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The late-Holocene origin of the modern Murray River course, southeastern Australia

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Abstract: The modern course of the Murray River flows south around the Cadell Tilt Block in southeastern Australia. The avulsion that took the river in this direction formed the Barmah Choke, a reach with an unusually straight planform. This morphology has been used to argue Holocene inertia of the modern river system. The avulsion was initially placed at ~10 ka on the basis of a single charcoal age. Optically stimulated luminescence (OSL) and AMS ^{14}C dating of deposits along the Barmah Choke demonstrates that the Murray has not been inert during this period. A digitate delta deposited on the floor of a palaeolake by the avulsion is only ~550 years old. Point bar deposition along the Choke also began around this time. The Murray River probably followed the course of Bullatale Creek for most of the Holocene. It formed large, inset meander scrolls of Pleistocene 'Kotupna-type' along this creek course but without source-bordering dunes. The persistence of Kotupna-type bedload along this course suggests that there was no simple switch to suspended load channels at the Pleistocene/Holocene transition. The Barmah Choke avulsion trebled the discharge of the Goulburn River causing morphological adjustment and formation of new reaches downstream. The extensive Barmah and Gunbower-Koondrook red gum forests probably arose from the increased flood flows. Pollen and spores from lacustrine sediments beneath the Choke show that the vegetation ~4000 years ago was very different. The lake and hinterland began to dry from this time and the lake became a swamp. A pedogenic interval shows that the swamp was dry for lengthy periods prior to deposition of the digitate delta.

Key words: Avulsion, digitate delta, optically stimulated luminescence, palaeohydrology, Cadell Tilt Block, Murray River, Australia, Holocene.

Introduction

The Murray River is the largest river in Australia. It is a long, low-energy anabranching river that has taken a course for the most part controlled by much larger palaeochannels (Pels, 1964; Currey and Dole, 1978; Rutherfurd, 1991, 1994). Late Quaternary movement of the Cadell Fault separated these ancestral channels and produced the modern anabranching river system (Figure 1). The ancestral Murray River initially followed Green Gully before switching to a course now occupied by the Edward River (Harris, 1939; Bowler, 1978). More recently it has taken a course to the southwest across the floor of a palaeolake (Lake Kanyapella) and into the ancestral course of the Goulburn River. The present Murray rejoins its ancestral course some 400 river km downstream at Wakool Junction. The avulsion of the Murray from the Edward was a significant event that transformed the Murray and Goulburn rivers.

The Murray River established a new channel more than 60 km from the Edward River. The Barmah Choke is the upstream reach formed by the avulsion. It runs for 45 river km, almost to Echuca. The morphology of this reach is uncharacteristic of the Murray. It has a relatively straight channel with little bankfull capacity and its floodplain is 'unconfined' by ancestral river trenches (Rutherfurd, 1994). This results in frequent flooding, which sustains the Barmah Forest, a large seasonal wetland dominated by river red gums (*Eucalyptus camaldulensis*) (Currey and Dole, 1978; Bren, 1988). The sediment load of the Barmah Choke is mostly suspended silt and clay. Point bar development is minimal (Bowler, 1978).

The Barmah Choke debouches into the ancestral trench of the Goulburn River incised in the floor of Lake Kanyapella. This trench confines the Murray River for the next 100 river km, controlling its morphology. One striking effect is a fourfold increase in the width of the meander belt compared with the Barmah Choke. This is inherited from the Goulburn's late Pleistocene 'Kotupna' palaeochannel system (Bowler, 1978). The conspicuous meander scrolls of this system

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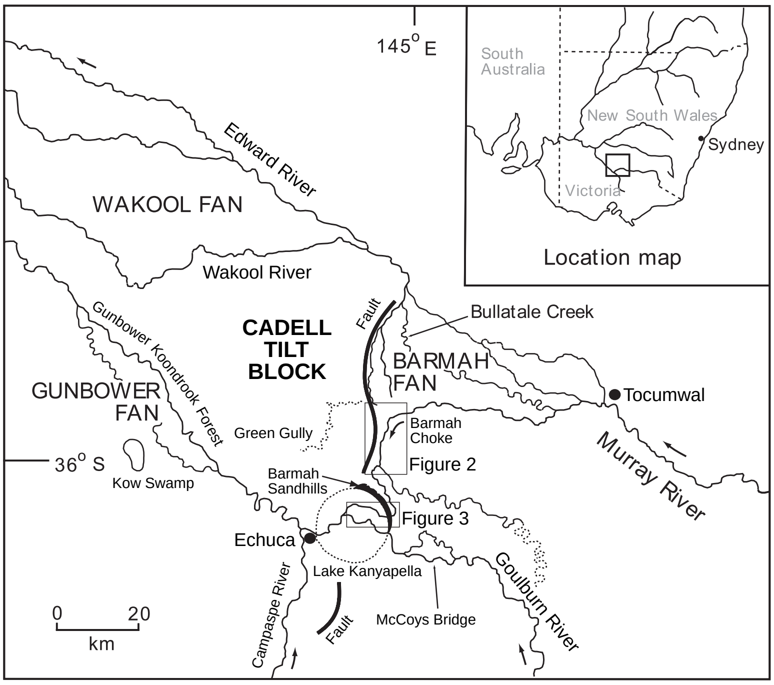

