Quaternary Science Reviews 30 (2011) 1681–1695

Contents lists available at ScienceDirect

Quaternary Science Reviews

journal homepage: www.elsevier.com/locate/quascirev

A 100 ka record of fluvial activity in the Fitzroy River Basin, tropical northeastern Australia

Jacky Croke[a,b,*], John D. Jansen[a,c], Kathryn Amos[a,d], Timothy J. Pietsch[e,b]

[a] *School of Physical, Environmental and Mathematical Sciences, University of New South Wales @ADFA, Canberra ACT 2600, Australia*
[b] *Australian Rivers Institute, Nathan Campus, Nathan, Griffith University, QLD 4111, Australia*
[c] *Department of Physical Geography and Quaternary Geology, Stockholm University, SE -106 91, Stockholm, Sweden*
[d] *Centre for Tectonics, Resources and Exploration (TRaX), Australian School of Petroleum, The University of Adelaide, Adelaide, SA 5005, Australia*
[e] *CSIRO Land and Water, GPO Box 1666, Canberra ACT 2601, Australia*

ARTICLE INFO

Article history:
Received 21 December 2010
Received in revised form
22 March 2011
Accepted 25 March 2011
Available online 29 April 2011

Keywords:
Quaternary fluvial change
Optically stimulated luminescence
Floodplains
Tropical
Large river basins

ABSTRACT

This study reports the nature and timing of Quaternary fluvial activity in the Fitzroy River basin, which drains a diverse 143,000 km^2 area in northeastern Queensland, before discharging into the Great Barrier Reef Marine Park. The catchment consists of an extensive array of channel and floodplain types that we show have undergone large-scale fluvial adjustment in-channel planform, geometry and sinuosity. Optically stimulated luminescence (OSL) dating of quartz sediments from fifteen (3–18 m) floodplain cores throughout the basin indicates several discrete phases of active bedload activity: at ~105–85 ka in Marine Isotope Stage (MIS) 5, at ~50–40 ka (MIS 3), and at ~30–10 ka (MIS 3/2). The overall timing of late Quaternary fluvial activity correlates well with previous accounts from across Australia with rivers being primarily active during interstadials. Fluvial activity, however, does not appear to have been synchronous throughout the basin's major sub-catchments. Fluvial activity throughout MIS 2 (i.e. across the Last Glacial Maximum) in the meandering channels of the Fitzroy correlates well with regional data in tropical northeastern Queensland, and casts new light on the river response to reduced rainfall and vegetation cover suggested by regional palaeoclimate indicators. Moreover, the absence of a strong Holocene signal is at odds with previous accounts from elsewhere throughout Australia. The latitudinal position of the Fitzroy across the Tropic of Capricorn places this catchment at a key location for elucidating the main hydrological drivers of Quaternary fluvial activity in northeastern Australia, and especially for determining tropical moisture sources feeding into the headwaters of Cooper Creek, a major river system of the continental interior.

1. Introduction

The value of reconstructing alluvial sequences for our understanding of global Quaternary climate change and fluvial dynamics is widely acknowledged (Bridgland et al., 2007; Bridgland and Westaway, 2008a, 2008b; Westaway et al., 2009). In Australia, palaeoenvironmental reconstructions of Quaternary fluvial, lacustrine and aeolian activity provide a picture of marked climatic oscillation spanning the last two glacial cycles (Nanson et al., 1992, 1995, 2008; Kershaw and Nanson, 1993; Magee et al., 1995; Magee and Miller, 1998). Nanson et al. (1992) noted the persistence of substantially increased fluvial activity throughout northern, central and southeastern Australia during interglacial periods over the last 300 ka. Magee et al. (2004) provide a continuous moisture record from inland Lake Eyre, which suggests that during the last interglacial the basin was wetter than any other time in the past 150 ka. They also note the failure of the Holocene monsoon to establish a deep-water lake as occurred between 65–60 ka leading to suggestions of altered boundary conditions linked to human activities such as burning (Miller et al., 2005).

Much of this existing work has taken place in two key regions of the continent: the interior arid landscapes of the Lake Eyre Basin (Nanson et al., 1992, 1995; Magee et al., 1995; Croke et al., 1996, 1998), and the extensive meandering river systems of southeastern Australia (Page et al., 1996; Bowler, 1978; Yonge and Hesse, 2009; Kemp and Rhodes, 2010). Fluvial and lacustrine activity in the former has, until recently, been seen to reflect variations in the intensity and landward extension of the Indo-Australian monsoon (Magee et al., 1995, 2004; Croke et al., 1999). Fluvial activity in southeastern Australia, recently

---

* Corresponding author. Australian Rivers Institute, Nathan Campus, Nathan, Griffith University, QLD 4111, Australia. Tel.: +61 7 33999521.
E-mail address: JackyCroke@gmail.com (J. Croke).

0277-3791/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.quascirev.2011.03.012

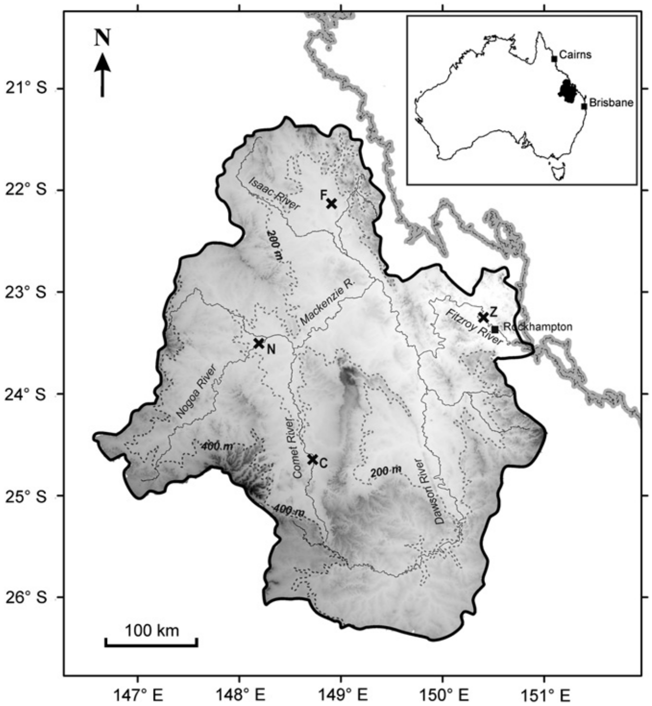

Fig. 1. Location of the Fitzroy River Basin (FRB) in eastern Queensland and location of its six major sub-catchments; Isaacs, Comet, Nogoa, McKenzie, Dawson and Fitzroy. The location of sampled sites in four of these sub-catchments is also identified.

reviewed in Kemp and Rhodes (2010), is considered to be a response to variations in the intensity of the westerly circulation system. Recent palaeoenvironmental reconstruction in the Lachlan River has greatly refined our understanding of Murray-Darling Basin palaeohydrology (Kemp and Spooner, 2007; Kemp and Rhodes, 2010).

Most regions investigated have evidence of enhanced fluvial activity during some period of MIS 5, but important regional differences emerge after this time. In northern Australia higher discharges occurred during the Last Glacial Maximum (LGM) (23–20 ka) and the Holocene climatic optimum (8–5 ka) (Nott et al., 1996; Nanson et al., 2008), but in the southeast, enhanced fluvial activity was split into two phases: 30–25 ka and 20–15 ka, with evidence for a short dry interval around 20–22 ka, preceded and followed by periods of greatly enhanced discharge relative to the present (Page et al., 1991, 1996; Nanson et al., 1992; Nanson et al., 2008; Kemp and Rhodes, 2010).

As a result of this earlier work, research is now moving on from defining broad spatial and temporal patterns to investigating more detailed hypotheses regarding the distribution, intensity and timing of palaeo-precipitation sources. Regional synchroneity between northern and southeastern Australia, for example, is used as key evidence of the likely climatic drivers of fluvial activity across the continent (Nanson et al., 2008). The debate on the relative importance of the Indo-Australian monsoon continues (Miller et al., 2010).

Catchment location has a profound influence on both the length and nature of the alluvial record (Lewin and Macklin, 2003; Lewin et al., 2005). In Australia major differences in the preservation of fluvial units both geographically and over time are evident in the most recent synthesis of luminescence dates of fluvial activity in northern and central Australia (see Nanson et al., 2008). Regional aggregation of fluvial sedimentary records is considered essential, therefore, to ensure that sampling biases can be systematically assessed (Macklin et al., 2010). Key regional gaps exist in the palaeoenvironmental database in Australia. For example, little is known of fluvial systems in the northeast of the continent, which lie in latitudinal positions that may prove relevant to determining the key sources, and variations in the intensity of precipitation both for inland central Australia and systems further south in the Murray-Darling Basin.

The aim of this paper is, firstly, to provide a preliminary Quaternary chronology of fluvial behaviour in one of Australia's largest, coastal catchments: the Fitzroy River Basin (FRB) of eastern Queensland. Little is known of the fluvial geomorphology of subtropical Australia, yet it straddles a key transitional zone influenced by both the southern Trade Winds and tropical moisture sources to the north (Lough, 1997, 2007). The chronology of fluvial activity in the FRB will provide further information on continental and regional differences in river response to Quaternary climate change in Australia. Secondly, the substantial size of this catchment (>140,000 km^2) provides the opportunity to explore intra-catchment variations in fluvial activity. A supplementary aim is to provide a meaningful temporal framework with which to assess perceived rapid environmental changes that are hypothesized to have occurred in the catchment since European settlement (Prosser et al., 2001; McKergow et al., 2005).

2. Regional setting

The FRB, (~143,000 km^2) is the second largest exoreic catchment in Australia and the main drainage into the Great Barrier Reef lagoon (Fig. 1). The basin contains large areas of low gradients (~65% of the catchment is <300 m ASL), studded with isolated ranges up to 700 m ASL (Fig. 1).

2.1. Channels and floodplains

The FRB consists of five sub-catchments: Isaac/Connor, Nogoa, Comet, Mackenzie and Dawson (Table 1), and a range of river patterns including anabranching, single-channel meandering and

Table 1
Characteristics of the six sub-catchments within the Fitzroy River Basin.

Attribute	Issac Sub-catchment	Comet Sub-catchment	Dawson Sub-catchment	McKenzie Sub-catchment	Nogoa Sub-catchment	Fitzroy Sub-catchment
Catchment Area (km^2)	22,446	17,253	50,864	13,078	27,989	10,005
Minimum Altitude (m ASL)	72.8	136.6	41.5	41.3	136.7	0
Maximum Altitude (m ASL)	1049.3	1231.3	943.4	943	1156.7	737.8
Mean Annual Discharge (ML)	1,960,000	448,000	1,066,000	4,470,000	614,000	5,160,000
Predominant Contemporary channel pattern	Anabranching	Anabranching	Anabranching	Meandering	Anabranching/meandering	Meandering
Sinuosity[a] (P)	1.07	1.10	n/a	1.5	“-”	1.8
Total Channel Length (km)	13,300	9380	29900	6020	20400	6530
Mean Slope[b] (m/m)	0.031–0.09	0.011	“-”	“-”	0.043	0.0006

ASL = Australian sea level.

[a] Sub-catchment sinuosity estimate is derived from data presented in the National land and Water Resources Audit (NLWRA, 2001).

[b] channel slope estimate is derived from data presented in the National land and Water Resources Audit (NLWRA, 2001).

confined meandering (Amos et al., 2008). Anabranching reaches occur in all sub-catchments, though less so in the Fitzroy segments of the main stem (Amos et al., 2008). The Isaac and Comet are predominantly anabranching systems, and based on morphometric analyses, such systems were found to have lower valley slopes as a function of drainage area relative to single-channels (Amos et al., 2008). The Mackenzie and Fitzroy main stems are predominantly unconfined meandering rivers with locally discontinuous floodplain segments reflecting structural influences. Detailed accounts of the basin's channel and floodplain morphologies and changes in recent (post 1960) floodplain sedimentation rates and sediment sources are documented elsewhere (Amos et al., 2008, 2009; Croke et al., 2008; Hughes et al., 2008a, 2008b, 2009, 2010; Thompson et al., 2011; Hughes and Croke, in press).

Initial large-scale process modelling (SedNet) in the catchment predicted a total annual input of 7.3 million tonnes of sediment to the river system from predominantly hillslope sources (Prosser et al., 2001), of which, 62% is predicted to be delivered to the estuary (Dougall et al., 2005). Measured floodplain deposition rates over the past 60 yrs ranged from 0 (net erosion) to 15 mm yr^{-1} in low-lying floodplain areas subject to backwater inundation (Amos et al., 2009; Thompson et al., 2011). A comparison between SedNet predictions, sediment tracing and floodplain accretion data suggests that end-of-catchment sediment delivery predictions are likely to be over-estimated due to poor conceptualisation, and quantification, of key sediment storage processes within the main channel boundary and floodplain (Hughes et al., 2010; Hughes and Croke, in press).

