Death of a palaeochannel: slow abandonment of an avulsed channel on the Riverine Plains, SE Australia

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Abstract

Avulsion of rivers can be a gradual process that is associated with a metamorphosis of channel pattern or changed channel characteristics. The processes controlling avulsion, and hence anastomosis, often operate too slowly to study by measuring active river systems, and hence well preserved Late Quaternary rivers offer one of the best ways to study the long-term development of avulsive systems. The modern and ancient channels of the Murrumbidgee River provide a classic example of long-lived, semi-static anastomosis, operating on timescales that include stadial and interstadial climate cycles. Over the last glacial cycle, regional avulsions have occurred every ~ 12 ka while maintaining an anastomosing pattern through the slow infill of abandoned channels. The Yanco Creek Palaeochannel System emerged from a period of high discharge linked to snowmelt in the terminal Pleistocene. Here, geomorphological mapping of the Yanco System was conducted together with single-grain, optically stimulated luminescence dating of sediments in the channel belt. Since the main phase of channel construction during the Last Glacial Maximum, the Yanco system has functioned as a flood conduit and minor anabranch of the Murrumbidgee River, with reworking of ancient channel sediments by an underfit stream that is ongoing to the present day. Our new ages of ~ 13–14 ka are interpreted as channel sedimentation during an underfit phase following avulsion. The prevalence of full and partial avulsion in this environment may be complicating palaeohydrological interpretations of ages for channel activity, and reworking has gone unrecognised. We contend that some previous interpretations of the significance of ages for sediments collected from Riverine Plain palaeochannels may need revision.

Introduction

Once considered an oddity, anastomosing rivers have become a focus of fluvial research with increasing recognition of their distinctive channel pattern and processes (Schumm, 1985; Smith, 1986; Nanson and Knighton, 1996; Carling et al., 2014; Latrubesse, 2015). Anastomosing rivers have been broadly defined by Makaske (2001) as two or more interconnected channels that enclose flood basins or near level overbank areas, but the term “anabranching” is sometimes used synonymously (e.g. Bridge, 1993). We use the term “anabranch” here to indicate a single channel in an anastomosing network, which forms through out-of-bank erosive processes, i.e., avulsion (Carling et al., 2014). Anastomosing rivers form in a range of geological and climatic settings, from arctic to temperate and tropical latitudes, and humid to arid and semiarid climates. The range of fluvial sedimentary environments in which anastomosing rivers occur that have been described include (1) distributary fluvial systems and megafans along mountain fronts (Hartley et al., 2010; Weissman et al., 2010; Makaske et al., 2012; Donselaar et al., 2022), (2) sediment-laden confined mountain valleys (Smith and Smith, 1980; Makaske et al., 2009), (3) distributary networks of inland and coastal deltaic plains (Gibling et al., 1998; Schumm et al., 1996; Stouthamer and Berendsen, 2001; Gouw and Erkens, 2007), and (4) channel networks of wide, low gradient valleys that experience regime change on Milankovitch timescales (Page and Nanson, 1996; Pietsch et al., 2013). Anastomosing forms are increasingly recognised as an important, if not dominant, component of the fluvial rock record (Kraus, 1996; Kraus and Gwinn, 1997; Hartley et al., 2010; Weissman et al., 2010; 2015; Fielding et al.,
Work on the classification, terminology, and processes controlling anabranch behaviour and form is ongoing. Recent advances have been made through the use of mapping from remotely sensed imagery (e.g. Marinho et al., 2022), and from detailed investigations of bar sedimentology (Nicholas et al., 2013; Slowik, 2016). However, the development of anastomosing patterns often occurs over substantial time periods. On long-lived, semi-static anastomosing rivers (sensu Makaske, 2001) where anastomosis depends upon intermittent avulsion, the processes need to be studied on timescales that encompass the late Quaternary.

To date, studies of anastomosing channel evolution have focused on the stratigraphic development of newly-formed channels, progressing from crevasse splay formation through the avulsion belt stage and culminating in the development of a single channel belt (Smith et al., 1989; Schumm et al., 1996; Farrell, 2001; Makaske, 2001). Detailed studies of channel changes in Holocene avulsion belts have been conducted on the Rhine-Meuse delta (Stouthamer & Berendsen, 2000, 2001; 2007; 2011; Cohen et al, 2012; 2013). Surprisingly little is known, however, about decaying channel belts. Detailed descriptions of sedimentary architecture and abandonment phases of avulsed channels have been produced for the Rhine delta apex over the last 2000 years (Toonen et al., 2012; Van Dinter et al., 2017). On longer timescales, avulsions associated with regional climate change during the Late Glacial and early Holocene have been studied in the Rhine-Meuse delta (Berendsen et al., 1995; Vandenberghe, 1995), elsewhere in Europe (Mol et al., 2000; Tumer et al., 2013; Kadlec et al., 2015) and Australia (Schumm, 1968; Fielding et al., 2006; Page et al., 2009; Kemp and Rhodes, 2010). Anastomosis caused by the slow switching or failed channel avulsions are known from the late Holocene evolution of the Rhine-Meuse (Cohen et al., 2012; 2013) with avulsions occurring over periods of < 1000 years (Stouthamer and Berendsen, 2007; Toonen et al., 2012; Van Dinter et al., 2017). Documented examples of the duration of large-scale avulsion processes range from $10^2$-$10^3$ years. The sedimentary effects of these slow, partial avulsions (sensu Slingerland and Smith, 1994) is often the deposition of fine-textured infill and levee sedimentation by an underfit stream in the position of the old (pre-avulsion) channel (Kraus, 1996, Aslan and Blum, 1999). However, substantial sedimentation and a change in channel pattern from braided to meandering was recognised in the Brahmaputra River following partial or gradual avulsion of the parent channel (Bristow et al., 1999). Elsewhere, reoccupation of avulsed channels is manifest as stacked levee deposits or a multistoreyed channel fill adjoining unusually thick levee sediments (Stouthamer, 2001).