Figure 1 Map of the Cadell Tilt Block showing three low-angle alluvial fans built by anabranching of the Murray River. The modern course of the Murray flows south of the Barmah Fan and is renewing construction of the Gunbower Fan. Earlier courses built the large Wakool Fan to the north. The Barmah Choke is the south-flowing reach that joins the Goulburn River on the floor of Lake Kanyapella

have been incised to a depth of around 15 m. The Murray River meanders within this ancestral belt and is almost twice as sinuous as the Barmah Choke (Bowler, 1978).

The timing of the avulsion that formed the Barmah Choke is critical to understanding the factors that control the modern Murray River. A single radiocarbon age of 9.80 ± 1.45 cal. ka BP (ANU 877) from the base of a point bar along this reach suggests that the river avulsed at the start of the Holocene and has been remarkably stable ever since (Urquhart, 1973; Bowler, 1978). The modern Goulburn River appears similarly inert, although its unconfined reach at McCoys Bridge (Figure 1) has a well-developed meander belt, unlike the Barmah Choke. The radiocarbon age from the Barmah Choke and one of 8.98 ± 0.48 cal. ka BP (N-303) from a modern Goulburn point bar have been used to infer major hydrological change at the Pleistocene/Holocene transition (Bowler, 1978). The wide, bedload channels of the late Pleistocene ceased to flow and were replaced by narrow, suspended load channels with reduced discharge.

The age and morphology of the Barmah Choke is an integral component of Bowler's (1978) model of climatically controlled channel evolution for the region. The Barmah Choke is the final fluvial episode and represents the Holocene Murray, with its almost straight planform illustrating the long-term stability of the river. Bowler's (1970) initial impression, based on the 'youthful' morphology of the Barmah Choke alone, was that it was only 1000 or 2000 years old. Bowler (1973) later claimed that it was probably not more than a few hundred years old, a view he recanted when Urquhart's ^{14}C results became known (Bowler, 1978).

This paper presents a new Holocene history for the Murray River. Three OSL and two AMS ^{14}C ages challenge the existing chronology, which is based on one charcoal age. These new ages suggest that the Holocene Murray River is more dynamic than previously believed. A pollen and spore assemblage from beneath the Barmah Choke preserves a record of the pre-avulsion environment.

Regional setting and geomorphology

The Murray River anabranch system is part of the Riverine Plain, a distributary plain built by rivers flowing inland from the Southeastern Highlands (Butler, 1950; Butler *et al.*, 1973). The surface sediments of the Riverine Plain comprise the Plio-Pleistocene Shepparton Formation (Lawrence, 1966; Brown and Stephenson, 1991). These alluvial sands, silts and clays represent the most recent phase of infilling of the Tertiary Murray Basin. Traces of the distributary channels that built the Riverine Plain are preserved on the surface of the Shepparton Formation. These are leveed or 'prior' streams and bear little resemblance to the modern drainage network (Butler, 1950).

The meander belts of the modern river system are incised in the older prior stream topography. These contain terraced Coonambidgal Formation sediments (Butler, 1958; Lawrence, 1966). Terraces of the Murray River upstream of Tocumwal and downstream of the Wakool Junction record three phases of incision and aggradation (Pels, 1966, 1971). The highest, and therefore oldest, terraces have distinctive red-brown earth soil profiles with carbonate segregation at depth (Bowler, 1978). The soils of the younger terraces are weakly developed with no textural contrast.

Uplift of the Cadell Tilt Block separated the fluvial soil-stratigraphic sequence into a series of divergent palaeochannels. Lake Kanyapella formed in the fault-angle depression of the tilt block (Bowler, 1978). Thermoluminescence (TL) dating of a palaeochannel on the uplifted block (Green Gully) suggests that the Murray River was defeated by the Cadell Fault some 60 000 years ago (Page *et al.*, 1991). The Barmah Sandhills, part of the lunette on the northeastern shore of Lake Kanyapella, were TL dated to around 30 ka (Page *et al.*, 1991). This was an unexpected age discrepancy because Lake Kanyapella is supposed to have formed when the Cadell Fault truncated the Goulburn River (Bowler, 1978). At face value, these TL ages support Pels' (1966) view that the palaeolake is too young to have been formed by the tectonic event.