2.2. *Climate*

The FRB experiences a humid sub-tropical climate influenced by the southeast Trade Winds and occasional incursions of tropical moisture from the north. Across most of the FRB, mean rainfall is 600–700 mm/y, and mean potential evapotranspiration is 1500–1700 mm/y (BoM, 2007). A small area close to the coast, within the Isaac sub-catchment, receives heavier rainfall (700–1600 mm/y), thus the Isaac River provides a disproportionately large contribution to the Fitzroy's discharge (Table 1). Rainfall and streamflow are summer dominant and highly variable, both on an inter- and intra-annual timescale. Many channels throughout the FRB are ephemeral, with high flow events and floods mostly resulting from intense cyclonic or monsoonal depressions (Lough, 2007).

2.3. *Geology*

Rocks outcropping in the FRB are predominantly Permian to Palaeogene in age (Jones, 2006). Widespread Permo-Triassic sedimentary and volcanic deposits of the Bowen Basin are overlain in the south by Surat Basin Triassic and Jurassic sedimentary rocks, and small areas of Palaeozoic granitic basement in the east. Upland erosion during the Palaeogene resulted in extensive fluvial and lacustrine deposition, the remnants of which are now widespread. These materials were later reworked resulting in a series of dissected tablelands, terraces and extensive areas of subdued relief (Jones, 2006).

2.4. *Landuse*

Prior to the expansion of European pastoralism much of the catchment was covered by *Acacia*-dominated woodland, which was effectively destroyed during two episodes of intensive land clearing in the 1960s and 1970s under the Brigalow Development Scheme (Dougall et al., 2005). More recently, between 1991 and 2001 an average of ~270 km^2/y of woodland was cleared, primarily for grazing (Anon, 2006). As of 2000, over 80% of the catchment was classified as grazing, 7% as cropping and less than 4% reserved for conservation purposes (Calvert et al., 2000).

3. Methods

3.1. *Spatial analysis of fluvial change*

Based on the range of channel types previously described (Amos et al., 2008), four sites were selected representing each type of modern channel in four sub-catchments: Isaac, Comet, Nogoa and Fitzroy (Fig. 1). Depositional units within these sites were selected for drilling and dating (Fig. 2). Detailed information on channel form and floodplain topography was obtained using a Real-Time Kinematic Global Positioning System (RTK-GPS) which yielded x, y, z data to ±2 cm accuracy, and from visual analysis of air photographs and satellite images.

3.2. *Alluvial sediments*

Fifteen sediment cores from floodplain and channel environments ranging in depth from ~3–18 m (total core-length ~152 m) were obtained using an Edson Rotary 350 drill rig. Due to the highly compacted nature of many of the fine-grained cohesive units, open-head auguring was conducted until a target interval for OSL sampling was reached, and the core was then extracted in stainless steel barrels. Cores were described in terms of colour, paedogenic alteration, grain size, sedimentary structures, and the nature of unit boundaries.

Particle size analysis was conducted on selected units by dry sieving at 0.5Φ intervals (2 mm to 63 um) and particle settling techniques (Folk, 1954). Interpretations of depositional environments are based on sediment calibre and stratigraphic position. The terminology used (e.g. coarse-grained channel and fine-grained vertical accretion) broadly differentiates major depositional environments into coarse bedload and fine, suspended sediment load transport.

3.3. *Timing of fluvial change*

Floodplain and within-channel depositional environments reflecting past and present flow regimes were sampled to determine the timing of fluvial activity using OSL dating (Huntley et al., 1993; Aitken, 1998; Murray and Wintle, 2000; Olley et al., 2004a). OSL analyses were conducted on quartz grains from a total of 42 samples collected from 18 identifiable units (Tables 2 and 3). Sample preparation was designed to isolate pure extracts of 180–212 μm light-safe quartz grains, collected from the centre of the cores, following standard procedures (e.g. Aitken, 1998). Treatments were applied to remove contaminant carbonates, feldspars, organics, heavy minerals and acid soluble fluorides. The outer ~10 μm alpha-irradiated rind of each grain was removed by double etching each sample in 48% hydrofluoric acid. Radiation doses were determined from measurement of the OSL signals emitted by large (5 mm disc) aliquots of quartz using Risoe TL-DA-12 instrumentation and the modified single-aliquot regenerative dose protocol described in Olley et al. (2004b). The reported OSL palaeodose is the weighted average, estimated using the equations of Drosg (2009), of a sub-set of 24–48 individual aliquot determinations. This sub-set is identified using a radial plot (Galbraith, 1990), and is defined as those single-aliquot palaeodose measurements observed to fall within the 2-σ uncertainty band encompassing the lowest palaeodose aliquot. This approach approximates the 'minimum age model' results of Galbraith et al. (1999), and is

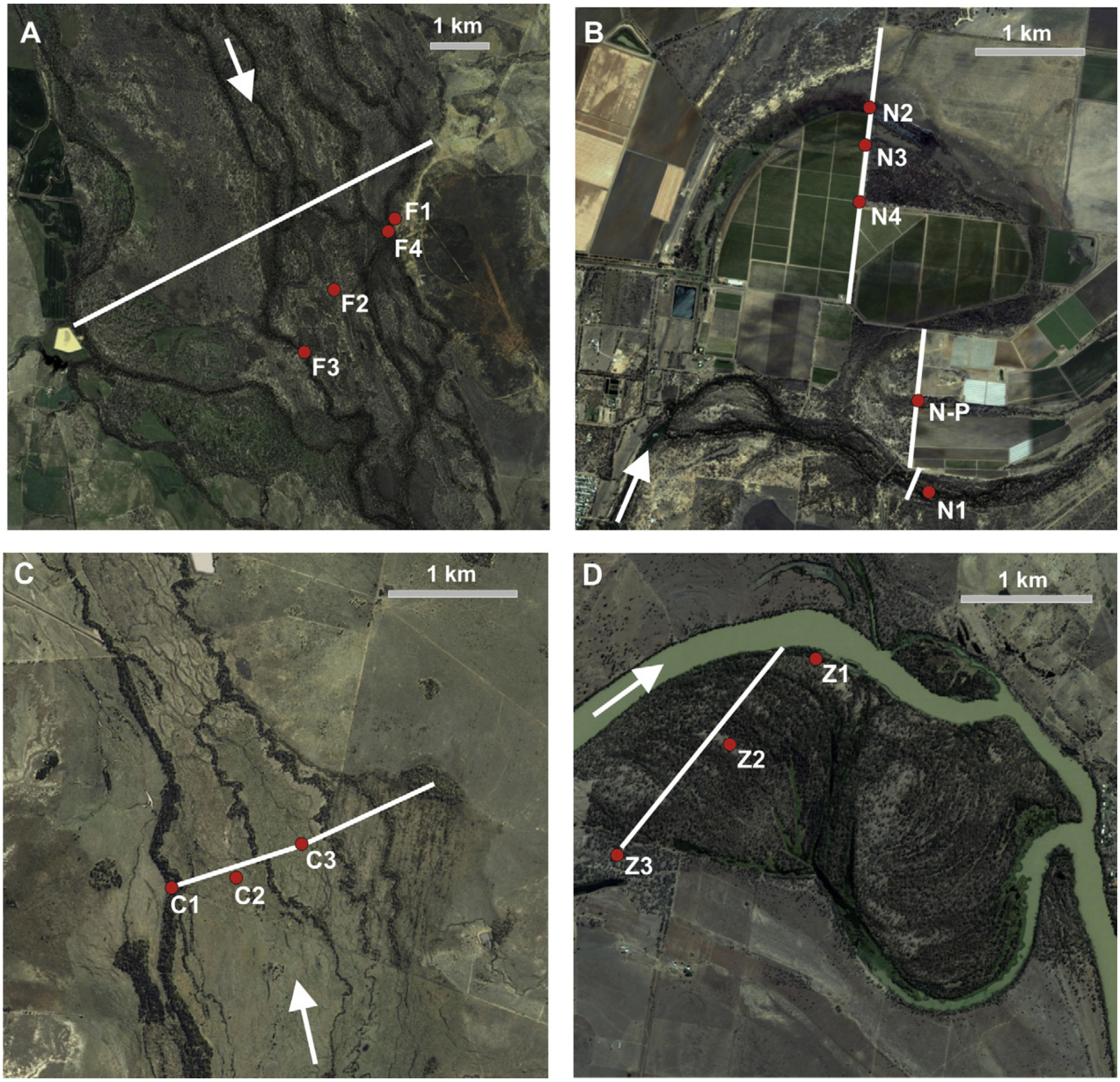

Fig. 2. Satellite images of the selected cross-sections and drill-core locations on the (A) Funnel/Isaac, (B) Nogoa, (C) Comet and (D) Fitzroy River sites.

based on the assumption that the lowest dose aliquots have the lowest proportion of emitted luminescence derived from unbleached grains. It is possible that this approach will provide over-estimates of the true age for samples consisting of poorly bleached grains, but two experimental procedures were used to anticipate this possibility. Firstly, sedimentary cores were sampled multiple times where possible, to allow investigation of geochronological consistency. The age for each unit is represented by the weighted average of all the OSL dates (up to four) from that unit. Secondly, two samples (F2-8.15, F1-6.15) were analysed using single-grain OSL, allowing the extent of partial bleaching to be identified.

Lithogenic radionuclide activity concentrations were determined using high-resolution gamma spectrometry (Murray et al., 1987), with dose rates calculated using the conversion factors of Stokes et al. (2003). β-attenuation factors were taken from Mejdahl (1979), and cosmic dose rates were calculated from Prescott and Hutton (1994). Concentrations of ^{238}U, ^{226}Ra and ^{210}Pb are consistent with secular equilibrium in most samples (Table 2). The minor secular disequilibrium observed in some samples is not sufficient to appreciably offset ages derived by assuming equilibrium persistent conditions. Hence, the ages reported here reflect the radionuclide contents 'as-measured'.

4. Results and analysis

4.1. Funnel ck-Isaac

Funnel Creek, in the Isaac sub-catchment (Fig. 1), was selected to represent the long, linear anabranching river pattern (Amos et al., 2008). Numerous (3–7) low-sinuosity channels occupy wide valley floors, frequently with no dominant channel (Fig. 2A). The selected transect has a drainage area of 6500 km^2, and the 7 km-wide alluvial valley floor is occupied by six low-sinuosity channels that range in width from 30 to 110 m, and 5 to 10 m in depth (Fig. 3). Channel banks are generally steep sided, owing to their cohesive mud composition and tree-lined vegetation cover, and natural levees stand ~1.5 m above the surrounding floodplain. Channel

Table 2
OSL ages and radionuclide concentrations for the 42 fluvial samples analysed in this study. All radionuclide values are in Bq kg^{-1}. Values less than 10 (and their uncertainties) reported to 2 decimal places. Values between 10 and 30 (and their uncertainties) rounded to 1 decimal place. Values above 30 (and their uncertainties) rounded to nearest integer.