Australia's Riverine Plain provides a classic case study of river evolution and hydrological change, with low rates of sedimentation and channel infill preserving a record of erosion and runoff that extends over more than a glacial cycle (Schumm, 1968; Bowler, 1978; Bowler et al., 1978; Page et al., 1991; Page et al., 2001; Page and Nanson, 1996; Page et al., 1996; Banerjee et al., 2002; Kemp and Spooner, 2007; Page et al., 2009; Kemp and Rhodes, 2010, Kemp et al., 2014; 2017). The region includes distributary and anastomosing rivers transporting mixed and suspended sediment loads with low or medium unit stream powers of 2–20 W m$^{-2}$ (Fig. 1; Kemp et al., in prep.). Channel planforms are irregularly sinuous and actively meandering. A single, dominant channel conveys most of the discharge, but long anabranches develop at the entrance to the alluvial plains and cross the boundaries between the major river basins.
Palaeochannels in various stages of abandonment often continue to function as anabranches during floods and/or lower flows.

Nanson and Knighton (1996) excluded from their classification of anastomosing channels those that formed over periods of major climate change, as well as channels that enclosed large areas of ancient alluvium. However, Makaske (2001) recognised long-lived (>10^3 yr), semi-static anastomosing channels that appear to be in a state of dynamic equilibrium. On longer timescales, the channel belts might collectively be regarded as distributary systems - or distributive fluvial systems as they are sometimes called - where the vast majority of sedimentation occurs within continental sedimentary basins (Hartley et al., 2010; Weissman et al., 2010). In either case, an important mechanism for creating a multichannel form is slow, partial or failed channel avulsion leading to the co-existence of young and old channels (Makaske, 2001). The ‘palaeochannel’ then becomes a subordinate branch of an anastomosing network.

Triggers for avulsion in the Riverine Plain are poorly understood, but at least some examples in the region have a tectonic origin. At least five movements of the Cadell Tilt Block triggered major river diversions in the Murray Basin between 73 ka and 0.5 ka (Bowler, 1978; Page et al., 1991; Stone, 2006; Clark et al., 2015), and movement along the Iona Fault may have been responsible for successive, southward avulsions of Willandra Creek after 18 ka (Kemp et al., 2017). Elsewhere in the Murray Basin, low sedimentation rates and low relief combined with high flood variability seem to be important pre-conditions for avulsion (Kemp, 2010). The incursion of woody vegetation during periods of low flow may also have been a factor in the past (Pietsch and Nanson, 2011). Generally, major avulsions on the Riverine Plain have been attributed to aggrading bed levels and the development of levees that become prone to crevassing (Page and Nanson, 1996).

Today, abandoned, “dead” river systems comprise much of the surface of the Riverine Plain (Butler, 1950; Langford-Smith, 1960). These old palaeochannels typically have straight or gently winding channels with wide beds that are elevated above the plain. At depth, coarse sandy gravel of the palaeo-river bed occurs at variable depths in different channels, suggesting frequent avulsion (Pels, 1964a). Originally described as a distributary palaeochannel complex known as “prior streams” (Butler, 1950), they were later recognised as the final phase of laterally migrating channels that were buried by vertical accretion (Pels, 1964a; Bowler, 1978). Bowler (1978) surmised that these sandy, aggraded palaeochannels were the result of either channel diversion (i.e. avulsion) or climate change. In the Murrumbidgee, Page and Nanson (1996) reconstructed the full stratigraphic profile of two well-preserved aggradational palaeochannels from borehole logs and described an evolutionary sequence beginning with actively migrating, mixed-load channels, which they termed “migrational palaeochannels”. The evolutionary sequence of Page and Nanson describes changes in sediment load and flood frequency instigating a transformation from “migrational” to “aggradational” stages (Fig. 2). The sequence concludes with decreasing fluvial competence and shoaling sands, followed by avulsion and the formation of a new migrational channel elsewhere on the plain.
There are a number of reasons to question the universality of this model. Firstly, as Page and Nanson recognised at the time, younger migrational palaeochannels at the surface (i.e. the *ancestral* channels of Pels, 1964b) do not conclude with a terminal aggradation phase despite major environmental changes in their upland environment during Marine Isotope Stages 2 and 3 (Page and Nanson, 1996). Secondly, local preconditions for avulsion cannot be identified in the younger, migrational palaeochannels. The older, aggraded streams were vulnerable to avulsion through crevassing with numerous examples of this process visible on the surface (Pels, 1964a; Page et al., 1996). In contrast, the younger Gum Creek and Yanco systems remained incised in their channel belts, yet both concluded with (partial) avulsion.

Environmental controls on channel metamorphosis in the region remain poorly understood. The transformation from migrational to aggrading channels has not clearly been tied to environmental changes in the catchment. Wide, bedload channels combined with aggradation requires bedload transport and/or supply to be enhanced in concert with reduced stream competence. It is difficult to ascribe this to a known environmental scenario in the late Quaternary, hence multiple hypotheses have emerged. The change to aggradational palaeochannels has been interpreted as a shift to semi-aridity (Butler, 1958; Pels, 1964a), or higher discharges (Langford-Smith, 1960), or a change in flood frequency (Page and Nanson, 1996), or to subtle shifts in stream competence, sediment supply and runoff (Page et al., 1996).

Some of the difficulties in interpretation are owing to problems dating the various palaeochannel phases. Page et al. (1996) dated the final infill stages of their Coleambally and Kerarbury Fluvial Systems (Fig. 1) as 105 – 80 ka and 45 – 35 ka, respectively, and related enhanced fluvial activity to wetter climates during MIS 3 and MIS5. No attempt has been made to date the buried floodplains of the migrational phases. This is important because the timescale over which infill, aggradation and abandonment occurs is largely unknown. Likewise, timescales associated with the fluvial response to change in the catchment sediment supply, vegetation cover and soils are not well understood. More analyses have been conducted on the surface palaeochannels (Gum Creek and Yanco Systems), but post-avulsion alteration has not always been recognised, leading to difficulties with the geomorphic and environmental interpretation. Higher resolution chronologies for channel incision, sedimentation, avulsion, and post-avulsion modification are now required to build a long-term understanding of processes governing palaeochannel morphology and sediments in the Riverine Plain.