Rutherfurd (1991) recognized that uplift of the Cadell Tilt Block had changed the grade of the Murray River, indirectly producing three large, low-angle alluvial fans that are the major depositional systems of the Riverine Plain (Figure 1). The Barmah Fan extends from its apex at Tocumwal to the 14 m high Cadell Fault scarp. This fan was initiated by backwater deposition, which resulted in the Murray River building an alluvial ridge in response to the gradual rise of the block (Rutherfurd, 1991). The Wakool and Gunbower Fans emerge from confined ancestral trenches downstream of the fault. The Wakool Fan was built by palaeochannels of the Murray and is by far the largest. Palaeochannels of the Goulburn River built the Gunbower Fan, which appears incipient by comparison.

The upstream reach of the Barmah Choke incises the Moira Marshes, a wetland that formed in the palaeolake at the foot of the Cadell Fault scarp (Figure 2). The extent of this palaeolake is shown by the sand ridges developed on the former lake shore. The northern shore has a crescentic sand lunette about 5 m high that continues along the eastern shore as an irregular sand ridge. The western shore at the foot of the fault scarp has deposits ranging from indurated limonitic gravel beaches to spits composed of clean quartz sand, including a cuspate spit.

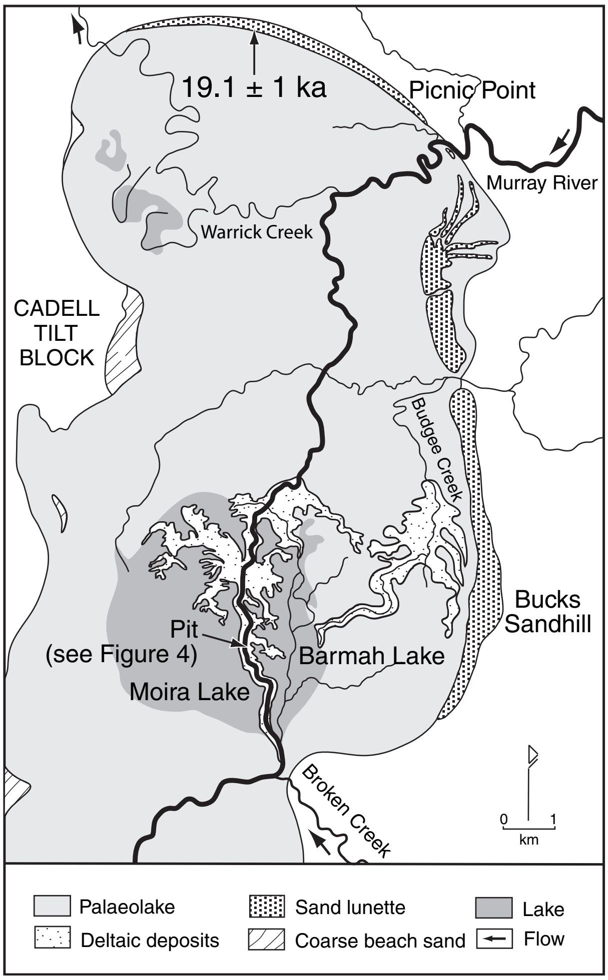

Figure 2 The upstream reach of the Barmah Choke on the floor of the Moira Marshes palaeolake. The digitate delta was deposited in the basin depocentre by the avulsion that formed the Choke. The minor deltaic feature to the east is probably the result of river regulation. The Broken Creek outfall is also artificial

This high-energy lake system was gradually reduced to a small depocentre now occupied by Moira Lake and Barmah Lake.

The avulsion of the Murray River across the floor of the palaeolake deposited 'paired silt jetties' in the depocentre of the lake (Currey, 1978; Figure 2). These are natural levees built on either side of the river channel that have splayed at their entrance to the Moira Lake basin. This feature is a digitate delta (Bird, 1962; Barberis, 1983). A minor deltaic feature composed of fine silt has also been constructed by Budgee Creek at the foot of Bucks Sandhill (Figure 2). This creek is a distributary of the Murray River and may flow either way. The delta it is building is possibly the result of river regulation upstream, which has changed the flood flow regime (Barberis, 1983).

