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Late quaternary stratigraphy and chronology of the Riverine Plain, Southeastern Australia

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LATE QUATERNARY

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ABSTRACT

This project examines the Late Quaternary fluvial, aeolian and lacustrine evolution of the Riverine Plain of southeastern Australia during the last glacial cycle since approximately 100 ka. The study employs image interpretation, field mapping, stratigraphic investigations and absolute dating of sediments by thermoluminescence (TL).

The present landscape of the Plain is dominated by a variety of palaeochannels subdivided by Pels (1971) into two essentially distinctive sequential categories. TL dating of the palaeochannel stratigraphy shows this interpretation to be simplistic. Oscillations between different channel types occurred repeatedly in the last 100 ka with large sinuous mixed load 'ancestral' type rivers evolving into bedload dominated 'prior type' streams, quite the reverse of Pels' interpretation. The stratigraphic record in the Murrumbidgee sector of the Plain shows that four major palaeochannel phases occurred during the last full glacial cycle commencing with the Coleambally from 105 to 80 ka and progressing through the Kerarbury (55 to 35 ka), Gum Creek (35 to 25 ka) and Yanco (20 to 13 ka) phases. All but the last palaeochannel phase included earlier mixed-load laterally migrating channels and terminal aggrading bedload channels. The mixed-load channel phases carried substantially more bedload than the modern rivers and cannot be regarded as simply larger versions of the latter.

The Coleambally and Kerarbury palaeochannel phases coincide with enhanced fluvial activity recorded elsewhere in Oxygen Isotope Stages 5 and 3 respectively. The Kerarbury phase during the Stage 3 Sub-pluvial of Nanson et al. (1992a) was also a time of higher water levels at Lakes Urana and Cullivel and appears to coincide with Bowler's (1986a) Mungo lacustral episode.

During Oxygen Isotope Stage 2 the Riverine Plain exhibited enhanced fluvial activity and higher lake levels both immediately before and after the Last Glacial Maximum (LGM) and the evidence is consistent with a short arid interval at the LGM itself. The transition to essentially modern environments occurred near the Oxygen Isotope Stage 2/1 boundary between 15 and 10 ka.

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CHAPTER 1

INTRODUCTION

The Riverine Plain, which occupies much of the eastern part of the Murray Sedimentary Basin of southeastern Australia, consists of the coalescing floodplains of westward flowing rivers of the Murray system that emanate from gaps in the foothills of Australia's southeastern highlands. The Plain covers an area of 77,000 km^2 and has been accumulating sediments throughout the Cainozoic (Brown and Stephenson, 1991). Despite sea level fluctuations which impacted greatly upon patterns of sedimentation in the western (Mallee) part of the Basin the Riverine Plain has maintained continuous terrestrial conditions during the last 60 Ma and provides an excellent record of episodic fluvial, lacustrine and aeolian sedimentation (Bowler, 1986a). Although fluvial deposition has dominated, the smaller lacustrine and aeolian components are associated with distinctive styles of deposition and their interpretation significantly enhances the environmental record provided by the rivers alone.

The last full glacial cycle from about 125 ka is of particular interest to Quaternary science because it provides a model for the pattern of climatic and hydrologic events that is probably similar to that accompanying each glacial cycle back to 500 ka and perhaps beyond (An et al., 1986). Because much of the record of the last glacial cycle on the Riverine Plain occurs within the present landforms and associated surficial deposits it is readily accessible to scientific study.

The first detailed research into the sediments of the Riverine Plain grew out of the need for accurate soil and groundwater maps for the region's expanding agriculture in the period following the Second World War when large areas along the Murrumbidgee and Murray Rivers were selected for the establishment of new irrigation areas. Aerial photograph surveys at this time provided an impetus to research on the Plain because they revealed that patterns of soil and sediment variation were largely controlled by the courses of ancient river systems and not by modern drainage. Bowler (1986a) regards this pedogenic correlation as one of the best examples of a fluviatile soil-sediment association in Australia today.

Pioneering studies by Butler (1950, 1958) and Langford-Smith (1958, 1960a) showed that the Riverine Plain was deposited by an extensive distributary network of ancient sand-bed prior streams very dissimilar to the sinuous, suspended load channels of the Murray, Murrumbidgee and Lachlan Rivers today. Pels (1964b) drew attention to a second set of palaeochannels, similar in planform to the present rivers, but with bankfull discharges believed to be about five times greater (Schumm, 1968). He considered that the meandering channels were fundamentally different to the sand bed types and accordingly introduced the term ancestral rivers to distinguish them. On the basis of radiocarbon dating Pels (1964a, 1969) believed that both the prior streams and the earlier phases of the ancestral rivers were active before 30 ka. Of course, this meant that any attempt to correlate the majority of the palaeochannel phases on the Riverine Plain with interglacial or glacial conditions remained largely speculative. In addition, not all workers embraced the simple prior-ancestral model of stream activity (Bowler, 1978).

Although little new research on the chronology of palaeochannels of the Plain was carried out between 1970 and 1990, considerable insight into Late Quaternary environmental change was provided by detailed studies of relict lakes and their distinctive crescentic marginal dunes (lunettes). On the Willandra chain of lakes, in particular, Bowler (1971,1973,1983, 1986a) documented impressive evidence for patterns of hydrologic change and human settlement extending up to, and possibly beyond, the limit of radiocarbon dating at about 35 ka. The key elements in the record of hydrologic change were a prolonged early phase of high water levels from before 50 ka until 36 ka, generally oscillating levels until about 20 ka and then, at the peak of the glacial maximum from 18 to 16 ka, a dramatic shift to aridity with falling lake levels and the construction of transverse dunes dominated by clay. Bowler (1986a) believes that this phase of dune construction has equivalent expression over a wide range of southern Australia. Paradoxically, the evidence of river activity in the Murray Basin at this time (Bowler, 1978; Bowler et al., 1978) is consistent with increased runoff, at least seasonally, and considerably enhanced rates of lateral channel migration.

In recent years the scope for regional and even global correlation of local evidence of climatic change in Australia has been greatly increased by refinement of the chrono-stratigraphic framework provided by the deep sea

oxygen isotope record. Accurate U/Th dating of reef corals and orbital tuning of the 340 ka ^{18}O record from east equatorial Pacific core V19-30 have permitted the reliable dating of oxygen isotope stages for the last full glacial cycle to 125 ka and beyond (Chappell and Shackleton, 1986). Calibration of the oxygen isotope stages against temperature variation (Jouzel et al., 1987) and the dust flux record (Petit et al., 1990) in the Antarctic Vostok core has now resulted in an impressively consistent model of southern hemisphere climatic change (Nanson et al., 1992a; Kershaw and Nanson, 1993). Low sea levels and temperatures in Stages 2 and 4 correlate with dust peaks and higher temperatures and sea levels in Stages 1, 3 and 5 correlate with low dust flux. The Vostok dust record also correlates well with dust flux in North Pacific marine core V21-146 (Horan et al., 1989) and Chinese loess episodes (Kukla, 1987) and thus provides encouraging support for the globally stacked and smoothed SPECMAP oxygen isotope record from five low and middle latitude deep sea cores (Porter, 1989). Figure 1.1 summarises some of the important elements of the global record provided by deep sea muds, sea levels, ice temperatures and dust flux.

