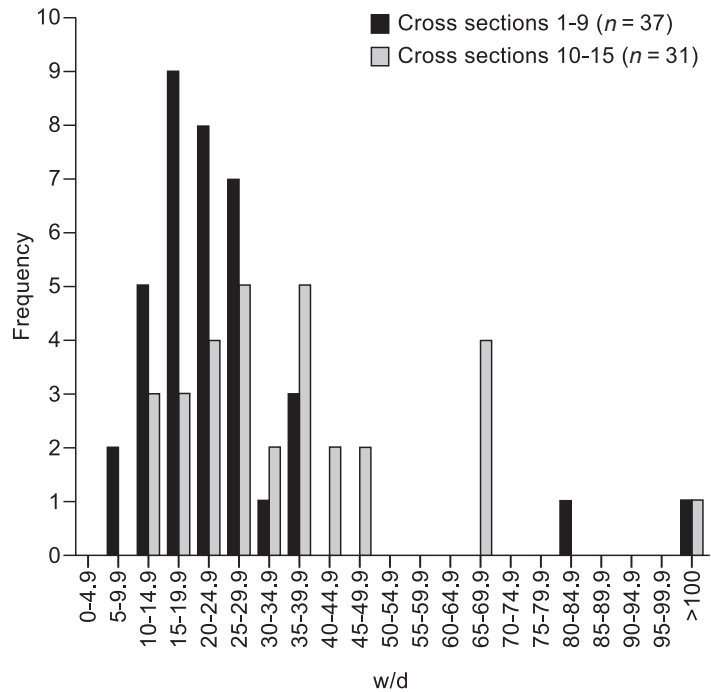


Figure 6. Frequency histogram of w/d for anabranches along Magela Creek, grouped for cross sections 1–9 (upstream and middle reaches) and 10–15 (downstream reaches), illustrating an overall downstream shift to wider, shallower anabranches. Note the near absence of anabranches with $w/d < 10$, and the limited number of anabranches with $w/d > 30$ in the upstream and middle reaches.

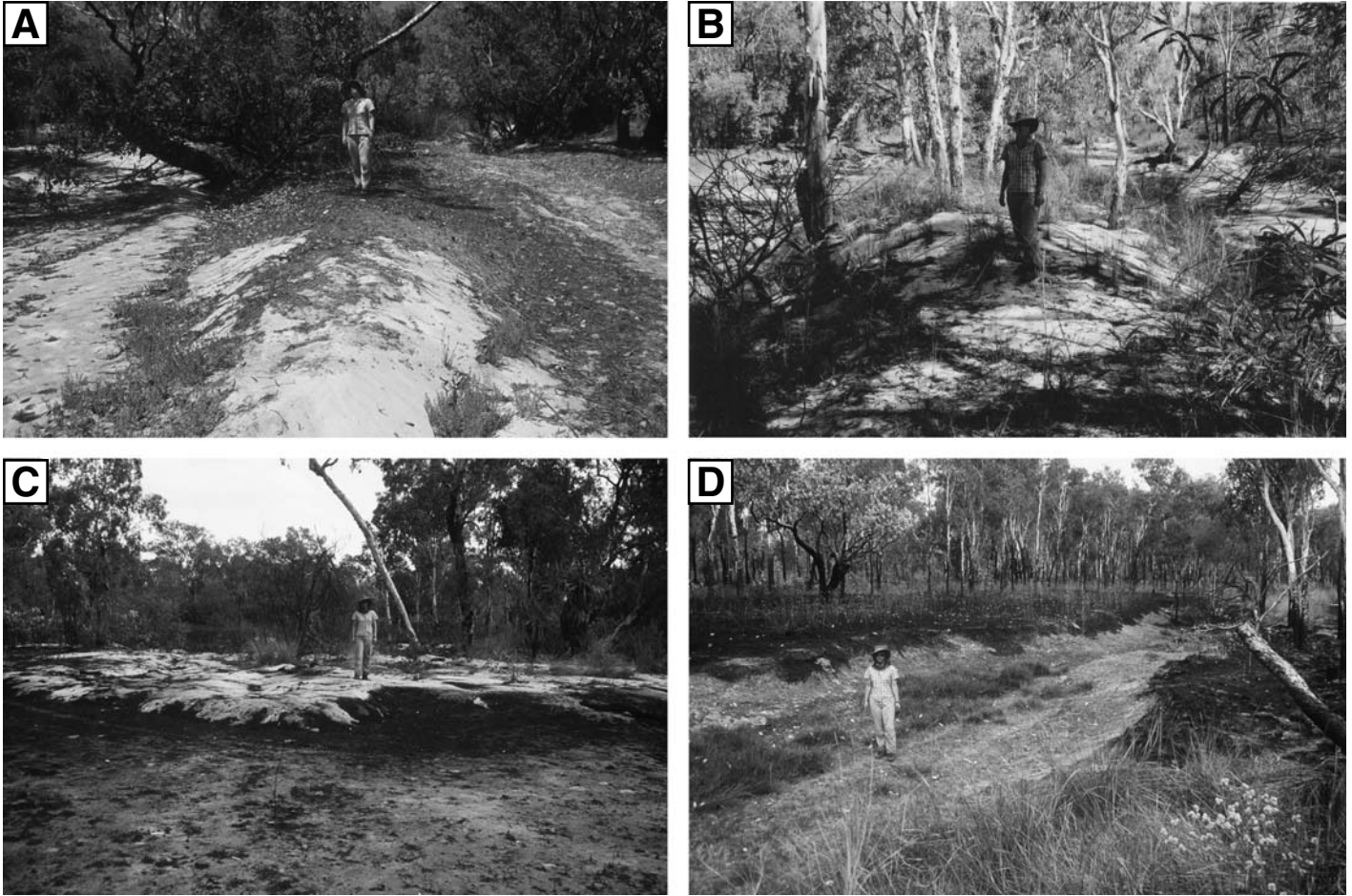


Figure 7. Photographs illustrating depositional and erosional mechanisms of anabranch, ridge, and island formation: (A) small sandy ridge (~0.5 m high) deposited in the lee of a tree growing in an anabranch bed in the downstream reaches (flow direction toward camera); (B) large, sandy ridge (~2 m high) colonized with trees and grasses, which separates two well-defined anabranches in the upstream reaches (flow direction toward camera); (C) sandy splay prograding across a floodplain surface (recently burnt) in the middle reaches (flow direction toward camera); and (D) ~1.5-m-deep scoured depression on a floodplain in the middle reaches, possibly representing the early stages of anabranch formation (flow direction from upper right to lower left).