Sub-Catchment	Core #/depth (m)	^{238}U	^{226}Ra	^{210}Pb	^{232}Th	^{40}k	D.R. (Gy ka^{-1})	De (Gy)	Age (ka)
Funnel	F4/3.0	16.6 ± 1.4	15.0 ± 0.2	15.2 ± 1.9	26.1 ± 0.3	706 ± 6	2.88 ± 0.34	38 ± 3	13.2 ± 1.9
Funnel	F4/4.65	19.8 ± 1.5	25.0 ± 0.3	23.9 ± 1.9	38 ± 0	348 ± 5	2.15 ± 0.28	240 ± 30	112 ± 20
Funnel	F4/5.35	21.2 ± 2.9	21.5 ± 0.6	24.5 ± 3.6	37 ± 1	346 ± 13	2.13 ± 0.28	260 ± 15	122 ± 18
Funnel	F4/6.15	22.5 ± 1.4	15.3 ± 0.2	16.9 ± 1.7	32 ± 1	319 ± 4	1.87 ± 0.24	160 ± 20	86 ± 16
Funnel	F2/3.0	16.3 ± 2.8	20.6 ± 0.5	19.1 ± 3.8	29.9 ± 0.8	446 ± 12	2.24 ± 0.28	140 ± 10	63 ± 9
Funnel	F2/5.0	27.2 ± 2.3	24.8 ± 0.4	21.1 ± 2.6	35 ± 1	444 ± 8	2.36 ± 0.30	165 ± 10	70 ± 10
Funnel	F2/6.2	35 ± 3	25.7 ± 0.6	26.0 ± 4.2	35 ± 1	411 ± 14	2.35 ± 0.31	135 ± 10	57 ± 9
Funnel	F2/8.15	23.9 ± 2.2	21.1 ± 0.4	20.2 ± 2.5	39 ± 1	399 ± 8	2.24 ± 0.29	105 ± 10	47 ± 8
Funnel	F2/8.2	22.7 ± 3.1	28.5 ± 0.7	24.4 ± 3.7	39 ± 1	400 ± 13	2.29 ± 0.30	100 ± 10	44 ± 7
Funnel	F3/2.9	35 ± 2	31 ± 0	29.4 ± 2.8	44 ± 1	403 ± 8	2.57 ± 0.33	100 ± 5	39 ± 6
Funnel	F3/5.9	13.9 ± 2.0	23.0 ± 0.4	17.8 ± 2.5	26.6 ± 0.5	400 ± 8	1.99 ± 0.25	200 ± 15	101 ± 15
Funnel	F3/7.9	11.3 ± 1.5	11.5 ± 0.2	10.8 ± 1.9	18.4 ± 0.6	468 ± 8	1.93 ± 0.23	150 ± 10	78 ± 11
Funnel	F3/10.35	5.08 ± 1.60	8.72 ± 0.25	5.08 ± 2.28	13.7 ± 0.3	497 ± 11	1.82 ± 0.21	175 ± 10	96 ± 13
Nogoa	N1/5.24	16.5 ± 1.2	14.7 ± 0.2	14.2 ± 1.6	22.0 ± 0.3	270 ± 4	1.51 ± 0.19	18 ± 2	11.9 ± 2.0
Nogoa	N1/8.00	16.0 ± 2.1	16.2 ± 0.4	14.8 ± 2.8	26.2 ± 0.5	272 ± 9	1.56 ± 0.20	15 ± 2	9.62 ± 1.82
Nogoa	N2/7.70	28.4 ± 2.4	35 ± 1	35 ± 3	45 ± 1	484 ± 10	2.81 ± 0.37	33 ± 2	11.7 ± 1.7
Nogoa	N2/8.20	28.2 ± 2.6	31 ± 1	28.4 ± 3.4	46 ± 1	509 ± 13	2.80 ± 0.37	30 ± 3	10.7 ± 1.8
Nogoa	N3/5.95	12.2 ± 1.4	13.7 ± 0.3	15.9 ± 1.6	20.3 ± 0.5	366 ± 8	1.76 ± 0.21	40 ± 3	22.7 ± 3.3
Nogoa	N3/6.10	12.8 ± 1.4	15.7 ± 0.3	19.8 ± 1.9	22.3 ± 0.8	415 ± 9	1.99 ± 0.24	35 ± 3	17.6 ± 2.7
Nogoa	N3/7.25	15.3 ± 1.7	15.3 ± 0.4	19.9 ± 2.2	22.3 ± 0.7	375 ± 10	1.87 ± 0.23	40 ± 2	21.4 ± 3.0
Nogoa	N3/8.75	19.4 ± 1.7	20.7 ± 0.4	20.9 ± 1.8	28.1 ± 0.4	379 ± 8	1.99 ± 0.25	38 ± 2	19.1 ± 2.7
Nogoa	N4/3.20	21.0 ± 1.6	20.5 ± 0.4	22.8 ± 2.0	30 ± 0	385 ± 9	2.14 ± 0.27	24 ± 2	11.2 ± 1.7
Nogoa	N4/5.8	6.16 ± 1.05	7.22 ± 0.20	6.63 ± 1.43	9.57 ± 0.34	175 ± 5	0.88 ± 0.10	20 ± 2	22.7 ± 3.6
Nogoa	N4/7.25	6.14 ± 1.52	8.32 ± 0.26	8.67 ± 2.10	11.9 ± 0.3	195 ± 7	0.99 ± 0.12	24 ± 2	24.2 ± 3.7
Nogoa	N4/8.75	6.86 ± 1.07	7.35 ± 0.19	6.98 ± 1.34	10.6 ± 0.3	176 ± 5	0.88 ± 0.11	20 ± 2	22.7 ± 3.6
Nogoa	N4/10.40	4.36 ± 1.35	6.40 ± 0.20	6.01 ± 1.55	7.64 ± 0.24	63 ± 3	0.47 ± 0.06	13 ± 2	27.7 ± 5.6
Nogoa	N-P/5.85	11.9 ± 1.0	11.7 ± 0.2	14.0 ± 1.2	17.5 ± 0.4	246 ± 5	1.34 ± 0.16	40 ± 3	29.9 ± 4.4
Nogoa	N-P/6.05	17.1 ± 1.1	20.4 ± 0.3	16.5 ± 1.3	33 ± 1	194 ± 4	1.49 ± 0.20	160 ± 5	107 ± 15
Comet	C1/4.00	34 ± 2	28.4 ± 0.4	32 ± 3	40 ± 1	469 ± 8	2.71 ± 0.35	120 ± 10	44 ± 7
Comet	C1/7.25	20.6 ± 2.4	23.7 ± 0.5	18.7 ± 2.6	33 ± 1	347 ± 10	1.97 ± 0.26	100 ± 5	51 ± 7
Comet	C1/10.40	25.6 ± 1.5	26.9 ± 0.3	27.4 ± 1.5	39 ± 1	319 ± 6	2.10 ± 0.28	100 ± 5	48 ± 7
Comet	C1/11.85	12.0 ± 1.0	12.1 ± 0.2	14.1 ± 1.1	16.0 ± 0.3	177 ± 4	1.07 ± 0.14	55 ± 5	51 ± 8
Comet	C1/15.28	32 ± 2	29.3 ± 0.4	26.3 ± 1.6	39 ± 0	427 ± 8	2.40 ± 0.32	250 ± 30	104 ± 19
Comet	C1/17.70	13.8 ± 2.0	13.3 ± 0.3	13.5 ± 2.8	15.7 ± 0.7	133 ± 4	0.92 ± 0.13	180 ± 10	196 ± 30
Comet	C2/4.75	26.1 ± 2.5	26.4 ± 0.5	27.1 ± 3.3	37 ± 1	397 ± 10	2.35 ± 0.31	100 ± 5	43 ± 6
Comet	C2/8.00	16.7 ± 2.6	23.9 ± 0.6	20.6 ± 3.3	28.5 ± 0.7	305 ± 12	1.78 ± 0.24	135 ± 5	76 ± 11
Comet	C2/10.45	17.5 ± 3.0	19.8 ± 0.6	21.7 ± 4.1	30 ± 1	286 ± 12	1.76 ± 0.24	80 ± 5	45 ± 7
Comet	C2/13.33	13.6 ± 2.3	12.1 ± 0.4	14.9 ± 3.2	16.8 ± 0.6	186 ± 7	1.12 ± 0.15	50 ± 5	45 ± 8
Comet	C3/13.5	12.1 ± 1.1	13.0 ± 0.2	15.9 ± 1.4	16.5 ± 0.5	166 ± 3	1.07 ± 0.14	46 ± 3	43 ± 6
Fitzroy	Z1/3.55	9.06 ± 1.37	7.63 ± 0.25	9.83 ± 1.83	11.6 ± 0.3	241 ± 8	1.19 ± 0.14	20 ± 2	16.8 ± 2.7
Fitzroy	Z2/4.14	5.26 ± 2.84	5.58 ± 0.26	9.71 ± 2.51	7.00 ± 0.34	125 ± 6	0.75 ± 0.09	20 ± 5	26.7 ± 7.5
Fitzroy	Z3/11.00	25.7 ± 1.3	26.8 ± 0.3	26.2 ± 1.6	37 ± 1	408 ± 7	2.31 ± 0.30	55 ± 5	23.8 ± 3.9

Table 3
OSL ages with uncertainties rounded to nearest 1 ka for active bedload units. Weighted average ages are reported where $n > 1$.

Active Bedload Samples	N	Age (ka)
Funnel F1/3.0	1	13 ± 2
Funnel F1 Lower	3	105 ± 15
Funnel F2	2	45 ± 5
Funnel F3	3	89 ± 10
Nogoa N1	2	11 ± 2
Nogoa N2	2	11 ± 1
Nogoa N3	4	20 ± 2
Nogoa N4	4	24 ± 2
Nogoa N-P/	1	30 ± 4
Comet C1 upper	3	50 ± 4
Comet C1/15.3 m	1	104 ± 19
Comet C1/17.7 m	1	196 ± 30
Comet C2	2	45 ± 5
Comet C3	1	43 ± 6
Fitzroy Z1	1	16.8 ± 2.7
Fitzroy Z2	1	26.7 ± 7.5
Fitzroy Z3	1	23.8 ± 3.9

bed sediment varies between channels and is mainly medium to coarse sand and gravel.

4.1.1. Isaac alluvial sediments

Four cores were extracted across the valley floor (Fig. 3). Core F1 was taken to a depth of ∼10m and consists almost entirely of fine-grained silts and mud which proved unsuitable for dating. Core F4 was augered to a depth of ∼7.5 m from a within-channel environment on the eastern valley margin (Fig. 2A) and is characterized predominantly by coarse sands and gravels within a muddy matrix.

The F2 drill site was located on the floodplain, between anabranching channels 1.8 km wide and 6 km long (Fig. 3). The core penetrated 10m, and contains two sets of alternating coarse and fine-grained units. The basal unit consists of some gravel and pebbles (∼4 cm) within a ∼2 m thick unit of silty coarse, to very coarse, sands. This is overlain by a ∼2.5 m unit of brown cohesive fine-very fine sandy silt and clay (Fig. 3). This fine-grained unit is overlain by a ∼1.5 m unit of silty medium sands with rare pebbles, which fines upwards to cohesive fine-medium sandy mud present in the top 3m of the core. Core F3 was located on a within-channel bench and was augered to a depth of 16m (Fig. 3). Channel bed material at this location is very-coarse-to coarse sand with abundant gravel (5–20 mm axis length). The basal ∼10 m of the

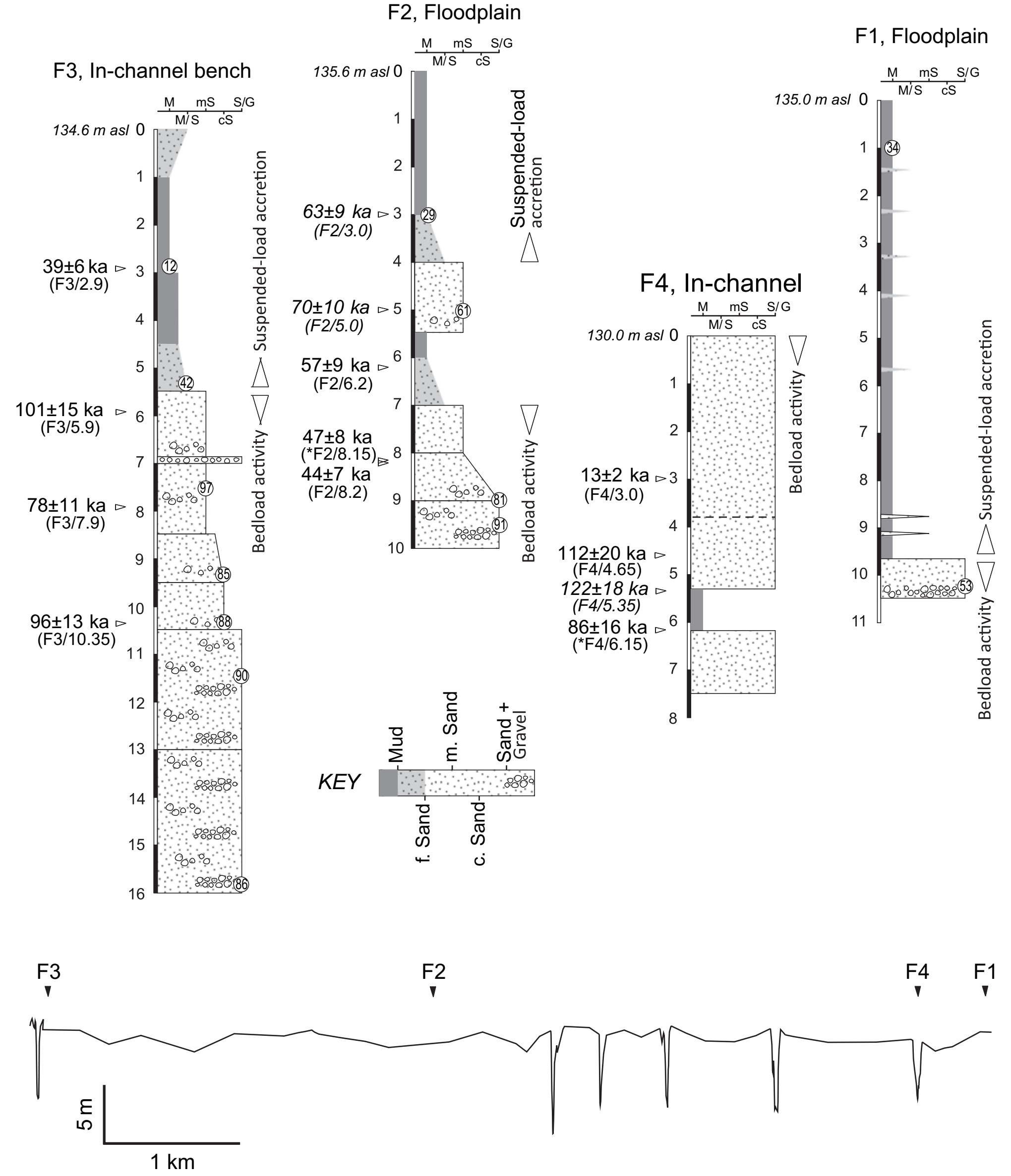

Fig. 3. Surveyed floodplain transect, core log stratigraphy and OSL data for the Isaac/Funnel site (Fig. 2A). Percentage sand is indicated in the circle adjacent to each sample unit. Core elevation is denoted in metres above Australian Height Datum = Australian Sea Level (ASL).

sequence is sandy, and fines upwards from dominantly very-coarse sand at the base to dominantly medium sand at 7 m depth. The upper ~5.5 m of core is fine-grained. There is sandy mud from ~6.5 m to 3 m, the sand grain sizes fining upwards from medium to very fine, and sand proportion decreasing upwards from 41% to 12%. There is a clay-rich cohesive mud deposit from 3 to 1 m, overlain by a metre of siltier mud.

