Connecting the disconnected: longitudinal correlation of river terrace remnants

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Abstract Terrace sequences provide insights into flood plain development. Many studies have examined the cross-sectional morphology and correlation of terraces, but this is only part of the story. Longitudinal correlation can provide a far greater insight into flood plain development processes and the spatial significance of these processes. Here we examine flood plain development from the longitudinal correlation of river terrace sequences in a sand-dominated flood plain. The terrace remnants are discontinuous, having been separated longitudinally by the partial erosion of the flood plain. Terraces along the study reach ranged from recently abandoned (490 ± 60 yBP), poorly developed, vertically accreted flood plains to weathered, early Holocene deposits (10 050 ± 260 yBP). They occurred as inset, fill features which indicated successive phases of alluvial erosion and deposition as well as burial of previous terrace surfaces. Terrace morphology alone did not provide sufficient evidence of longitudinal correlation. Sedimentology and chronology were also vital in correlating these remnants. Four terraces (the Baramul Sequence) were identified in the reach showing progressively younger characteristics and ages. The longitudinal correlation of each discontinuous terrace remnant shows considerable variation over time in response to gradient changes, discharge, sediment size and stream sinuosity. Results show that climate and the local exceedence of geomorphic thresholds have influenced river terrace formation and highlight the significance of chronology in establishing longitudinal correlation of terrace remnants with varying morphology. The Baramul Sequence shows a progressive relative fall in bed-level and reduction in slope over the Holocene. This is likely to have been accompanied by progressive contraction of the channel and indicates a reduction in mean discharge over the last 6–7 ka.

Key words stratigraphy; chronology, fluvial geomorphology, terrace sequences, sedimentology

INTRODUCTION

River terraces are lateral benches between a river channel and its valley sides (Richards, 1982), initially formed by vertical and lateral accretion under prior flow conditions as a flood plain. With tectonic uplift, a change in base level, or shifts in sediment-load and discharge regime, down-cutting into valley floor deposits results in abandonment of the former flood plain (Leopold *et al.*, 1964; Brierley & Fryirs, 2005). Partial destruction of this elevated flood plain by actively migrating streams renders most terraces discontinuous, and the internal sedimentology and sedimentary structures must be investigated to distinguish between the number and type of river terraces (Richards, 1982). Successive phases of alluvial filling and incision in a valley create flights of terraces if each younger depositional surface is inset into the trench formed by the previous incision (Richards, 1982). However, overlapping alluvial fills may bury previous surfaces making it difficult to trace particular terrace surfaces (Leopold & Miller, 1954). This is also the case when successive fills are deposited on different gradients. Terraces formed by rapid incision may be paired, with benches at matching elevations on each valley side, but the classic morphology is unpaired terraces formed by meanders sweeping from side to side as slow incision progresses (Richards, 1982).

Warner (1972) suggests the following three ways in which a flood plain can be abandoned: (1) a decrease in discharge will reduce sediment deposition and the channel will narrow and abandon its flood plain (which becomes the terrace), forming a new, lower flood plain. Channel migration will erode the abandoned flood plain, forming the new flood plain; (2) changes in base level (general or local) or climate can induce higher flood discharges, such that aggradation will occur and the flood plain will be buried under a new flood plain; (3) natural progressive down cutting, uplift or a lower base level can lead to channel incision. The channel can then cut deeper into the underlying bedrock abandoning the original flood plain and creating a new lower flood plain. Based on this understanding of flood plain development, Warner (1972) classified river terraces based on their degree of weathering or alteration after abandonment: (1) unaltered Alluvia: the terrace(s) above in-channel benches and flood plain are massive units with no soil development and complete stratigraphy; (2) altered Alluvia: the terrace(s) above the unaltered terrace show degrees of alteration and a relatively complete stratigraphy; (3) residual Alluvia: all older terraces in upstream parts at higher elevations, with an incomplete stratigraphy of basically weathered lag gravels.