TABLE 1. SAMPLING DETAILS AND ANALYTICAL RESULTS FOR OSL SAMPLES COLLECTED FROM ISLANDS ALONG THE STUDY REACH*

Island	Sample	Depth (cm) [†]	²³⁸ U	²²⁶ Ra	²¹⁰ Pb	²³² Th	⁴⁰ K	Overdispersion, σ_g (%) [‡]	Dose Rate (Gy k.y. ⁻¹)	Burial dose, D_b (Gy)	Age (ka)
1	M1A	123	60 ± 9	130 ± 2	112 ± 7	68 ± 2	122 ± 6	12	3.41 ± 0.36	6.77 ± 0.11	1.99 ± 0.22
	M2	110	6.27 ± 1.23	9.40 ± 0.28	17.3 ± 1.8	8.46 ± 0.33	9.33 ± 2.18	3	0.60 ± 0.06	1.36 ± 0.03	2.27 ± 0.24
2	M4	165	22.3 ± 3.1	25.8 ± 0.7	27.5 ± 3.9	18.4 ± 0.8	25.1 ± 4.4	14	1.00 ± 0.11	2.75 ± 0.06	2.75 ± 0.33
	M5	175	22.0 ± 2.7	23.8 ± 0.5	25.1 ± 3.2	18.4 ± 0.5	24.2 ± 3.1	18	0.96 ± 0.10	3.27 ± 0.08	3.40 ± 0.39
3	M7	145	7.98 ± 2.17	13.3 ± 0.4	11.9 ± 2.3	10.7 ± 0.5	13.0 ± 3.6	22	0.57 ± 0.06	0.91 ± 0.04	1.59 ± 0.19
	M9	155	11.8 ± 1.5	26.1 ± 0.5	38 ± 3	14.4 ± 0.4	27.8 ± 3.0	14	1.04 ± 0.10	1.72 ± 0.04	1.65 ± 0.17
4	M10B	115	1.21 ± 2.11	8.36 ± 0.27	8.33 ± 1.93	7.65 ± 0.31	11.4 ± 2.2	0	0.45 ± 0.05	0.31 ± 0.01	0.69 ± 0.08
	M11	115	8.86 ± 1.44	17.7 ± 0.3	21.2 ± 2.0	10.4 ± 0.4	11.6 ± 1.8	16	0.70 ± 0.07	0.42 ± 0.02	0.60 ± 0.07
5	M14	120	7.15 ± 1.29	12.7 ± 0.3	9.99 ± 1.64	8.57 ± 0.47	7.89 ± 2.1	0	0.50 ± 0.05	0.25 ± 0.01	0.50 ± 0.06
	M15	118	8.69 ± 1.64	10.7 ± 0.3	11.9 ± 2.0	8.75 ± 0.52	13.4 ± 2.5	0	0.55 ± 0.06	0.11 ± 0.01	0.20 ± 0.03

Notes: All radionuclide values are in Bq kg⁻¹. Values less than 10 (and their uncertainties) are reported to 2 decimal places. Values between 10 and 30 (and their uncertainties) are rounded to 1 decimal place. Values above 30 (and their uncertainties) are rounded to the nearest integer.

*For location, see Figure 3.

[†]Depth below surface. Sample depths are the mid-points of each sample tube (20 cm long).

[‡]The relative standard deviation of the single-grain dose distribution after taking into account the measurement uncertainty for each grain. These estimates of σ_g were obtained using the "central age model" of Galbraith et al. (1999). If measurement uncertainties were the only source of variation among single-grain doses, the σ_g would be zero. For comparison, samples with σ_g values less than about 20% are considered to have been uniformly bleached at the time of deposition (Olley et al., 2004b, 2006; Galbraith et al., 2005).

Rutherford, 2000; Millar, 2000; Simon and Collison, 2002; Micheli and Kirchner, 2002; Simon et al., 2004; van de Wiel and Darby, 2004), but qualitative field evidence suggests that this occurs in several ways along Magela Creek. For instance, many of the tree and shrub species develop extensive surface layers of exposed roots (root mats) that help to bind the unconsolidated sand and provide a protective bank covering. Experiments along Magela Creek using a small hydro jet on banks with different vegetation covers demonstrate this influence (L. Erskine, 2002; W. Erskine et al., 2005): application of known water volumes to fixed bank areas at constant pressure and over a given duration show that 3–6 times less sediment is eroded from banks with root mats than from tree-lined or grass-lined banks without root mats. Even where root mats are absent or poorly developed, however, trees and shrubs growing on bank tops typically have rooting depths that exceed bank heights, while many others establish at or near the base of the banks. Together, these growth characteristics help to reinforce or buttress the bank and, in many places, enable bank angles to reach 55–65°, which is far greater than the angle of repose for dry or wet sand. In addition, velocity gradients measured to the boundary during floods demonstrate that submerged vegetation (including root mats, individual roots, grasses and debris) also contributes significantly to flow resistance (L. Erskine, 2002; Jansen and Nanson, 2004; W. Erskine et al., 2005) by retarding near-bank and mean flow velocities and minimizing the potential for sand entrainment.

The stabilizing effect of vegetation is countered to some degree, however, by the erosive influence of some trees or shrubs that grow on anabranch beds. Locally, large (up to 1 m deep) scour holes form around the extensive root-stocks of many in-channel species (especially *P. spiralis*), and flow may also be diverted against adjacent ridges or islands, causing erosion. Continued erosion ultimately can result in destabilization and collapse of channel-margin vegetation, contributing to a breach in the ridge or island, or to island or floodplain scour (see previous). On balance, however, our field evidence suggests that the stabilizing effect of vegetation is by far the more important, especially in the upstream part of the study reach, where only minor examples of destabilized trees or recent ridge or island erosion can be identified (see also Nanson and Knighton, 1996; Jansen and Nanson, 2004). With the exception of minor extension of some splays in the transitional middle reaches, and delta growth in the lowermost reaches, aerial photographs reveal little change to the anabranching pattern since

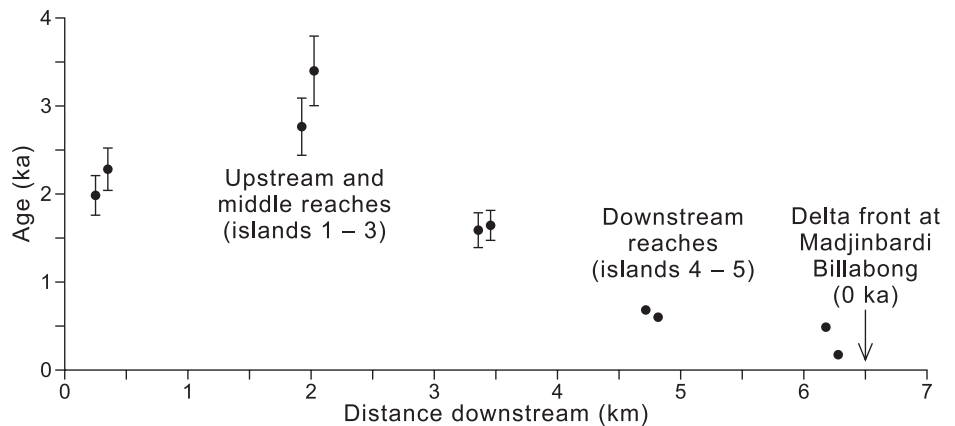


Figure 8. Graph of optically stimulated luminescence (OSL) ages for island alluvium along the study reach, showing the distinct younging trend through the downstream reaches. Note that the error bars (1σ) for islands 4 and 5 are less than the size of the symbol. Distance downstream is determined from an arbitrary starting point at the head of the study reach.