4.1.2. Dating and interpretation of fluvial deposits in the Isaac sub-catchment

OSL estimated ages for the selected samples in these cores are outlined in Fig. 3 and Table 2. Specific consideration of OSL reversals is given in more detail in Section 5, but in general, three dates from this site appear to be unreliable due to partial bleaching. Some apparent stratigraphic reversals occur in the upper samples of Core F2, where upper units are dated as older than the underlying coarse-grained channel facies, but all samples within this core date to within uncertainties of each other. In addition, sample F2/8.2, which returned an age of 44 ± 7 ka was dated using single-grain OSL techniques and compares very favourably to the overlying F2/8.15 sample yielding a date of 47 ± 8 ka.

In Core F4, the OSL date for the coarse-grained deposits at 3m below the modern channel bed returned a relatively young age of 13.2 ± 1.9 ka, suggesting that bedload channel activity has continued from at least this time period to present. Although no distinct change in grain size occurred from the surface (modern channel bed material) to >5 m, a diffuse unit boundary is marked by mottling at ~3.8 m. Three samples collected at depth in Core F4 yield ages an order of magnitude greater than that at 3 m. These dates overlap within uncertainties and taken together, produce a weighted average age of 105 ± 15 ka.

The coarse-grained unit at the base of Core F2, likely to be within-channel bedload deposits, was sampled twice for OSL dating, yielding ages of 47 ± 8 ka and 44 ± 7 ka, the latter age via single-grain analysis. The weighted average age for this unit is 45 ± 5 ka (Table 3). The sample at 6.2 m, within finer sediments interpreted as either channel bench accretion, channel-fill (following channel abandonment) or vertical floodplain accretion, yielded an age of 57 ± 9 ka (Fig. 3). Two samples, higher in the sequence, yielded ages of 70 ± 10 ka and 63 ± 9 ka, which we interpret as over-estimates due to partial bleaching. Dates from the basal coarse unit in this core suggest that the channel was transporting bedload material in its current location by approximately 50 ka and, while acknowledging associated dating errors, the persistence of an anabranching channel throughout this time seems probable.

The fine-grained upper ~6 m of Core F3 represents the in-channel bench deposit and the thick sand unit below is interpreted to be channel bed material deposits. As in Core F4, a change in sediment colour and the appearance of mottling and oxidation was noted at a depth of ~4 m below the surface. The OSL sample at 2.9 m, within the upper unit of core F3 returned an age of 39±6 ka, while three samples from depths 5.9 m, 7.9 m and 10.35 m produced ages which were equivalent within uncertainties, together having a weighted average age of 89 ± 10 ka (Table 3). Interestingly, both cores F3 and F4 returned basal ages of much older alluvial material: between 70 and 110 ka. Unfortunately, the augering technique did not enable detailed description of the boundary or contact between the older and the overlying younger channel facies, evident in cores F3 and F4.

4.2. Nogoa

The Nogoa site has a drainage area of ~16,000 km^2 and consists of an anabranching pattern with two to three channels of 30–50 m width that appears to be inset within an older meandering river pattern (Fig. 2B). Islands separating the anabranches lie 4–6 m below a broad floodplain up to 5 km in width, displaying a well-preserved single amplitude, palaeomeander assemblage including cutoffs, scroll bars and abandoned channels (Fig. 2B). Although the present Nogoa at this location occupies an anabranching pattern, there is no evidence to suggest that the adjacent palaeomeanders were multi-thread channels.

4.2.1. Alluvial sediments in the Nogoa sub-catchment

Five cores (N1–N4 and N-P in Fig. 4) were augered from this site to a depth of 10-11m. Approximately 5 m of basal coarse sand are preserved in core N1, located on a contemporary mid-island ridge between anabranching channels. This is overlain by 3.75 m of fine-grained sediments, which display decreasing sand content with height, from sandy mud at the base of the unit to mud at the top.

Cores N2, N3 and N4 are located on the palaeofloodplain surface at an average elevation of 4–6 m higher than the mid-island core at N1. Core N2 was extracted from the centre of the palaeomeander and contains an 8m thick fine-mud deposit overlying a gravelly and muddy very-coarse sand deposit. Gravel clasts of up to 2.5 cm were recorded in this unit. The upper facies consists of cohesive muds with some sand and gravel clasts in the basal 1.3 m of the unit. Cores N3 and N4 were taken from remnant scroll bars on the inside bend of the palaeomeander and display upper units of very fine sand and silt overlying coarser deposits (Fig. 4). In Core N3, the basal deposit is comprised of slightly gravelly fine sand. In Core N4, the basal deposit is composed of medium-coarse sand and gravel.

Core N-P was collected from the scroll bar of another adjacent palaeomeander, and comprises a similar sequence of mud overlying a sand deposit, although this core also penetrated an underlying fine-grained deposit, at ~6 m depth. The sand deposit in Core N-P contained thin muddy drapes between 1 and 4.5 m that were mostly between 10 and 50 mm thick, but with some up to 100 mm thick.

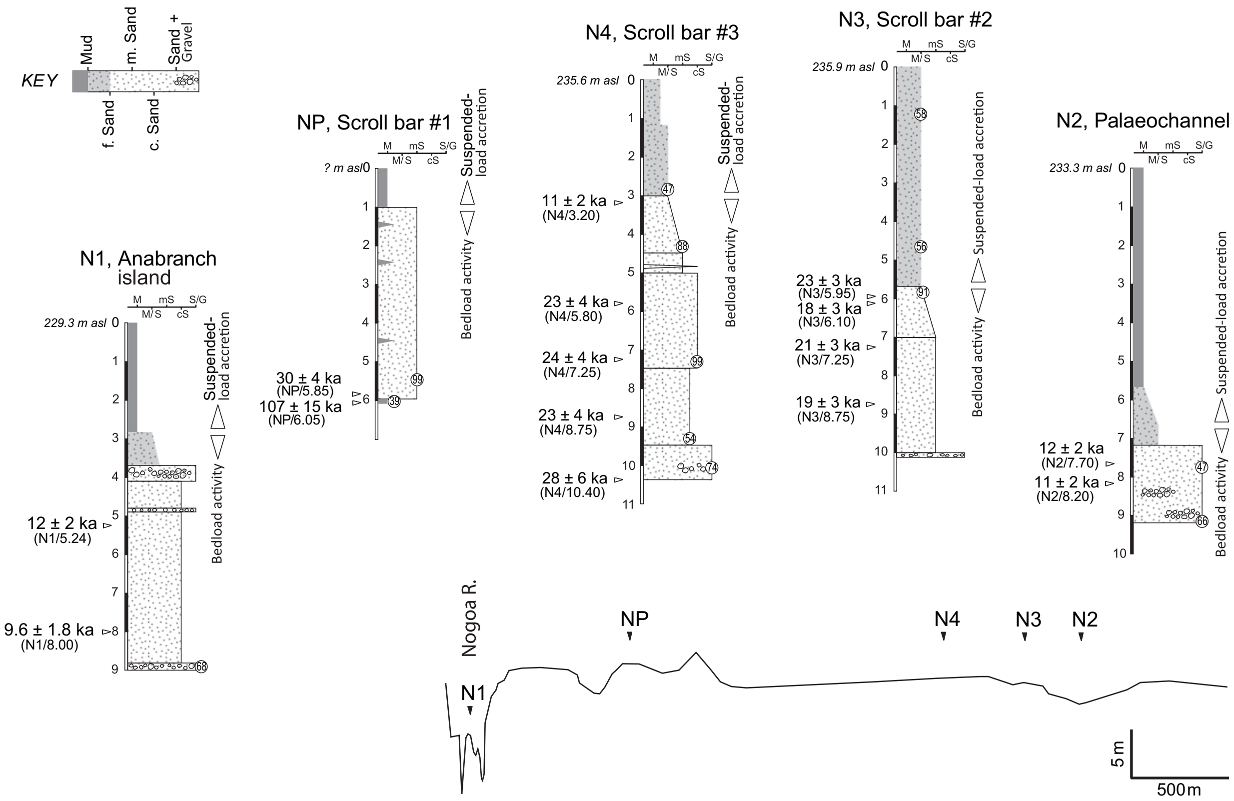

Fig. 4. Surveyed floodplain transect, core log stratigraphy and OSL data for the Nogoa site (Fig. 2B). Percentage sand is indicated in the circle adjacent to each sample unit. Core elevation is denoted in metres above Australian Height Datum = Australian Sea Level (ASL).

4.2.2. Dating and interpretation of fluvial deposits in the Nogoa sub-catchment

The OSL ages for the dated fluvial deposits at this site are indicated in Fig. 4. The ~5 m thick basal channel facies identified in N1 is considered typical of a fining upward sequence with coarse channel facies overlain by fine-grained vertical accretion deposits and is likely to reflect island aggradation through coarse bedload transport and progressive fining upwards with increasing island height. Two OSL samples from these deposits returned a weighted average age of 11 ± 2 ka (Table 3). Interestingly, the basal coarse-grained unit from core N1 is essentially coeval with the channel-fill deposit of the mid-palaeomeander core N2, which yielded two ages of 11.7 ± 1.7 ka and 10.7 ± 1.8 ka (weighted average: 11 ± 1 ka). Sediment calibre and stratigraphy in both N3 and N4 cores are considered typical of a meandering channel sequence with coarse channel facies indicative of point-bar accretion deposits, which fine upwards to vertical-accretion floodplain sediments. Coarse-grained units from cores N3 and N4 have each been sampled four times for OSL dating, and in both cores, all four ages are equivalent within uncertainties. Weighted average ages of 20 ± 2 ka and 24 ± 2 ka have been calculated for coarse-grained units in N3 and N4 respectively (Table 3). The fine-grained facies from N4 has a single OSL date of 11.2 ± 1.7 ka suggesting that deposition of fine-grained sediment in this location was broadly coincident with coarse-grained in-channel deposition in both the contemporary anabranching channel and the palaeomeander.

The sample from the channel sands from 5.8 m depth in the outer palaeomeander site (N-P) produced an age of 29.9 ± 4.4 ka, suggesting deposition occurred coeval with, or just before, deposition of the coarse scroll-bar facies dated from N3 and N4. The sample taken from the fine-grained unit at the base of core N-P produced an age of 107 ± 15 ka, suggesting an old floodplain deposit, overtopped by a later episode of channel deposition probably following channel avulsion.

Collectively, OSL dates from this site suggest that the palaeomeander was laterally migrating between 29.9 ± 4.4 ka and 19.9 ± 1.8 ka and appear to have been abandoned between 10–12.5 ka. The present Nogoa anabranching system was active around 9.9 to 11.4 ka which is roughly coincident with palaeomeander abandonment. It is possible both channels may have remained active during this time and the core at N1 reflects sediment transport of coarse sands within a flood chute channel in he palaeomeander. Alternatively, abandonment of the meandering channel system occurred between 11.4–12.5 ka and subsequent island aggradation within the current anabranching system commenced from 11.4 ka. Under either scenario, a change in-channel planform from laterally active meandering to contemporary anabranching had commenced by ~11 ka.