Porter (1989) considers that Quaternary scientists have generally been too ready to view the glacial ages simplistically as a succession of glacial and interglacial culminations during which the extent and volume of glacier ice were at a maximum or minimum. As important as these peaks may have been, the deep sea oxygen isotope cores and sea level records show that they occupied relatively brief periods compared to the more typical conditions over the long span of the glacial ages. Average Quaternary glacial conditions, based on the marine isotope record, approximated those near the Stage 2 - Stage 1 transition and during Stages 5b and 5d. Isotope Stages 3, 4, 5a and 5c were within one standard deviation of the mean value. Stages more than one standard deviation from the mean include the present interglacial (Stage 1), the peak of Stage 2 and the Stage 5e interglacial but these account for less than 25 per cent of the last full glacial cycle. Therefore, the study of Late Quaternary climatic and hydrologic change should not unduly emphasise these periods but instead seek to comprehend landscape evolution in terms of the much more typical conditions approximately mid-way between the glacial and interglacial extremes.
In general, correlation of continental evidence of climatic change with the deep sea isotope stages and ice core records has been impeded by the inability to date depositional episodes older than the effective range of radiocarbon.

However, during the last ten years, refinement of thermoluminescence (TL) dating (Wintle and Huntley, 1982; Aitken, 1985; Berger, 1988; Nanson et al., 1988) has permitted the reliable dating of continental aeolian and fluvial deposits from the last full glacial cycle, and in favourable cases, beyond 300 ka. Radiocarbon and other methods, including U/Th dating of indurated pedogenic calcretes, ferricretes and gypcretes (Nanson et al., 1991), have provided corroboration of the TL chronologies. In Australia, evidence from the Lake Eyre Basin and the Shoalhaven and Nepean catchments of coastal New South Wales (Nanson et al., 1992a) has shown that enhanced fluvial activity by sand bed streams occurred during Oxygen Isotope Stage 5 and to a lesser extent during Stage 3 between 55 and 35 ka. The latter episode appears to correlate with high lake levels radiocarbon dated in southeastern Australia by Bowler (1986). TL dating of continental dunes (Gardner et al., 1989; Wasson, 1989, 1990) shows peak activity during Stages 2 and 4 with a lesser peak in Stage 5d.

Kershaw and Nanson (1993) have summarised the latest Australian continental records of fluvial activity, dune building and vegetation change and found encouraging correlations with the broad southern hemisphere and global records of deep ocean ^{18}O concentrations, sea level change, Vostok temperatures and dust flux. Of course, puzzling discrepancies remain, not the least being the apparently simultaneous occurrence of aridity as evidenced in dunes and lakes, and increased runoff as evidenced in large palaeochannels from the last glacial maximum in the Murray Basin (Bowler, 1986; Bowler et al., 1978).

Following initial success in TL dating of palaeochannels up to 100 ka on the Riverine Plain (Page et al., 1991) a detailed program of field mapping, stratigraphic investigation and dating was undertaken between 1990 and 1993. The project was broadened and given further impetus when a stratum containing human remains was discovered in a sandy lunette at Lake Urana during the summer of 1988-89. TL dating of the sediments containing the remains yielded an age of 30 to 25 ka and demonstrated the antiquity of both the skeleton and the lunette system (Page et al., 1994a; 1994b). It was clear that the well preserved compound lunette at Lake Urana in the eastern region of the Riverine Plain was pre Holocene in age and offered potentially valuable evidence of Late Quaternary hydrologic change in the region. Given previous discrepancies in evidence provided by rivers and lakes in the Murray Basin, the opportunity

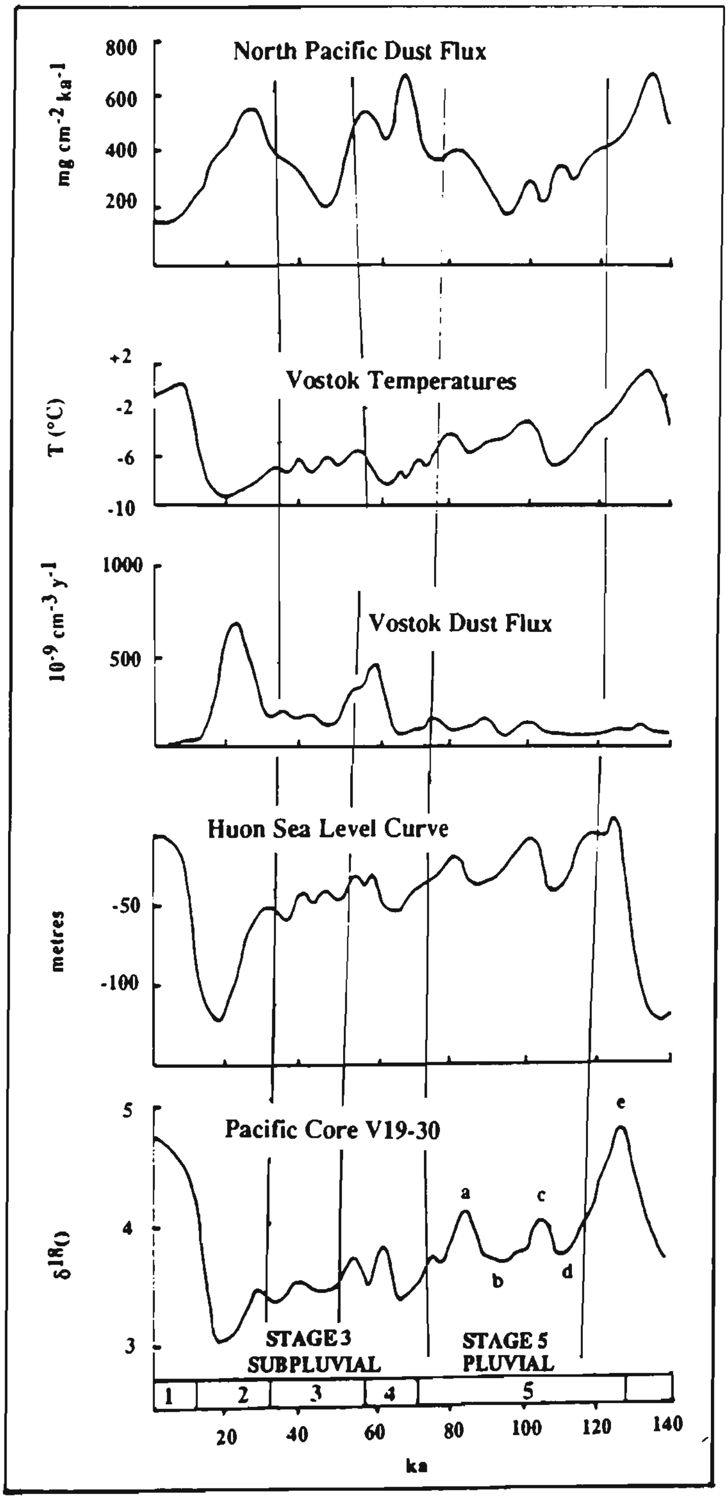


Figure 1.1. Last full glacial cycle data for North Pacific dust flux (Hovan et al., 1989), Vostok temperatures (Jouzel et al., 1987), Vostok dust flux (Petit et al., 1990), Huon sea levels (Chappell and Shackleton, 1986) and oxygen isotopes for Core V19-30 (Porter, 1989). Stage 5 Pluvial and Stage 3 Sub-pluvial from Nanson et al. (1992a). Oxygen Isotope Stages from Shackleton and Opdyke, 1973.

to establish TL chronologies for both the palaeochannels and a large lunette complex on the Riverine Plain offered the possibility of further exploring differences between the two hydrologically related systems. Potential also existed for the comparison of TL chronologies established from fluvial and aeolian sediments.