1950. In addition, the OSL ages for island alluvium (Table 1; Fig. 8) demonstrate that many ridges and islands are stable, long-lived (centuries to millennia) features and point to the overall slow rate of channel change.

Influence of Channel Processes on Vegetation Dynamics

While vegetation clearly influences flow and sediment-transport processes along Magela Creek, fluvial processes in turn can influence vegetation dynamics. Flooding provides a regular supply of moisture and nutrients, thereby helping to promote and maintain vegetation growth, and it also enables seed dispersal. Alternatively, flooding can introduce an element of disturbance, adversely affecting individual mature plants, saplings, and seedlings through prolonged inundation, sediment burial, or root destabilization, and/or by causing damage to soft tissue through the impact of transported sediment or debris. These different flooding effects may favor some riparian plant populations more than others, since some species are dependent on physical disturbance to eliminate competition and provide moist, open sites conducive to germination and growth. For instance, as has been documented in other Australian rivers (Fielding et al., 1997; Tooth and Nanson, 2000b), once established, populations of many in-channel species such as *Melaleuca* spp. can “engineer their own environment” by diverting flow and encouraging deposition, and creating conditions favorable to seedling germination and growth. Indeed, along Magela Creek, there are numerous examples of ridges that have older, larger *Melaleuca* trees at the head and younger saplings in their protected lee.

Spatial and Temporal Trends in Channel-Vegetation Interactions

Along Magela Creek, gradient, discharge, channel-belt width, and grain size do not vary significantly or systematically downstream, whereas trends in variables such as anabranch w/d ratio and obstacle densities (Figs. 4–6) strongly suggest subtle spatial changes in the nature of channel-vegetation interactions. In the upstream and middle reaches (XS1–XS9), relatively narrow anabranches (w/d typically 10–30) divide around well-vegetated ridges and islands but remain largely unobstructed (Figs. 2–6), indicating that while vegetation is able to establish in protected channel-margin and ridge- or island-top locations, colonization of anabranch beds is largely prevented by confined flows, unstable substrates, and flood erosion or damage to any seedlings and saplings. By contrast, in the downstream reaches (XS10–XS15), many wider anabranches (w/d up to ~70) also divide around vegetated ridges and islands but contain an increasing number of obstacles (Figs. 2–6), reflecting more abundant vegetation colonization of channel beds. Here, in-channel vegetation strongly influences fluvial processes and initiates new ridges or islands by depositional mechanisms or, less commonly, by erosional mechanisms.

The OSL ages demonstrate that the islands between anabranches become younger toward Madjinbardi Billabong (Fig. 8), strongly suggesting that the spatial changes along Magela Creek are coupled with a temporal trend. Ergodically, this suggests that a time sequence of anabranch development is represented along Magela Creek, from downstream (young, early stages) to upstream (older, later stages). The

sequence starts with relatively wide, obstructed channels and small, incipient ridges, and over a few centuries to a few millennia, there is an adjustment toward narrower, less obstructed anabranches that divide around well-vegetated ridges and islands.

DISCUSSION

The proposition that the younger, downstream reaches of Magela Creek adjust over time toward an anabranching configuration similar to that in the older, upstream reaches raises two key questions: (1) Are there any underlying principles governing the development of anabranching?; (2) What are the implications of anabranch development for downstream water and sediment flux?

Relative Flow Efficiency of Single-Channel and Anabranching Rivers

Previously published empirical data sets and theoretical analyses help to address these questions. In particular, Jansen and Nanson (2004) collected detailed hydraulic and sediment-transport measurements from an anabranching cross section (XS1 of this study) and single-channel cross sections (XS2 and XS5 of this study) and demonstrated that up to and just above bankfull flow, the anabranches exhibit substantially greater flow efficiency (defined as sediment-transport capacity per unit available stream power). These field results were corroborated by simple flume experiments (Jansen and Nanson, 2004) and verified the results from Nanson and Huang's (1999) mathematical model. Once well above bankfull, however, increasing vegetation drag reverses the situation, and sediment-transport rates in the anabranches decline such that the single channels become more efficient. In these upstream reaches, this reversal helps to maintain mass-flux balance over the full range of flows, supporting Roberts' (1991) earlier findings.

Based on these results, Jansen and Nanson (2004) argued that, under such equilibrium conditions, anabranches exhibit maximum flow efficiency (MFE), in accordance with Huang and Nanson's (2000) least action arguments for alluvial channel adjustment. Huang and Nanson's (2000) analysis showed that in straight, rectangular, adjustable channels with a given discharge, gradient, and grain size, MFE can be attained by varying w/d within a narrow range. Attainment of MFE implies maximum stability or the special stationary (stable) equilibrium state wherein a minimum level of energy is demanded by the flow for the water and sediment loads, with the result that there is no net

aggradation or incision. A more recent analytical approach by Eaton et al. (2004), although not based on the least action principle and using a coarser (gravel) grain size, also showed that for a given discharge, gradient, and grain size, maximum sediment transport is achieved within a relatively narrow range of w/d values that vary slightly with bank strength, as provided by cohesive sediment or vegetation.

Significantly, both Huang and Nanson's (2000) and Eaton et al.'s (2004) analyses demonstrated that the optimum condition for sediment transport is represented by moderately narrow channels ($w/d \sim 10\text{--}45$). Below the optimum w/d , sediment-transporting capacity decreases sharply, while above this optimum, transporting capacity also decreases, but more gradually. Furthermore, Huang and Nanson (2007) showed how multiple, narrow (anabranching) channels in certain situations can transport their sediment loads more efficiently than a single, wider channel with an equivalent total discharge. These findings as to the importance of w/d for sediment-transport capacity provide

an explanation for the survey data from the upstream and middle reaches of Magela Creek (Fig. 6, XS1–XS9), as well as from numerous other transport-limited rivers in central Australia (Fig. 9), which show that anabranches tend to be moderately narrow ($w/d \sim 10\text{--}45$) and that there are fewer very narrow ($w/d < 10$) or very wide ($w/d > 45$) anabranches.