4.3. Comet

The Comet site has a drainage area of ~4000 km^2 and is representative of an anabranching pattern with more sinuous anabranches (relative to the Funnel-Isaac site) and one to two dominant channels (Amos et al., 2008) (Fig. 2C). The transect consists of five channels, each 30–50 m in width, and a 6 km-wide floodplain (Fig. 5). Channel cross-sections are typically U-shaped, and densely tree-lined with in-channel islands. No evidence of lateral activity or erosion was observed at the site, though satellite images reveal evidence of a relict meandering system elsewhere in the Comet sub-catchment.

4.3.1. Alluvial sediments in the Comet sub-catchment

Three cores were extracted across the main channels of the Comet at this site (Fig. 5). Core C1 was extracted within the channel boundary of one of the main anabranch channels to a total depth of ~18 m. The basal ~1 m of the core consists of coarse sand, with pebbles (>2 cm) in the lowermost 40 cm. This is overlain by approximately 12 m of dominantly orange-brown muddy fine-grained sand. The sand:mud ratio varies through this unit, with sandier and muddier intervals. The upper facies is a brown cohesive mud unit that occupies the upper 4m of the core and contains occasional slightly sandier beds up to 100 mm thick. Cores C2 and C3 were collected from the floodplain to a depth of 13 m. These display similar sedimentary sequences with basal sand units (fine to very coarse) overlain by cohesive muds (Fig. 5).

4.3.2. Dating and interpretation of fluvial activity in the Comet sub-catchment

The coarse-grained sediments are interpreted as channel facies and the two finer grained units as vertical accretion on islands and/or floodplain environments. Although they cannot be easily divided on the basis of the core log data, the OSL-derived ages of samples from the basal 14 m sandy unit from Core C1 are assumed to represent at least two distinct periods of deposition, possibly represented by two fining-upwards units. The basal channel facies yields OSL ages of 196 ± 30 ka at 17.7 m, and 104 ± 19 ka at 15.3 m, topped by four statistically equivalent ages from 11.85 m up to 4.00 m that taken together yield a weighted average of 50 ± 4 ka. The uppermost OSL age from sands at 4.00 m indicates fine-grained deposition was dominant after 44 ± 7 ka. The age for the upper coarse unit in C1 compares well to the dates obtained from coarse-grained facies in Cores C2 and C3. Four OSL dates were obtained from the coarse-grained unit in Core C2, with a clear age reversal present. The sample at 8 m produced an age of 76 ± 11 ka, in contrast to the two lower samples which are equal within uncertainties and together provide a weighted average age of 45 ± 5 ka (Table 3). This younger age is clearly the correct one, as it is unlikely that two separate samples could provide the same incorrect age. Furthermore, the age calculated for the fine-grained unit capping these coarse bedload deposits is 43 ± 6 ka, providing further support for a mid MIS 3 age for the underlying coarse-grained unit, and a single OSL age from the stratigraphically equivalent coarse-grained unit in Core C3 returned an age of 43 ± 6 ka.

Overall at this site, OSL dates provide evidence for mid MIS 3 coarse-grained fluvial transport in the main anabranching channels, with evidence for fine-grained vertical accretion deposition in upper parts of islands or floodplains broadly synchronous with this time period.

4.4. Fitzroy

The Fitzroy (main stem) site is located ~60 km upstream of the tidal limit and has a drainage area of ~136,000 km^2. This site is representative of the large, unconfined meandering river pattern and consists of a single, sinuous ($P = 1.8$) meandering channel ~250 m wide and ~10 m deep (Amos et al., 2008) (Fig. 2D). Channel banks are typically well-vegetated, and a 3 to 5 km-wide floodplain preserves evidence of lateral channel migration in the form of scroll bars on the inside of the meander bend (Fig. 2D). Eight major scroll bars range in height from ~17 to 20 m above the present channel bed, and these lie inset within an older alluvial surface standing 5–6 m above the scroll crests (Fig. 6).

4.4.1. Alluvial sediments in the Fitzroy sub-catchment

Three cores were taken across the scroll ridges and swales at this site. Core Z1 is located proximal to the main channel and consists of basal medium to very coarse sand overlain by 2.2 m of very fine to fine-grained sandy mud. Core Z2 is located on a central scroll-bar ridge, and comprises basal very coarse sand overlain by 2.2 m of

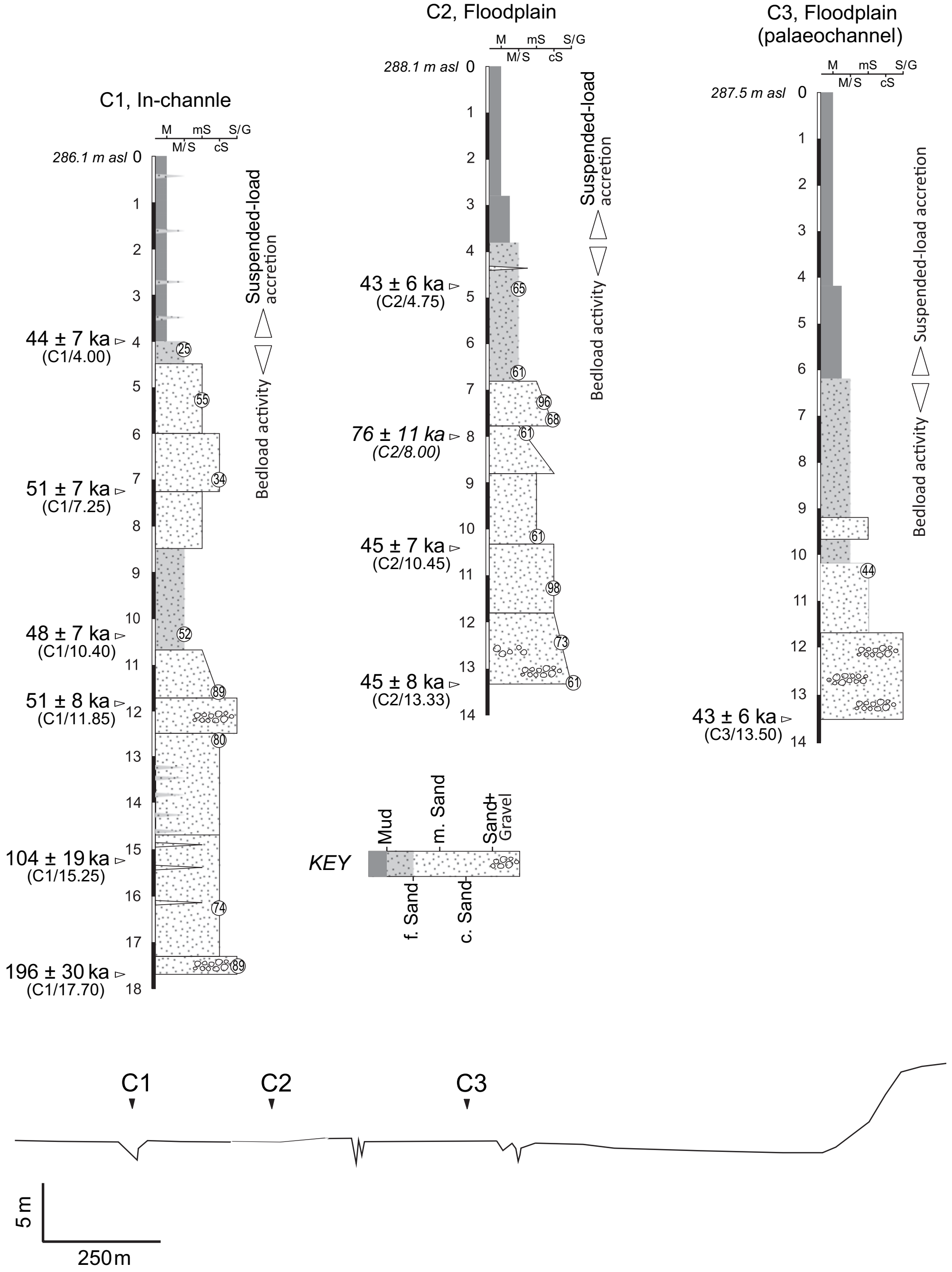

Fig. 5. Surveyed floodplain transect, core log stratigraphy and OSL data for the Comet site (Fig. 2C). Percentage sand is indicated in the circle adjacent to each sample unit. Core elevation is denoted in metres above Australian Height Datum = Australian Sea Level (ASL).

mud. Core Z3 is located on the terrace and penetrated 11 m. It has silty, fine sand at its base, overlain by a ~5.5 m thick sandy mud unit containing interbedded sandier and muddier units with occasional sandy beds of 20–30 cm thick. An upper unit comprised of red-brown cohesive mud overlies this.

4.4.2. Dating and interpretation of fluvial activity in the Fitzroy

Samples for age dating from these cores were collected from the basal sand units, within 1-2m of the sand–mud transition (Fig. 6). Core Z1 returned the youngest age, of 16.8 ± 2.7 ka, Core Z2 returned an age of 26.7 ± 7.5 ka, and Core Z3 returned an age of 23.8 ± 3.9 ka. The resolution of these ages is not sufficient to allow us to determine the period over which this channel migration occurred, however we can say that the most recent migration of the Fitzroy River to its current position in this location had been completed by 16.8 ± 2.7 ka.

5. The Fitzroy river basin OSL chronology

As anticipated, the large aliquot technique used in this study resulted in the determination of some OSL ages that are stratigraphically inconsistent (<10% of all determinations). In four samples (i.e. F4/5.35, F2/3.0, F3/5.0, and C2/8.0) partial bleaching produced age over-estimates, though in two of those cases the ages

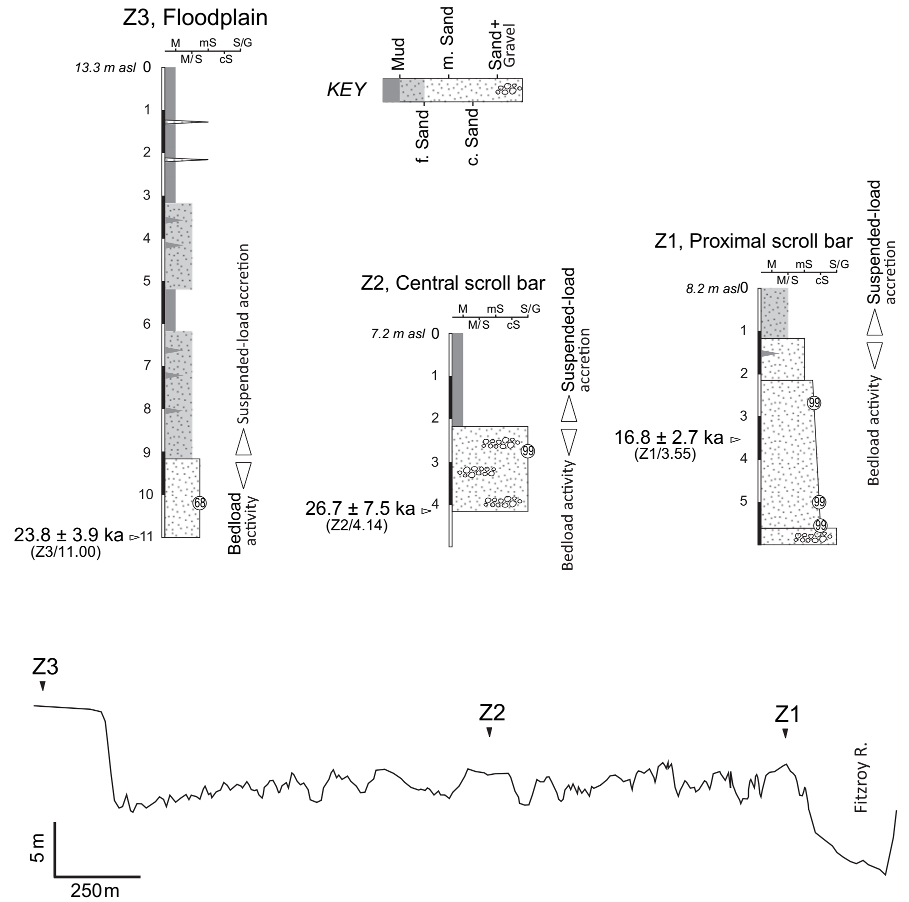

Fig. 6. Surveyed floodplain transect, core log stratigraphy and OSL data for the site at Long Island on the Fitzroy (Fig. 2D). Percentage sand is indicated in the circle adjacent to each sample unit. Core elevation is denoted in metres above Australian Height Datum = Australian Sea Level (ASL).

fail to overlap (at 2-σ) by a very small margin. These four results are excluded from further consideration.