In this paper we present new geomorphic investigations of the Yanco Palaeochannel System at three locations. We present new ages based on single-grain OSL techniques for one site and review published ages for the Yanco Creek System. We infer that partial avulsion upstream was the cause of channel changes in the Yanco and we evaluate the evolutionary model of Fig. 2 in the youngest Pleistocene channel belt in the Riverine Plain. Together, this information provides an insight into the timescales for evolution and change in decaying channel belts.

**Study Area**
The Murrumbidgee River is a major tributary of the Murray River with a catchment of 84,000 km\(^2\) (Fig. 1). Its mountainous upper catchment lies in the Australian Alps with ranges > 2000 m above sea level. Snow falls on the highest peaks in winter, but snowmelt presently contributes little to river discharge (Schumm, 1968). Average annual precipitation decreases westwards from 1160 mm at Yarrangobilly in its headwater ranges (1070 m elevation) to 440 mm at Narrandera (173 m) to 320 mm at Balranald (61 m) (Bureau of Meteorology, 2015) (Fig. 1). Downstream from Wagga Wagga there is no significant tributary input and at Narrandera the river enters extensive alluvial plains. Bankfull discharges decrease from 710 m\(^3\)s\(^{-1}\) at Wagga Wagga to 260 m\(^3\)s\(^{-1}\) at Maude (Fig. 1) as flood waters are progressively stored in secondary channels and lagoons (Schumm, 1968; Frazier and Page, 2009). Nowadays, the river is regulated by major reservoirs in the highland catchment, and flows are augmented by interbasin transfers from the Snowy Mountains Scheme. The modern Murrumbidgee is a mixed load, meandering river flowing over a gradient of 0.0022 m at Narrandera (Schumm, 1968). Modelled bankfull discharge near Wagga Wagga suggests that prior to river regulation bankfull flows had a return period of 1.5 years on the annual series (Page et al., 2005).

Since its inception in the Tertiary, the Murray Basin has infilled with marine and fluvio-lacustrine sediments under conditions of slow subsidence and sedimentation, producing an extensive plain with subdued geomorphic features. Basin infill rates since the early Pliocene are 13 m Ma\(^{-1}\) measured from the bottom of the ~ 70 m thick Shepparton Formation (Brown and Stephenson, 1991). Sediment yields are among the lowest in the world with yields of < 12 t km\(^{-2}\) yr\(^{-1}\) in headwater basins < 300 km\(^2\) (Douglas, 1973). On the Riverine Plain, repeated, random avulsion (\textit{sensu} Leeder, 1978) through the Late Quaternary has produced a network of anabranches and abandoned channels between the Murrumbidgee and Murray Rivers (Fig. 1). This is particularly pronounced downstream from Narrandera, where the Murrumbidgee forms a large, low-angle alluvial fan. Thermoluminescence (TL) dating of major channel belts ("arms" of Page et al., 1996) within the Murrumbidgee Palaeochannel Systems implies that at least eight large avulsions have occurred in the last ~ 100 ka with an average frequency of once every ~ 12 ka. Before 35 ka, the Murrumbidgee flowed westward as the Gum Creek System (Fig. 1, Page et al., 1996; Mueller et al., 2018). Subsequent avulsion, dated to ~ 20 ka by Page et al. (1996) created the Yanco Palaeochannel System. The avulsion node has since been reworked by lateral migration of the Murrumbidgee River, but the new Yanco channel belt was constructed along a new path southwest of the Gum Creek System and the modern Murrumbidgee River. The Yanco System was characterised by a large, meandering, gravel and sand-bed river with anastomosing reaches. Its channel belt was 2 to 5 km wide with a floodplain surface lying 1–3 m below the general level of the plains (Page and Nanson, 1996). Bankfull channel widths averaged 225 m with a bankfull depth near the offtake of 5.5 m, varying little over 100 km downstream to an average depth of 5–6 m at Rhyola (Fig. 1). Width varied from an average of 400 m in its upper reaches to 250 m at Rhyola, giving a width-depth ratio that declined from 70 to 45 (Fig. 1; Page, 1994; Page and Nanson, 1996). The Yanco System is best preserved downstream from Wanganella where the modern and palaeochannel rivers are geographically separate. TL- and OSL-dated fluvial sand from four locations suggested the Yanco phase was active during Marine Isotope Stage (MIS) 2 (29 – 12 ka) (Page et al., 1996; Mueller et al., 2018; Hesse et al., 2018) (Fig. 3). Banerjee et al.
tested the TL chronology against small aliquot OSL and obtained an age of 9.4 ± 0.8 ka for a fluvial source-bordering dune flanking the main Yanco channel belt (Fig. 3).

The middle and upper reaches of the Yanco channel belt are presently occupied by Yanco Creek from which the System gets its name, and are fed by distributary flow from the Murrumbidgee River. Nowadays, Yanco Creek is a perennial stream with a bankfull flow of 6 m$^3$s$^{-1}$, and a bankfull width and depth of 22 m and 2.3 m, respectively (Tarabah Weir 410036: NSW Office of Water, 2015; Fig. 1). Much of the modern-day Yanco Creek has an anastomosing pattern with major branches including Billabong Creek, Forest Anabranch, Gum Creek, Columbo Creek, Turn Back Jimmy Creek, Sheep Wash Creek and Swampy Creek, hereafter collectively referred to as modern Yanco Creek.

Methods

Geomorphic mapping of the study reach was performed from orthophoto maps, from Google Earth and from LiDAR (Geoscience Australia, 2021). Samples for OSL dating were obtained from the aggregate quarry at Thurrowa Rd (35.152353 °S, 145.937843 °E) and the source-bordering dune that overlies the eastern margin of the Yanco channel belt, 1.8 km ENE. Sampling was located as closely as possible to the original studies by Page et al. (1996) and Banerjee et al. (2002) (Fig. 3), and was conducted to compare the dating results of thermoluminescence to single-grain optically stimulated luminescence (OSL).

OSL samples were extracted from stainless steel tubes hammered into the exposed E and N faces of the quarry. The dune sample was extracted by a light-proofed auger head, wrapped, and returned to the laboratory at Griffith University for further analysis. Sample preparation was designed to isolate pure extracts of 180–212 µm light-safe quartz grains 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 etching in 48% hydrofluoric acid for 40 min.