Downstream Changes in Efficiency

Jansen and Nanson's (2004) investigation of flow efficiency concentrated on the upstream part of the study reach considered in this paper. To document downstream changes in flow efficiency, additional flow and sediment data for a range of floods would be required from more cross sections toward Madjinbardi Billabong. Logistically, this is a very difficult task in a system as complex as Magela Creek, with its numerous anabranches, highly variable flow regime, and wet-season wildlife (crocodiles). Nevertheless, an important corollary of the analyses of Huang and Nanson (2000), Jansen

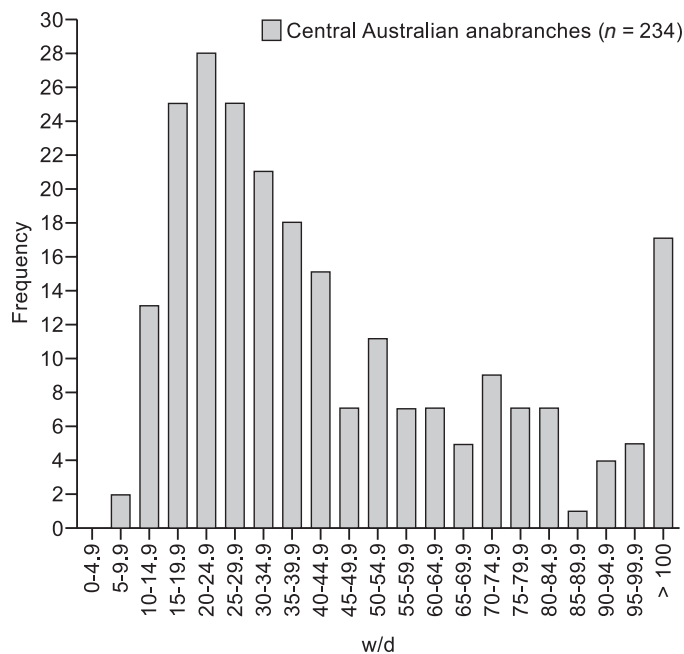


Figure 9. Frequency histogram of anabranch w/d for various ephemeral rivers in central Australia (Q for individual anabranches is $< 330 \text{ m}^3 \text{ s}^{-1}$, $S = 0.0005\text{--}0.0021$, and $D_{50} = 0.5\text{--}2.0 \text{ mm}$), illustrating the numerous anabranches with moderate w/d ($\sim 10\text{--}45$), and the lower numbers of anabranches with very low or very high w/d ratios (based largely on data presented in Tooth [1997] and Tooth and Nanson [2004]). The class interval with $w/d > 100$ mainly incorporates either relatively young anabranches that are in the process of forming, or older, largely infilled anabranches. Note the similarity to the frequency distribution for anabranch w/d in the upstream and middle reaches (XS1–XS9) of Magela Creek (Fig. 6).

and Nanson (2004), and Eaton et al. (2004) is that for flows up to and just above bankfull, and other than for very small, very narrow ($w/d < 10$) channels, efficiency is inversely related to w/d ; in other words, for a given unit stream power, efficiency decreases as w/d increases. Hence, in the absence of actual hydraulic and sediment-transport measurements, w/d can be used as an expedient surrogate for the relative efficiency of different channels. This implies that across a reach with variable anabranch w/d , efficiency varies from anabranch to anabranch. Nevertheless, for a given discharge, gradient, and grain size, a system composed of anabranches that are relatively narrow and deep (e.g., $w/d \sim 10\text{--}30$) overall is more efficient than a system of wider, shallower anabranches (e.g., $w/d \sim 80\text{--}100$). Furthermore, for anabranches of a given w/d , efficiency is higher where the vegetation grows mainly on the ridges and islands between anabranches, and efficiency is lower where it grows in abundance on the channel beds.

Along the study reach, gradient, discharge, channel-belt width, and grain size do not change significantly or systematically downstream, but there are increases in anabranch w/d , obstacle densities, and the numbers of splays and locally scoured island and floodplain surfaces (Figs. 4–7). These trends are indicative of greater aggradational and/or erosional (disequilibrium) tendencies, strongly suggesting that there is an overall decline in efficiency from the upstream reaches, through the transitional middle reaches, and farther downstream toward Madjinbardi Billabong. Nevertheless, a few anabranches in the downstream reaches have moderate w/d and/or are relatively unobstructed (Figs. 4–6) and thus can be regarded as efficient as many anabranches in the middle and upstream reaches. On the basis of iterative channel change and increasing stability (Nanson and Huang, 2008), it is reasonable to expect that such efficient anabranches persist longer than those that are less efficient (i.e., very low or very high w/d and densely obstructed) because anabranches that cannot maintain onward transport of supplied sediment aggrade and/or become obstructed by colonizing vegetation. In-channel vegetation in turn may promote ridge formation and subdivision into narrower, more efficient anabranches or, less commonly, may accelerate bed aggradation and initiate splays and/or floodplain scours that ultimately form new, less obstructed, more efficient anabranches (Fig. 7). Through this combination of depositional and erosional mechanisms, anabranch w/d ratios in the downstream reaches over time tend to converge toward those characteristic of the reaches farther upstream, resulting in a system of anabranches that overall exhibits greater

efficiency. As anabranching system efficiency increases, sediment transfer is enhanced, and the locus of sedimentation advances downstream, further infilling Madjinbardi Billabong. Delta progradation in turn provides new surfaces for vegetation to colonize, so that, in time, new incipient ridges and anabranches are initiated. Along Magela Creek, vertical aggradation has been minimal over the last few millennia, so depositional ridge and island ages mainly reflect the relative lateral stability of anabranches. In this system, bank vegetation contributes to anabranch lateral stability, and lateral stability is linked with efficiency, so one would expect island ages to increase upstream, but then level off where efficient anabranches have developed. Indeed, the OSL ages for island alluvium (Table 1; Fig. 8) illustrate this pattern, demonstrating that a recognizable but relatively inefficient anabranching system can develop within a few centuries, while adjustment to a more efficient system occurs over a few millennia.

Globally, not all anabranching rivers are strongly influenced by vegetation, and as Jansen and Nanson (2004) and Huang and Nanson (2007) have stressed, not all are adjusted to a sediment mass-flux balance; some instead are geared toward sediment dispersal and long-term storage (Makaske, 2001; Tabata and Hickin, 2003; Abbado et al., 2005). Nonetheless, based on the results of this study, we suggest that in some circumstances, riparian vegetation can influence equilibrium river patterns, even in situations where flows are capable of moving the sediment forming the bed and banks. This suggestion is contrary to the assertions of some researchers (e.g., Bridge, 1993, 2003) but is in accordance with the results of numerous field, experimental, and computational modeling studies (e.g., Millar, 2000; Gran and Paola, 2001; Gurnell et al., 2001; Brooks and Brierley, 2002; Murray and Paola, 2003; Tooth and McCarthy, 2004; Tal et al., 2004; Coulthard, 2005; Tal and Paola, 2007), which have demonstrated the marked influence of vegetation in influencing the morphology and dynamics of various other river styles (straight, meandering, wandering, braided).