A frequency histogram of the 38 OSL ages (Fig. 7) was devised to broadly identify patterns in fluvial activity as done in previous studies (Nanson et al., 1992, 2008; Cheetham et al., 2010). This method provides an approximate estimation of fluvial age distributions which may be affected by preservation (Lewin and Macklin, 2003; Bridgland and Westaway, 2008b), accessibility (Cheetham et al., 2010) and dating precision (Nanson et al., 2008). All of these factors are likely to have contributed to the distribution of ages presented in Fig. 7. The histogram approach also has the associated risk of directly linking changes in the scale of frequency peaks with changing magnitude of fluvial activity. In addition, the inclusion of all OSL 'depositional' ages in such histograms ignores any of the information linking each age to particular fluvial environment or process. In order to utilise such potentially valuable 'process' information, OSL ages determined from bedload-dominated (sandy or gravelly) channel-fill units are taken to indicate 'fluvial activity', or more precisely, the bedload depositional age and cessation of fluvial re-working; conversely OSL ages from

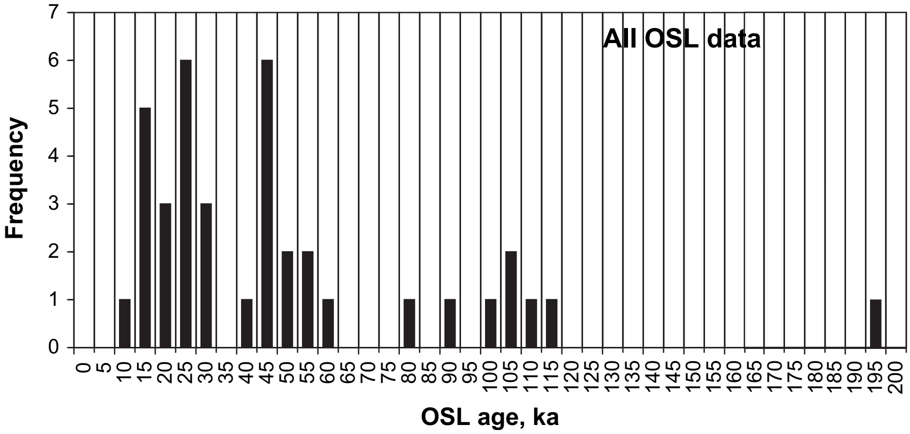

Fig. 7. Frequency histogram of all depositional OSL ages obtained in this study. Bin size 5 ka.

fine-grained units (i.e. suspended/wash-load environments) overlying channel-fills are taken to indicate vertical accretion on point-bars, floodplains, channel contraction or abandonment.

Fig. 8 shows the ages of bedload channel units, weighted according to uncertainty using a probability density function to illustrate concentrations in our data. The differences in peak height do not indicate differences in the magnitude of fluvial activity but rather our confidence in the integrity of the age intervals assigned to different deposits.

6. Discussion

The reconstruction of fluvial dynamics from preserved sedimentary sequences and river terraces has contributed to our understanding of global Quaternary climate change (Bridgland et al., 2007). Detailed reconstructions throughout many parts of Europe (Vandenberghe et al., 1994; Kasse et al., 1995; Fuller et al., 1998; Starkel, 2003; Macklin et al., 2006, 2010) and Australia (see Nanson et al., 2008 for review) demonstrate the potential for such studies to infer the nature and extent of past hydrological events. The absence of extensive river terrace sequences in many of Australia's low-lying, tectonically stable regions, however, has meant that issues of preservation potential as a result of fluvial re-working (Lewin and Macklin, 2003; Bridgland and Westaway, 2008b; Macklin et al., 2010) and systematic regional biases (Macklin et al., 2010) are important to address in the accurate interpretation of fluvial archives. Widespread sampling of sedimentary sequences across a range of physiographic, climatic and geomorphic environments is essential. Within the context of Australian studies, this study presents the first alluvial chronology that outlines the timing of fluvial activity over the last glacial cycle (~110 ka) from the tropical northeast of the continent. The FRB's geographic position in the pathway of tropical air masses that potentially influence the inland Cooper Creek (Lake Eyre Basin), and the Murray-Darling and coastal river systems to the southeast, makes this an important, yet hitherto unexplored, palaeoenvironmental record. Published data from other well-studied regions (e.g. Bowler, 1978; Page et al., 1996, 2009; Magee et al., 1995; Magee and Miller, 1998, Nanson et al., 2008; Kemp and Rhodes, 2010) provide a useful framework for comparison with our new OSL chronology.

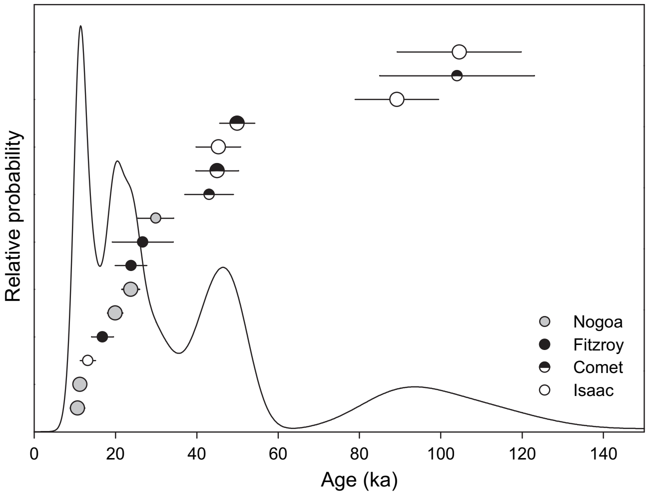

Fig. 8. OSL ages with uncertainties for the active bedload channel deposits in the four sub-catchments overlain with a probability density function. Large symbols represent weighted means of multiple samples (see Table 3 for *n*. Small symbols indicate single ages).

6.1. Basin-wide fluvial activity

Data presented in Fig. 8 allows some commentary on the timing of fluvial activity throughout the Fitzroy Basin as a whole. The channel pattern in both the Isaac and the Comet sub-catchments is anabranching and, interestingly, both catchments contain evidence (at F2, C1, C2 and C3) of a significant fluvial episode occurring near 45 ka. Channel facies dated to this time are overlying an older fluvial unit dated to between 99 ± 26 and 104 ± 19 ka. These ages are quite different to those obtained for the Nogoa and Fitzroy sub-catchments which preserve evidence of more recent episodes of fluvial activity spanning a time period from 30 ± 4.4 ka to 11 ± 1 ka. Limited evidence, in the form of a single dated deposit for such an episode was found in the Isaac (F4/3.0 m) and Comet catchments for the period immediately before, and including the LGM.

It is possible that such an episode did occur in these catchments and that the most likely fluvial response to changes in sediment load and discharge was increased frequency of channel avulsion and subsequent infilling within an anabranching system. To detect this within the wide alluvial valleys present in these sub-catchments would require a more spatially dense sampling design. However, it is also possible that fluvial response to late Quaternary climate changes in the basin were diachronous and that the Isaac and Comet sub-catchments may not have responded dramatically to changes in flow and sediment load at this time for reasons which relate primarily to aspects of 'landscape sensitivity' (Thomas, 2004). For example, one obvious feature of these two anabranching sub-catchments is the extent of hillslope-channel decoupling with both river systems occupying very broad alluvial valley floors with long distances between channels and the adjacent hillslopes. Climate-induced changes to sediment loads via reduced vegetation cover on hillslopes (Kershaw, 1992; Moss and Kershaw, 2000) may have increased delivery of sediment to footslopes and valley margins, but is unlikely to have significantly increased sediment flux along major drainage lines. Further exploration of the nature and chronology of sediment stores along the piedmont zone in this region is warranted.

Complexities induced by spatial variability in sources and intensities of rainfall are also likely to contribute to variations in sub-basin responses. Under present climatic conditions, the Isaac sub-catchment is the main hydrological driver of the basin, contributing 50% of the Fitzroy's discharge (Dougall et al., 2005; Amos et al., 2008). Its headwaters rise ~200 km north of Rockhampton (Fig. 1) and the catchment's proximity to the coast ensures higher precipitation from warm air masses off the Coral Sea. Reductions in precipitation due to changes in climate and vegetation dynamics in tropical areas at the LGM are likely to have registered within this sub-catchment. In contrast, the Nogoa rises in the higher relief of the Carnarvon Ranges (~250 km inland) where the effects of local, spatially discrete high intensity rainfall events from the adjacent uplands on flood hydrology and floodplain sedimentation have been noted (Ciesiolka, 1987; Croke et al., 2008; Thompson et al., 2011). These aspects will also affect the preservation of fluvial sequences throughout the basin, as the higher intensity, 'flashier' nature of rainfall in the Nogoa is likely to lead to enhanced fluvial re-working of older alluvial deposits.

Further stratigraphic investigation is required in both sub-catchments, but it is possible that the basin may have responded to varying sources and intensities of moisture at this time. The data certainly advise caution when assuming that site-specific data from one part of a basin may be indicative of environmental responses throughout the basin as a whole. Such was also the case in the detailed study of post European floodplain deposition rates across a similar range of sites in the basin (Amos et al., 2009). Floodplain deposition rates based on the distribution of radionuclide's caesium

C^{137} was found to be extremely low, to non-existent, in the anabranching site on the Isaacs, compared to higher rates of deposition in both the Nogoa and the lower Fitzroy sites (Amos et al., 2009).

6.2. *Tropical Queensland*

The preliminary chronology for the FRB also has important implications for our understanding of fluvial behaviour within regional sub-tropical and tropical Queensland. The region contains well-known proxy data sets from Lynch's Crater (Kershaw, 1994; Moss and Kershaw, 2000), and the ODP drill-core 820 extracted offshore from Cairns (Moss and Kershaw, 2000, 2007). Indications of river and slope response to late Quaternary environmental change are provided by thermoluminescence (TL) and ^{14}C dating of alluvial fan sequences in the Cairns region 800 km to the north (Fig. 1) (Nott et al., 2001; Thomas et al., 2001). Alluvial fan aggradation coincided with substantial changes in vegetation cover as inferred from Lynch's Crater and the ODP drill-core 820 (Kershaw et al., 1993; Moss and Kershaw, 2000, 2007). Specifically, proxy data suggest that increasing aridity caused a regional development of grassland or very open woodland between 24 and 12 ka. The Lynch's Crater record indicates a reduction in rainfall by more than 60%, making this period the driest in the region over the last glacial cycle (Kershaw et al., 1993; Moss and Kershaw, 2000). Nott et al. (2001) argued that alluvial fan aggradation reflects a climate-driven increase in sediment yield.

We note that enhanced fluvial activity in the Fitzroy Basin is roughly coincident with this same time period before, during and after the LGM. Bedload-dominated channels are actively laterally migrating at the Fitzroy site during the period 23.8 ± 3.9 ka to 16.8 ± 2.7 ka. Likewise, lateral migration is active on the Nogoa River during 30.1 ± 4.4 to 11.2 ± 2.5 ka, and we note that morphologically similar large palaeomeanders and abandoned cutoffs are spatially widespread on satellite images throughout the Fitzroy main stem, McKenzie and Dawson Rivers. A summary of meander wavelength and amplitude measurements for representative ($n = 17$) palaeo and modern channel reaches is presented in Fig. 9. Whilst displaying some scatter, an overall reduction in meander wavelength is apparent between the two sets of channels. Part of the explanation for the observed variability is also that, in many locations, the contemporary river occupies a palaeochannel of enlarged dimensions, as is currently exemplified by the meander at the Fitzroy River site (Z1–Z3). Bankfull discharge (Q_{bf}) for this site, estimated from gauging records at the Gap (Gauging Station number 130005 A) which has a similar sinuosity and wavelength to those now preserved across the valley floor, is 9000 m^3 s^{-1} with a recurrence interval of 20 years (Dougall et al., 2005; Joo et al., 2005).

The prevalence of bedload sedimentation during this period of presumed low rainfall suggests that these rivers had sufficient transport capacity to remain laterally active and progressively build floodplains. The common occurrence of gravels within the MIS 2 bedload units also suggests a sediment transport capacity which is greater than that observed in the basin today (Douglas et al., 2006). These findings challenge the widely held expectations of drier conditions inferred throughout the region at this time.

6.3. *Continental Australia*

Fluvial activity within the Fitzroy, as defined by bedload channel deposits, occurred within three fairly well defined and discrete phases over the last glacial cycle (Fig. 8): ~110–90 ka (MIS-5), ~50–40 ka (MIS-3), ~30–10 ka (MIS-2/3). This pattern is broadly consistent with that described from the Lake Eyre Basin (Nanson et al., 2008) and southeastern Australia (Bowler, 1978; Page et al., 1991, 1996; Kemp, 2001; Kemp and Rhodes, 2010). Much of the recent debate, however, is concerned with what drives regional differences in fluvial activity. Nanson et al. (2008) recently suggested that the apparent synchroneity of fluvial activity between northern and southeastern Australia during the mid to late MIS 5 casts doubt upon the notion of an enhanced monsoon being the main driver. Nanson et al. propose the existence of a semi-permanent “La Niña” with Trade Winds crossing the Coral Sea and Queensland, thereby carrying moisture into the Lake Eyre Basin. The FRB lies at a pivotal position with respect to this argument, because any monsoon-related MIS-5 moisture recorded in the Lake Eyre Basin should likewise be recorded here as well.