The exceedences of critical geomorphic thresholds intrinsic to the fluvial system are often used to explain the formation of terrace sequences (Schumm, 1973; Young & Nanson, 1982). With reference to the Illawarra, Young & Nanson (1982) found that flood plain formation was dominated by either lateral accretion where the channel is migrating laterally in the steeply sloping upper catchment, or by overbank deposition in the mid to lower reaches, where the stream slope is gentler and the channel comparatively stable. The failure of the channel to migrate has been attributed to resistant banks and reduced stream power. However, the exceedence of a geomorphic threshold, according to Young & Nanson (1982), can result in rapid incision into the softer, overbank sediments, allowing channel migration and eventual flood plain abandonment and, therefore, development of terrace sequences. Terraces can be arranged in differing geomorphic settings, as incised, inset or overlapped terraces (Warner, 1972). Leopold & Miller (1954) refer to cut, fill and "strath" terraces. A cut terrace refers to one formed simply by lowering of a portion of the flood plain with no subsequent deposition. A fill terrace is formed when a portion of the valley floor is eroded and then filled by subsequent deposition. A "strath" terrace is one formed when a section of the flood plain is almost entirely eroded and the channel incises into the underlying bedrock. Stratigraphy is a reasonable indicator of changes to the fluvial regime and depositional environment during sedimentation (Warner, 1972; Young & Nanson, 1982). Soil development, sedimentology, surface morphology and chronology are used to correlate flood-plain terraces and to develop models to explain their occurrence. Characteristics of terrace sequences were used to establish a late Pleistocene perturbation, most likely of climatic origin, which was intense and widespread enough to affect most valleys in the Canberra region of eastern Australia, a large regional area (Walker, 1984). The recovery of each individual valley was variable. Walker (1984) postulates that this could be due to a complex response to the exceedence of geomorphic thresholds.

Terrace morphology provides useful insight to the history of a river's development, which assists in an understanding of fluvial processes on a local, regional and continental scale. However, the environmental significance of river terraces is not solely reliant on morphology; chronometric data is also crucial to this understanding. The continuity of terrace remnants is a primary criterion for correlation. Longitudinal continuity, in combination with relative elevation, is established by a range of appropriate stratigraphic and sedimentological criteria, including discontinuities between terrace fills, differences in particle size and sorting, and in primary sedimentary structures, evidence of buried soils (palaeosols), floral and faunal remains, ash horizons and archaeological artefacts (Leopold *et al.*, 1964). Our objective is to use the longitudinal correlation of a river terrace sequence to explore the processes of terrace abandonment and flood plain development in southeastern Australia.

METHODS

Widden Brook is a right bank tributary of the Goulburn River, itself a right bank tributary of the Hunter River, New South Wales. It has a catchment area of 700 km^2, and is one of five tributaries that join the Goulburn River from the south. All are dominated by partly confined valley settings. Planform and terrace-controlled discontinuous flood plains are present in these settings and little or no flood plain is found in the lower reaches where the valley narrows. The Widden Brook channel appears to have low rates of lateral movement when vegetated, but has distinct phases of incision and subsequent lateral expansion, followed by migration then recovery by bench deposition.

Widden Valley is incised into Permo-Triassic Narrabeen Group sandstones and conglomerates, underlain by Permian Wollombi Coal Measures. The headwaters of Widden Brook and much of the surrounding valley tops, which range from an elevation of around 500 m to 1250 m on the Australian height datum (AHD), are in the Wollemi National Park. The lower part of the valley can be separated into three geomorphic sections. There is an upstream and downstream constricted valley separated by a marked valley expansion. This study focuses on a reach of the upstream constriction. It begins 3 km downstream of the only substantial tributary, Blackwater Creek, and ends at the start of the valley expansion.

Three cross-sections over the reach were analysed for stratigraphic, topographic, pedological and chronological characteristics. The cross-sections were located where terraces were topographically pronounced. Fine resolution terrace sedimentology was determined from drill holes and used to construct the history of the stream's development. Survey data along cross-sections was used to characterise the terrace morphology. Topographic changes were determined similarly from surveying to establish the relative elevation of terrace surfaces. Radiocarbon dating by accelerator mass spectrometry (AMS) was used to compare terrace soil development and sedimentation rates. Air photo interpretation, oral histories, historical records and maps, historical channel survey data, flood-plain sedimentology and chronology were used to construct the alluvial history of the Widden Valley.

