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Nonsynchronous, episodic incision: Evidence of threshold exceedance and complex response as controls of terrace formation

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ABSTRACT

Terrace sequences can represent regional or continental scale factors such as climatic fluctuations, neotectonic activity, and base-level change. However, they can also reflect random incision events brought about by local scale, geomorphic threshold exceedance, and subsequent complex response. This study explores the formative processes of three discontinuous, but adjacent, late Pleistocene to late Holocene step-terrace sequences in southeastern Australia. Correlation of river terrace fills was undertaken by comparing terrace remnants based on topography, morphology, sedimentology, stratigraphy, and chronology. A geomorphic model of floodplain abandonment and terrace formation for this valley setting is presented. Most of southeastern Australia has shown no evidence of tectonic uplift during the late Quaternary. Bedrock bars on the Hunter River isolate the study reach from downstream base-level changes. The nonsynchronous, episodic behavior of incision events in this catchment strongly indicates that climate is not a dominant control on terrace formation. With the exclusion of climatic fluctuations, tectonic uplift and base-level change as causes of incision, catastrophic floods, and the exceedance of geomorphic thresholds emerge as the dominant controls of terrace formation.

1. Introduction

An understanding of fluvial terrace sequence development can provide insights into local and regional landscape evolution and the external factors involved with their formation. However, correlating terrace fills over larger distances as a result of a single external factor must be done with care (Erkens et al., 2009). Climatic, tectonic, and eustatic fluctuations are the most well-established causes of floodplain abandonment and terrace formation (Leopold et al., 1964; Born and Ritter, 1970; Merritts et al., 1994; Bridgland and Westaway, 2008). However, in addition to and in response to these allogenic influences, terraces can also result from the exceedance of geomorphic thresholds and complex response (Schumm, 1973; Young and Nanson, 1982; Erkens et al., 2009). Readjustments of stream grades by meandering and removal of channel obstructions (Hadley, 1960) and natural progressive downcutting (Warner, 1972) are also influences on floodplain abandonment. As such, fluvial terrace sequences can simply reflect random incision events brought about by intrinsic threshold exceedance, despite any correlation with regional or worldwide climatic fluctuations.

Previous studies in the Widden Valley identified three sedimentologically and chronologically distinct terrace sequences: named the Baramul, Widden, and Kewarra sequences (Cheetham et al., 2008b, 2010). The existence of a continuous chronology throughout the Widden Brook terrace sequences and the confinement of each sequence to a different valley setting are indications that localised processes have controlled their formation (Cheetham et al., 2010, in press). This is significant given that climate change is often seen as the primary control on terrace formation elsewhere in southeastern Australia and around the world (Warner, 1972; Bull and Knuepfer, 1987; Bridgland and Westaway, 2008).

Here we examine the processes of floodplain abandonment and terrace formation for the longitudinally correlated river terraces of Widden Brook. By investigating influences on terrace formation in a range of valley settings, we are able to explore the role of geomorphic thresholds and complex response as primary controls on terrace formation. In addition, we present a model of late Quaternary floodplain abandonment and landscape evolution for Widden Valley.

2. Regional setting

Widden Valley is a north-trending valley in the Upper Hunter region of New South Wales, Australia, and is shown in Fig. 1 (253506 E, 6410466 N–253578 E, 6390530 N, UTM). Widden Brook is a terrace and bedrock-confined, low sinuosity, sand bed stream with a 650-km^2 catchment area. The headwaters of Widden Brook and its only major tributary, Blackwater Creek, lie in Wollemi National Park and are incised into Triassic sandstones of the Narrabeen Group, which is

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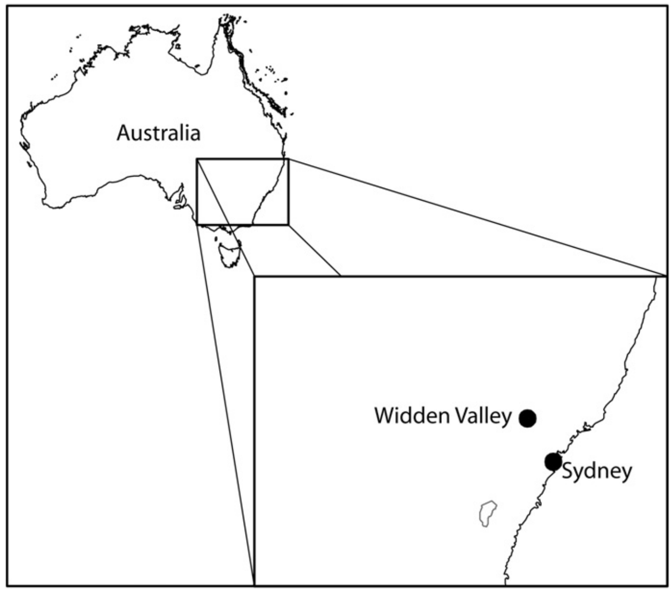

Fig. 1. Location map of Widden Valley, NSW, Australia.

capped by Tertiary basalts (Galloway, 1967) and Permian conglomerate, sandstone, and siltstone (Beckett, 1988). The study reach extends ~26 km upstream of Widden Brook's confluence with the Goulburn River, a tributary of the Hunter River. Three adjacent sedimentologically distinct terrace sequences were identified along the study reach (Cheetham et al., 2010). Each terrace sequence is located in a geomorphologically different valley setting: an upstream constriction (Baramul), a valley expansion (Widden), and a highly constricted downstream section (Kewarra) (Fig. 2).