6.3.1. *MIS-5*

Fluvial activity during MIS 5, as evidenced by bedload deposition, is recorded in three units. Alluvial sediments present in

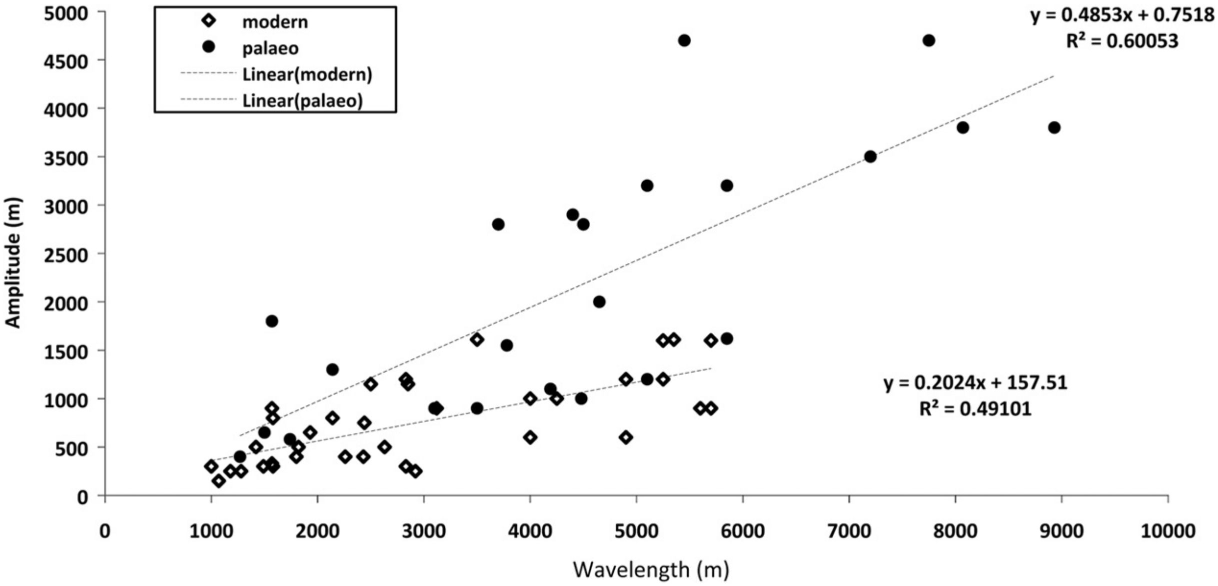

Fig. 9. Meander wavelength and amplitude for a representative array of palaeo and modern channels measured from 17 reaches in the Dawson, Mackenzie and Nogoa. The data represent a total of 59 measurements of meander wavelength and amplitude, each obtained from a section of channel comprising 2 bend apexes and 3 inflection points.

both anabranching reaches of the Isaac and Comet sub-catchments were dated to MIS 5 together with a single fine-grained unit in the Nogoa reach. It is likely, therefore, that more fluvial units of MIS 5 age are present in the valley-fills at depths exceeding those reached by the drill rig. For reasons due primarily to preservation potential and alluvial re-working, the absence of fluvial deposits from older stages is not interpreted here as indicative of causal climatic variability. Further dating within the basin is required, therefore, to advance the hypothesis that a western Pacific warm pool off the coast of Queensland is the dominant source of enhanced moisture in the Lake Eyre Basin (Nanson et al., 2008).

6.3.2. MIS 3

The FRB data concur with the dominance of a MIS 3 fluvial episode noted previously in southeastern Australia and correlates very well with dated episodes on the Riverine Plain (Page et al., 1991, 1996; Nanson et al., 2003) and in the Lachlan catchment (Kemp and Spooner, 2007; Kemp and Rhodes, 2010). Little comment can be made here of the relative magnitude of fluvial activity between MIS 5 and 3 based on our data. However, the presence of ~10 m thick MIS 3 bedload units of coarse gravels suggests that bedload transport during later phases of MIS 3 was of sufficient magnitude presumably to overtop, and erode, fine-grained MIS 5 floodplain deposits. Likewise, the occurrence of coarse gravels within these MIS 3 units implies either conditions of enhanced sediment transport capacity relative to those experienced in later phases up to today or, changes in sediment source supply,. Further stratigraphic work is required to elucidate the relative role of sediment transport and supply conditions.

6.3.3. MIS 2

The presence of sandy bedload fluvial transport in large meandering channels in the Nogoa and Fitzroy catchments immediately before, during and after the LGM in MIS 2 is an anomaly within the context of existing studies in Australia where fluvial, lacustrine and aeolian records indicate a relatively dry LGM (Nanson et al., 2008). Further dating is required but it seems likely that basin-wide responses to the proposed reduction in precipitation were not uniform or synchronous.

6.3.4. MIS 1

A notable difference between the FRB chronology and that described previously is the absence of a notable Holocen fluvial signal. Alluvial chronologies throughout the Lake Eyre Basin and southeastern Australia suggest that the Holocene saw a return to wetter conditions during MIS 1 (see Nanson et al., 2008 for summary). Significant valley floor aggradation and floodplain construction is not evident in our sites for this time period. At the Nogoa site, the late Pleistocene–early Holocene marked a change in-channel planform from meandering to anabranching. Channel infilling and abandonment is indicative of a decline in system energy and a change to anabranching channels, which return the few post-14 ka ages recorded in this study, may also be indicative of a reduction in stream power (e.g. Nanson and Knighton, 1996). It is possible that much of the alluvial material transported during later episodes of the Holocene is stored elsewhere on unsampled parts of the floodplain or within the confines of the main channel boundary on islands or within-channel benches. Inset benches formed within the main channels are widely observed throughout the catchment and in the upper, headwater catchments, are believed to be the primary store for sediments derived from Post European landuse changes (Hughes et al., 2010).

6.4. Future work

In terms of future work, the Fitzroy Basin preserves an excellent record of fluvial change by way of extensive palaeomeanders and channel cutoffs that, due largely to basin size, have only been selectively dated and partially described in this study. Likewise, the hypothesis that much of the basin's Holocene fluvial record is stored within the main boundary of enlarged channel systems is worthy of further pursuit. It may lead to a new conceptual understanding of how Australia's rivers and floodplains have adjusted to a pattern of declining discharges over an extended timescale. Further investigation of the diachronous behaviour of the basin throughout the late Quaternary period could also elucidate important detail on the role of variable sources of rainfall throughout the period of MIS 2. Together with the chronology and interpretation presented here, these aspects are likely to improve existing understanding of the key hydrological drivers in Quaternary fluvial activity in Australia.

7. Conclusion

This study provides an alluvial chronology for fluvial activity in a large river basin in northeast Queensland over the last glacial cycle. The latitudinal position of the Fitzroy across the Tropic of Capricorn places this catchment at a key location for elucidating the main hydrological drivers of Quaternary fluvial activity in northeastern Australia and the headwaters of Cooper Creek, a major river system of the Lake Eyre Basin. OSL dating indicates several discrete phases of active bedload sedimentation: at ~105–85 ka in MIS 5, at ~50–40 ka MIS 3, and at ~30–10 ka MIS 3/2. The overall timing of late Quaternary fluvial activity correlates well with previous accounts from across Australia. Fluvial activity, however, does not appear to have been synchronous throughout the basin's major sub-catchments. Fluvial activity in the meandering channels of the Fitzroy during the period immediately before, during and after the LGM, presents preliminary evidence on fluvial response to reduced rainfall and vegetation cover suggested by regional palaeoclimate indicators. The absence of a strong Holocene signal is at odds with previous accounts from elsewhere throughout Australia. The alluvial sequences of the FRB indicate a decline in system energy and floodplain re-organisation since at least MIS 3, and possibly the past 100 ka.

Acknowledgements

This work was funded through an Australian Research Council (ARC) Discovery Grant (DP0449886) awarded to JC. and support from the School of Physical, Mathematical and Environmental Sciences, University of New South Wales, Canberra. The authors are particularly grateful to Dirk Platzen who performed the laboratory analyses for the OSL dating of alluvial sediments. Simon Mockler, Chris Thompson, Celia Thompson, Andrew Hughes, Rachel Nanson and Lisa Bush, are also thanked for their assistance with field and laboratory work. We thank Damien Kelleher and Eugene Wallensky (Australian National University) for their assistance with drilling. We are also grateful to Chris Carroll (QDERM) and Bob Packett (QDERM) for valuable discussions on the basin. We are grateful to local landholders in the basin for providing access to sites and important local knowledge. John Magee provided encouraging feedback on an earlier version of this manuscript. We appreciate the comments of the two reviewers which have improved this manuscript.

References

Aitken, M.J., 1998. An Introduction to Optical Dating: The Dating of Quaternary Sediments by the Use of Photon-Stimulated Luminescence. Oxford University Press, Oxford.

Amos, K., Croke, J.C., Hughes, A., Chapman, J., Takken, I., Lymburner, L., 2008. A catchment-scale assessment of anabranching in the 140 000 km^2 Fitzroy River catchment, northeastern Australia. Earth Surface Processes and Landforms 33, 1222–1241.

Amos, K.J., Croke, J.C., Timmers, H., Owens, P.N., Thompson, C., 2009. The application of caesium-137 measurements to investigate floodplain deposition in a large semi-arid catchment in Queensland, Australia. Earth Surface Processes and Landforms 34, 515–529.

Anon, 2006. Ensham Central Project Environmental Impact Statement. Unpublished report prepared for Ensham Resource Pty. Ltd. by Hansen Consulting. June 2006.http://www.ensham.com.au/updated/eis.asp.

Bowler, J.M., 1978. Quaternary chronology of Goulbourn valley sediments and their correlation in southeastern Australia. Journal of the Geological Society of Australia 14, 287–292.

Bridgland, D.R., Westaway, R., 2008a. Climatically controlled river terrace staircases: a worldwide Quaternary phenomenon. Geomorphology 98, 285–315.

Bridgland, D.R., Westaway, R., 2008b. Preservation patterns of late Cenozoic fluvial deposits and their implications. Quaternary International 189, 5–38.

Bridgland, D.R., Keen, D.H., Westaway, R., 2007. Global correlation of late Cenozoic fluvial deposits: a synthesis of data from IGCP 449. Quaternary Science Reviews 26, 2694–2700.

Bureau of Meteorology, 2007. http://www.bom.gov.au/climate/averages.

Calvert, M., Simpson, J., Adsett, K., 2000. Land Use Mapping of the Fitzroy Catchment. The State of Queensland, Department of Natural Resources, Cooparoo.

Cheetham, M., Keene, A., Erskine, W., Bush, R., Fitzsimmons, K., Jacobsen, G.E., Fallon, S.J., 2010. Resolving the Holocene alluvial record in southeastern Australia using luminescence and radiocarbon techniques. Journal of Quaternary Science 25, 1160–1168.

Ciesiolka, C., 1987. Catchment Management in the Nogoa Watershed. Australian Water Resources Council (AWRC) Report No. 80/128. Australian Water Resources Council, Canberra, Australia.

Croke, J., Magee, J., Price, D., 1996. Major episodes of Quaternary activity in the lower Neales River, northwest of Lake Eyre, central Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 124, 1–15.

Croke, J., Magee, J., Price, D., 1998. Stratigraphy and sedimentology of the lower Neales River, West lake Eyre, central Australia: from Palaeocene to Holocene. Palaeogeography, Palaeoclimatology, Palaeoecology 144, 331–350.

Croke, J., Magee, J., Wallensky, E., 1999. The role of the tropical monsoon in the western catchments of Lake Eyre central Australia during the Last Interglacial. Quaternary International 57, 71–80.

Croke, J.C., Purvis-Smith, D., Thompson, C.J., Lymburner, L., 2008. The effect of valley constrictions on flood inundation and catchment scale sediment delivery in the Fitzroy River Basin, Australia. In: Schmidt, J., Cochrane, T., Philips, C., Elliot, S., Davies, T., Basher, L. (Eds.), Sediment Dynamics in Changing Environments. International Association of Hydrological Sciences Publication, vol. 325, pp. 200–208.

Dougall, C., Packett, R., Caroll, C., December 2005. Application of the SedNet model in partnership with the Fitzroy Basin community. In: Zerger, A., Argent, R.M. (Eds.), MODSIM 2005 International Congress on Modelling and Simulation, Melbourne. Modelling and Simulation Society of Australia and New Zealand, Melbourne, Australia, pp. 1119–1125.