The downstream reach of the Barmah Choke is deflected through the Barmah Sandhills by a late Pleistocene gravel fan that supplied sediment for lunette construction (Figure 3). The river continues across the floor of Lake Kanyapella in a very narrow belt, abruptly changing course and morphology where it is captured by the Kotupna palaeochannel system. A radiocarbon age of 15.6 ± 1.7 cal. ka BP (ANU 29) dates the end of the Kotupna phase on the floor of Lake Kanyapella (Bowler, 1978). The age for the Barmah Choke of 9.80 ± 1.45 cal. ka BP (ANU 877) is from charcoal fragments buried in this downstream reach (Figure 3). Urquhart (1973) recounts that these 'were collected from hardened, clayey sand, probably the remains of an *in situ* burnt stump or log lying along the former channel bank'.

Methods

Geomorphic features of the Barmah Choke were traced from remote imagery contained in the River Murray Mapping Digital Colour Infrared Orthophotomap series (Murray-Darling Basin Commission, 1998). Field survey confirmed the image interpretation and identified three sites for subsurface investigation. The first was the outer crescentic lunette breached by the avulsion, where gullying has exposed the base of the lunette. The second was the western side of the digitate delta. A traxcavator had exposed this deposit and the underlying sediments in a 6 m × 8 m pit to a depth of 5 m (Figure 2). The third was a point bar sequence built by the Barmah Choke downstream. Bank erosion has exposed the oldest point bar sediments.

The stratigraphy of the deposits was described and OSL samples collected from vertical faces cleaned back with a shovel. Those from the lunette, digitate delta and point bar sequence were collected by hammering in 40 mm diameter stainless steel tubes. One from a lacustrine unit below the digitate delta was bulk-sampled because of its friable structure. The samples were prepared for OSL dating under subdued, red light using standard procedures (Galbraith *et al.*, 1999). The 180–212 μm quartz fraction was used for the digitate delta sequence and 90–125 μm quartz for the remainder.

Equivalent doses (D_e) were measured using a single aliquot regenerative dose (SAR) protocol (Murray and Roberts, 1998; Galbraith *et al.*, 1999; Murray and Wintle, 2000). Single grains were loaded into aluminium discs, each containing 100 chambers with diameters and depths of 300 μm (see Bøtter-Jensen *et al.*, 2000). The single grains (or very small single aliquots in the case of the 90–125 μm samples) were preheated at 240°C for 10 s and the OSL signals measured with a Risø TL-DA-15 apparatus. A green (532 nm) laser was used for optical stimulation (2 s at 125°C) and the ultraviolet luminescence recorded by an Electron Tubes 9235QB15