Bedrock bars on the Hunter River at Scotts Flat (downstream of Singleton) and at Woodlands (downstream of Denman) act as barriers to the effects of base-level changes further upstream at our study location. Thus, despite changes in relative sea level since the last glacial maximum (LGM) (Sloss et al., 2007), base-level change is

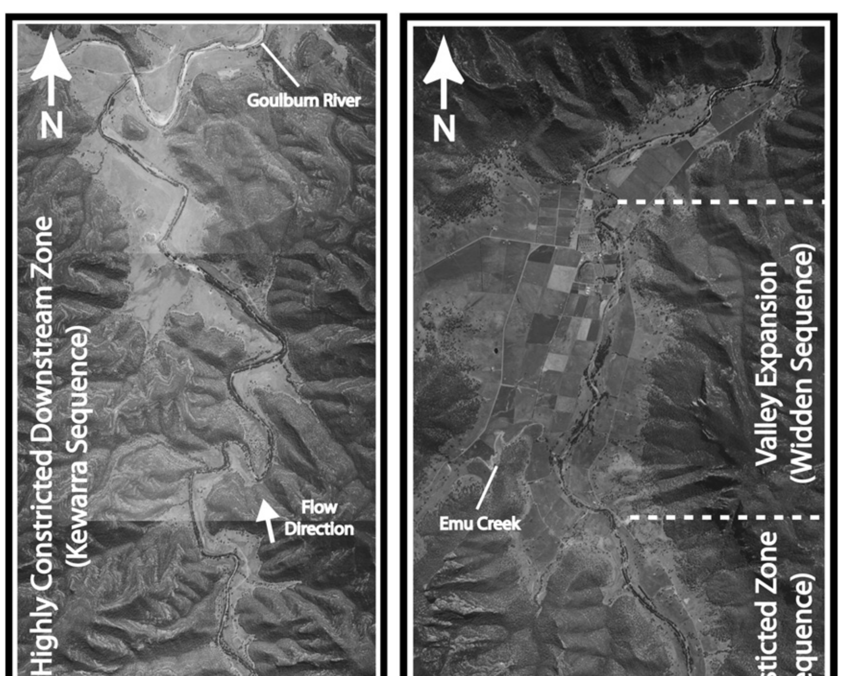

Fig. 2. Study location of Widden Brook, Australia showing the three adjacent but distinct valley settings identified by Cheetham et al. (2010) and examined in this study.

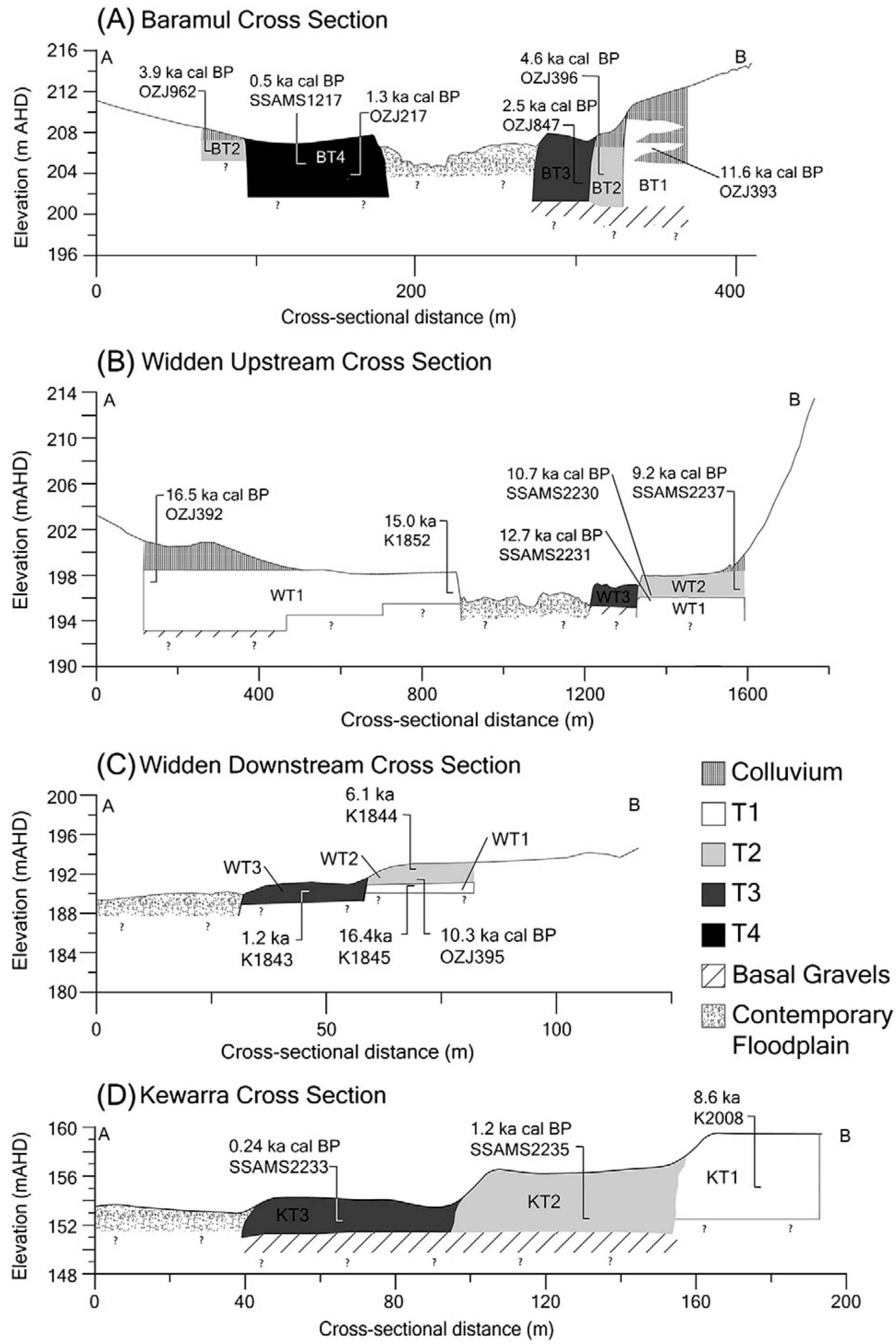

Fig. 3. Representative cross sections for each terrace sequence on Widden Brook. Cross sections of the Widden terrace sequence include interpretational changes based on a revised chronology from that of Cheetham et al. (2010).

unlikely to have had any impact on Widden Valley during this time. Likewise, tectonic uplift has not occurred in this region over the timeframe assessed in this study (Roy and Thom, 1981).