The broad aim of this PhD research program was to use field mapping, TL dating and stratigraphic evidence to establish a record of hydrologic change on the Riverine Plain for the last full glacial cycle. This broad aim was then subdivided into four specific objectives:

- To identify and TL date all major phases of Murray and Murrumbidgee River palaeochannel activity on the Riverine Plain during the last full glacial cycle (ie, from 125 ka). Dating was initially concentrated in the Murray - Goulburn confluence region near the Cadell Fault (Page et al., 1991). Subsequent palaeochannel dating concentrated on the Murrumbidgee sector of the Plain where the different phases of channel activity have not been complicated by tectonism.

- To TL date and interpret the stratigraphy of well preserved lunettes at Lake Urana and nearby Lake Cullivel at the eastern margin of the Plain.

- To develop an explanatory stratigraphic model of Late Quaternary palaeochannel activity on the Riverine Plain. An important objective of the model was the resolution of the present difficulties attending Pels (1971) division of palaeochannels into distinctive early prior streams and later ancestral rivers.

- To resolve the apparent discrepancy between aridity indicated by the aeolian and lacustine record and enhanced stream flow as indicated by the fluvial record at about the time of the last glacial maximum.

CHAPTER 2

THE RIVERINE PLAIN STUDY AREA

LOCATION AND TOPOGRAPHY

The Riverine Plain is one of seven major geomorphically distinct regions of the Murray Basin (Fig. 2.1) in southeastern Australia (Brown and Stephenson, 1991). It covers an area of 77,000 km^2 and extends 500 km from north to south and 300 km from east to west. The Plain consists of the coalescing alluvial floodplains of the westerly flowing Murray, Murrumbidgee and Lachlan Rivers and their tributaries, distributaries and anabranches. The surface of the Riverine Plain is characterised by extremely low gradients and is virtually flat-lying with an average elevation of 120 m where it borders the highlands in the east and 65 m in the west. The average gradient over the Plain is approximately 20 cm per km.

To the east and south the Late Cainozoic sediments of the Plain onlap the marginal highlands and to the west they are partly blanketed by the encroaching Mallee dunefield. The arcuate shape of the western margin of the Riverine Plain, as well as the flow directions of many of its rivers, are primarily structurally controlled and reflect the arcuate configuration of underlying basement elements and the orientation of fracture sets (Brown and Stephenson, 1991). For example, in New South Wales, the westerly courses of the Lachlan and its Willandra Creek distributary are thought to have been defeated by the concealed ridges of the Ivanhoe Block. In the southwest, the Plain is separated from the Wimmera Plain and Mallee landscape by the Gredgwin Ridge which overlies shallow basement rock uplifted to the west of the Leaghur Fault (Fig. 2.1).

All of the major rivers of the Riverine Plain rise in Australia's rugged and generally well-watered southeastern highlands where they flow through confined bedrock valleys before debouching onto the Plain. The Lachlan and Murrumbidgee form subtle low angle fan-like features which, over a few tens of km, gradually merge with the alluvial plain which is traversed by an initially radiating pattern of interconnected channels. However, the major trunk streams reconverge towards the central-western apex of the Plain near Balranald (Fig. 2.2), where the Lachlan River joins the Murrumbidgee (via a

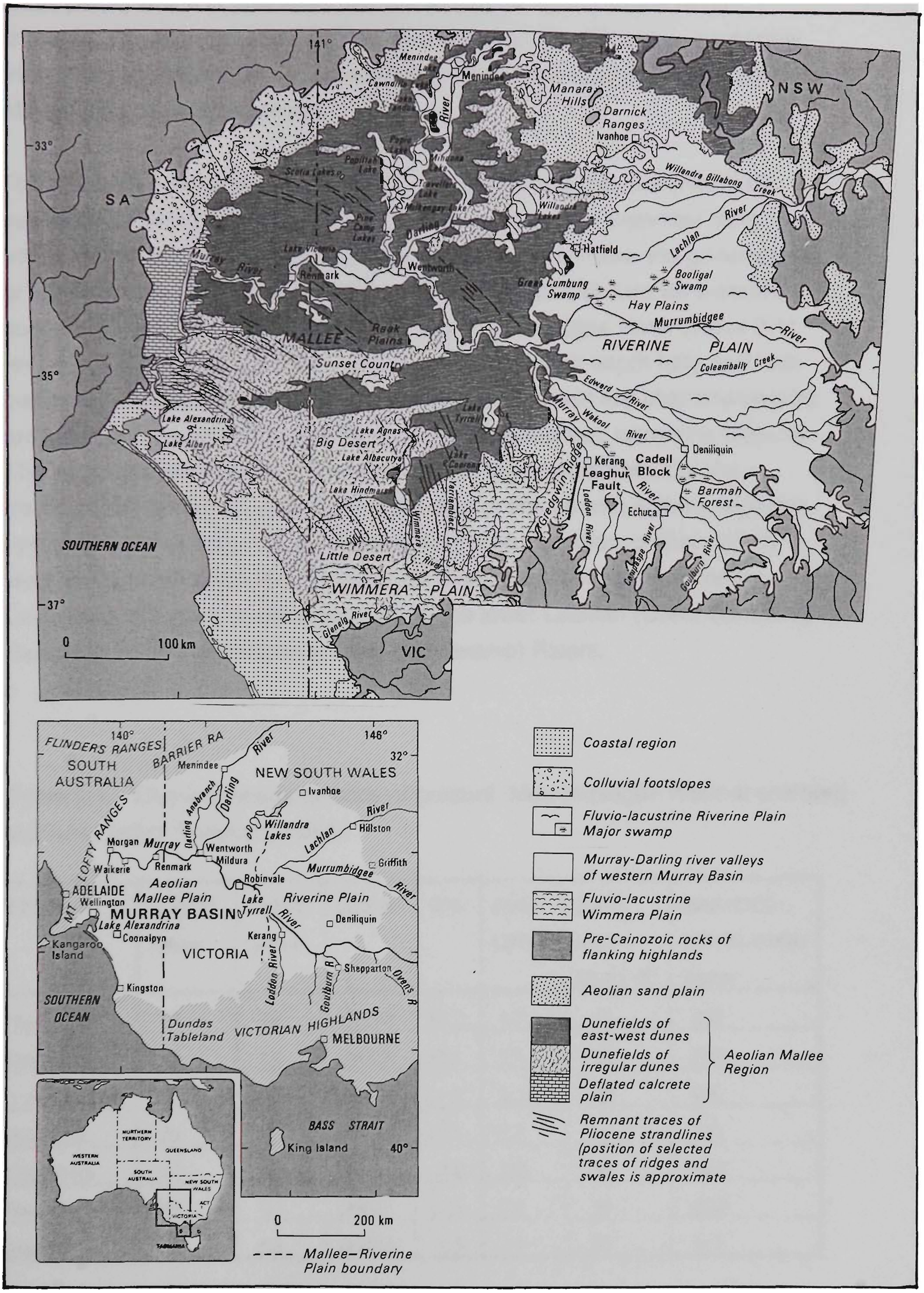


Fig. 2.1. Major physiographic regions and features of the Murray Basin, southeastern Australia (Brown and Stephenson, 1991).

small creek) which in turn flows into the Murray to form a single large channel. The Murray exits the Riverine Plain and then flows along a narrow trench through the Mallee dunefield before finally reaching the sea at Lake Alexandrina in South Australia.