Charcoal and wood for AMS ^{14}C dating were collected in the field from trenches, pits and drill cores and are reported as Conventional Radiocarbon ages (years BP) (Stuiver & Pollack, 1977). Radiocarbon dates represent a maximum age of deposition. In an inset/incised flight of terraces, the age of the next youngest terrace provides a minimum age for the next older or higher terrace. With multiple dates from terrace sediments, the inferred age of each phase of terrace formation becomes increasingly precise. Hence, the age of terrace formation has been constrained between these two ranges of dates, provided that terrace formation was not diachronous.

Preliminary cross-sections were drawn in the field. Sediment profiles from pit, auger and probe holes, along with those from the trenches and drill holes were described in the field for sedimentary structures, texture, colour, artefacts and boundaries. Samples were then taken for later chemical and physical analyses. Samples were analysed for grain size, using a combination of sieve/hydrometer and laser diffraction techniques (Cheetham *et al.*, 2008).

RESULTS AND DISCUSSION

The study reach consists of three cross-sections at 0, 1.8 and 3.9 km down the study reach. These cross-sections are referred to as XS1, XS2 and XS3, respectively (Figs 1 and 2). Table 1 gives their description, age, longitudinal extent and slope. The terrace sequence has been named the "Baramul Sequence" and the terraces are numbered consecutively in order of abandonment.

Terrace one (T1) is dated at 10 050 ± 260 and 12 030 ± 260 years BP and is present at both XS1 and XS2 (Figs 1 and 2). It consists of altered, vertically accreted flood-plain sediments underlain by coarse channel sediments. At the upstream cross-section (XS1), T1 is found on the right bank and terrace alluvium is interdigitated with, and capped by colluvium. At XS2, T1 is only found as a buried "toe" under T2 and as channel sand on the left bank. Its position on the left bank indicated that T1 was indeed paired and as such was abandoned rapidly. It was also partially overlapped sometime after 12 030 ± 260 years BP, indicating significant erosion and subsequent deposition, possibly due to a catastrophic flood.

Terrace two (T2) consists of slightly altered, vertically-accreted flood-plain sediments overlying channel sands and is capped by colluvium (Fig. 1). It is dated at 4140 ± 60 – 3670 ± 80 years BP. It is paired at XS1 and XS3, indicating it was abandoned by rapid incision. T2 was likely to be abandoned due to an extreme event, such as a catastrophic flood.

Terrace three (T3) consists of unaltered, vertically accreted flood-plain sediments overlying channel sands (Fig. 1) and is dated at 2490 ± 40 – 2240 ± 60 years BP. Its abandonment is attributed to the exceedence of an intrinsic geomorphic threshold as no major climatic event can be found to coincide with these ages. T3 is not present at XS3.