CONCLUSION

The study of Magela Creek represents a natural field experiment whereby spatial changes in the character of anabranching can be used to infer processes and temporal trends in anabranch development, and the results can then be compared with empirical and theoretical models (Nanson and Huang, 1999; Jansen and Nanson, 2004; Huang and Nanson, 2007). Along the creek, gradient, discharge, channel-belt width, and grain size do not change sig-

nificantly or systematically, but a broad time sequence of anabranches and dividing ridges and islands exists, from younger (downstream) to older (upstream). In the downstream reaches, anabranches are relatively wide, shallow, and obstructed, representing conduits of varying efficiency for flow and sediment transport. Interactions among flow, sediment, and vegetation growth mean that inefficient anabranches are likely to fail or subdivide as a result of vegetation colonization, aggradation, and/or local floodplain scour, while more efficient anabranches persist. Hence, over time, anabranches similar to those in the upstream reaches develop, and they become relatively narrow, deep, and clear of in-channel obstructions, representing efficient conduits that limit the ability of vegetation to establish or survive on the beds. OSL ages for island alluvium demonstrate that this adjustment to a relatively efficient system of anabranches occurs over a few millennia.

The strong inference is that riparian vegetation is essential to the development and persistence of anabranching along Magela Creek. Although vegetation dynamics are partly influenced by patterns of flow and sediment movement, vegetation plays a key role in the initiation of channel-dividing ridges and islands through depositional or erosional mechanisms, and vegetation helps ridges and islands to grow and survive by promoting deposition, increasing sediment cohesion, and decreasing flow erosivity. Owing to the very low silt-clay content in the dominantly sandy sediment, ridges and islands would not be stable without colonizing vegetation, and Magela Creek would be a wider, shallower, and more laterally active system. While not all anabranching rivers are strongly influenced by vegetation, and not all are adjusted to a sediment mass-flux balance, the findings from Magela Creek indicate how, even without a supply of cohesive sediment, anabranching patterns can form and persist on centennial to millennial time scales, thus enhancing downstream water and sediment flux. As such, these findings contribute to the growing body of research that demonstrates the critical yet diverse influence of riparian vegetation on many aspects of river process, form, and behavior.

ACKNOWLEDGMENTS

Field work was funded by Natural Environment Research Council grant NER/B/S/2002/00336 to Tooth and Coulthard. Generous logistical support for field work was provided by the Environmental Research Institute of the Supervising Scientist, and our field visits were facilitated particularly by the efforts of Mike Saynor, Bryan Smith, and Don Elphick. We acknowledge the traditional Aboriginal owners of this country and thank them and Energy Resources of Australia Ltd. Ranger Mine, Parks

Australia North, and the Northern Land Council for permission to access Magela Creek on the mine lease and in Kakadu National Park. Maggie Cooper provided valuable field assistance under difficult conditions. Cartographic expertise was provided by Ian Gulley and Anthony Smith (University of Wales, Aberystwyth). Constructive comments and criticisms by Editor Karl Karlstrom, Associate Editor Ellen Wohl, Jonathan Friedman, Waite Osterkamp, and Chris Paola helped to contribute to the final shape of the manuscript.