The present rivers of the Riverine Plain are highly sinuous, dominated by suspended load (Schumm, 1968) and flow along narrow meander belts which are 1.5 to 5 km wide and entrenched 1.5 to 5 m below the general level of the landscape (Butler et al., 1973). Schumm's (1968) data for selected sections on the Riverine Plain reach of the Murrumbidgee River (Table 2.1) reveal a low gradient, sinuous channel with a low width-depth ratio and high perimeter silt-clay content. The trunk rivers on the Plain are characterised by anastomosing channels as well as an array of associated lacustrine features. The anabranches reconverge several tens of km downstream, but the distributaries terminate in swamps and lakes or link up with entirely separate systems. For example, Yanco Creek exits the Murrumbidgee River to the west of Narrandera but finally enters the Murray system near Moulamein. Large swamps are well-developed along the lower Lachlan (Great Cumbungi Swamp) and Murrumbidgee (Lowbidgee Swamp) Rivers.

Table 2.1. Channel characteristics of present Murrumbidgee River at selected stations. (After Schumm, 1968).

STATION	WIDTH metres	DEPTH metres	SLOPE	W/D	SINU-OSITY	BANK SILT-CLAY %	MEANDER WAVELENGH metres
Narrandera	75	5.9	.00020	12.7	1.7	82	800
Darl Point	67	5.1	.00013	13.1	1.9	70	630
Yarradda Lag.	70	4.7	.00013	14.9	2.0	40	660
Bringagee	59	4.8	.00013	12.3	2.3	64	450
Carrathool	65	6.6	.00013	9.8	2.3	55	420
Hay	75	6.7	.00011	11.2	2.1	69	630
Maude	50	6.3	.00008	7.9	1.9	87	430

The complex drainage of the Plain can partly be related to subtle structural control and partly to the extremely low gradients. In the southern region of the Plain, the northwesterly flow of the Murray River has been disrupted by uplift of the Cadell Block (Pels, 1964b; Bowler and Harford, 1966). At first, the main Murray channel was deflected to the north around the uplifted block near the present site of Deniliquin. The most recent diversion by minor tectonism has resulted in the Murray flowing to the south to join the Goulburn River to the east of Echuca and then following a northwesterly course. The down-faulted area to the east of the fault, known as Barmah State Forest, is subject to present day seasonal flooding.

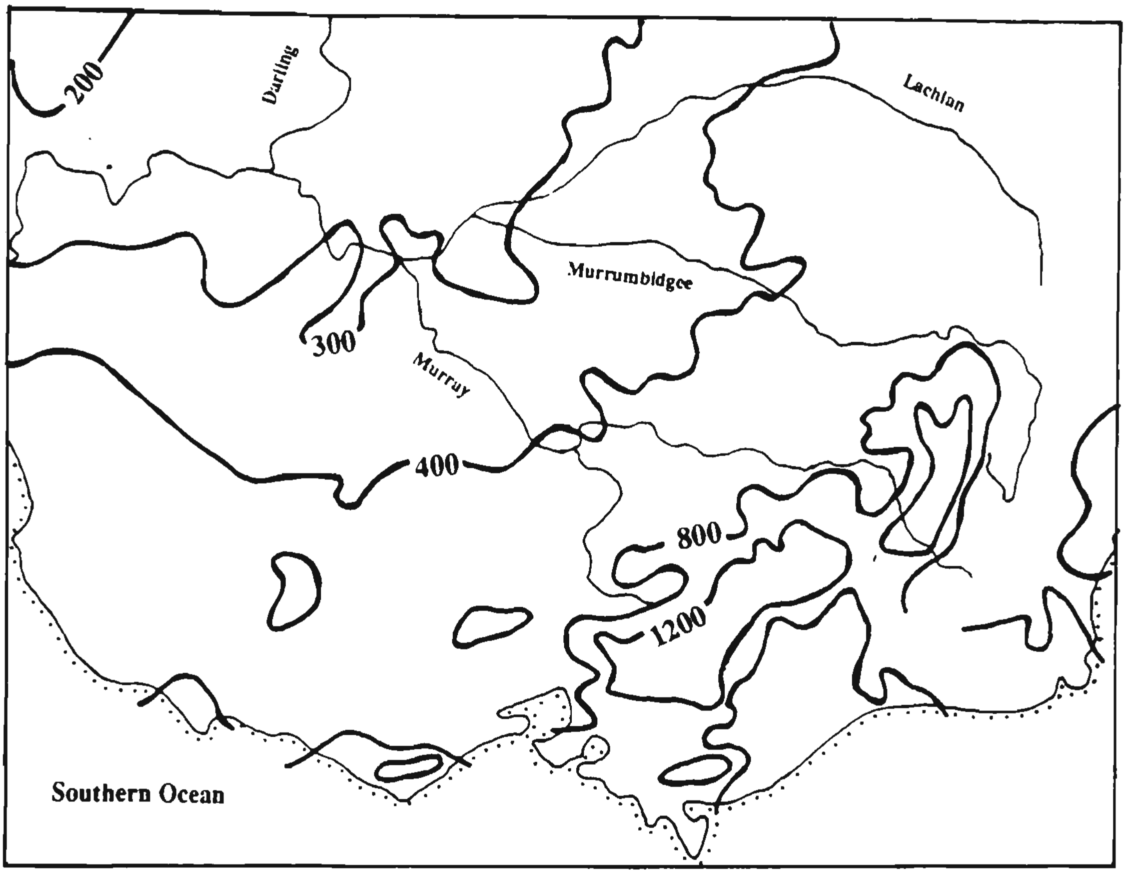
Away from the present rivers and their associated floodplains the Riverine Plain is essentially a fossil landscape consisting of fluvial, aeolian and lacustrine elements that developed during the Late Quaternary in response to climatic and hydrologic regimes rather different from those of the present (Porter, 1989). Although they are not always readily apparent at ground level because of their subdued topographic expression, palaeochannels dominate the Riverine Plain landscape as viewed on air photographs and satellite images and exert strong controls over the present distribution of sediments, groundwater and soil types on the Plain (Butler, 1950). The channels differ in their characters and were subdivided by Pels (1964b) into two major types, prior streams and ancestral rivers. Fossil lakes are found throughout the Riverine Plain but are most common in the western region close to the boundary with the Mallee. The crescentic transverse dunes (lunettes) at the eastern margins of these lakes provide a record of past lake environments. At Lake Mungo, in the Willandra chain, detailed studies by Bowler (1971) and others have formed the basis of a model of Late Quaternary climatic change that has found support in other areas of southern Australia (Bowler, 1986a). Source bordering sand dunes are often found along the northern and eastern palaeochannel margins. These occasionally rise to an elevation of 20 m above the Plain and form conspicuous landforms. Aeolian dust (parna) deposits are also found over large areas of the surface of the Riverine Plain and are sometimes intercalated with the subsurface fluvial sediments (Butler, 1956, 1958).

CLIMATE AND STREAM FLOW

The Riverine Plain experiences sub-humid to semi-arid climatic conditions with annual rainfall varying from a little over 450 mm in the east to about 300 mm in the west at Balranald (Fig. 2.2). Summers are hot with daily maxima in the low 30s (°C) and winters cool with daily maxima around 14°C. The headwaters of the major rivers occur in the southeastern highlands where precipitation levels are considerably higher and much of the stream discharge is produced. On the highest peaks around Mount Kosciusko median annual precipitation exceeds 3000 mm, much of it falling as snow during the winter months. Most of the country above 1500 m receives more than 1200 mm of precipitation per year (Atlas of Australian Resources, Volume 4, 1986) and snow lies on the ground for about 60 days (Slatyer et al., 1984). Below 1000 m snowfalls are light and do not contribute significantly to total precipitation. Because the area above 1500 m is small relative to total catchment area the contribution of snow melt to major river floods is not great, particularly in the Murrumbidgee and Lachlan catchments. Schumm (1968) estimated that average precipitation of the Murrumbidgee catchment above Narrandera was around 650 mm. This is probably a reasonable average for the headwater regions as a whole.