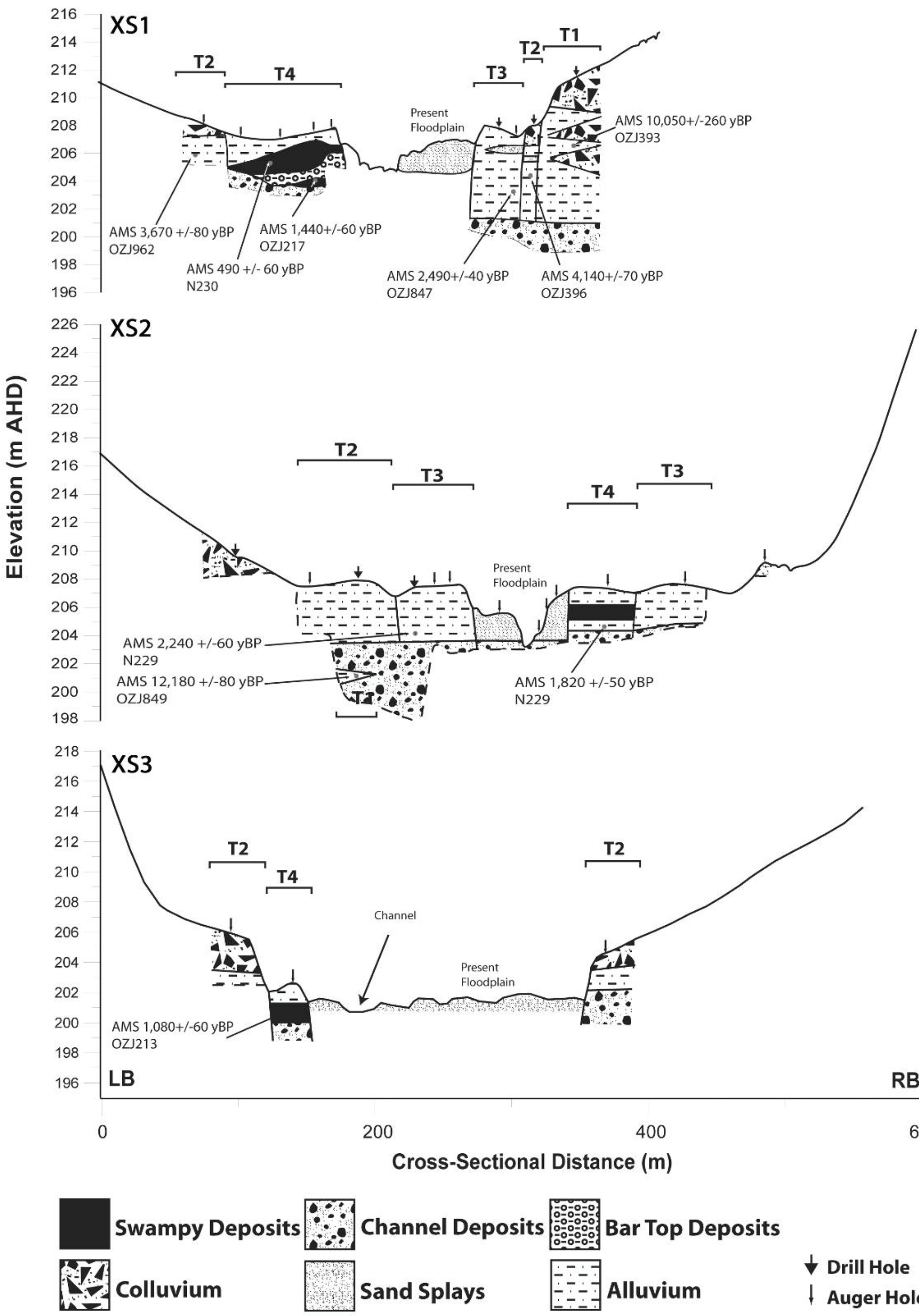

Fig. 1 Cross-sections 1, 2 and 3 from upstream to downstream. For cross-section locations, see Fig. 2.

The lower terrace in this reach (T4) was, in part, deposited under a backwater environment and was abandoned sometime after 490 ± 60 years BP. It consists of unaltered, vertically accreted, flood-plain and bar top sediments overlying channel sands. T4 is distinct because of units of very fine silty organic muds (Fig. 1). T4 is found on the left bank at XS1 and on the right bank at XS2, indicating that it was paired and that its abandonment was rapid.

The time of terrace abandonment can only be constrained by the youngest date of the terrace itself and the oldest date for the subsequent terrace. Even then the assumption that no other terrace formation and erosion occurred between these dates must be made. T1 was abandoned sometime between 10050 ± 260 and 4140 ± 60 years BP. T2 was abandoned sometime between 3670 ± 80