A burial dose was determined from measurement of the OSL signals emitted by 1000–1500 single grains of quartz. The etched quartz grains were loaded on to custom-made aluminium discs drilled with a 10 x 10 array of chambers, each of 300 µm depth and 300 µm diameter (Botter-Jensen et al. 2000). The OSL measurements were made on a Risø TL/OSL DA-20 reader using a green (532 nm) laser for optical stimulation, and the ultraviolet emissions were detected by an Electron Tubes Ltd. 9235QA photomultiplier tube fitted with a 7.5 mm Hoya U-340 filter. Laboratory irradiations were conducted using a calibrated $^{90}$Sr/$^{90}$Y beta source mounted on the reader.

Equivalent doses ($D_e$) were determined using a modified SAR protocol (Olley et al., 2004). A dose-response curve was constructed for each grain. OSL signals were measured for 1 s at 125°C (laser at 90% power) using a preheat of 240°C (held for 10 s) for the ‘natural’ and regenerative doses, and a pre-heat of 160°C (held for 10 s) for the test doses (5 Gy). The OSL signal was determined from the initial 0.1 s of
data, using the final 0.2 s to estimate the background count rate. Each disc was exposed to infrared (IR) radiation for 40 s at 125°C prior to measurement of the OSL signal to bleach any IR-sensitive signal. Grains were rejected if they did not produce a measurable OSL signal in response to the 5 Gy test dose, had OSL decay curves that did not reach background after 1 s of laser stimulation, produced natural OSL signals that did not intercept the regenerated dose-response curves, or had unacceptable sensitivity changes throughout the measurement cycle, i.e. they were rejected if either of the second or third Test Dose signals varied in sensitivity from the first Test Dose (associated with the Natural Dose) by more than 20%.

Lithogenic radionuclide activity concentrations of material extracted from sampling tubes were determined using high-resolution gamma spectrometry (Murray et al. 1987). Samples were counted for 24–144 h on an Ortec HPGe co-axial gamma detector. The average radionuclide activity was calculated from two sub-samples. Dose rates were calculated using the conversion factors of Liritzis et al. (2013) with β-attenuation factors taken from Mejdahl (1979). Cosmic dose rates were calculated from Prescott and Hutton (1994). Burial doses were calculated using age modelling techniques of Galbraith and co-workers (Galbraith and Laslett, 1993; Galbraith et al., 1999; Roberts et al., 2000).

**Results**

**Geomorphology and sediments**

Geomorphic mapping of the Yanco System between Bundure and Moulamein shows a largely reworked channel belt in which much of the channel and floodplain deposited by the large, meandering phase of the palaeo-Yanco have been eroded by laterally active streams and minor (flood) anabranches with irregular, smaller meanders of moderate to low sinuosity (Fig. 1). The three subreaches selected for detailed geomorphic analysis are representative of the downstream evolution of the Yanco System with chronological data available. The three reaches are described from downstream, where the Yanco Fluvial Palaeochannel System is well preserved and provide a Type Reach for the system, to upstream, where it has been extensively reworked (Figs. 4–6).

In its lower reaches downstream from Wanganella to downstream of Rhyola, the Yanco System is very well preserved owing to divergence of the younger creeks, Forest Anabranch and Billabong Creek, from the palaeochannel system (Fig. 4). Geomorphic reconstructions show the Yanco to have been a low to moderately sinuous channel with scrolled point bars indicating downstream translation, mild rotation, and sometimes exaggerated extension of meander bends. Flood flows in a un-named distributary of Forest Anabran branch have reworked typically half of the former channel width. Reworking of cut-off Yanco channels has occurred to a lesser extent. Source-bordering dunes have accumulated on the eastern flanks of palaeochannels. The chronology for this reach is based on the type reach at the cut-off meander three kilometres west of Rhyola Station (Fig. 4) with TL and OSL samples augered from the former channel bed, source-bordering dunes, and lateral migration deposits (Page et al., 1996, Page and Nanson, 1996).
Fifty kilometres further upstream between Wanganella and Conargo, the Yanco channel belt is recognisable as a sandier, scrolled and sparsely wooded floodplain 1300 m wide (Fig. 5). Outside, within, and cutting the Yanco channel belt, low sinuosity anabranches are presently active along Brown’s Creek and Sheep Wash Creek, which has reworked Yanco channel deposits, at least surficially. Modern Billabong Creek diverges from the Yanco channel belt five kilometres downstream from Conargo forming an irregular but actively meandering, forested channel belt 330 m wide. Billabong Creek develops an anabranch along Forest Creek; and both are joined by Sheep Wash Creek three kilometres upstream from Wanganella Pit. Wanganella Pit is cut into the sandy channel deposits where the modern drainage again converges on the Yanco channel belt, making it difficult to identify the geomorphic characteristics associated with the parent channel.

Upstream from Conargo, the Yanco channel belt is sinuous but narrow at 890 m wide in relation to its meander wavelength of ~ 5070 m. Downstream from Thurrowa Road, abandoned meander cutoffs and younger palaeochannels likely to be Holocene in age indicate lateral activity that is ongoing to the present day (Fig. 6). The meander wavelength of the Holocene Yanco Creek is 550 m measured over 3.3 km, which is similar to the modern Murrumbidgee at Narrandera (620 m). Most surface evidence of former channels and its scrolled point bar have been removed by lateral migration of the Yanco Creek anabranches and flood channels. Isolated segments of the Yanco Palaeochannel System are preserved, largely infilled, as indistinct channel fragments and dissected, scrolled point bars. The channel belt broadens to 1700 m at Thurrowa Road (Fig. 6), but, in places, traces of the former meander path are apparent in the bimodal sinuosity of Yanco Creek, which reaches a maximum value of 3.2 upstream of Thurrowa Road. Yanco Creek is intermittently divided into two main anabranches with laterally reworked floodplains that tend to occupy either side of the larger channel belt. Between these inset channel belts, flood anabranches are apparent within the trough and cutting across sinuous reaches into the surface of the plain. These flood anabranches act as floodways that are active during higher flows and are often formed along the former courses of palaeochannels (Kemp, 2010). Here, they are irregularly sinuous, follow former scroll bars and flood chutes, and have reworked the Yanco channel belt to varying depths.