REFERENCES CITED

- Abbado, D., Slingerland, R., and Smith, N.D., 2005, Origin of anastomosis in the upper Columbia River, British Columbia, Canada, in Blum, M.D., Marriott, S.B., and Leclair, S.F., eds., *Fluvial Sedimentology VII: International Association of Sedimentologists Special Publication* 35, p. 3–15.
- Abernethy, B., and Rutherford, I.D., 1998, Where along a river's length will vegetation most effectively stabilise stream banks?: *Geomorphology*, v. 23, p. 55–75, doi: 10.1016/S0169-555X(97)00089-5.
- Abernethy, B., and Rutherford, I.D., 2000, The effect of riparian tree roots on the mass-stability of riverbanks: *Earth Surface Processes and Landforms*, v. 25, p. 921–937, doi: 10.1002/1096-9837(200008)25:9<921::AID-ESP93>3.0.CO;2-7.
- Acreman, M.C., ed., 2001, *Hydro-ecology: Linking hydrology and aquatic ecology: International Association of Hydrological Sciences (IAHS) Publication* 266, 176 p.
- Aitken, M.J., 1998, *An introduction to optical dating: the dating of quaternary sediments by the use of photon-stimulated luminescence: Oxford, Oxford University Press*, 267 p.
- Bendix, J., and Hupp, C.R., 2000, Hydrological and geomorphological impacts on riparian plant communities: *Hydrological Processes*, v. 14, p. 2977–2990, doi: 10.1002/1099-1085(200011/12)14:16/17<2977::AID-HYP130>3.0.CO;2-4.
- Bennett, S.J., and Simon, A., eds., 2004, *Riparian vegetation and fluvial geomorphology: Washington, D.C., American Geophysical Union, Water Science and Application Series* 8, 282 p.
- Better-Jensen, L., Bulur, E., Duller, G.A.T., and Murray, A.S., 2000, Advances in luminescence instrument systems: *Radiation Measurements*, v. 32, p. 523–528, doi: 10.1016/S1350-4487(00)00039-1.
- Bridge, J.S., 1993, The interaction between channel geometry, water flow, sediment transport and deposition in braided rivers, in Best, J.L., and Bristow, C.S., eds., *Braided Rivers: Geological Society [London] Special Publication* 75, p. 13–71.
- Bridge, J.S., 2003, *Rivers and Floodplains: Forms, processes and the sedimentary record: Oxford, Blackwell*, 491 p.
- Brookes, C.J., Hooke, J.M., and Mant, J., 2000, Modelling vegetation interactions with channel flow in river valleys of the Mediterranean region: *Catena*, v. 40, p. 93–118, doi: 10.1016/S0341-8162(99)00065-X.
- Brooks, A.P., and Brierley, G.J., 2002, Mediated equilibrium: The influence of riparian vegetation and wood on the long-term evolution and behaviour of a near-pristine river: *Earth Surface Processes and Landforms*, v. 27, p. 343–367, doi: 10.1002/esp.332.
- Brooks, A.P., Brierley, G.J., and Millar, R.G., 2003, The long-term control of vegetation and woody debris on channel and flood-plain evolution: Insights from a paired catchment study in southeastern Australia: *Geomorphology*, v. 51, p. 7–29, doi: 10.1016/S0169-555X(02)00323-9.
- Coulthard, T.J., 2005, Effects of vegetation on braided stream pattern and dynamics: *Water Resources Research*, v. 41, p. W04003, doi: 10.1029/2004WR003201.
- Darby, S., 1999, Effect of riparian vegetation on flow resistance and flood potential: *Journal of Hydraulic Engineering*, v. 125, p. 443–454, doi: 10.1061/(ASCE)0733-9429(1999)125:5(443).
- Dyer, F.J., Thoms, M.C., and Olley, J.M., eds., 2002, *The Structure, function and management implications of fluvial sedimentary systems: International Association of Hydrological Sciences (IAHS) Publication* 276, 486 p.
- Eaton, B.C., Church, M., and Millar, R.G., 2004, Rational regime model of alluvial channel morphology and response: *Earth Surface Processes and Landforms*, v. 29, p. 511–529, doi: 10.1002/esp.1062.
- Eriksson, P.G., Condie, K.C., Tirsgaard, H., Mueller, W.U., Altermann, W., Miall, A.D., Aspler, L.B., Catuneanu, O., and Chiarenzelli, J.R., 1998, Precambrian clastic sedimentary systems: *Sedimentary Geology*, v. 120, p. 5–53, doi: 10.1016/S0037-0738(98)00026-8.
- Erskine, L., 2002, The relationship between riparian vegetation, bank erosion and channel pattern, Magela Creek, Northern Territory [B.Sc. Honors thesis]: Wollongong, University of Wollongong, 117 p.
- Erskine, W.D., Saynor, M.J., Erskine, L., Evans, K.G., and Moliere, D.R., 2005, A preliminary typology of Australian tropical rivers and implications for fish community ecology: *Marine and Freshwater Research*, v. 56, p. 253–267, doi: 10.1071/MF04078.
- Fielding, C.R., and Alexander, J., 2001, Fossil trees in ancient fluvial channel deposits: Evidence of seasonal and longer-term climatic variability: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 170, p. 59–80, doi: 10.1016/S0031-0182(01)00227-9.
- Fielding, C.R., Alexander, J., and Newman-Sutherland, E., 1997, Preservation of in situ, aborescent vegetation and fluvial bar construction in the Burdekin River of north Queensland, Australia: *Palaeogeography, Palaeoclimatology, Palaeoecology*, v. 135, p. 123–144, doi: 10.1016/S0031-0182(97)00022-9.
- Francis, R.A., 2006, Allogenic and autogenic influences upon riparian vegetation dynamics: *Area*, v. 38, p. 453–464, doi: 10.1111/j.1475-4762.2006.00706.x.
- Friedman, J.M., Osterkamp, W.R., and Lewis, W.M., Jr., 1996, Channel narrowing and vegetation development following a Great Plains flood: *Ecology*, v. 77, p. 2167–2181, doi: 10.2307/2265710.
- Galbraith, R.F., Roberts, R.G., Laslett, G.M., Yoshida, H., and Olley, J.M., 1999, Optical dating of single and multiple grains of quartz from Jimmum rock shelter, northern Australia: Part I. Experimental design and statistical models: *Archaeometry*, v. 41, p. 339–364, doi: 10.1111/j.1475-4754.1999.tb00987.x.
- Galbraith, R.F., Roberts, R.G., and Yoshida, H., 2005, Error variation in OSL palaeodose estimates from single aliquots of quartz: A factorial experiment: *Radiation Measurements*, v. 39, p. 289–307.