Douglas, G.B., Ford, P.W., Palmer, M., Noble, R.M., Packett, R., 2006. Fitzroy River basin, Queensland, Australia. I. Identification of sediment sources in impoundments and flood events. Environmental Chemistry 3, 364–376.

Drosg, M., 2009. Dealing with Uncertainties: a Guide to Error Analysis. Springer, Heidelberg, pp. 235.

Folk, R.L., 1954. The distinction between grain size and mineral composition in sedimentary-rock nomenclature. Journal of Geology 62, 344–359.

Fuller, I.C., Macklin, M.G., Lewin, J., Passmore, D.G., Wintle, A.G., 1998. River response to high-frequency climate oscillations in southern Europe over the past 200 k.y. Geology 3, 275–278.

Galbraith, R.F., 1990. The radial plot: graphical assessment of spread in ages. Nuclear Tracks and Radiation Measurements 17, 207–214.

Galbraith, R.F., Roberts, R.G., Laslett, G.M., Yoshida, H., Olley, J.M., 1999. Optical dating of single and multiple grains of quartz from Jinmium rock shelter, northern Australia: part I, experimental design and statistical models. Archaeometry 41, 339–364.

Hughes, A.O., Olley, J.M., Croke, J.C., McKergow, L.A., 2008a. Sediment sources in a dry-tropical catchment: central Queensland, Australia. In: Schmidt, J., Cochrane, T., Phillips, C., Elliott, S., Davies, T., Basher, L. (Eds.), Sediment Dynamics in Changing Environments. International Association of Hydrological Sciences Publication, vol. 325, pp. 351–358.

Hughes, A.O., Olley, J.M., Croke, J.C., McKergow, L.A., 2008b. Sediment source changes over the last 250 years in a dry-tropical catchment, central Queensland, Australia. Geomorphology 104, 262–275.

Hughes, A.O., Olley, J.M., Croke, J.C., Webster, I.T., 2009. Determining sedimentation rates using 137Cs in a low fallout environment dominated by channel-and cultivation-derived sediment inputs, central Queensland, Australia. Journal of Environmental Radioactivity 100, 858–865.

Hughes, A.O., Croke, J.C., Pietsch, T., Olley, J.M., 2010. Changes in the rates of floodplain and in-channel bench accretion in response to catchment disturbance, central Queensland, Australia. Geomorphology 114, 338–347.

Hughes, A.O., Croke, J.C., Validation of a spatially distributed erosion/sediment yield model (SedNet) with empirically-derived data. Marine and Freshwater Research. in press.

Huntley, D.J., Hutton, J.T., Prescott, J.R., 1993. Optical dating using inclusions within quartz grains. Geology 21, 1087–1090.

Joo, M., Yo, B., Carroll, C., December 2005. 2005. Estimation of long term sediment loads in the Fitzroy catchment Queensland, Australia. In: Zerger, A., Argent, R.M. (Eds.), MODSIM 2005 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, pp. 1161–1167.

Jones, M.R., 2006. Cenozoic landscape evolution in central Queensland. Australian Journal of Earth Sciences 53, 433–444.

Kasse, C., Vandenberghe, J., Bohncke, S., 1995. Climatic change and fluvial dynamics of the Maas during the late Weichselian and early Holocene. In: Frenzel, B., Vandenberghe, J., Kasse, C., Bohncke, S., Gläser, B. (Eds.), European River Activity and Climatic Change During the Lateglacial and Early Holocene. Paläoklimaforschung 14, 123–150.

Kershaw, A.P., 1992. The development of rainforest-savanna boundaries in tropical Australia. In: Furley, P.A., Proctor, J., Ratter, J.A. (Eds.), Nature and Dynamics of Forest-Savanna Boundaries. Chapman & Hall, London, pp. 255–271.

Kershaw, A.P., 1994. Pleistocene vegetation of the humid tropics of northeastern Queensland, Australia. Palaeogeography, Palaeoclimatology. Palaeoecology 109, 399–412.

Kershaw, A.P., Nanson, G.C., 1993. The last full glacial cycle in the Australian region. Global and Planetary Change 7, 1–9.

Kershaw, A.P., McKenzie, G.M., McMinn, A., 1993. A Quaternary vegetation history of northeastern Queensland from pollen analysis of ODP site 820. Proceedings Ocean Drilling Program Science Results 133, 107–114.

Kemp, J., 2001. The hydrology, geomorphology and quaternary palaeochannels of the Lachlan Valley, New South Wales. Unpublished PhD Thesis, Australian National University, Canberra.

Kemp, J., Spooner, N.A., 2007. Evidence for regionally wet conditions before the last glacial maximum in southeastern Australia: OSL ages from large palaeochannels in the Lachlan valley, New South Wales. Journal of Quaternary Science 22, 423–427.

Kemp, J., Rhodes, E.J., 2010. Episodic fluvial activity of inland rivers in southeastern Australia: palaeochannel systems and terraces of the Lachlan River. Quaternary Science Reviews 29, 732–752.

Lewin, J., Macklin, M.G., 2003. Preservation potential for Late Quaternary river alluvium. Journal of Quaternary Science 18, 107–120.

Lewin, J., Macklin, M.G., Johnstone, E., 2005. Interpreting alluvial archives: sedimentological factors in the British Holocene fluvial record. Quaternary Science Reviews 24, 1873–1889.

Lough, J.M., 1997. Regional indices of climate variation: temperature and rainfall in Queensland, Australia. International Journal of Climatology 17, 55–66.

Lough, J.M., 2007. Tropical river flow and rainfall reconstructions from coral luminescence: great barrier reef. Australia. Paleooceanography 22, PA2218. doi:10.1029/2006PA001377.

Macklin, M.G., Benito, G., Gregory, K.J., Johnstone, E., Lewin, J., Michczynska, D.J., Soja, R., Starkel, L., Thorndycraft, V.R., 2006. Past hydrological events reflected in the Holocene fluvial record of Europe. Catena 66, 145–154.

Macklin, M.G., Jones, A.F., Lewin, J., 2010. River response to rapid Holocene change: evidence and explanation in British catchments. Quaternary Science Reviews 29, 1555–1576.

Magee, J.W., Miller, G.H., 1998. Lake Eyre palaeohydrology from 60ka to the present: beach ridges and glacial maximum aridity. Palaeogeography, Palaeoclimatology, Palaeoecology 144, 307–329.

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

Magee, J.W., Miller, G.H., Spooner, N.A., Questiaux, D., 2004. Continuous 150 k.y. monsoon record from Lake Eyre, Australia: insolation-forcing implications and unexpected Holocene failure. Geology 32, 885–888.

Mejdahl, V., 1979. Thermoluminescence dating: beta dose attenuation in quartz grains. Archaeometry 21, 61–73.

McKergow, L.A., Prosser, I.P., Hughes, A.O., Brodie, J., 2005. Sources of sediment to the great barrier reef world heritage area. Marine Pollution Bulletin 51, 200–211.

Miller, G.H., Fogel, M.L., Magee, J.W., Gagan, M.K., Clarke, S.J., Johnson, B.J., 2005. Ecosystem collapse in Pleistocene Australia and a human role in megafaunal extinction. Science 309, 287–290.

Miller, G.H., Fogel, M., Magee, J.W., Gagan, M.K., Newsome, S.D., 2010. Climate of Australia over the Past 100 ka Inferred from Stable Isotope in Avian Eggshells. American Geophysical Union Abstracts. 2010AGUFMPP34B.05.M.

Moss, P.T., Kershaw, A.P., 2000. The last glacial cycle from the humid tropics of northeastern Australia: comparison of a terrestrial and marine record. Palaeogeography, Palaeoclimatology, Palaeoecology 155, 155–176.

Moss, P.T., Kershaw, A.P., 2007. A late Quaternary marine palynological record (oxygen isotope stages 1 to 7) for the humid tropics of northeastern Australia based on ODP site 820. Palaeogeography, Palaeoclimatology, Palaeoecology 251, 4–22.

Murray, A.S., Marten, R., Johnston, A., Martin, P., 1987. Analysis for naturally occurring radionuclide's at environmental concentrations by gamma spectrometry. Journal of Radio Analytical and Nuclear Chemistry 115, 263–288.

Murray, A.S., Wintle, A.G., 2000. Luminescence dating of quartz using an improved single-aliquot regenerative-dose protocol. Radiation Measurements 32, 57–73.

Nanson, G.C., Knighton, A.D., 1996. Anabranching rivers: their cause, character and classification. Earth Surface Processes and Landforms 21, 217–239.

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

Nanson, G.C., Chen, X.Y., Price, D.M., 1995. Aeolian and fluvial evidence of changing climate and wind patterns during the past 100 ka in the western Simpson Desert, Australia. Palaeogeography, Palaeoclimatology, Palaeoecology 113, 81–102.

Nanson, G.C., Cohen, T.J., Doyle, C.J., Price, D.M., 2003. Alluvial evidence for major late-Quaternary climate and flow regime change on the coastal rivers of New South Wales, Australia. In: Gregory, K.J., Benito, G. (Eds.), Palaeohydrology: Understanding Global Change. Wiley, Chichester, pp. 233–257.

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

National Land and Water Resources Audit, 2001. Australian Agricultural Assessment, vol. 1 (National Land and Water Resources Audit, Canberra).

Nott, J.F., Price, D.M., Bryant, E.A., 1996. A 30,000 year record of extreme floods in tropical Australia from relict plunge pool deposits: implications for future climate change. Geophysical Research Letters 23, 379–382.

Nott, J.F., Thomas, M., Price, D.M., 2001. Alluvial fans, landslides and late Quaternary climate change in the wet tropics of northeast Queensland. Australian Journal of Earth Sciences 48, 875–882.

Olley, J.M., Pietsch, T., Roberts, R.G., 2004a. Optical dating of Holocene sediments from a variety of geomorphic setting using single grains of quartz. Geomorphology 60, 337–358.

Olley, J.M., De Deckker, P., Roberts, R.G., Fifield, L.K., Yoshida, H., Hancock, G., 2004b. Optical dating of deep-sea sediments using single grains of quartz: a comparison with radiocarbon. Sedimentary Geology 169, 175–189.

Page, K.J., Nanson, G.C., Price, D.M., 1991. Thermoluminescence chronology of late quaternary deposition on the Riverine plain of southeastern Australia. Australian Geographer 22, 14–23.

Page, K.J., Nanson, G.C., Price, D.M., 1996. Chronology of palaeochannels on the Riverine Plain of southeastern Australia. Journal of Quaternary Science 11, 311–326.

Page, K.J., Kemp, J., Nanson, G.C., 2009. Late quaternary evolution of Riverine plain palaeochannels, southeastern Australia. Australian Journal of Earth Sciences 56, 19–33.

Prescott, J., Hutton, J., 1994. Cosmic-ray contributions to dose-rates for luminescence and ESR dating – large depths and long-term time variations. Radiation Measurements 23, 497–500.

Prosser, I.P., Rutherfurd, I.D., Olley, J.M., Young, W.J., Wallbrink, P.J., 2001. Patterns and processes of erosion and sediment transport in Australian rivers. Marine and Freshwater Research 52, 81–99.

Starkel, L., 2003. Climatically controlled terraces in uplifting mountain areas. Quaternary Science Reviews 22, 2189–2198.

Stokes, S., Ingram, S., Aitken, M.J., Sirocko, F., Anderson, R., Leuschner, D., 2003. Alternative chronologies for late Quaternary (Last Interglacial – Holocene) deep-sea sediment via optical dating of silt-size quartz. Quaternary Science Reviews 22, 925–941.

Thomas, M.F., Nott, J.M., Price, D.M., 2001. Late Quaternary stream sedimentation in the humid tropics: a review with new data from NE Queensland, Australia. Geomorphology 39, 53–68.

Thomas, M., 2004. Landscape sensitivity to rapid environmental change – a Quaternary perspective with examples from tropical areas. Catena 55, 107–124.

Thompson, C., Croke, J., Purvis-Smith, D., 2011. Floodplain sedimentation at a tributary junction and valley constriction site in the Fitzroy River Basin, Queensland, Australia. Geomorphology 125, 293–304.

Vandenberghe, J., Kasse, C., Bohnke, S., Kozarski, S., 1994. Climate-related river activity at the Weichselian-Holocene transition: a comparative study of the Warta and Maas rivers. Terra Nova 6, 476–485.

Westaway, R., Bridgland, D.R., Sinha, R., Demir, T., 2009. Fluvial sequences as evidence for landscape and climatic evolution in the late Cenozoic: a synthesis of data from IGCP 518. Global and Planetary Change 68, 237–253.

Yonge, D., Hesse, P.P., 2009. Geomorphic environments, drainage breakdown and channel and floodplain evolution on the lower Macquarie River, central-western New South Wales. Australian Journal of Earth Sciences 56 (S1), S35–S53.