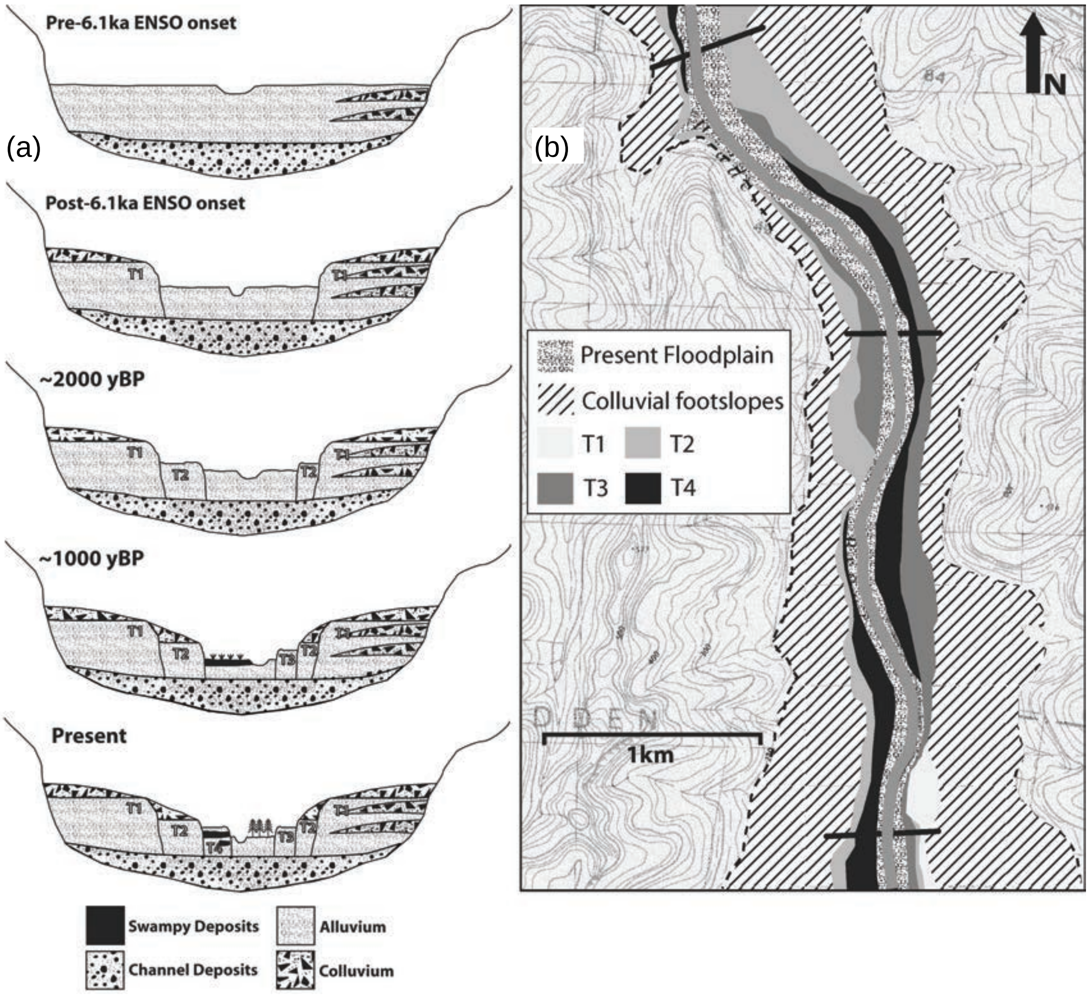

Fig. 2 Cross-sectional model for terrace abandonment for upstream reach based on cross-section 1 (a). Planform map of present terrace locations in the reach (b).

Table 1 Description of terraces, their longitudinal extent down valley and their age of deposition.

Terrace	Description	Longitudinal extent within study reach	Age range (years BP)	Terrace slope (m/km)
T1	Altered, vertically accreted flood-plain sediments	3.9 km	12 180 ± 80 – 10 050 ± 260	–
T2	Slightly altered, vertically-accreted flood-plain sediments	3.9 km	4140 ± 60 – 3670 ± 80	1:0.65
T3	Unaltered, vertically-accreted flood-plain sediments	1.8 km	2490 ± 40– 2240 ± 60	1:0.83
T4	Unaltered, vertically-accreted flood-plain sediments and backwater deposits	3.9 km	1820 ± 50– 490 ± 60	Terrace: 1:0.78 Swamp: 1:0.51
FP	Post European flood-plain sediments	3.9km	<200	1:1.41

and 2490 ± 40 years BP. T3 was abandoned sometime between 2240 ± 60 and 1820 ± 50 years BP. T4 was abandoned sometime after 490 ± 60 years BP. Once an age range for abandonment was established, a mid point of that range could be determined and the Holocene climate record for the region could be assessed for any correlation, indicating that terrace abandonment may be due to climatic effects. Part of the terrace abandonment appears to correlate with a major climatic event.