Aboriginal and natural fire activity and palynological studies have been used to infer the Holocene climatic history in the region. These studies show low magnitude climatic variability during the Holocene when compared to that of the Pleistocene. Kershaw (1998) and Kershaw et al. (2002) reported increased rainfall and seasonality between 7 and 5 ka with conditions becoming cooler and drier between 4 and 2 ka. This is consistent with the warmer and wetter periods of the El Niño-Southern Oscillation (ENSO) dominated climate, which began at ~6.1 ka BP (Singh et al., 1981; Dodson, 1994; Black and Mooney, 2007; Mooney et al., 2007; Black et al., 2008). This was a period of variable climatic conditions known as the Holocene climatic optimum (Bryant, 1997; Black et al., 2008).

3. Materials and methods

Morphology, elevation, and continuity assist in correlating terrace fills, both in cross section and long-profile (Leopold and Miller, 1954; Leopold et al., 1964). However, the environmental significance of river terraces is also dependent on chronologic and sedimentologic criteria. Chronometric data is fundamental to the determination of the contemporaneity of terrace remnants. Stratigraphic and sedimentologic

Table 1
Sedimentary characteristics for all Widden Brook terrace sequences.

Terrace	Morphology	Description	Interpretation	Chronology
BT1	Valley margin terrace. Right bank only.	Altered, mottled, medium to coarse sandy clay with Fe, $CaCO_3$ concretions. (Fl)	Frequent sand splay deposits 0.1–0.5 m thick. Overbank deposits overlying basal gravels.	14.0 ± 1.20 ka cal BP–11.7 ± 1.34 ka cal BP
BT2	Inset below BT1. Paired terrace.	Slightly altered, medium clayey sand, with fewer $CaCO_3$ concretions. (Fl)	Sand splay deposits 0.1–0.4 m thick. Overbank deposits overlying basal gravels.	6.82 ± 0.22 ka cal BP–3.92 ± 0.33 ka cal BP
BT3	Inset below BT2. Paired terrace.	Unaltered, fine to medium interbedded sand and mud. (Fl)	Sand splay deposits 0.2–0.3 m. Overbank deposits overlying basal gravels.	2.53 ± 0.25 ka cal BP–2.17 ± 0.24 ka cal BP
BT4	Inset below BT3. Paired terrace	Unaltered, fine to medium laminated sand and mud with distinct fine organic unit. (Fl, Fsm)	1-m thick sand splay deposit within organic unit, overlying basal gravels.	1.69 ± 0.19 ka cal BP–0.44 ± 0.17 ka cal BP
WT1	Valley margin terrace. Paired terrace.	Altered, mottled, medium sandy clay and silt. (Fl, Fm)	Frequent sand splay deposits 0.1–0.7 m thick. Overbank deposits overlying basal gravels.	16.4 ± 1.70 ka BP (OSL)–12.5 ± 0.46 ka cal BP
WT2	Overlapping WT1 on right bank only.	Slightly altered clayey sand with frequent sand splay deposits 0.1–0.3 m thick. (Fl, Fm)	Overbank deposits overlying basal gravels.	10.94 ± 0.35 ka cal BP–6.1 ± 0.6 ka BP (OSL)
WT3	Inset below WT2 on right bank only.	Massive, unaltered fine to medium sand. (Fl)	Significantly reworked.	2.5 ± 0.2 ka BP (OSL)–0.57 ± 0.08 ka cal BP
KT1	Valley margin terrace Paired terrace.	Altered fine, silty sands overlying coarse sands and gravels. Yellowish-red Kandosol. (Fl)	Lateral migration deposits overlying basal gravels.	16.7 ± 0.57 ka cal BP–8.85 ± 0.99 ka cal BP
KT2	Inset below KT1. Paired terrace.	Slightly altered, medium sand and sandy loams. (Fl)	Some sand splay deposits 0.2–0.3 m thick. Overbank deposits overlying basal gravels.	6.84 ± 0.23 ka cal BP–0.66 ± 0.05 ka cal BP
KT3	Inset below KT2 at 1 cross section only.	Unaltered, medium sands. (Fl)		0.65 ± 0.03 ka cal BP

Miall (2006) facies codes in brackets.

characteristics are indicators of changes to the fluvial regime and depositional environments during sedimentation (Born and Ritter, 1970; Warner, 1972; Young and Nanson, 1982; Merritts et al., 1994; Miall, 2006). Soil development can provide additional insights into post-depositional weathering and environments (Brewer and Walker, 1969; Walker and Coventry, 1976).

Orthorectified aerial photographs were also studied to determine longitudinal terrace extent and area. Mapping was based on 2004 aerial photographs, and ground truthing was accomplished using the previously mentioned surveys and hand-held Garmin GPS.

Cross sections were located at representative sites along Widden Brook. Australian Height Datum (AHD) elevations and Universal Trans-Mercator (UTM) coordinates of the cross sections were surveyed using a Leica TPS 400 total station. Trenches were excavated at cross sections where landholders allowed. Drilling was undertaken at locations deemed unsuitable for trenching. Natural exposures were logged where present, and hand augering was used to infill gaps.