In the vicinity of the Thurrowa Pit, indistinct palaeochannel traces belonging to a stream of similar dimensions to the modern Yanco Creek are cut by low sinuosity flood anabranches (Fig. 6). The source-bordering dune that formed east of the Yanco palaeochannel rises 5 m above the plain on its southern margin. Thurrowa Pit exposes 4 m of fluvial sand, gravel and silt from the central part of the reworked channel belt (Fig. 7A). The uppermost sediments are 0.7 m of pale greyish brown, silty, fine sand and coarse, poorly sorted sand, interpreted as flood anabranch and overbank sediments of the modern creek. These overlie at least 3.2 m of channel bed and bar sediments, with cross-bedded coarse sand and fine gravel below 3.5 m, fining upwards to cross-bedded medium and coarse sand with fine gravel lenses, and overlain by reddish brown, fine silty sand. Samples were extracted from the reworked point bar at 1.85 m and 3.0 m. Hand augering of the source-bordering dune nearby revealed structureless, pale reddish brown, silty fine and medium sand (Fig. 6; 7A). An OSL sample was extracted from 2.0 m depth.
Further upstream between Thurrowa Road and the Yanco Creek offtake near Narrandera 130 km upstream, the Yanco System channel belt is between 2.8 km and 0.8 km wide (Fig. 3A). Upstream from Morundah, impressively large meander cutoffs are preserved as oxbow lakes including Dry Lake (Fig. 3A). The Columbo Creek anabranch takes off in the middle of this reach and can be traced along 180 km parallel to the Yanco channel belt, returning to it at Wanganella as Billabong and Forest Creek (Fig. 3A; Fig. 5). In its upstream reaches, the Columbo channel belt is incised and includes palaeochannels with larger meander cutoffs than the present creek. The creek has a bimodal meander pattern in places such as 11 km downstream from the take-off, where a sinuosity of 3.1 and meander wavelengths of 1400 m and 475 m have been measured. Preservation of these surface palaeochannels is similar to the Yanco Palaeochannel, and the shorter meander wavelength suggests it was formed by smaller discharges. Together, the evidence suggests Collumbo Creek was an active anabranch of the Yanco palaeochannel, and therefore that the Yanco palaeochannel was experiencing avulsions. Sinuous palaeochannel belts north of Jerilderie (following dashed lines on Fig. 3A) may represent abandoned reaches of Collombo Creek, indicating that some avulsions would have occurred in the Holocene, possibly under a different discharge regime. Both modern and palaeochannels discharged via a distributary into Lake Urana during high flow stages.

**OSL dating**

Table 1 provides the results of radionuclide analysis, along with the dose rates calculated using the relevant water contents and cosmogenic factors (latitude, longitude, altitude, time-averaged depth and density). The radionuclide data shows some evidence for disequilibrium in the $^{238}$U decay chain for GU29.3 in that activity-concentrations of $^{226}$Ra are lower than its parent $^{238}$U. Considering the uranium activity in the other samples and that $^{226}$Ra is mobile in saline environments, $^{226}$Ra is most likely to be in decit as a result of loss to the surrounding environment. The effect of disequilibrium in the final age estimates is small, therefore measured radionuclides were used for dose rate calculations.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$^{238}$U Bq/kg</th>
<th>$^{226}$Ra Bq/kg</th>
<th>$^{210}$Pb Bq/kg</th>
<th>$^{232}$Th Bq/kg</th>
<th>$^{40}$K Bq/kg</th>
<th>Dose Rate Gy/ka</th>
</tr>
</thead>
<tbody>
<tr>
<td>GU29.1</td>
<td>16.2 ± 1.2</td>
<td>13.1 ± 0.1</td>
<td>16.1 ± 0.9</td>
<td>22.0 ± 0.7</td>
<td>517 ± 2</td>
<td>2.34 ± 0.11</td>
</tr>
<tr>
<td>GU29.2</td>
<td>15.6 ± 0.4</td>
<td>12.2 ± 0.1</td>
<td>11.6 ± 0.5</td>
<td>19.3 ± 0.5</td>
<td>564 ± 1</td>
<td>2.33 ± 0.10</td>
</tr>
<tr>
<td>GU29.3</td>
<td>24.4 ± 1.4</td>
<td>13.5 ± 0.2</td>
<td>16.1 ± 1.4</td>
<td>25.7 ± 0.7</td>
<td>655 ± 4</td>
<td>2.84 ± 0.13</td>
</tr>
<tr>
<td>GU29.4</td>
<td>14.6 ± 1.2</td>
<td>10.1 ± 0.2</td>
<td>12.4 ± 1.3</td>
<td>23.1 ± 1.1</td>
<td>546 ± 4</td>
<td>2.34 ± 0.11</td>
</tr>
</tbody>
</table>

Recovery (i.e. the proportion of grains that yielded an acceptable luminescence signal) ranged from 3–5% in the fluvial samples, and was 3% in the dune (Table 2). Overdispersion ($\sigma_d$) was 29–37% for the fluvial
samples: the Central Age Model (CAM) was used to calculate the depositional age. In the dune, overdispersion was 60% with apparently two populations of grains (Fig. 7). The older population was assumed to represent the main depositional event with subsequent re-exposure of grains owing to bioturbation and other disturbance. The Finite Mixture Model (FMM) was used to describe these populations; this indicated two components at an initial overdispersion of 15%. Modelled equivalent dose ($D_e$) has been converted to age by dividing by the measured dose rates given in Table 1, taking into account cosmic dose factors and the water content. Measured water contents ranged from 1–4% for these samples, but may have been affected by land drainage, drying during transport and collection, and seasonal factors. The long-term water content for these samples is likely to have been around 7%, and this estimate was used for all samples.