- Graeme, D., and Dunkerley, D.L., 1993, Hydraulic resistance by the river red gum, *Eucalyptus camaldulensis*, in ephemeral desert streams: *Australian Geographical Studies*, v. 31, p. 141–154.
- Graf, W.L., 1978, Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region: *Geological Society of America Bulletin*, v. 89, p. 1491–1501, doi: 10.1130/0016-7606(1978)89<1491:FATTSO>2.0.CO;2.
- Graf, W.L., 1979, Fluvial adjustments to the spread of tamarisk in the Colorado Plateau region: Reply: *Geological Society of America Bulletin*, v. 90, p. 1183–1184, doi: 10.1130/0016-7606(1979)90<1183:FATTSB>2.0.CO;2.
- Gran, K., and Paola, C., 2001, Riparian vegetation controls on braided stream dynamics: *Water Resources Research*, v. 37, p. 3275–3286, doi: 10.1029/2000WR000203.
- Griffin, G.F., Smith, D.M.S., Morton, S.R., Allan, G.E., and Masters, K.A., 1989, Status and implications of the invasion of Tamarisk (*Tamarix aphylla*) on the Finke River, Northern Territory, Australia: *Journal of Environmental Management*, v. 29, p. 297–315.
- Gurnell, A.M., Hupp, C.R., and Gregory, S.V., eds., 2000, *Linking hydrology and ecology: Hydrological Processes*, v. 14, p. 2813–2815, doi: 10.1002/1099-1085(200011/12)14:16/17<2813::AID-HYP120>3.0.CO;2-Q.
- Gurnell, A.M., Petts, G.E., Hannah, D.M., Smith, B.P.G., Edwards, P.J., Kollmann, J., Ward, J.V., and Tockner, K., 2001, Riparian vegetation and island formation along the gravel-bed Fiume Tagliamento, Italy: *Earth Surface Processes and Landforms*, v. 26, p. 31–62, doi: 10.1002/1096-9837(200101)26:1<31::AID-ESP155>3.0.CO;2-Y.
- Hart, B.T., Ottaway, E.M., and Noller, N.B., 1987, Magela Creek system, northern Australia: I. 1982–83 wet season water quality: *Australian Journal of Marine and Freshwater Research*, v. 38, p. 261–288, doi: 10.1071/MF9870261.
- Heritage, G.L., Moon, B.P., Broadhurst, L.J., and James, C.S., 2004, The frictional resistance characteristics of a bedrock-influenced river channel: *Earth Surface Processes and Landforms*, v. 29, p. 611–627, doi: 10.1002/esp.1057.
- Huang, H.Q., and Nanson, G.C., 1998, The influence of bank strength on channel geometry: An integrated analysis of some observations: *Earth Surface Processes and Landforms*, v. 23, p. 865–876, doi: 10.1002/(SICI)1096-9837(199810)23:10<865::AID-ESP903>3.0.CO;2-3.
- Huang, H.Q., and Nanson, G.C., 2000, Hydraulic geometry and maximum flow efficiency as products of the principle of least action: *Earth Surface Processes and Landforms*, v. 25, p. 1–16, doi: 10.1002/(SICI)1096-9837(200001)25:1<1::AID-ESP68>3.0.CO;2-2.
- Huang, H.Q., and Nanson, G.C., 2007, Why some alluvial rivers develop an anabranching pattern: *Water Resources Research*, v. 43, p. W07441, doi: 10.1029/2006WR005223.
- Hupp, C.R., and Osterkamp, W.R., 1996, Riparian vegetation and fluvial geomorphic processes: *Geomorphology*, v. 14, p. 277–295, doi: 10.1016/0169-555X(95)00042-4.
- Ikeda, S., and Izumi, N., 1990, Width and depth of self-formed straight gravel rivers with bank vegetation: *Water Resources Research*, v. 26, p. 2353–2364, doi: 10.1029/90WR00812.
- Jansen, J.D., and Nanson, G.C., 2003, Sedimentation rates at Madjinbardi Billabong (1980–2002): Report for Kakadu National Parks Research Permit 560: Darwin, Parks Australia, 2 p.
- Jansen, J.D., and Nanson, G.C., 2004, Anabranching and maximum flow efficiency in Magela Creek, northern Australia: *Water Resources Research*, v. 40, p. W04503, doi: 10.1029/2003WR002408.
- Johnson, W.C., 1997, Equilibrium response of riparian vegetation to flow regulation in the Platte River, Nebraska: *Regulated Rivers: Research and Management*, v. 13, p. 403–415, doi: 10.1002/(SICI)1099-1646(199709/10)13:5<403::AID-RRR465>3.0.CO;2-U.
- Johnson, W.C., 2000, Tree recruitment and survival in rivers: Influence of hydrological processes: *Hydrological Processes*, v. 14, p. 3051–3074, doi: 10.1002/1099-1085(200011/12)14:16/17<3051::AID-HYP134>3.0.CO;2-1.
- Johnson, W.C., Dixon, M.D., Simons, R., Jensen, S., and Larson, K., 1995, Mapping the response of riparian vegetation to possible flow reductions in the Snake River, Idaho: *Geomorphology*, v. 13, p. 159–173, doi: 10.1016/0169-555X(95)00048-A.
- Kean, J.W., and Smith, J.D., 2004, Flow and boundary shear stress in channels with woody bank vegetation, in Bennett, S.J., and Simon, A., eds., *Riparian Vegetation and Fluvial Geomorphology: Washington, D.C., American Geophysical Union, Water Science and Application Series* 8, p. 237–252.
- Knighton, A.D., 1998, *Fluvial Forms and Processes: A New Perspective: London, Arnold*, 383 p.
- Makaske, B., 2001, Anastomosing rivers: A review of their classification, origin and sedimentary products: *Earth-Science Reviews*, v. 53, p. 149–196, doi: 10.1016/S0012-8252(00)00038-6.
- Mejdahl, V., 1979, Thermoluminescence dating: Beta-dose attenuation in quartz grains: *Archaeometry*, v. 21, p. 61–72, doi: 10.1111/j.1475-4754.1979.tb00241.x.
- Merritt, D.M., and Cooper, D.J., 2000, Riparian vegetation and channel change in response to river regulation: A comparative study of regulated and unregulated streams in the Green River Basin, USA: *Regulated Rivers: Research and Management*, v. 16, p. 543–564, doi: 10.1002/1099-1646(200011/12)16:6<543::AID-RRR590>3.0.CO;2-N.
- Miall, A.D., 1996, *The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology: Berlin, Springer-Verlag*, 582 p.
- Micheli, E.R., and Kirchner, J.W., 2002, Effects of wet meadow riparian vegetation on streambank erosion: 2. Measurements of vegetated bank strength and consequences for failure mechanics: *Earth Surface Processes and Landforms*, v. 27, p. 687–697, doi: 10.1002/esp.340.
- Millar, R.G., 2000, Influence of bank vegetation on alluvial channel patterns: *Water Resources Research*, v. 36, p. 1109–1118, doi: 10.1029/1999WR000346.