Sedimentologic cross sections were constructed using data obtained from trenches, exposures, drill holes, pits, and auger holes. The sediments were described in the field following the textural classification of Northcote (1984), and moist soil colour determined with reference to Munsell Soil Color Charts. Sedimentary structures (such as laminations and trough sets) and other pedological features (such as concretions, infilled mesofaunal channels, and charcoal abundance) were also noted. Samples were analysed for grain size distribution using a combination of the sieve/hydrometer method (Folk, 1980) and laser diffraction (Agrawal et al., 1991). The combined use of these methods on fluvial sandy sediments was shown to produce consistent results (Cheetham et al., 2008a). Terrace fill sediments were analysed for stratigraphic, sedimentologic, and chronologic characteristics and classified according to Warner's (1972) geomorphic scheme. Detailed field observations were also made of numerous exposures to confirm correlations.

3.1. Geochronologic analysis

3.1.1. Radiocarbon dating

Charcoal for AMS radiocarbon dating was sampled from trenches, exposures, and drill and auger holes to determine the alluvial chronology. Samples were pretreated according to the methods outlined by Hua et al. (2001) and Gupta and Polach (1985). Charcoal samples were prepared and analysed at the Australian National University (ANU code) and at the Australian Nuclear Science and Technology Organisation (OZ code).

Radiocarbon dates were calibrated using CALIB 5.0 (Stuiver and Reimer, 1993) using the Libby half life of 5568 years and following the conventions of Stuiver and Pollack (1977) and Hua et al. (2001). Dates < 11 ka BP were calibrated using the southern hemisphere

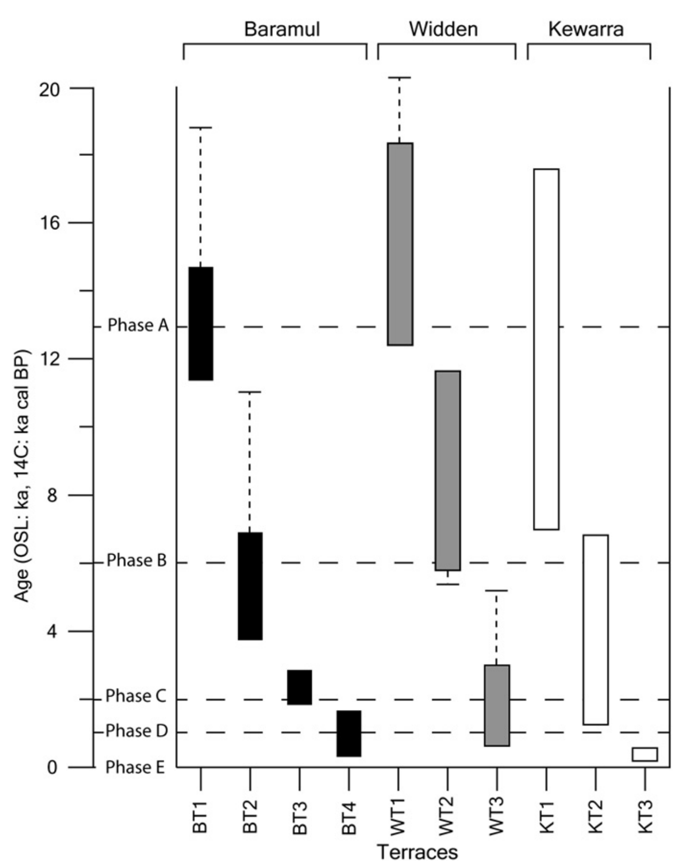

Fig. 4. Depositional durations of the Baramul, Widden and Kewarra terrace sequences of Widden Valley. Dashed error bars indicate estimated onset of infill based on distance from basal gravels to maximum age. Age ranges include maximum associated errors at 1σ. Illustrative phases are shown with dashed lines. Modified from Cheetham et al. (2010).

Table 2
Calibrated radiocarbon dates and OSL ages for each terrace showing associated terrace and sedimentary unit sampled.

Terrace code	Sedimentary unit	^{14}C Date (ka cal BP ± 1σ)	OSL Age (ka BP ± 1σ)
BT1	OZJ393	Very fine sandy clay	11.70 ± 1.34
BT1	OZJ849	Very fine sandy clay	14.04 ± 0.32
BT2	OZJ962	Loam fine sandy	3.92 ± 0.33
BT2	SSAMS2401	Loam fine sandy	4.93 ± 0.15
BT2	OZJ396	Loam fine sandy	4.63 ± 0.29
BT2	K1850	Fine loamy sand	5.1 ± 0.5
BT2	OZK799	Fine sand	6.82 ± 0.22
BT3	OZJ848	Medium sand	2.17 ± 0.24
BT3	OZJ847	Medium sand	2.53 ± 0.25
BT4	OZJ213	Fine sandy clay	0.93 ± 0.19
BT4	SSAMS1217	Fine sandy clay	0.44 ± 0.17
BT4	K1851	Fine sandy clay	0.53 ± 0.32
BT4	OZJ053	Fine sandy clay	0.80 ± 0.19
BT4	SSAMS1223	Medium sands	1.69 ± 0.19
BT4	OZJ215	Fine clayey silt	1.11 ± 0.21
BT4	OZJ217	Fine clayey silt	1.29 ± 0.16
BFP	OZI447	Granular coarse sand?	0.09 ± 0.04
WT1	OZJ392	Fine sandy clay	16.45 ± 1.27
WT1	K1845	Medium sandy clay	16.4 ± 1.7
WT1	K1852	Fine sandy clay	15.0 ± 1.3
WT1	SSAMS2231	Medium sandy clay	12.53 ± 0.46
WT2	OZJ395	Medium sandy clay	10.43 ± 0.3
WT2	K1844	Medium sandy loam	6.1 ± 0.6
WT2	SSAMS2237	Fine sandy clay	9.26 ± 0.24
WT2	SSAMS2230	Fine sandy clay	10.94 ± 0.35
WT3	K1841	Fine loamy sand	2.5 ± 0.2
WT3	K1853	Fine loamy sand	2.6 ± 0.5
WT3	K1840	Fine sand	1.3 ± 0.1
WT3	K1843	Fine Loamy Sand	1.2 ± 0.3
WT3	OZJ850	Fine loamy sand	0.83 ± 0.13
WT3	SSAMS1232	Medium sand	0.57 ± 0.08
WFP	OZI436	Granular coarse sand?	0.18 ± 0.06
KT1	SSAMS2239	Fine sandy clay	8.54 ± 0.16
KT1	SSAMS1236	Very fine sandy clay	7.04 ± 0.19
KT1	SSAMS1238	Fine sandy clay	9.61 ± 0.13
KT1	SSAMS1218	Fine clayey sand	16.70 ± 0.57
KT1	OZK796	Medium sand	11.65 ± 0.49
KT1	SSAMS2236	Fine sandy clay	9.72 ± 0.25
KT1	OZK797	Medium sand	10.36 ± 0.22
KT1	K2008	Fine sandy clay	9.4 ± 0.7
KT2	K2009	Medium sand	4.8 ± 0.3
KT2	SSAMS1234	Medium sand	3.21 ± 0.20
KT2	SSAMS2232	Medium sand	1.91 ± 0.31
KT2	SSAMS2235	Very fine sandy clay	1.22 ± 0.11
KT2	OZK798	Medium sand	6.84 ± 0.23
KT3	SSAMS2233	Fine sand	0.08 ± 0.11
KT3	SSAMS1233	Fine sand	0.65 ± 0.03