In southern areas of the Riverine Plain most rain falls in winter when cold fronts embedded in low pressure troughs sweep the area from the west. Precipitation is less reliable in the northern areas where summer thunderstorms bring most of the rain (Brown and Stephenson, 1991). Remnants of tropical depressions also occasionally travel sufficiently far south to contribute to summer rainfall. Mean annual evaporation for the Riverine Plain is high with values rising from 1600 mm in the southeast to over 2000 mm in the northwest (Fig. 2.2). The dominant wind directions are from the west and south. This pattern is reflected in the location and orientation of aeolian dunes and suggests that dominant wind directions have not changed greatly throughout the Late Quaternary.

Despite their large catchment areas the streams of the Riverine Plain have extremely modest discharges by world standards. The Murray and the Murrumbidgee have mean annual flows of 200 m^3/s (Tocumwal) and 116 m^3/s (Wagga Wagga) respectively. Downstream of the Murrumbidgee - Murray confluence the mean annual discharge is 313 m^3/s (Mildura). These



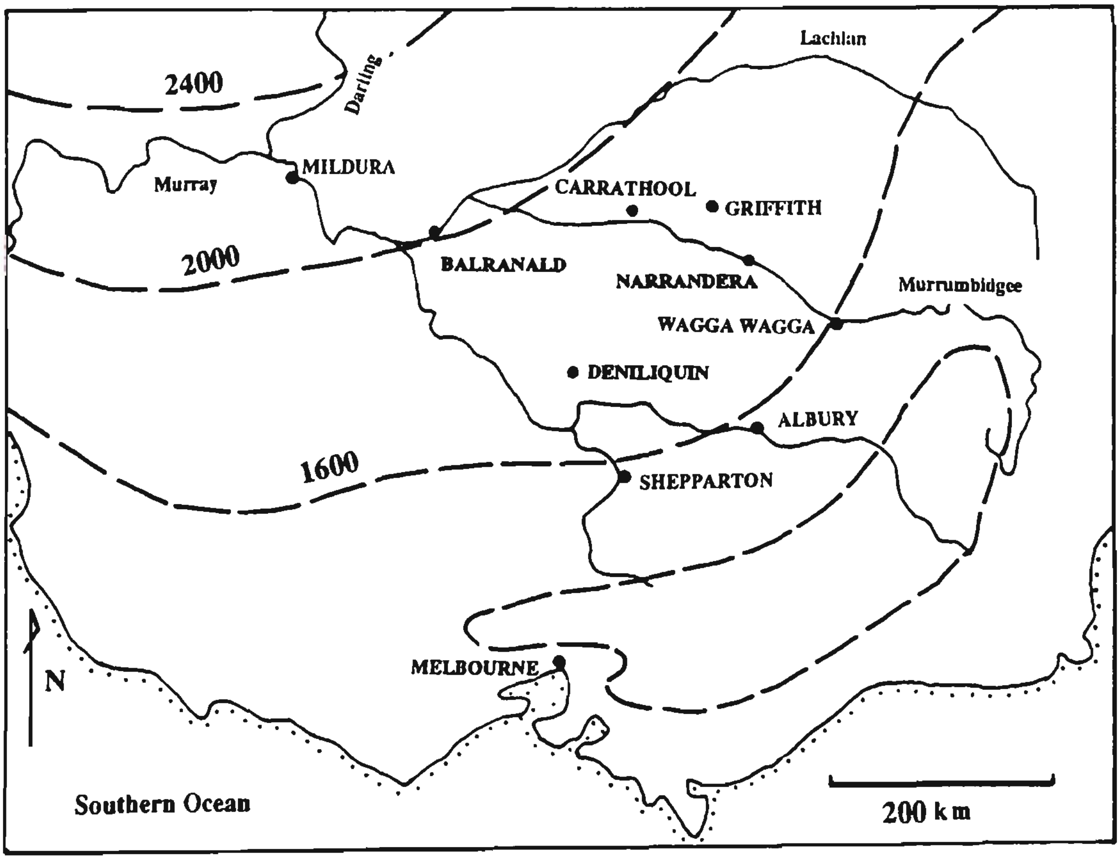


Fig. 2.2. Murray Basin climate data. Top: median annual precipitation in mm. Bottom: mean annual pan evaporationin mm. (Atlas of Australian Resources, Volume 4, 1986).

mean flows may be compared with 180,000 m^3/s for the Amazon, 18,000 m^3/s for the Mississippi and 2,800 m^3/s for the Nile to gain a global perspective (Stoddart, 1969). Discharges per unit of catchment area in the Murray Basin are commonly more than one order of magnitude less than those of overseas rivers of comparable catchment area. Even the Nile, which flows across arid North Africa, produces twice as much discharge per unit of catchment area as the Murray (Stoddart, 1969).

On the Murrumbidgee Water Resources Department records show that mean flow decreases downstream from 116 m^3/s at Wagga Wagga to 97 m^3/s at Narrandera (a distance of 100 valley km) to only 77 m^3/s at Balranald (a further 300 valley km). This downstream decrease partly reflects increasing aridity to the west but also results from the loss of water to irrigation schemes along the river. Flood peaks also decrease markedly downstream on the Murrumbidgee and Lachlan, primarily because channel and floodplain storage combine with an absence of tributaries to produce severe hydrogaph attenuation such that flood flow durations increase downstream but peaks decline markedly (Table 2.2). For example, the 10 year flood on the Murrumbidgee is approximately 2600 m^3/s at Wagga Wagga, 1350 m^3/s at Narrandera and only 350 m^3/s at Balranald (McElroy, 1979). This decline plainly exceeds that consistent with loss of water alone. In response to declining flows downstream, the channel of the Murrumbidgee decreases in capacity from a cross sectional area of 435 m^2 at Narrandera to 315 m^2 at Balranald (Schumm, 1968). Bankfull discharge near Wagga Wagga is equivalent to the mean annual flood (Page, 1988). Before dam construction and flow regulation the rivers of the Plain were characterised by seasonal flow regimes with peak discharges during late winter and early spring and generally low flows throughout summer. Although major floods are still most common during late winter and spring, moderate summer flow levels are maintained by dam releases to supply downstream irrigation areas.

Measurements of sediment loads of Murray Basin streams are few but negligible rates of reservoir and weir (Burrinjuck Reservoir on the Murrumbidgee and Hume Weir on the Murray) infilling are consistent with low volumes of bed and suspended load despite the turbid appearance of the rivers in their downstream reaches (Schumm, 1968). Measurements of suspended load of the Murray River downstream of Albury from 1974 to 1976 (Walker and Hillman, 1977) revealed average concentrations of 20 - 90

mg/l and a maximum annual load of approximately 300,000 tonnes (15 tonnes/km^2 of catchment) in 1975, a year characterised by major flooding. These catchment values are low by world standards (Stoddart, 1969). Limited sampling of suspended sediment on a major upland tributary of the Murrumbidgee, the Tumut River, by the Water Resources Department in 1964 (Schumm, 1968) likewise indicated a maximum concentration of only 92 mg/l. The slow infilling of deep holes excavated into the present river bed near Wagga Wagga during sand and gravel extraction (Pioneer Concrete records) provides evidence of low rates of bedload transport that is consistent with observations of the failure of coarse river bed gravels to be entrained by the present flow regime. Radiocarbon dating of modern floodplain sediments indicates relatively low rates of lateral channel migration averaging 0.01 - 0.07 m/yr on the Murray (Urquhart, 1973) and 0.08 m/yr on the Murrumbidgee River near Wagga Wagga (Owens, 1992). The combination of low lateral migration rates and minimal bedload flux is consistent with Neil's (1984) observations on rivers in Canada.