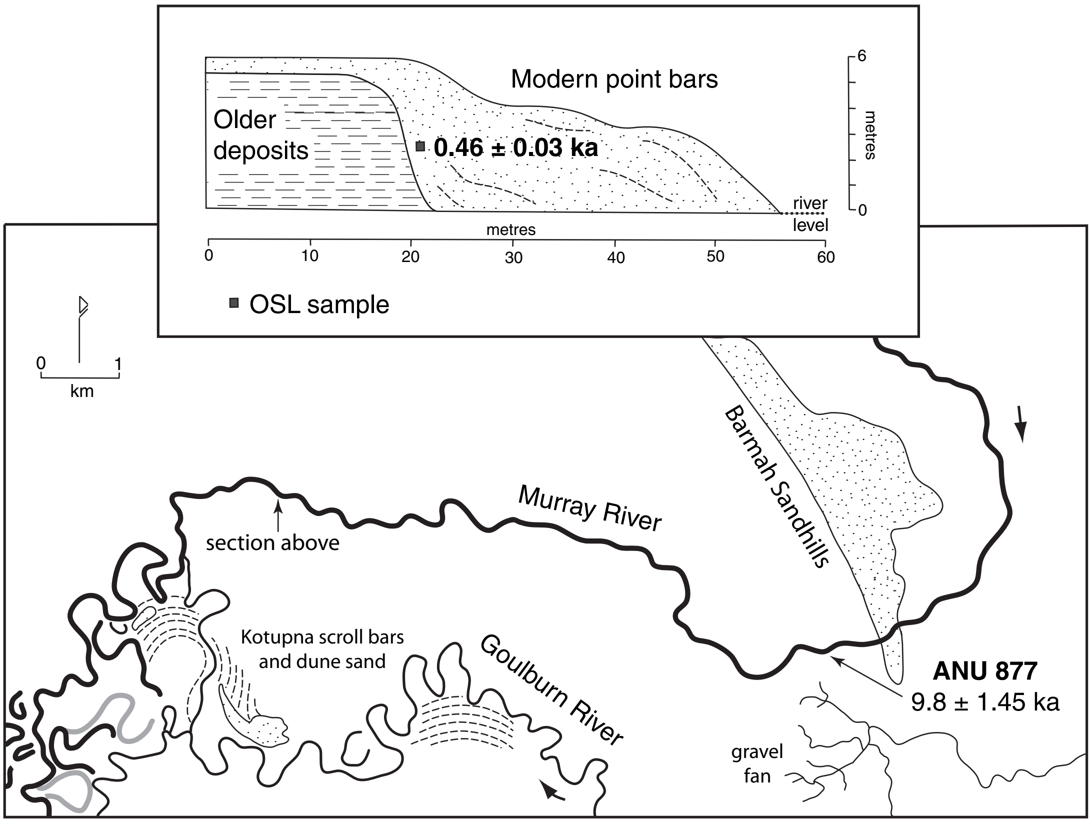

Figure 3 The downstream reach of the Barmah Choke where it joins the Goulburn River and Kotupna palaeochannel system. The point bar sequence shown in section is representative of the reach. The OSL sample was taken very close to a sharp contact between the modern point bars and older, limonitic deposits. The age establishes when point bars began to form along the Barmah Choke

photomultiplier tube with a 7.5 mm Hoya U-340 filter. The bleached grains were then dosed with a calibrated $^{90}Sr/^{90}Y$ beta-source and stimulated again to construct a dose-response curve using a minimum of five regenerative dose points. Most of the samples were given test-doses of 5 Gy to monitor for OSL sensitivity changes between the natural and regenerative cycles. Sample PPL received 10 Gy. Each analysis included a duplicate regeneration applied to test the reproducibility of the artificially-induced luminescence signals.

OSL data was processed using Analyst version 2.12 software (Duller, 1999). Each OSL signal was measured for 100 s × 0.02 s channels with data integrated from channels 6–9 and background subtracted using channels 90–100. After correcting the data for sensitivity changes, dose–response curves were constructed. The D_e derived from the intercept of the regenerated dose–response curve with the natural luminescence intensity. Central D_es were calculated using the central age model of Galbraith *et al.* (1999).

Dose rates were determined by measuring radionuclide concentrations in the sediment surrounding each sample. Gamma dose rates were measured with a field spectrometer and converted to dry values by oven-drying sediment from the sample location. Internal alpha dose rates were assumed to be 0.03 ± 0.01 mGy/yr. K-40, U-238, R-226, Pb-210, Th-228 and Ra-228 activities for samples PPL, MM205 and MM280 were analysed by high-resolution gamma spectrometry at CSIRO Land and Water. Total K, Th and U contents were measured by Becquerel Laboratories using Neutron Activation Analysis (NAA) for sample BCS. These results were converted to beta dose rates using the conversion factors of Adamiec and Aitken (1998) with beta attenuation factors of 0.88 ± 0.03 and 0.93 ± 0.03 for the 180–212 µm and 90–125 µm samples respectively (Mejdahl, 1979). Cosmic-ray dose rates were determined from established equations (Prescott and Hutton, 1994). Sample depths are unchanged since burial and field water contents assumed to be representative of long-term averages.

Two AMS ^{14}C ages were obtained on buried organic material to 'pair' with the OSL ages from the digitate delta sequence. One dated Cyperaceae seeds and the other beetle sclerites. The ANSTO AMS Facility determined the conventional radiocarbon ages. These were converted to calendar years using the tree-ring calibration INTCAL98 (Stuiver *et al.*, 1998) in the OxCal version 3.5 package (Bronk Ramsey, 2000) for comparison with the OSL ages. The Southern Hemisphere ocean reservoir effect was adjusted for by subtracting 24 years (Stuiver *et al.*, 1998).

Results

Stratigraphy and chronology

The crescentic Picnic Point lunette is composed of coarse beach sand and fine gravel overlain by fine aeolian sand (Figure 2). The structure rests on nearshore silt underlain by clayey lake-floor silt. Gullying of a disused quarry floor has exposed the lowermost beach facies. These contain unbroken illuvial iron bands, which show that the beach sediments below the quarry floor are undisturbed. A sample of beach sediment from 1 m below the quarry floor, beneath unbroken iron bands, returned an OSL age of 19.1 ± 1 ka (Figure 2, Tables 1 and 2). This shows that the Moira Marshes palaeolake was at its fullest extent around the time of the last glacial maximum (LGM).

Three depositional units have been recognized for the digitate delta sequence (Figure 4). The lowermost is a massive blue-green silty clay to an undetermined depth. It contains no laminae and scant pollen. This unit is interpreted as a floodplain deposit post-dating the LGM palaeolake phase.