Table 2
OSL results and ages

<table>
<thead>
<tr>
<th>Lab No.</th>
<th>Depth (m)</th>
<th>Recovery (%)</th>
<th>Over-dispersion ($\sigma_d$, %)</th>
<th>$D_e$</th>
<th>Proportion ($D_e$ Proportion)</th>
<th>Age (ka)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GU29.1</td>
<td>2.0</td>
<td>3</td>
<td>60</td>
<td>$29.6 \pm 2.0 \text{FMM - } k_1$</td>
<td>54 ± 0.1</td>
<td>46 ± 0.1</td>
</tr>
<tr>
<td>GU29.2</td>
<td>3.0</td>
<td>4</td>
<td>29</td>
<td>$33.1 \pm 1.5 \text{CAM}$</td>
<td>24.6 ± 2.1 $\text{MAM}$</td>
<td>14.2 ± 0.9</td>
</tr>
<tr>
<td>GU29.3</td>
<td>1.35</td>
<td>4</td>
<td>32</td>
<td>$36.3 \pm 1.7 \text{CAM}$</td>
<td>27.7 ± 2.2 $\text{MAM}$</td>
<td>12.8 ± 0.8</td>
</tr>
<tr>
<td>GU29.4</td>
<td>3.85</td>
<td>5</td>
<td>37</td>
<td>$31.0 \pm 1.6 \text{CAM}$</td>
<td>23.9 ± 2.1 $\text{MAM}$</td>
<td>13.3 ± 0.9</td>
</tr>
</tbody>
</table>

FMM = Finite Mixture Model; CAM = Central Age Model; MAM = Minimum Age Model

Preferred age/model is shown in bold.

Samples extracted from the reworked point bar at depths of 1.35 m and 3.0 m yielded CAM ages of 12.8 ± 0.8 ka and 14.2 ± 0.9 ka, respectively (Fig. 7C, Table 2). A sample from a finer sand lense from within the gravel bed deposit at 3.85 m sampled 30 m E from an adjacent face of the pit yielded an age of 13.3 ± 0.9 ka. Ages for the lower two fluvial samples are equivalent, within the uncertainties. The depositional age may be decreasing towards the upper sand bed. For the dune, the OSL sample from 2.0 m depth yielded a dominant age using the Finite Mixture Model of 12.7 ± 1.0 ka (54 ± 0.1%) with a secondary population at 4.6 ± 0.4 ka (46 ± 0.1%). This would appear to suggest that channel sedimentation and aeolian sedimentation occurred together. A later phase of reworking may have occurred around 4.5 ka, although bioturbation of sand within the dune makes it difficult to be certain about the depositional age of this sample.
Discussion

Climatic changes over the last 100 ka preserved a range of of fluvial features on the surface of the Riverine Plain. Palaeochannels with distinctive scrolled floodplains and large channel dimensions similar to the Yanco System can be found across the inland Murray-Darling Basin in catchments with high-altitude headwaters, including the Kotupna (Bowler, 1978), the Ulgetherie (Kemp and Spooner, 2007; Kemp and Rhodes, 2010), and the Kamilaroi Palaeochannel Systems (Pietsch et al., 2013). Regionally, these large, laterally active channels are the consequence of valley floor incision, soil erosion and increased periglacial activity in the mountainous upper catchments under conditions that reached 9–12°C cooler than present at the LGM (Galloway, 1965; Slee et al., 2015; 2022; Barrows et al., 2022). Discharge was enlarged by lower evapotranspiration and a larger snowmelt flood (Bowler, 1978; Kemp and Spooner, 2007; Kemp and Rhodes, 2010). Using the modern relationship between runoff and elevation as a proxy for temperature change, Reinfelds et al. (2014) estimate that increased seasonality and higher runoff efficiency during the LGM would produce a fourfold increase in runoff. This is consistent with the magnitude of change observed in the Yanco at Rhyola, where bankfull discharge based on Manning’s formula and a reconstructed cross-sectional area of 1375 m$^2$ is estimated as 1240 m$^3$s$^{-1}$ (Page, 1994: 136). This is 4.4 times the present bankfull discharge of the Murrumbidgee at an equivalent downstream position at Hay noting that errors associated with palaeodischarge estimates from former channel dimensions may be large (Reinfelds et al., 1998). The diverged channel belt at Rhyola (Fig. 4) holds the best evidence for floodplain construction by the Yanco System. Ages for basal infill of 18.2 ± 1.5 ka (Page et al., 1996; Fig. 5) and 20.4 ± 1.1 ka (Forbes et al., 2020) provide a minimum age for the system at this location. The timing coincides with high lake levels at Lake Urana at 20 ka, which reflects high runoff from its own catchment supplemented by flows along a minor anabranch of Columbo Creek (Fig. 3A; Page et al., 1994). It is also consistent with ages for large meandering channels elsewhere in the southern riverine plains, which indicate lateral floodplain construction occurred between 34 ka and 19 ka (Bowler et al., 1978; Page et al., 1991; 1996; Kemp and Spooner, 2007; Kemp and Rhodes, 2010).

By 13–15 ka, smaller creeks with dimensions similar to the modern Murrumbidgee were actively reworking the Yanco channel belt as at Thurrowa Road Pit (Fig. 3A, 6). These lateral migration deposits produced smaller channel belts within the Yanco trough and were comprised of sediments coarser than the modern Murrumbidgee that may have been plundered from coarse-textured sediment stores of the Yanco System. Two possibilities account for the reduction in channel size. Firstly, partial avulsion redirected the channel upstream, or secondly, regional runoff was reduced to near-modern levels. Channel avulsion and relocation to the former Gum Creek channel belt (i.e. the modern Murrumbidgee position) certainly occurred, but the timing is presently unknown. The earliest evidence for sedimentation in the modern Murrumbidgee channel belt is 6.6 ± 0.6 ka (Kemp et al., in prep.). It is possible that the Yanco System responded to the substantial reduction in discharges that occurred at the end of the Pleistocene (Reeves et al., 2013, Petherick et al., 2013). This suggests a trigger for avulsion in declining channel gradients as smaller, sinuous channels became trapped, underfit within the larger meander train (Fig. 8).
However, the regional evidence suggests that discharges remained relatively high at 13–15 ka. Meandering channels with larger dimensions than the present-day are known from the lower and middle Lachlan Valley (13 ka, Kemp et al., 2017), the Goulburn River (Kotupna Complex, 13–16 ka Bowler, 1978), and the lower Darling River (Bowler et al., 1978). In the Murrumbidgee Basin at Lake Urana, high lake levels produced active beach sedimentation until 12 ka (Page et al., 1994). In the catchment headwaters at Lake George, OSL dating of the Vault Embankment suggests a consistent lake level of ~11 m depth at 14.1 ± 0.9 ka (Fitzsimmons and Barrows, 2010) with periglacial conditions enhancing runoff in the region until 13 ka (Barrows et al., 2022). In this situation, the absence of a large Yanco channel draining the Australian Alps requires explanation. The possibility of a partially abandoned or highly seasonal channel is supported by ages for marginal dune sedimentation in the Yanco System at 9–19 ka (Fig. 3).