Table 2.2. Annual flood peaks on the Murrumbidgee River 1937-1976. Discharges in m^3/s, distances in km. (After McElroy, 1979).

STATION	VALLEY DISTANCE	Q2.3	Q5	Q10	Q20
Gundagai	0	740	1630	2840	3940
Wagga Wagga	80	695	1505	2570	3670
Narrandera	180	434	870	1340	1980
Darlington Point	235	313		747	
Hay	350	278	515	695	860
Balranald	500	127	278	342	690

VEGETATION, SOILS AND LAND USE

The pre-European settlement pattern of vegetation has been greatly modified by clearing and crop growing, particularly in irrigated areas. It appears that the natural vegetation of the eastern part of the Plain at the time of early european settlement consisted of mixed eucalypt and acacia open woodlands. These graded westwards into the almost treeless plains typical

of the region between Hay and Balranald today where native saltbush shrublands and grasslands reflect increased aridity and soil salinity. The saltbush provides excellent feed for sheep but overgrazing has seen a partial replacement with less palatable species. The present river courses and floodplains carry open forests dominated by river red gums (*Eucalyptus camaldulensis*) in frequently flooded sites and black box (*E. largiflorens*) at slightly elevated sites and along intermittent streams. Native cypress pines (*Callitris columellaris*) favour well drained sandy soils and often form single species stands of trees on the source bordering dunes and sandy lunettes. The native pines also occur on well-drained palaeochannel levees in the eastern region of the Plain.

The pattern of soils on the Plain is strongly controlled by the palaeochannel system. Indeed, the understanding of soil variation on the Plain was not achieved until aerial photographs became more readily available in the post World War II years. At slightly elevated marginal channel levee sites freely drained calcareous red-brown earths are the dominant soil type. These grade into brown and grey sodic soils of heavy texture on the back plain (Butler, 1950). In addition soil clay content and salinity generally increase to the west. Because the region has experienced numerous episodes of dust accession from the west (Butler, 1956; Beattie, 1970) many of the soils of the Plain reveal features that cannot be explained by a simple consideration of the local parent materials. The subplastic texture character of many of the clay dune soils and the high carbonate content of soils developed over fluvial sand deposits are examples of the effects of aeolian accession (Dare-Edwards, 1984).

Over the past 100 years the Murray Basin has become one of Australia's most important agricultural regions. The Riverine Plain's contribution takes the form of large irrigation areas along the major rivers, particularly the Murray and Murrumbidgee, whose natural flows have been augmented by flow diversions made following the completion of the Snowy Mountains Scheme during the 1950s and 1960s. Unfortunately, the Murray Basin has become an area beset by daunting environmental problems. Clearance of natural vegetation and irrigation have increased infiltration to underlying sediments resulting in rising groundwater levels and the discharge of saline groundwater into the landscape and river systems. The gradual worsening of these problems now threatens the economy and natural environments of the

region. However, as Brown and Stephenson (1991) point out, many of the reasons for salinisation lie in the subsurface geology and can be related to the stratigraphic development of the Basin during Cainozoic times. Any attempt to ameliorate the environmental problems must be based upon a sound understanding of both the hydrogeological systems and the processes contributing to salinisation.

CHAPTER 3

LATE CAINOZOIC EVOLUTION OF THE MURRAY BASIN

INTRODUCTION

The Murray Basin extends over more than 300,000 km^2 as a low-lying saucer shaped intracratonic structure containing horizontally bedded sediments that have accumulated since the early Tertiary (Brown, 1985). It is flanked by low mountain ranges of Proterozoic and Palaeozoic rocks which also form the majority of the basement structure. The infilling Cainozoic sediments are from predominantly shallow-marine and fluvial environments and are quite thin, averaging less than 200 metres in the north, south and east but attaining a maximum thickness of more than 500 metres in the west-central basin depocentre. Within the thin Cainozoic sequence subtle basement tectonic movements have considerably influenced both the geometry of Cainozoic sedimentation and groundwater and surface flow patterns (Brown and Stephenson, 1991).

Surface sediments of the Murray Basin slope gently to the central west where parts of the present landscape are only 20 metres above sea level. Pliocene uplift of the Pinnaroo Block and Padthaway Ridge in the south west formed a basin rim that effectively separates the groundwater basin from the Southern Ocean and results in groundwater flow towards the central western depocentre (Brown and Stephenson, 1991). Surface drainage reaches the sea from this low-lying area via the Murray River which has cut a gorge into elevated Tertiary sediments. The gorge appears to date from approximately 0.7 Ma (An et al., 1986).

Quaternary landscapes of the Murray Basin represent the culmination of prolonged sedimentation throughout the Cainozoic. The geological history of the Basin has recently been comprehensively documented by Brown and Stephenson (1991). Because the Cainozoic inheritance has an important bearing upon the Quaternary landscape the main features of Brown and Stephenson's (1991) review are outlined below.

MAJOR TERTIARY DEPOSITIONAL EPISODES

Three major Tertiary depositional sequences have been identified, each consisting of a distinctive set of related formations. An important aspect of the Basin's evolution has been marine invasion from the southwest and subsequent retreat. Given the low gradients and elevation of the Basin, partial flooding by epicontinental seas has occurred repeatedly. Figure 3.1 summarises the principal elements of the Tertiary stratigraphy of the Murray Basin.

Palaeocene - Lower Oligocene Sequence

Basin sedimentation commenced approximately 60 Ma when fluviatile quartz sands were deposited in irregularities in the otherwise relatively flat pre-Cainozoic topography (Brown and Stephenson, 1986). These deposits were then covered by silt, sand and clay with lignite and peat interbeds (Olney Formation of the Renmark Group). Depositional environments were predominantly fluvio-lacustrine with coal seams being deposited in extensive swamps which developed at the margins of forested meandering river floodplains. Palynological studies indicate that Eocene palaeoclimates in southeastern Australia were characterised by warm temperatures and high rainfall (Kemp, 1978; Macphail and Truswell, 1989). In the westem Murray Basin deposition of the Olney Formation ceased in the Early Oligocene, but in the north and east continued until the Middle Miocene (Fig. 3.1). Despite the prolonged period of deposition a maximum thickness of only 300 metres of sediment was preserved suggesting that deposition was intermittent.

Oligocene - Middle Miocene Sequence

This sequence was initiated by a major marine transgression at about 32 Ma (Ludbrook, 1961). As the sea moved in from the south-west paralic marshes and swamps were drowned. The 20 to 30 metre thick Ettrick Formation marls (Fig. 3.1) were deposited initially but as water depths increased, over 100 metres of shallow marine limestone (Murray Group) were formed on the floor of the embayment. The limestone grades east and north into a zone of glauconitic calcareous clay and thin limestone of the Winnambool Formation deposited in marginal shallow marine platform and lagoonal environments.