Table 1 Summary optical age data

Sample	Depth (m)	Radionuclide contents[a]			Water[b] (%)	α radiation[c] (Gy/ka)	β radiation[d] (Gy/ka)	γ radiation[e] (Gy/ka)	Cosmic dose[f] (Gy/ka)	Dose rate (Gy/ka)	D_e^g (Gy)	Optical age (ka)
		K (%)	Th (ppm)	U (ppm)								
PPL	3.0	1.92±0.04	7.1±0.15	2.23±0.61	6±2	0.03±0.01	1.76±0.08	0.80±0.04	0.14±0.01	2.73±0.12	52.14±1.69	19.08±1.04
MM205	2.05	1.59±0.02	3.60±0.05	1.14±0.11	4±2	0.03±0.01	1.42±0.07	0.98±0.05	0.16±0.02	2.59±0.10	1.38±0.06	0.55±0.03
MM280	2.8	1.58±0.04	17.0±0.23	4.09±0.27	10±4	0.03±0.01	2.00±0.11	1.32±0.06	0.14±0.01	3.49±0.19	12.86±0.5	3.81±0.26
BCS	3.5	1.31±0.02	18.3±0.15	2.91±0.02	8±4	0.03±0.01	1.71±0.1	1.38±0.07	0.13±0.01	3.25±0.18	1.49±0.05	0.46±0.03

[a]Derived from high-resolution Ge detector gamma spectrometry for samples PPL, MM205 and MM280. Neutron Activation Analysis for BCS.
[b]Estimated time-averages based on measured field water contents.
[c]Assumed internal alpha dose rate.
[d]Derived from radionuclide contents, corrected for attenuation by water and beta attenuation.
[e]Derived from field spectrometry, corrected for attenuation by water.
[f]Calculated using the equation of Prescott and Hutton (1994), based on sediment density, time-averaged depth and site latitude, longitude and altitude.
[g]Including a ±2% systematic uncertainty associated with calibration of the laboratory beta-source.

The second unit shows the return of lacustrine conditions. It is a very finely laminated deposit of humic, clayey silt with a subfossil assemblage of plant macrofossils, pollen, insects and diatoms. A buried soil at the top of this unit shows that the lake had dried before deposition of the final unit, the digitate delta. This deposit has a basal subunit of micaceous coarse sand and gravel, which fines upward to mottled clayey silt. Charcoal flecks are present throughout the uppermost unit.

Figure 4 and Tables 1 and 2 show the OSL and AMS ^{14}C ages obtained for the digitate delta sequence. Those for the lacustrine unit are in close agreement and suggest that the lake formed around 4000 years ago. AMS ^{14}C dates from near the top of this unit suggest that the lake may have been relatively short-lived, perhaps as little as 1000 years. The OSL age of 0.55 ± 0.03 ka from the base of the digitate delta is consistent with the pedological evidence of a significant break between the final drying of the lake and the deposition of the delta. The lack of soil profile development on the delta also supports a young age for the avulsion event.

Point bars of the Barmah Choke downstream have sediments similar to the digitate delta. Bank exposures show point bars composed of fine, sandy silt in sharp contact with older fine-grained deposits (Figure 3). The point bar sediments are characteristically pale brown with orange mottles and charcoal flecks. Soil development is absent. The older deposits are reddish-brown clayey silt capped by recent overbank silt. An OSL age of 0.46 ± 0.03 ka was obtained on upstream-facing point bar sediments close to the contact between these two units (Figure 3, Tables 1 and 2). This dates the earliest episode of point bar deposition in the Barmah Choke. It also corroborates the OSL age from the base of the digitate delta, which places the timing of the avulsion that formed the Barmah Choke at $\sim$550 years ago.

Pollen and spore assemblage

Pollen and spores from the digitate delta sequence (analysed by C. Kenyon) record the drying of the mid-Holocene lake. The blue-green silty clay (Unit 1, Figure 4) below the lacustrine unit has scant pollen apart from some eroded *Eucalyptus*, *Allocasuarina*, Cupressaceae, Poaceae, Asteraceae and Cyperaceae types. The low pollen count and poor condition of the pollen suggest occasional inundation of a surface that was dry for long periods, consistent with a floodplain deposit.

Wetland pollen taxa appear in the lacustrine unit (Unit 2, Figure 4) indicating the formation of a shallow lake with swampy margins. *Polygonum* and *Persicaria* species and Cyperaceae dominate the wetland pollen taxa. Riparian vegetation is also present, with *Tasmannia* pollen, ground fern spores and spores of the tree ferns *Dicksonia* and *Cyathea*. The presence of riparian taxa suggests that the lake was probably fed by a distributary of the Murray River.