It is important to remember that despite sea-level falling over the last 2000 years, from +1.5 m to present day levels (Sloss *et al.*, 2007), base level change is unlikely to have had any impact on the Baramul Sequence. Bedrock bars at Scotts Flat, downstream of Singleton, and at Woodlands, downstream of Denman, would act as barriers to the effects of sea level changes further upstream. All terraces below T1 are relatively narrow and straight, indicating that the channel has, for the last 4000 years at least, been of low sinuosity.

The colluvial interdigitation with T1 sediments indicates periods of infill between periods of valley side instability. The abandonment of T1 roughly coincides with the onset of ENSO at 6.1 ka (Singh *et al.*, 1981; Dodson, 1994; Black & Mooney, 2007; Mooney *et al.*, 2007). The dry conditions that were initiated at this time would have forced the channel to contract and to abandon its flood plain due to a decrease in discharge (Warner, 1972). This is further supported by the decrease in slope from 1:0.65 to 1:0.83 (Schumm, 1973). T1 is also separated from the lower terraces by the largest topographic relief, indicating a relatively major event was responsible for its abandonment. T1 is classified as an altered, inset fill terrace (Leopold & Miller, 1954; Warner, 1972).

T2 was abandoned approx. 3080 ± 120 years BP. Other than increasing climate variability with an overall increase in temperature, there is no major climatic event or shift at this time that is likely to have caused this abandonment. T2 is only separated from its subsequent terrace by minor topographic relief, indicating a relatively minor change in depositional environment. This is also supported by a relatively low change in slope from 0.83 to 0.78. The terrace extends from above XS1 to below XS3; however, it does not continue into the valley expansion further downstream. This terrace was more likely abandoned due to the exceedence of one or more geomorphic thresholds (Schumm, 1973) or due to natural progressive down-cutting. T2 is classified as a slightly altered, inset fill terrace.

Abandonment of T3 appears to have occurred progressively upstream over time (Figs 1 and 2). T4 backswamp deposit ages at XS1 are younger by 590 ± 120 years than at XS3; and the T3 basal overbank deposits above channel material at XS1 are younger by 380 ± 110 years than at XS2. This could indicate a knickpoint recession type process of abandonment for T3, leading to a progressively younger age for T4 abandonment upstream. This knickpoint recession process could have been initiated downstream at a critical geomorphic location, such as the valley expansion and worked progressively upstream (Leopold & Miller, 1954; Schumm, 1973). T3 is classified as unaltered, inset fill terrace.

There appears to be a change to a low energy depositional environment during the deposition of T4, starting at 1080 ± 60 years BP at XS3 and continuing to 490 ± 60 years BP at XS1. T4 was abandoned sometime after 490 years BP. This occurred sometime after a change from a backwater environment to overbank type deposition. It is unlikely that this is associated with clearing following European settlement, as clearing should increase sediment load and increase coarse-grained deposition. It is more likely that T4 was abandoned due to a catastrophic flood at a time when T4 was nearing a critical stage of development. The flood could have then stripped the terrace surface, eroded the channel and re-deposited overbank sediments before coming to its new level and forming today's contemporary flood plain. T4 is classified as an unaltered, inset fill terrace. It is not active and flood levels did not reach its surface at any location in the reach during the last 1 in 30 year flood (flood occurring in June 2007).

The Baramul Sequence shows a progressive relative fall in bed-level and reduction in slope during the Holocene. This is likely to have been accompanied by progressive contraction of the channel and indicates a reduction in mean discharge over the last 6–7 ka. The terraces were all abandoned when ground surface slope was almost twice as steep as the present flood plain, indicating that increased valley slope and decreased bed load are critical thresholds (Schumm, 1973). The question of what occurred before T1 also remains to be answered. At this point, without further information, a total valley cleanout is assumed, possibly due to increased discharge following or during the last glacial maximum. The processes driving the abandonment of these terraces are complex and require further investigation of each terrace to unravel aspects of the processes behind this system's complex response.