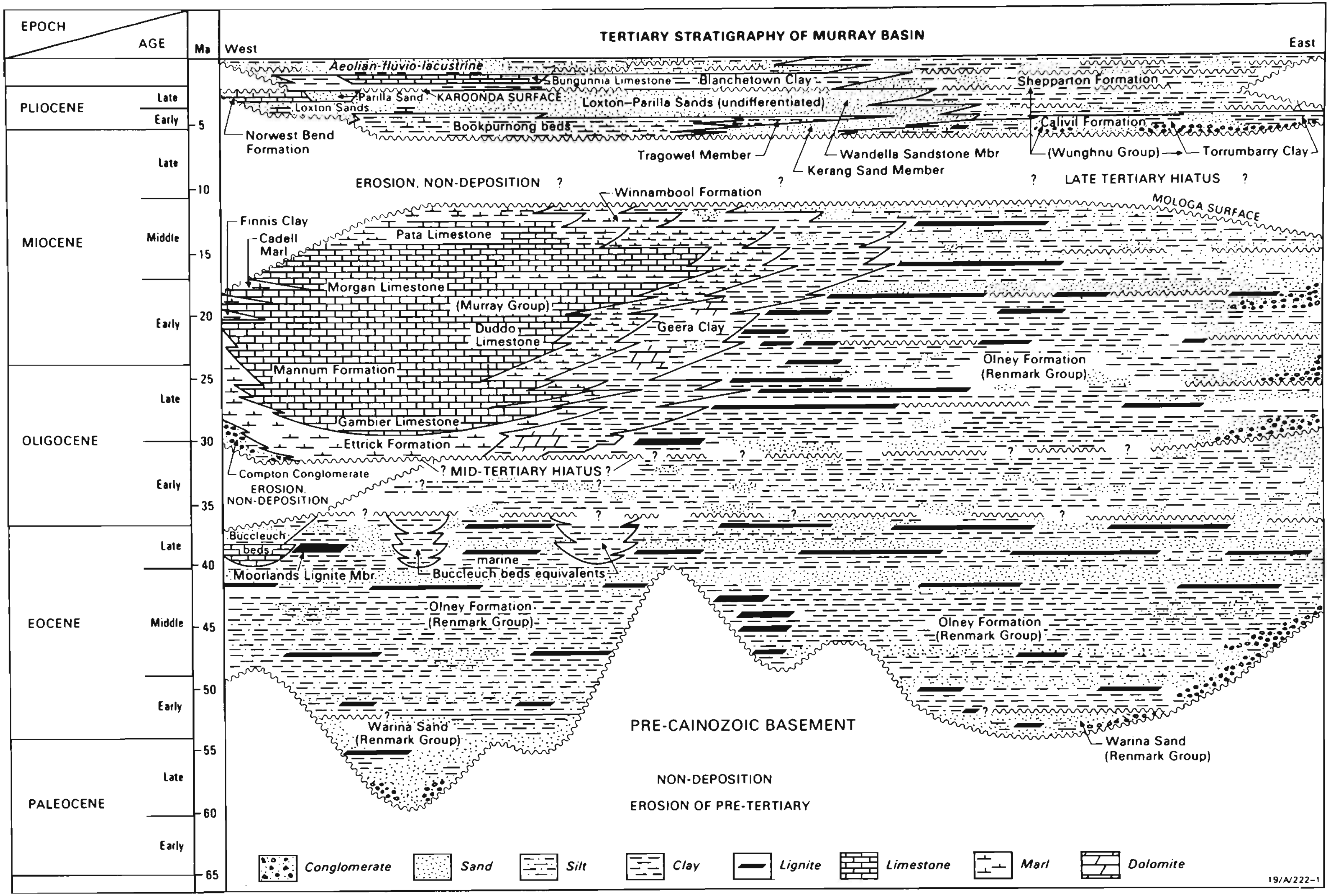


Fig. 3.1. Schematic west-east section showing Tertiary and Quaternary stratigraphy of the Murray Basin (Brown and Stephenson, 1991)

The Winnambool Formation is the lateral facies equivalent of the Murray Group limestone. It grades eastwards into the Geera Clay which was also deposited in shallow to marginal marine environments. The Geera Clay in turn interfingers with deltaic and fluvio-lacustrine sediments of the Upper Olney Formation. Palynologicial evidence from the Geera Clay indicates that the regional vegetation was dominated by evergreen rainforests with abundant *Nothofagus brassi* and attendant high annual precipitation. Investigations of the Olney Formation beneath the Riverine Plain also indicate the existence of humid conditions until at least the Middle Miocene.

Although minor sea level fluctuations occurred, no major retreat of the sea from the basin has been identified until the late Miocene (10 Ma) when the Olney Formation, Geera Clay and Winnambool Formation appear to have prograded back over the top of the platform limestone of the Murray Group (Fig. 3.1). In the east the major sea level fall is correlated with the development of the erosional Mologa surface which was associated with weathering and erosion in the basin and active entrenchment of adjacent highland valleys.

Upper Miocene - Pliocene Sequence

The final major Tertiary depositional episode commenced with a short-lived marine transgression which resulted in deposition of the Bookpurnong beds (Brown, 1983). To the north and east are found the marginal marine Loxton-Parilla Sands which themselves pass into coarse grained sands and gravels of the fluvial and fluvio-lacustrine Calivil Formation. The latter forms an extensive sand sheet underlying much of the eastern and northern Basin margins but occurs as a surface outcrop near Urana and Oaklands. Elevation of the Calivil Formation here may have been associated with minor Late Pliocene or Early Quaternary upwarping.

As the final marine regression occurred in the Pliocene an extensive strandplain sand sheet prograded to the southwest (Firman, 1973). These Loxton-Parilla Sands consisted of shallow marine and beach ridge sands, as well as inter-ridge and locally cross cutting fluvial and estuarine quartz sands. In much of the western Murray Basin the Loxton-Parilla Sands form an extensive near-surface sand sheet underlying the Quaternary Blanchetown Clay and Woorinen Formation dunefields.

In the east and north the major Pliocene regression correlates with the deposition of fine grained clastics and polymictic sand of the Shepparton Formation floodplain deposits. Although palaeoclimates in the Late Pliocene were probably characterised by increasing seasonal aridity the presence of the laterised surface of the Loxton-Parilla Sands suggests that climates were at least seasonally humid.

EARLY QUATERNARY SEDIMENTATION

Between 5 and 2 Ma, uplift of the Pinaroo Block in the southwest of the Basin led to the damming of the Murray River and the formation of the large freshwater Lake Bungunnia (Stephenson, 1986). Based on the extent of its lake floor sediments, the Blanchetown Clay and Bungunnia Limestone, the maximum lake area is estimated at 33,000 km^2. Palaeomagnetic studies show that the lake persisted from before 2.4 Ma until the Brunhes-Matuyama reversal at about 0.7 Ma. Stephenson (1986) showed that although Lake Bungunnia did not maintain a permanent outlet its size is consistent with catchment precipitation levels well above those of today. Large rivers emptying into Lake Bungunnia were associated with continued deposition of the Shepparton Formation in the north and east of the Basin. Following the development of a permanent outlet at about 0.7 Ma water levels dropped rapidly and Lake Bungunnia fragmented into several smaller basins of which Lake Tyrrell in the Victorian Mallee country is the largest surviving remnant.

LATE QUATERNARY SEDIMENTATION

Following the demise of Lake Bungunnia gradual but significant changes in sedimentation patterns became apparent and culminated in the onset of semi-arid conditions by about 0.4 or 0.5 Ma (An et al., 1986) when the modern aeolian landscapes of the Mallee region were established.

What are believed by Bowler and Magee (1978) to be the oldest Mallee dunefields (Woorinen Formation) are characterised by west-east trending longitudinal to tear drop shaped dunes which are presently stabilised by vegetation and soil formation. Apparently these dunes were derived predominantly from sands of the Loxton-Parilla strandplain and formed by west to southwest winds. The clay content of the dunes can be attributed to deflation of the underlying Blanchetown Clay and younger saline lakes. The

Woorinen Formation dunes contain numerous palaeosols and calcrete horizons consistent with episodic activation and restabilisation (Churchwood, 1963). The high clay content (> 10%), rubification of quartz grains, calcrete content and orientation all suggest that the oldest components of these dunes were deposited during arid conditions. Alternate episodes of activation and stabilisation are presumed to have accompanied the climatic and hydrologic changes accompanying each glacial cycle.