Questions surrounding the relative role of avulsion and environmental change may be resolved by further chronological studies of channels and the regional climate stratigraphy, but the available dating analyses has perpetuated some of the uncertainties. Our single grain OSL ages for the Thurrowa Pit calculated using the Central Age Model are similar to those obtained by Page et al. (1996) of 14–18 ka using TL techniques in a near identical location. Hesse et al. (2018) obtained single-grain (Minimum Age Model) OSL ages for fluviol and aeolian sand at Dry Lake on the upper Yanco System of 15 ± 2 ka and 5 ± 1 ka, respectively. However, CAM ages for these samples are 53 ka and ~68 ka. Such high overdispersion makes it difficult to pinpoint a depositional age at this locality. It is more troubling that Mueller et al. (2018) report ages from the Thurrowa Pit of 25.0 ± 1.8 ka (UoW1488) at 2.5 m, which is nearly twice our age of 14.2 ± 0.9 ka at 3.0 m (GU29.2) (Fig. 3). A similar discrepancy occurs in ages from Wanganella and Rhyola Pits, with Page et al. (1996) reporting 13.6 ± 1.6 ka compared to 24.4 ± 1.6 ka (Mueller et al., 2018; Fig. 3B). At Rhyola, the TL age for basal channel sediments is 18.2 ± 1.5 ka (Page et al., 1996) compared to a range of ages between 22.6 ± 1.3 ka and 32.4 ± 1.4 ka (Mueller et al., 2018). Mueller's analysis is based on similar techniques to those used in this study, incorporating single-grain OSL with central age modelling. Their burial dose for UoW1488 is 42 ± 2 Gy, somewhat higher than our result of 33 ± 2 Gy (GU29.2) at a similar (but not identical) depth, suggesting the OSL measurements are broadly compatible. However, their dose rate is substantially lower at 1.7 ± 0.1 Gy ka⁻¹ compared to our measurements of 2.3 ± 0.1 Gy at 3.0 m and 2.8 ± 0.1 Gy ka⁻¹ at 1.35 m. Differences in average water content account for 9% of the discrepancy, but their (depth-adjusted) dry dose rates are 31% lower on average than our dry dose rates for GU29.2 and GU29.3. Measurement of the background dose rate for the Thurrowa Rd Pit by Page et al (1996) is 2.5 Gy ka⁻¹, which is similar to our average measurement of 2.55 Gy ka⁻¹ from the same sand unit (Fig. 3). It may be that apparent problems with the radionuclide measurements identified in Mueller et al. (2018) have not yet been resolved.

Further investigations of well-preserved parts of the Pleistocene channel belts of the Murrumbidgee riverine plains may add further insights into the role of avulsion in channel change. This relies on awareness of the phenomenon of reworking during the protracted abandonment phase of palaeochannels. Use of the more accessible sites in existing quarry pits, or to reworked channel bed sediments, could lead to sample bias in dating and misinterpretation of their geomorphic significance for
the functioning of the whole system. Similar dangers apply to the surficial sediments (upper ~ 4 m) of marginal sandy dunes, which are subject to rapid and deep bioturbation. Our model for channel evolution in Fig. 8 assumes the avulsion to have occurred at the end of the Pleistocene, but remains speculative about the timing of avulsion. In either case, evidence for active lateral reworking of the Yanco channel belt does not support stagnation and straightening by shoaling sands, or aggradation and levee development as predicted by Page and Nanson (1996). The sequence describes

1. Establishment of a mixed-load, migrational-anastomosing sand and gravel bed channel with marginal dunes in a seasonal flow regime.

2. Partial channel avulsion is triggered by a change in the flow regime or sediment load. A significant component of the discharge is transferred to the new channel. Channel modification is achieved by smaller and less regular flows which remain sufficiently competent to transport sand and gravel derived from upstream and from reworking of the floodplain. An inset floodplain develops. Marginal dunes continue to accumulate from a periodically exposed channel bed.

3. Gradual transfer of flow to the new channel belt further reduces flows, but flood flows continue to be diverted along the old channel belt. New floodplain construction within the palaeochannel belt occurs from lateral migration and sandy/silty sedimentation along flood channels and inset floodplains.

Given uncertainties in the relative timings of environmental change and channel response, and the marked differences between the older aggraded channels studied by Page and Nanson (1996) and the younger channel belts, it is valid to ask how typical is Yanco Creek of abandoned channel sequences elsewhere on the Riverine Plains. Why, for example, is there no terminal phase of sandy aggradation and straightening? Part of the answer might lie in differing downstream expression of abandonment along an avulsed reach. Page and Nanson (1996) reported changing characteristics between upper and lower reaches of the major palaeochannel belts, with the meandering channels showing a tendency to straighten and shoal in their lower reaches. Abandoned channels on Rhine-Meuse delta are characterised by sandy infilling and channel narrowing and shallowing following an avulsion, but sedimentation is concentrated at the avulsion node (Kleinhans et al., 2012; Toonen et al., 2012). An alternative explanation is that the channel belt has had insufficient time to infill. Low sedimentation rates with some limited functionality of palaeochannels (as floodways) frequently have extended the life of anabranches 20–30 ka after the avulsion event. The Gum Creek System also lacks a terminal aggradation phase, and was likely to be a partial avulsion as it presently confines the modern Murrumbidgee floodplain upstream from Carathool. It is also possible that avulsions near the Yanco avulsion site may be particularly prone to reoccupation because of the concentration of stream power at the fan apex. The shift to sandy aggradation may require flow diversion to a new part of the Riverine Plain, releasing additional sand sources through incision.