CONCLUSIONS

The Baramul Sequence consists entirely of inset, fill type terraces. Apart from T1, the terraces are separated by relatively constant periods of time. The large age gap between T1 and T2 suggests the possibility that more cut and fill events may have occurred before the deposition of T2; however, any evidence of terraces in the interim has not been found and could well have been removed completely by a large event. These terraces have been formed by a combination of climatic events and complex response to the exceedence of geomorphic thresholds, such as valley slope, sediment load, discharge and sinuosity. The Baramul Sequence does not extend into the downstream valley expansion and further work is required to assess the coeval, location specific, driving forces behind terrace sequence formation in this catchment. This work is currently being conducted.

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REFERENCES

Black, M. P. & Mooney, S. D. (2007) The response of Aboriginal burning practices to population levels and El Nino-Southern Oscillation events during the mid- to late Holocene: a case study from the Sydney Basin using charcoal and pollen analysis. *Australian Geographer* **38**, 37–52.

Brierley, G. J. & Fryirs, K. (2000) River Styles, a geomorphic approach to catchment characterization: implications for river rehabilitation in Bega catchment, New South Wales, Australia. *Environ. Manage.* **25**(6), 561–679.

Brierley, G. J. & Fryirs, K. A. (2005) *Geomorphology and River Management: Application of the River Styles Framework.* Blackwell Publishing, Carlton, Victoria, Australia.

Cheetham, M., Keene, A., Bush, R., Sullivan, L. & Erskine, W. A (2008) Comparison of grain-size analysis methods for sand-dominated sediments. *Sedimentology* (in press).

Dodson, J. R. (1994) Quaternary vegetation history. In: *Australian Vegetation* (ed. by R. H. Groves), 37–56, Cambridge University Press, Cambridge, UK.

Leopold, L. B. & Miller, J. P. (1954) A postglacial chronology for some alluvial valleys in Wyoming. *US Geol. Survey, Water Supply Paper 1261*.

Leopold, L. B., Wolman, M. G. & Miller, J. P. (1964) *Fluvial Processes in Geomorphology*. W.H. Freeman and Co., San Francisco, USA.

Mooney, S. D., Webb, M. & Attenbrow, W. (2007) A comparison of charcoal and archaeological information to address the influences of Holocene fire activity in the Sydney Basin. *Australian Geographer* **38**, 177–194.

Richards, K. (1982) *Rivers: Form and Process in Alluvial Channels*. Blackburn Press, New Jersey, USA.

Schumm, S. A. (1973) Geomorphic thresholds and complex response of drainage systems. In: *Fluvial Geomorphology* (ed. by M. Morisawa), 299–310. George Allen & Unwin, London, UK.

Schumm, S. A. (1977) *The Fluvial System*. John Wiley and Sons, New York, USA.

Singh, G., Kershaw, A. P. & Clark, R. (1981) Quaternary vegetation and fire history in Australia. In: *Fire and the Australian Biota* (ed. by A. M. Gill, R. H. Groves & I. R. Noble), 23–50. Australian Academy of Science, Canberra, Australia.

Sloss, C. R., Murray-Wallace, C. V. & Jones, B. G. (2007) Holocene sea-level change on the southeast coast of Australia: a review. *The Holocene* **17**(7), 999–1014.

Stuiver, M. & Pollack, H. A. (1977) Discussion Reporting C-14 data. *Radiocarbon* **19**(3), 355–363.

Walker, P. H. (1984) Terrace formation in the Illawarra region of New South Wales. *Australian Geographer* **16**, 141–143.

Warner, R. F. (1972) River terrace types in the coastal valleys of New South Wales. *Australian Geographer* **12(1)**, 1–22.

Young, R. W. & Nanson, G. C. (1982) Terrace formation in the Illawarra region of New South Wales. *Australian Geographer* **15**, 212–219.