An open mixed woodland of *Eucalyptus*, *Allocasuarina* and Cupressaceae was present in the hinterland when the lake formed. Up to a depth of 250 cm (Unit 2, Figure 4), *Allocasuarina* and Cupressaceae pollen increase in abundance whereas *Eucalyptus* pollen declines. The amount of Chenopodiaceae pollen also increases toward 250 cm. This part of the sequence records a drying trend. At 250 cm, there is a large increase in charcoal and the lake becomes a swamp.

The swamp phase above 250 cm is indicated by the disappearance of *Polygonum* and *Persicaria* and the return of *Eucalyptus*. *Myriophyllum* and Cyperaceae become the dominant wetland taxa. The abundance of *Myriophyllum* pollen suggests frequently fluctuating water levels. Riparian species, barely visible since the drying of the lake, reappear at the top of

Table 2 Radiocarbon and OSL chronology of the Barmah Choke

Location	Depth (m)	Material[a]	Conventional ^{14}C age[b] (years BP)	Lab number	Calibrated ^{14}C age[b] (ka)	OSL age (ka)
Picnic Point Lunette	3	Q				19.08 ± 1.04
Barmah Choke South	6	BW	8640 ± 550	ANU 877	9.8 ± 1.45	
Barmah Choke South	3.5	Q				0.46 ± 0.03
Moira Marshes	2.05	Q				0.55 ± 0.03
Moira Marshes	2.2	CS	3100 ± 40	OZE 895	3.29 ± 0.09	
Moira Marshes	2.2	BS	4270 ± 40	OZE 896	4.84 ± 0.04	
Moira Marshes	2.8	Q				3.81 ± 0.26

[a]Q, quartz; BW, burnt wood; CS, Cyperaceae seed; BS, beetle sclerites.
[b]^{14}C ages were converted to calendar years using INTCAL98 (Stuiver *et al.*, 1998) in the OxCal version 3.5 package (Bronk Ramsey, 2000). The Southern Hemisphere ocean reservoir effect was adjusted for by subtracting 24 years (Stuiver *et al.*, 1998).
[c]ANU 877 is from Urquhart (1973). The OZE results are AMS radiocarbon ages.

the lacustrine sequence. Their presence could indicate channel incision of the swamp during its final stages.

Discussion

This new chronology for the Barmah Choke supports Bowler's (1973) age estimate that was based solely on its youthful morphological expression. The OSL and AMS ^{14}C ages from the digitate delta sequence and point bar downstream suggest that the age of 9.80 ± 1.45 cal. ka BP (ANU 877) obtained by Urquhart (1973) for the Barmah Choke is anomalously old. It is possible that he had taken charcoal fragments for dating from an older alluvial unit or that these had been reworked prior to point bar deposition (see Blong and Gillespie, 1978). In any case, morphostratigraphic and pedological evidence supports the new ages. It is difficult to relate the old date to any particular event.

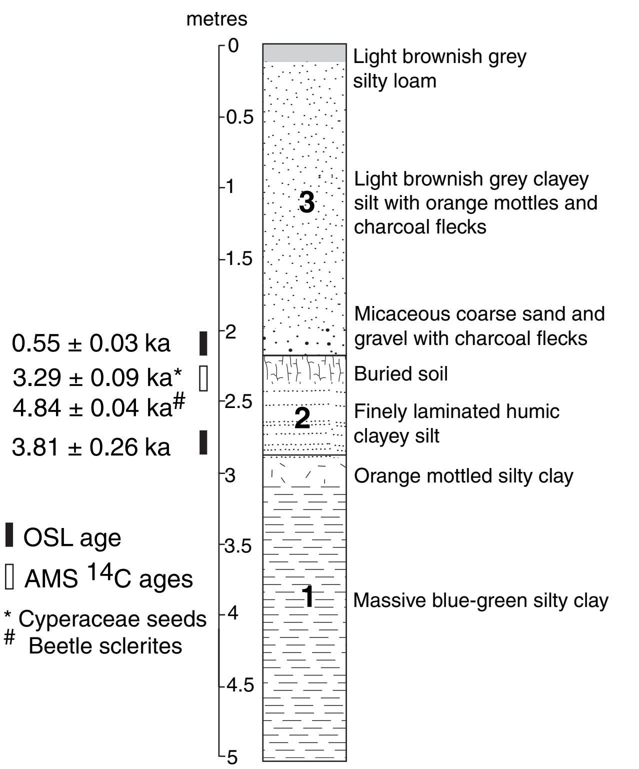

Figure 4 Stratigraphic profile of the digitate delta sequence with positions of OSL and AMS ages. Unit 1, floodplain; Unit 2, lacustrine; Unit 3, digitate delta. For location of pit, see Figure 2

Comparison of the Barmah Choke with the unconfined McCoys Bridge reach of the Goulburn River (Figure 1) casts further doubt on the earlier chronology. The McCoys Bridge reach is an incised meander belt with frequent cutoffs that avulsed from the Kotupna palaeochannel system. Its morphology is very different from that of the Barmah Choke and was achieved with only one-third of the discharge. Yet both reaches have been assigned an early Holocene age (Bowler, 1978). The Barmah Choke cannot be this age or it would have a meander belt much wider than the unconfined Goulburn with comparable morphological features.