The average frequency of major avulsion on the Murrumbidgee at around 12 ka provides corroboration for channel switching to some climatic trigger as it concurs with stadial-interstadial frequencies. It remains difficult to explain channel metamorphosis into the aggrading, straightened planforms that are the characteristic feature of the older palaeochannels such as the Kerarbury and Coleambally Systems.
The development of grassland and periglacial erosion during the extended LGM in southeastern Australia triggered widespread bank erosion and point bar deposition on the Riverine Plain, yet channel aggradation did not occur. Much more recently, a regional phase of gullying in the headwater streams of the Riverine Plain was triggered by widespread forest clearance and the introduction of European land-use practices (Olley and Wasson, 2003), but the substantial release of sediment during a time of lower discharge produced little discernable change to rivers on the Riverine Plain (Kemp et al. in prep.). The sandy infill of the Yanco channel belt may be awaiting a new progression in the glacial cycle. Given the variety of palaeochannel types and positions on the Riverine Plain, and the differences in the magnitudes and directions of Milankovitch climate change, it is likely that more than one evolutionary model may be required to describe channel abandonment processes. Nevertheless, the ability of partial and complete avulsions to cause an immediate shift in channel characteristics should be considered as a possible cause of channel metamorphosis in some cases.

Conclusions

We examine the model of palaeochannel evolution on the Riverine Plain with reference to geomorphic changes in the youngest channel belt, noting that the current model does not account for the effect of partial avulsion and ongoing deposition over many millennia in modifying and transforming ancient channel belts. Age estimates in the Yanco channel belt are in general agreement with TL ages obtained by Page et al. (1996) and Banerjee et al. (2002), but most likely relate to reworking of Yanco System sediments that were deposited during and before the Last Glacial Maximum. These findings are consistent with ages from large, laterally active rivers elsewhere in the Murray-Darling Basin. Targeted dating programmes should be conducted to pinpoint the timing of high discharges as distinct from the relatively longer period of palaeochannel reworking under the influence of declining flows. Anastomosis appears to be an enduring characteristic of these river systems owing to very low sedimentation rates, with partial, incomplete and failed avulsions likely to be a common phenomenon. Avulsed channels are maintained for extended time periods, and complete abandonment of channels takes >10,000 years to accomplish. Site selection for palaeohydrological and sedimentological reconstruction and dating should focus on well-preserved floodplains with surface expression, avoiding infilled channels that may have functioned as floodways on extended timescales.

Declarations

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Data availability statement

Data is available from the corresponding author upon request.

Conflict of interest statement

The authors have no conflicts of interest to declare.

References


Figures

Figure 1

Location of the Fluvial Palaeochannel Systems of Page et al. (1996) within the Murray-Darling Basin (inset) and places mentioned in the text. Dated sites on the Yanco System are shown in Figure 3. Detailed geomorphic maps are given in Figures 4, 5 and 6.

Figure 2

Page and Nanson's (1996) model of palaeochannel evolution on the Riverine Plain. Horizontal and vertical scales are approximate and are based on sections described by Page and Nanson (1996).
Figure 3

Map of Yanco channel belts showing locations of dated sites (see overview in Fig. 1) (A) between Dry Lake at the Murrumbidgee River offtake to Conargo including anabranches and Lake Urana, and (B) between Conargo and Moulemein, modified after Page (1994). Sample codes relate to W: TL, University of Wollongong (Page et al., 1994; Page et al., 1996); Yan: small aliquot OSL (Banerjee et al., 2002); UoW: single grain OSL (Mueller et al., 2018); Yanco: single grain OSL, Macquarie University; MGB: single-grain OSL UoW (Forbes et al., 2020); GU: single grain OSL, Griffith University. The published MAM Yanco ages are given for Dry Lake. CAM ages are given in brackets to allow comparison with other laboratories. Italicised ages on the Yanco channel belt are for marginal aeolian source-bordering dunes,
otherwise Yanco fluvial sediments retrieved from augers and quarry pits. Italicised ages at Lake Urana lunette are aeolian sediments, otherwise beach sediments. Note that Lake Urana also receives inflows from its local catchment as well as overflows from the Colombo Creek anabranch south from Morundah.

Figure 4

Geomorphic map of the lower Yanco Palaeochannel System (Fig. 1) at the Rhyola type reach showing Yanco System palaeochannels and floodplain features, source-bordering dunes and the modern stream network.
Figure 5

Geomorphic map of the middle reaches of the Yanco Palaeochannel System and modern Yanco Ck anabranches 15 km downstream from Conargo (Fig. 1). The Yanco channel belt here is between 1.0 and 1.8 km wide.
Figure 6

Geomorphic map of the Yanco Palaeochannel System (Fig. 1) at Thurrowa Road (35°9′9″S, 146°1′52″E) in its incised channel belt. The locations of sampling sites at Thurrowa Pit (Page et al., 1996, Mueller et al., 2018; this study) and Thurrowa Dune (Banerjee et al., 2002; this study) are shown at centre. Rare traces of Yanco palaeochannel sediments are visible outside the Yanco Creek floodplain and associated flood anabranches and palaeochannels.
Figure 7

Stratigraphic section of sample site at A. Thurrowa Pit fluvial sediments and B. Bundure marginal dune. C. Radial plots are shown for all OSL samples.
Establishment of a mixed-load, laterally migrating channel. Rates of sandy point bar construction are higher in cold episodes with forest retreat, cold-climate weathering and mass wasting of highland soils. Marginal dunes may develop in highly seasonal/snowmelt floods.

Changes in flow regime or sediment load associated with climate change trigger avulsion and the formation of a new channel belt. Transfer of basin flow from the older channel occurs slowly and lateral floodplain sediment is supported by medium and flood flows with coarse sediments supplied by erosion of the old channel belt. Higher flow variability regularly exposes the channel bed, which deflates to the marginal dune field.

Flows are further reduced in the now minor anabranch. Floodplain construction and erosion occur from laterally migrating, anastomosing and flood channels, gradually reworking parts of the old channel belt.

**FUTURE....**

Decline in flows and conversion to flood channel causes sandy/clayey infill of the former channel belt. Sediment texture depends on glacial stage and the direction of climate change, and the position of active channel belts in the system. Vertical aggradation accompanies shoaling, straightening and levee development. Construction of marginal dunes occurs in situations of sandy flood deposition. Silt-clay channel fill and levee deposition precedes final abandonment.

**Figure 8**

Schematic model of palaeochannel evolution following a partial avulsion.