radiocarbon calibration data set ShCal04 (McCormac et al., 2004). Dates over 11 ka BP were calibrated using the international radiocarbon calibration data set IntCal04 (Reimer, 2004). These radiocarbon ages represent the maximum age of deposition from the possibility of fluvial reworking and elapsed time before incorporation of charcoal into the floodplain (Blong and Gillespie, 1978).

3.1.2. Luminescence dating

Optically stimulated luminescence samples were collected from natural exposures or trenches using light-proof aluminium tubes inserted into the profile. Samples were prepared and analysed at the Australian National University (K code). Material from the central part of the sample tubes was extracted for processing under low intensity red and yellow–orange light. Samples were treated following Huntley et al. (1993) and Rhodes (1988). The 0.3-mm-diameter aliquots composed of 3–5 grains were measured for equivalent dose (D_e) using the single-aliquot, regenerative-dose (SAR) protocol (Murray and Wintle, 2000).

The D_e for each sample was calculated using the central age model of Galbraith et al. (1999), except where evidence of incomplete bleaching was observed, indicated by a range of D_e values skewed toward younger ages representing better-bleached grains (Clarke, 1996; Olley et al., 1998; Colls et al., 2001). For these samples, the minimum age was used to calculate the D_e based on the leading edge of the dose distribution of accepted aliquots.

Dose rates were calculated from the concentrations of the radioactive elements K, Th, and U using the conversion factors of Adamiec and Aitken (1998). Cosmic-ray dose rates were determined following the formulae of Prescott and Hutton (1994), incorporating sample depth, sediment density, and site altitude, latitude, and longitude. Cheetham et al. (in press) provide more detail on OSL methodology used in this study.

4. Results

4.1. Terrace correlation

The terraces of Widden Brook occurred as partially eroded, discontinuous pockets. Where step-like topography was observed, each subsequent inset terrace was younger than the one upslope. An overlapped terrace was detected in the Widden sequence where WT2 had been deposited over the severely eroded right bank portion of WT1 (Fig. 3). As a general trend, the sediments of each subsequent terrace became coarser with each incision, with the younger terrace