Formation of the Barmah Choke ~550 years ago shows that the Murray River has not been inert for most of the Holocene. Prior to the avulsion, it probably maintained a course along Warrick Creek, north to the Edward River (Figure 2). This course may have been short-lived because the Murray River appears to have occupied Bullatale Creek for most of the Holocene (Figure 1). This creek has a highly sinuous planform characteristic of long-aggraded channels and large, inset meander scrolls without source-bordering dunes. The avulsion of the Murray from this course was a renewal of the vertical accretion processes that constructed the Barmah Fan (Rutherfurd, 1991). Backwater deposition at the foot of the Cadell Fault scarp is the most probable cause of the avulsion that formed the Barmah Choke.

A late Holocene age for the Barmah Choke shows that the relationship between river morphology and climate is tenuous. The Barmah Choke has a relatively straight planform because it is a modern avulsion not an inert Holocene river. The inset meander scrolls of Bullatale Creek show that Kotupna-type bedload channels persisted for most of the Holocene. A switch to suspended load channels at the Pleistocene/Holocene transition is not evident from the morphology of this river course. The only real distinction between late Pleistocene and Holocene rivers may be the presence or absence of source-bordering dunes, although with Holocene warming hydrological regime clearly did change.

The change of course by the Murray River had two hydrological effects. The flow of the Edward River was reduced by upwards of 60% and the discharge of the Goulburn trebled downstream of Echuca (Urquhart, 1973; Bowler, 1978). The Edward adjusted its morphology by producing a channel almost half the size of the original, which it incised more deeply because of a reduced sediment load (Urquhart, 1973). Small benches of fine sand and silt have been deposited in the abandoned channel. These sit below coarse-textured point bars built by the Murray prior to the avulsion. This sequence could be dated by OSL to test the proposed avulsion history.

Trebling of the discharge of the Goulburn River caused morphological adjustment within the confines of the Kotupna palaeochannel system and further avulsions downstream. The Goulburn widened and deepened significantly, increasing its meander wavelength, which reduced sinuosity (Urquhart, 1973). When floods of the Murray and Goulburn coincided, the increased discharge scoured the outer river bends, cutting platforms above the mean levels of the channel (Urquhart, 1973). These platforms are unvegetated, consistent with recent scouring by a larger channel.

The new course of the Murray River avulsed from the Goulburn (and Kotupna) course downstream to widen the Gunbower Fan (Figure 1). The fan floor is flooded by the Murray in a belt up to 18 km wide (the Gunbower-Koondrook Forest, Figure 1). No lateral accretion is evident along this reach and the only signs of vertical accretion are crevasse splays, suggesting levee development (Rutherfurd, 1991). The lack of sediment accumulation in the Gunbower-Koondrook Forest further supports a young age for the avulsion that formed the modern Murray River.

The present-day vegetation of the Murray River in its middle reaches is strikingly different from that recorded by the mid-Holocene lacustrine unit beneath the Barmah Choke. A climate cooler than present is indicated by the riparian taxa *Tasmannia* (a subalpine species), *Dicksonia* and *Cyathea*. It was also dry in the hinterland as attested by the abundant *Allocasuarina*, Cupressaceae and Chenopodiaceae pollen and reduced *Eucalyptus*. This record is consistent with others from the region that show drying from ~4000 years ago (Thomas *et al*., 2001; Cupper, 2005). The pedogenic disconformity between the lacustrine unit and digitate delta suggests that for several millennia the Moira Lake basin rarely flooded. Floodwaters of the Murray may have reached it occasionally but for most of this time the river was probably confined to the course of Bullatale Creek. Not until the recent avulsion is there any significant floodplain deposition. Flood flows were necessary for the establishment of the Barmah Forest, which may not have existed until ~550 years ago.

Conclusion

The late-Holocene avulsion of the Murray River from the course of the Edward River is an important geomorphic event. Not since uplift of the Cadell Tilt Block has the Murray River shifted so far from its ancestral course. This change of direction has effectively shut down the depositional system that constructed the Wakool Fan and invigorated the Gunbower Fan on the opposite side of the block. Morphological adjustment of the Murray to its new course may not be complete because the avulsion from the Edward happened only ~550 years ago. It is unlikely that the Barmah Choke will continue as a straight reach.

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