- Murray, A.B., and Paola, C., 2003, Modelling the effect of vegetation on channel pattern in bedload rivers: *Earth Surface Processes and Landforms*, v. 28, p. 131–143, doi: 10.1002/esp.428.
- Murray, A.S., Marten, R., Johnston, A., and Martin, P., 1987, Analysis for naturally occurring radionuclides at environmental concentrations by gamma spectrometry: *Journal of Radioanalytical and Nuclear Chemistry (Articles)*, v. 115, p. 263–288, doi: 10.1007/BF02037443.
- Nakayama, K., Fielding, C.R., and Alexander, J., 2002, Variations in character and preservation potential of vegetation-induced obstacle marks in the variable discharge Burdekin River of north Queensland, Australia: *Sedimentary Geology*, v. 149, p. 199–218, doi: 10.1016/S0037-0738(01)00173-7.
- Nanson, G.C., and Huang, H.Q., 1999, Anabranching rivers: Divided efficiency leading to fluvial diversity, in Miller, A., and Gupta, A., eds., *Varieties of Fluvial Form*: Chichester, John Wiley and Sons, p. 477–494.
- Nanson, G.C., and Huang, H.Q., 2008, Least action principle, equilibrium states, iterative adjustment and the stability of alluvial channels: *Earth Surface Processes and Landforms*, doi: 10.1002/esp.1584.
- Nanson, G.C., and Knighton, A.D., 1996, Anabranching rivers: Their cause, character and classification: *Earth Surface Processes and Landforms*, v. 21, p. 217–239, doi: 10.1002/(SICI)1096-9837(199603)21:3<217::AID-ESP611>3.0.CO;2-U.
- Nanson, G.C., East, T.J., and Roberts, R.G., 1993, Quaternary stratigraphy, geochronology and evolution of the Magela Creek catchment in the monsoon tropics of northern Australia: *Sedimentary Geology*, v. 83, p. 277–302, doi: 10.1016/0037-0738(93)90017-Y.
- Ogden, J., 1978, On the dendrochronological potential of Australian trees: *Australian Journal of Ecology*, v. 3, p. 339–356, doi: 10.1111/j.1442-9993.1978.tb01184.x.
- Ogden, J., 1981, Dendrochronological studies and the determination of tree ages in the Australian tropics: *Journal of Biogeography*, v. 8, p. 405–420, doi: 10.2307/2844759.
- Olley, J.M., Pietsch, T., and Roberts, R.G., 2004a, Optical dating of Holocene sediments from a variety of geomorphic settings using single grains of quartz: *Geomorphology*, v. 60, p. 337–358, doi: 10.1016/j.geomorph.2003.09.020.
- Olley, J.M., De Deckker, P., Roberts, R.G., Fifield, L.K., Yoshida, H., and Hancock, G., 2004b, Optical dating of deep-sea sediments using single grains of quartz: A comparison with radiocarbon: *Sedimentary Geology*, v. 169, p. 175–189, doi: 10.1016/j.sedgeo.2004.05.005.
- Olley, J.M., Roberts, R.G., Yoshida, H., and Bowler, J.M., 2006, Single-grain optical dating of grave-infill associated with human burials at Lake Mungo, Australia: *Quaternary Science Reviews*, v. 25, p. 2469–2474, doi: 10.1016/j.quascirev.2005.07.022.
- Osterkamp, W.R., and Costa, J.E., 1987, Changes accompanying an extraordinary flood on a sand-bed stream, in Mayer, L., and Nash, D., eds., *Catastrophic flooding*: Boston, Allen and Unwin, Binghamton Symposium in Geomorphology, Volume 18, p. 201–224.
- Osterkamp, W.R., and Hupp, C.R., eds., 1996, *Fluvial geomorphology and vegetation*: *Geomorphology*, v. 14, p. 275–351.
- Pickup, G., Wasson, R.J., Warner, R.F., Tongway, D., and Clark, R.L., 1987, Feasibility study of geomorphic research for the long term management of uranium mill tailings: Canberra, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Division of Water Resources Research, Division Report 87/2, 65 p.
- Pollen, N., Simon, A., and Collison, A.J., 2004, Advances in assessing the mechanical and hydrologic effects of riparian vegetation on streambank stability, in Bennett, S.J., and Simon, A., eds., *Riparian vegetation and fluvial geomorphology*: Washington, D.C., American Geophysical Union, Water Science and Application Series 8, p. 125–139.
- Prescott, J.R., and Hutton, J.T., 1994, Cosmic ray contributions to dose rates for luminescence and ESR dating: Large depths and long-term time variations: *Radiation Measurements*, v. 23, p. 497–500, doi: 10.1016/1350-4487(94)90086-8.
- Roberts, R.G., 1991, Sediment budgets and quaternary history of the Magela Creek Catchment, tropical northern Australia [Ph.D. thesis]: Wollongong, University of Wollongong, 569 p.
- Rowntree, K., 1991, An assessment of the potential impact of alien invasive vegetation on the geomorphology of river channels in South Africa: *Southern African Journal of Aquatic Sciences*, v. 17, p. 28–43.
- Sandercocq, P., 2004, Causes and nature of river channel changes in the upper Ord River Catchment [Ph.D. thesis]: Perth, University of Western Australia, 476 p.
- Schumm, S.A., 1968, Speculations concerning paleohydrologic controls on terrestrial sedimentation: *Geological Society of America Bulletin*, v. 79, p. 1573–1588, doi: 10.1130/0016-7606(1968)79[1573:SCPCOT]2.0.CO;2.
- Simon, A., and Collison, A.J., 2002, Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability: *Earth Surface Processes and Landforms*, v. 27, p. 527–546, doi: 10.1002/esp.325.
- Simon, A., Bennett, S.J., and Neary, V.S., 2004, Riparian vegetation and fluvial geomorphology: Problems and opportunities, in Bennett, S.J., and Simon, A., eds., *Riparian Vegetation and Fluvial Geomorphology*: Washington, D.C., American Geophysical Union, Water Science and Application Series 8, p. 1–10.
- Stokes, S., Ingram, S., Aitken, M.J., Sirocko, F., Anderson, R., and Leuschner, D., 2003, Alternative chronologies for late Quaternary (last interglacial–Holocene) deep sea sediment via optical dating of silt-size quartz: *Quaternary Science Reviews*, v. 22, p. 925–941, doi: 10.1016/S0277-3791(02)00243-3.
- Tabata, K.K., and Hickin, E.J., 2003, Interchannel hydraulic geometry and hydraulic efficiency of the anastomosing Columbia River, southeastern British Columbia, Canada: *Earth Surface Processes and Landforms*, v. 28, p. 837–852, doi: 10.1002/esp.497.
- Tal, M., and Paola, C., 2007, Dynamic single-thread channels maintained by the interaction of flow and vegetation: *Geology*, v. 35, p. 347–350, doi: 10.1130/G23260A.1.
- Tal, M., Gran, K., Murray, A.B., Paola, C., and Hicks, D.M., 2004, Riparian vegetation as a primary control on channel characteristics in multi-thread rivers, in Bennett, S.J., and Simon, A., eds., *Riparian vegetation and fluvial geomorphology*: Washington, D.C., American Geophysical Union, Water Science and Application Series 8, p. 43–58.
- Taylor, C.F.H., 1999, The role of overbank flow in governing the form of an anabranching river: The Fitzroy River, northwestern Australia, in Smith, N.D., and Rogers, J., eds., *Fluvial sedimentology VI: International Association of Sedimentologists Special Publication 28*, p. 77–91.
- Thoms, M.C., and Sheldon, F., eds., 2000, *Australian lowland rivers: Regulated rivers: Research and Management*, v. 16, p. 375–383, doi: 10.1002/1099-1646(200009/10)16:5<375::AIDRRR591>3.0.CO;2-#.
- Thorne, C.R., 1990, Effects of vegetation on riverbank erosion and stability, in Thornes, J.B., ed., *Vegetation and erosion: Processes and environments*: Chichester, Wiley, p. 125–144.
- Tooth, S., 1997, *The Morphology, Dynamics and Late Quaternary Sedimentary History of Ephemeral Drainage Systems on the Northern Plains of Central Australia* [Ph.D. thesis]: Wollongong, University of Wollongong, 433 p.
- Tooth, S., 2000, Downstream changes in dryland river channels: The Northern Plains of arid central Australia: *Geomorphology*, v. 34, p. 33–54, doi: 10.1016/S0169-555X(99)00130-0.
- Tooth, S., and McCarthy, T.S., 2004, Controls on the transition from meandering to straight channels in the wetlands of the Okavango Delta, Botswana: *Earth Surface Processes and Landforms*, v. 29, p. 1627–1649, doi: 10.1002/esp.1117.
- Tooth, S., and Nanson, G.C., 1999, Anabranching rivers on the Northern Plains of arid central Australia: *Geomorphology*, v. 29, p. 211–233, doi: 10.1016/S0169-555X(99)00021-5.
- Tooth, S., and Nanson, G.C., 2000a, Equilibrium and non-equilibrium conditions in dryland rivers: *Physical Geography*, v. 21, p. 183–211.
- Tooth, S., and Nanson, G.C., 2000b, The role of vegetation in the formation of anabranching channels in an ephemeral river, Northern Plains, arid central Australia: *Hydrological Processes*, v. 14, p. 3099–3117, doi: 10.1002/1099-1085(200011/12)14:16/17<3099::AID-HYP136>3.0.CO;2-4.
- Tooth, S., and Nanson, G.C., 2004, Forms and processes of two highly contrasting rivers in arid central Australia, and the implications for channel-pattern discrimination and prediction: *Geological Society of America Bulletin*, v. 116, p. 802–816, doi: 10.1130/B25308.1.
- van de Wiel, M.J., and Darby, S.E., 2004, Numerical modeling of bed topography and bank erosion along tree-lined meandering rivers, in Bennett, S.J., and Simon, A., eds., *Riparian vegetation and fluvial geomorphology*: Washington, D.C., American Geophysical Union, Water Science and Application Series 8, p. 267–282.
- Ward, P.D., Montgomery, D.R., and Smith, R., 2000, Altered river morphology in South Africa related to the Permian-Triassic extinction: *Science*, v. 289, p. 1740–1743, doi: 10.1126/science.289.5485.1740.
- Wasson, R.J., ed., 1992, *Modern sedimentation and late quaternary evolution of the Magela Creek Plain*: Canberra, Australian Government Publishing Service, Office of the Supervising Scientist for the Alligator Rivers Region, Research Report 6, 349 p.
- Wende, R., and Nanson, G.C., 1998, Anabranching rivers: Ridge-form alluvial channels in tropical northern Australia: *Geomorphology*, v. 22, p. 205–224, doi: 10.1016/S0169-555X(97)00085-8.
- Williams, G.P., 1978, Bank-full discharge of rivers: *Water Resources Research*, v. 14, p. 1141–1154.

MANUSCRIPT RECEIVED 13 DECEMBER 2006

REVISED MANUSCRIPT RECEIVED 14 NOVEMBER 2007

MANUSCRIPT ACCEPTED 17 NOVEMBER 2007

Printed in the USA