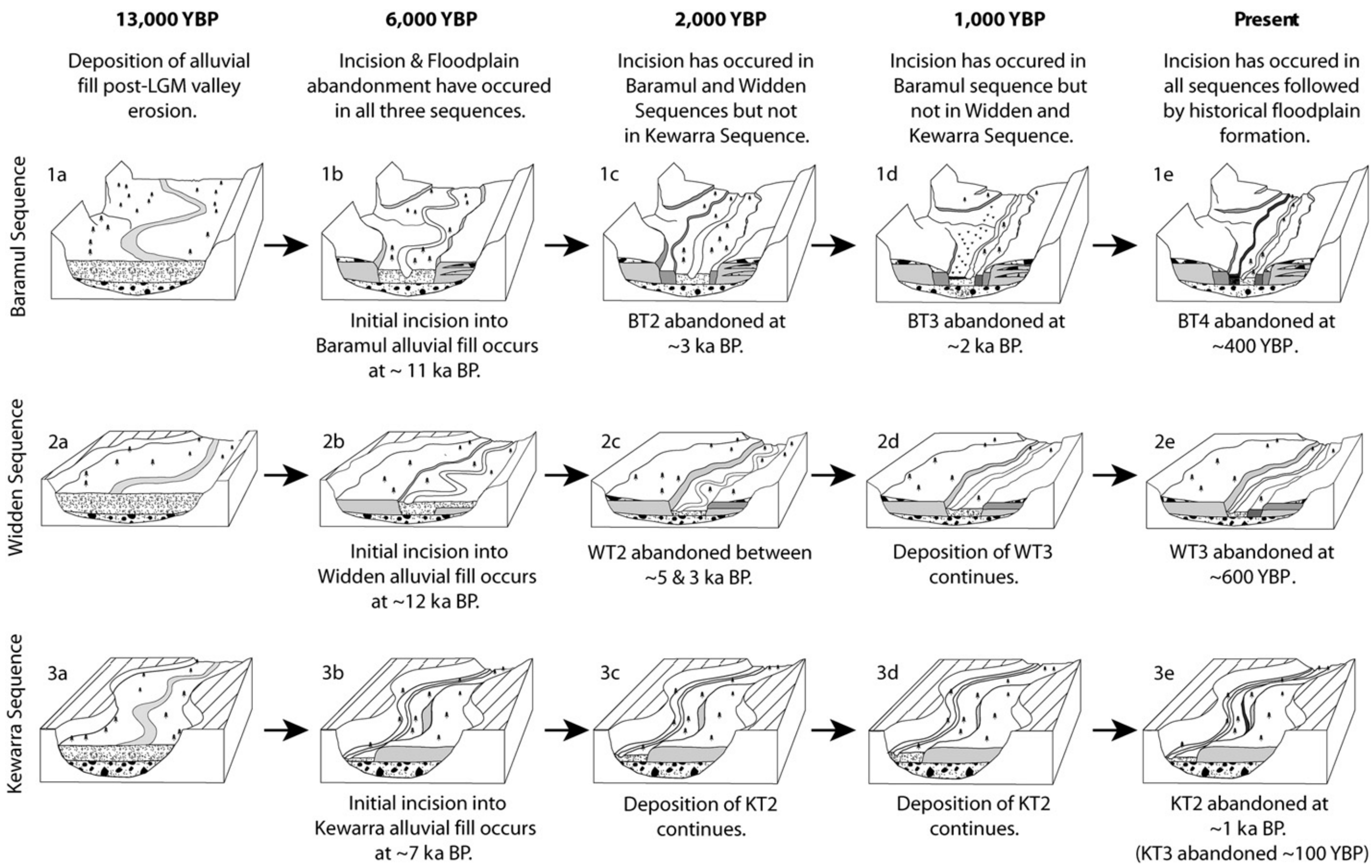

Fig. 5. Illustrated phases of floodplain abandonment and terrace development for the Baramul, Widden and Kewarra sequences on Widden Brook.

fills containing more sand than the older terrace fills. The terraces for each sequence are listed in Table 1 with associated sedimentological characteristics.

Terrace sequence correlation involved comparing terrace remnants based on their elevation, morphology, sedimentology, and stratigraphy. Interpretation of terrace sequences is therefore fundamentally dependent on the preservation of terrace fills and the inherent bias in the preservation of older terrace fills that are more resistant to erosion (Lewin and Macklin, 2003; Lewin et al., 2005). The continuous chronology established for the Widden Brook terrace sequences indicates that they have been relatively well preserved (Cheetham et al., in press). Assuming no intermediate terraces were formed, the time of floodplain abandonment lies between the youngest date of the terrace fill itself and the oldest date for the subsequent terrace fill. Dates obtained from the sedimentary unit immediately above the basal gravels are interpreted to represent the onset of infill for that particular terrace. Where the maximum age of a terrace fill was obtained above this lower unit, the onset of infill is interpreted to have occurred earlier.

The maximum ages for BT1, BT2, WT1, and WT3 were not basal ages, and hence the estimated timing for the onset of infill is shown as a dashed line in Fig. 4. Likewise, minimum ages obtained from a terrace profile can only represent the maximum age of abandonment because of the removal of younger surface sediments through erosion or stripping of the terrace surface. With basal ages for the subsequent terrace fill, the age of abandonment (and degree of erosion) can be constrained. Where basal ages were not obtained, chronological gaps will appear. These gaps can represent both erosion of the older terrace surface over time and deposition that occurred prior to the maximum age obtained for the younger terrace fill.

Representative cross sections for each terrace sequence are shown in Fig. 3. The cross sections for the Widden sequence differ slightly to that reported by Cheetham et al. (2010) following refinement of the OSL chronology (Cheetham et al., in press). For this reason, both cross sections of the Widden sequence are shown in Fig. 2. Radiocarbon dates and OSL ages are provided in Table 2.

In order to demonstrate the differential alluvial evolution of the Widden Brook terrace sequences, phases were established at different points in time during the late Pleistocene and Holocene. The chronology of the Widden Brook terrace sequences is shown in Fig. 4. These phases illustrate the history of terrace formation in Widden Valley.

4.2. Terrace development on Widden Brook

To demonstrate the post-LGM series of floodplain abandonment events for each terrace sequence, the three valley settings are illustrated for each phase (Fig. 5). We propose the following model of terrace formation in the Widden Brook study reach. Each phase (A:13 ka BP, B:6 ka BP, C:2 ka BP, D:1 ka BP and E:Present) is discussed in detail below.

4.2.1. Initial post-LGM valley fill (phase A)

The onset of infill for all three oldest terraces (BT1, WT1, and KT1) corresponds to the termination of the LGM (Barrows et al., 2002; Cheetham et al., 2010). No older sediment was obtained from the study reach. This indicates that either (i) large-scale valley cleanout occurred during or immediately after the LGM but prior to the deposition of the current valley fill; or (ii) the previous valley fill was the basal gravel found below each sequence. Nearby Nullo Mountain (station: 62,100; elevation: 1130 m) and Jerrys Plains (station: 61,086; elevation: 90 m) weather stations have current mean minimum temperature of 2.4 °C and 3.4 °C, respectively (Bureau of Meteorology, 2010). Temperatures during the LGM elsewhere in southeastern Australia were 2–6 °C lower than present, and the orographic snowline was 600–700 m lower (Barrows et al., 2001, 2004; Page et al., 2009; Williams et al., 2009). This – combined with the coarse periglacial deposits at Nullo Mountain (Galloway, 1967), a possible decrease in vegetation density, and the nature of the gravelly basal deposits observed in many of the profiles in Widden Valley – suggests a gravel-bed, glacial-style, braided stream in Widden Valley at this time. An influx of sediment resulting from a warmer and wetter climate following the LGM possibly assisted the formation of the oldest floodplains (BT1, WT1, and KT1).

4.2.2. First phase of incision (phase B)

By 6 ka BP, incision had occurred in all three sequences. Incision in the upstream constriction and valley expansion was large scale. The abandonment of WT1 occurred at ~12 ka cal BP. The abandonment of BT1 is constrained between 12 and 7 ka BP; however, no basal age was obtained from BT2. The onset of infill for BT2 is therefore interpreted as being much earlier, at approximately the same time as WT2 (Fig. 4). WT2 overlaps the eroded remnants of WT1 on the right bank side of the valley expansion (Fig. 3B).

BT1 was almost completely eroded, leaving only a small remnant. Similarly, the right bank portion of WT1 was almost entirely stripped back to its basal unit. The left bank portion of WT1 and KT1, however, was virtually untouched and the abandonment of KT1 did not occur until ~7 ka BP. This nonsynchronous behaviour indicates that climate was not responsible for the first phase of incision. We suggest a catastrophic flood as a mechanism for the abandonment of BT1 and WT1. This would explain the exclusive preservation of the left bank portion of WT1 in its protected location within the easterly protuberance of the valley expansion. The continuation of deposition for KT1 could simply represent the accumulation of sediments eroded from the Baramul and Widden sequences.

Calculations for KT1 indicate a decrease in sedimentation rates at ~9 ka cal BP from 19 cm/100 y to 2 cm/100 y (based on SSAMS2236, OZK797 & SSAMS1236, OZK797). This further supports the catastrophic flood theory. Increased sediment supply to the downstream constriction immediately following the flood, followed by reduced sediment supply from increased accommodation space upstream, would result in a general reduction in sediment accumulation rates. This reduction in sediment supply may have led to the eventual abandonment of KT1 at 7 ka BP.

4.2.3. Second phase of incision (phase C)

The second phase of incision occurred in the Widden sequence at ~5.8 ka BP with the abandonment of WT2. This brought about the terrace confinement of the channel in the valley expansion (Fig. 5–2d). The channel became significantly more constricted relative to the previous 14 ka with the incision of a narrow erosional trench that was 60% smaller than that which existed when the earlier floodplain was deposited (80% when compared to the initial post-LGM floodplain). WT2 was abandoned soon after KT1, suggesting knick-point recession as the most probable mechanism for its abandonment. In this case the incision into KT1 would be the trigger for knick-point recession into WT2. The confinement and likely straightening of the channel in the Widden sequence at that time would have increased stream power. This led to major reworking during the deposition of WT3, which helps to explain the inverted and incompletely bleached OSL ages obtained from WT3 (Cheetham et al., in press).

The abandonment of KT1 at ~7 ka BP brought about the bedrock/terrace confinement of the channel in the downstream constriction and the cessation of lateral migration. The channel in this downstream valley setting then became a highly constricted transfer zone with little space to accommodate sediment. The contemporary floodplain is inset against this terrace fill for the upper 9 km of the Kewarra reach before the occurrence of KT2 in the lower 7 km. This indicates that the floodplain in the upper 9 km has undergone major reworking over the past 7 ka.

In the upstream constriction, incision occurred with the abandonment of BT2 at ~3.5 ka BP. This is nonsynchronous with the Widden and Kewarra sequences, which experienced continued deposition, and indicates a complex geomorphic response.

4.2.4. Third phase of incision (phase D)

The onset of deposition of BT4 (1.7 ka BP) occurs immediately after the abandonment of BT3 (2.2 ka BP). The longitudinal chronology of BT3 and BT4 indicates knick-point recession as the process of abandonment for BT3, leading to progressively more recent deposition of BT4 at its upstream extent (Cheetham et al., 2008b).

The abandonment of KT2 occurred at ~1.2 ka BP. KT2 was only identified in the lower 7 km of the Kewarra reach, upstream of the confluence of Widden Brook and the Goulburn River. It is separated from the valley expansion by a 9-km reach of bedrock and terrace (KT1) confined channel. Therefore the abandonment of KT2 is unlikely to be linked to any subsequent upstream abandonment events. The abandonment of KT2 is likely to be a result of complex response, possibly from bed-level lowering of the Goulburn River.

4.2.5. Present valley landscape (phase E)

The abandonment of BT4, WT3, and KT3 all occurred within the last 600 YBP. KT3 is a very young terrace, only recently abandoned. It was not inundated by the last major flood in June 2007. The channel has become significantly terrace-confined compared with the post-LGM channel. This, along with the increasing grain size of these younger terrace fills, indicates a dramatic decrease in sinuosity or flood intensity.

5. Discussion

5.1. Tectonic uplift and base-level change

Tectonic uplift drives channel incision and floodplain abandonment on a regional and continental scale (Merritts et al., 1994; Bridgland et al., 2004). The study reach lies in a region of apparent tectonic stability throughout late Quaternary times (Roy and Thom, 1981). This is despite significant tectonic influence on the Murray River prior to the termination of the LGM (Bowler and Harford, 1966; Bowler, 1967, 1986; Page et al., 1991). Without detailed information of suballuvial bedrock morphology, it is impossible to determine the degree to which bedrock incision has taken place. However, the basal gravels at the bottom of all deep cores and auger holes indicate that this material was the erosive basal limit for all post-LGM cut-and-fill events in Widden Valley, rather than bedrock.

Relative base-level change, either through sea level or isostatic fluctuations, can drive channel incision on a regional or continental scale by lowering basal level (Merritts et al., 1994). Bedrock bars found at two locations on the Hunter River downstream of its confluence with the Goulburn River are known barriers to channel degradation upstream (Erskine et al., 1992). Likewise, these bars provide a barrier to the effects of base-level change during the late Quaternary. The effect of base-level lowering is generally to initiate knick-point recession, causing incision that progresses in an upstream direction (Leopold et al., 1964). The chronology of the Widden Brook terrace sequences does suggest episodes of knick-point recession causing floodplain abandonment; however, these are highly unlikely to be a result of base-level change.

5.2. Climate

The influence of climate on terrace formation is one that takes place on a regional scale (Walker, 1984; Bull and Knuepfer, 1987; Bridgland et al., 2004), not only affecting each sequence within a valley, but also sequences in neighbouring valleys (Bridgland and Westaway, 2008). This is not the case in Widden Valley where the stratigraphic and chronologic correlations of the terrace sequences in this and previous studies (Cheetham et al., 2010) demonstrate that the present fluvial landscape is a result of a series of nonsynchronous, episodic incision events. These events are not only out of phase with neighbouring valleys (Erskine and Melville, 2008) but with sequences within the study reach itself.

Walker (1984) argued that the intensity of external factors, such as climate, is such that they would override localised controls. This would result in synchronous, regional-scale behaviour, which is not the case here. Erkens et al. (2009) found that the onset of incision on the Rhine River, Germany, was triggered by allogenic influences (climatic warming) during the Late Pleniglacial, but that subsequent incision was perpetuated by autogenic processes. Similar studies in southeastern Australia have shown landscape response to a combination of climate and geomorphic thresholds (Cohen and Nanson, 2008). Within our study catchment, it is the initial phase of deposition, rather than incision, that appears to relate to climatic change, if only because of its association with the termination of the LGM. The subsequent landscape evolution and incision events then reflect rapid readjustments as geomorphic thresholds are exceeded (Schumm, 1973), possibly as a recovery from this climatic change (Walker, 1984).

5.3. Catastrophic events

Catastrophic events are capable of causing large-scale erosion and deposition by dramatically forcing the exceedance of geomorphic thresholds (Melville and Erskine, 1986; Nanson and Erskine, 1988; Erskine, 1996; Erskine and Peacock, 2002). These events can advance individual floodplains to the point of threshold exceedance depending on their sensitivity at the time (Brunsden and Thornes, 1979). As not all reaches must achieve a threshold at the same time (Schumm, 1973), large-scale events (such as catastrophic floods) do not necessarily affect catchments uniformly (Erskine, 2008). The sediments stored in one geomorphic zone (or terrace fill) are transported during the "stripping events" or after local thresholds have been exceeded (Leopold et al., 1964; Warner, 1972; Schumm, 1973, 1977; Nanson, 1986; Fryirs and Brierley, 2001; Thoms and Olley, 2004; Erskine and Melville, 2008). Depending on the geomorphology of the catchment, the scale of the event, and the sensitivity of the downstream floodplain, sediment can then accumulate in or pass through terrace sequences (Erskine, 2008). As such, catastrophic floods do not necessarily cause synchronous terrace formation and provide a framework to unravel the larger scale, nonsynchronous, episodic incision events of Widden Brook.

5.4. Geomorphic thresholds and complex response

The complexity of the fluvial geomorphic system, like Widden Brook, is such that many factors influence its evolution. Schumm (1973) discussed the relationship between valley floor gradient and valley floor stability, with failure of the valley floor occurring with steepening valley floor slope. This relationship has been further explored in terms of gully erosion and the propensity for landscape change in respect to slope stability thresholds (Patton and Schumm, 1975; Schumm, 1977; Erskine, 2005). Channel sinuosity and gradient along with sediment supply are also discussed as geomorphic thresholds (Schumm, 1973, 1977, 1985). These thresholds can be exceeded through natural progressive landscape evolution (Schumm, 1973; Young and Nanson, 1982) or forced by catastrophic events (Schumm, 1973; Melville and Erskine, 1986; Nanson and Erskine, 1988). Effectively, each terrace sequence can influence changes to the next terrace sequence in this way. For example, the exceedance of a local geomorphic threshold (such as gradient) in one sequence can cause erosion of sediment from that sequence and deposition in the next (Erskine and Melville, 2008). This process, in turn, contributes to the exceedance of another local geomorphic threshold (such as sediment supply or gradient) in the next sequence, leading to yet another floodplain abandonment event and so on.

Localised, complex morphology and stratigraphy, like that of Widden Brook, is indicative of a complex morphological and stratigraphic response to the exceedance of one or more geomorphic thresholds (Erskine, 2008). This complexity, when combined with the resultant discontinuous nature of remnant terrace pockets (Lewin and Macklin, 2003), often prevents the linking of a specific geomorphic threshold to a particular landscape response. Nevertheless, the Widden catchment does provide an ideal landscape to discriminate regional from local controls on terrace formation.

6. Conclusions

The adjacent, but sedimentologically and chronologically distinct, terrace sequences of Widden Brook demonstrate that localised processes have not affected an entire valley but have operated on subreaches of that valley. The stratigraphic and chronologic interpretations of these terrace sequences show that the present fluvial landscape is the result of a series of nonsynchronous, episodic incision events beginning in the late Pleistocene.

With the elimination of base-level change, tectonic uplift, and climatic change, geomorphic threshold exceedance through either natural progressive landscape evolution and/or catastrophic floods emerge as key controls on channel incision and floodplain abandonment in Widden Valley. Terrace formation has resulted from the cyclic erosion and deposition of alluvial sediments brought about when a local geomorphic threshold was reached. This process was intermittently interrupted or accelerated by large-scale events that stripped sections of the floodplain down to a basal gravel lag. Therefore, the controls on terrace formation in this catchment cannot be linked to any one allogenic factor. Further research in this catchment would involve microstudies to link specific geomorphic thresholds to particular landscape responses.

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