Significant areas of the linear Woorinen dunefields are interrrupted by fields of irregular to subparabolic dunes. These include the Sunset Country, Big and Little Deserts of South Australia and Victoria (Molineaux-Lowan Sands) and the dunefields east of the Darling River in New South Wales (Fig. 2.1). These dunes are locally active today as a consequence of vegetation clearing, overgrazing and bushfires. In general these dunes were formed by remobilisation of the Woorinen Formation but in South Australia deflation of the Bridgewater Formation and Loxton-Parilla Sands has also contributed.

When the predominantly arid to semi-arid landscapes of the past 0.5 Ma became established in the western Murray Basin previously perennial lakes became intermittent. During episodes of high water levels sandy beaches and foredunes (lunettes) developed at their eastern shorelines under the influence of the prevailing westerly winds. At times of transition between wet and dry periods (Bowler, 1986) deflation from the lake floor resulted in the formation of clay dunes (Fig. 3.2). Many of these transverse dunes have been investigated but the best known research has been associated with the Willandra Lakes (Bowler, 1971) where the pattern of hydrologic change, sedimentation, soil formation and human occupance since the last interglacial has formed the basis for a widely accepted model for southeastern Australia.

As arid conditions became established in the Mallee, fluvial deposition of the Shepparton Formation continued in the east and led to the formation of the present Riverine Plain landscape. Preserved palaeochannels and their deposits are widely preserved on the Plain and provide a record of Late Quaternary fluvial environments and climatic regimes (Schumm, 1968).

PRIOR AND ANCESTRAL STREAMS

During his early research on the Riverine Plain, Butler (1950, !958) established that ancient rivers, which he called *prior streams*, defined distinctive soil associations that extended as a vast network over the surface of the Plain. The prior streams were slightly leveed, aggraded bedload channels of low sinuosity and formed an overlapping distributary pattern that petered out towards the western margin of the Plain. Butler (1958) argued that phases of prior stream deposition demanded a copious supply of coarse sediment from an arid, and therefore, vegetation denuded catchment. Intervening pluvial phases were characterised by stream incision on the Plain and widespread soil formation. Central to Butler's model was the assumption that stream aggradation or soil formation prevailed over the Riverine Plain in any given period.

Langford-Smith (1959; 1960a; 1960b and 1962) questioned the synchronous regional development of soil surfaces and, on the basis of the known relationship between meander wavelength and discharge (Leopold and Wolman, 1957), argued that large prior stream channels demanded larger discharges associated with pluvial, rather than arid conditions. In the absence of absolute dates on the prior streams attempts to correlate depositional phases with glacial, interglacial or post-glacial periods (Schumm, 1968) remained speculative.

Pels (1964a, 1966, 1969) believed that the debate between Butler and Langford-Smith arose in part from a failure to identify two fundamentally different types of palaeochannel. He argued that Butler's (1958) youngest stratigraphic unit, the Coonambidgal, was more complex than previously supposed. On the basis of fieldwork near Deniliquin, where faulting had separated different episodes of stream activity, Pels identified a set of palaeochannels he called *ancestral rivers*. These were thought to post-date the prior streams and be the immediate precursors of the modern drainage. He described these channels as being deep, sinuous, without levees and dominated by suspended load. The large ancestral streams maintained their courses across the Riverine Plain which they exited as powerful rivers. Schumm (1968) estimated the bankfull discharge of the ancestral Murrumbidgee River near Darlington Point to be approximately five times that of the present river. Altogether Pels (1971) identified three phases of

ancestral stream activity, each initiated by channel incision during humid periods and terminated by aggradation during periods of waning discharge and increasing aridity. Radiocarbon dating showed the earliest, Green Gully, phase to be older than 30 ka* (see Chapter 4 for explanation of ka*) and later phases to date from the time of faulting at 30 to 25 ka* (Pels, 1969).

Despite its acceptance by Schumm (1968) the simple prior-ancestral palaeochannel model was not universally supported. Bowler (1978) noted that exposures of ancestral Goulburn River sediments in Victoria revealed abundant gravel and coarse sand similar to that found in prior streams. He also noted alternate reaches of apparently ancestral and prior character on Green Gully and hypothesised that, given time, aggradation of ancestral channels might result in the development of prior stream characters. Bowler (1978) also questioned Pels' (1969) cyclic incision-aggradation model of ancestral channel development and favoured instead, a long period of high discharge and greater transport of coarse bedload sediments during the late Pleistocene followed by a shift to the present suspended load, lower discharge regime at about the time of, or soon after, the last glacial maximum (Bowler, 1986a). Further progress on the chronology of prior streams was hampered by the inability to date deposits beyond the limit of radiocarbon.

LUNETTES AND RELICT LAKES

Many of the relict lakes of the Murray Basin are bordered on their down wind margins by crescentic transverse dunes called lunettes. Lunette sediments vary greatly in character from well-sorted siliceous sand, through silty clay, clay pellets, and gypseous clay pellets to white gypsite. The stratigraphy of these lunettes reveals fluctuating conditions of Late Quaternary sedimentation that reflect local lake palaeohydrological history.

All of the lunettes of the Murray Basin were deposited as transverse aeolian dunes by westerly or southwesterly winds. In detail the varied lithology and pedogenic alteration of the sediments reflect a considerable range of local hydrological environments. In general, sand dominated phases are thought to be the products of deflation from lake beach deposits formed by wave action in relatively deep, fresh, surface water dominated lakes during periods of more humid climate (Bowler, 1983). Lunettes predominantly formed of clay pellets are thought to be the products of periods transitional between wetter

and drier climates (Bowler, 1986b), such as occurred at the last glacial maximum when groundwater tables, inherited from the preceding less arid climatic phase, were still high but surface runoff was low . During these phases saline groundwater-dominated lake waters were seasonally evaporated and sand size clay pellets produced by the efflorescence of salts in the lake floor muds (Fig. 3.2). The pellets were then transported eastwards to form a drape over earlier quartz dunes. Commonly the pelletal clay is mixed with fine quartz sand to form characteristic bimodal distributions of primary sedimentary particles. The ratio of clay to sand varies from 5:1 to 0.2:1, even within a single dune, and considerably influences the type of dune bedding and the nature of pedogenesis (Dare-Edwards, 1982). At present, the formation of clay pellets on lake floors is not common but was observed by Bowler (1983) at Lake Tyrrell during the summer of 1982-83 when a severe drought was accompanied by high velocity winds.

The most comprehensively studied lunette is that at Lake Mungo in the Willandra chain where comparatively recent gully erosion has formed a spectacular feature known as the 'Walls of China'. Bowler (1971) identified three major stratigraphic units within this dune. At the lunette core the Golgol unit is composed of red quartz sand and has a well developed calcareous soil with large carbonate concretions. The overlying Mungo unit consists of well sorted beach sand with high angle bedding and abundant fresh water shell debris (Bowler, 1971). The upper part of the Mungo unit consists of red and yellowish sand under a dark humic calcareous soil. This unit is in turn overlain by 5 m of sub-horizontally bedded greenish-grey clayey sand with clay pellets. A soil on top of this unit is overlain by the light grey sand and pelletal clay of the Zanci unit whose surface is marked by a red-brown calcareous earthy soil (Bowler, 1971).

Bowler's (1986a) model of Late Quaternary climatic change in southeastern Australia was developed initially on the basis of the Lake Mungo lunette stratigraphy and radiocarbon dating. Although the Gol Gol unit was beyond the range of radiocarbon dating the lower Mungo was thought to indicate a period of high lake levels from before 50 ka* (undated) until about 36 ka* when a phase of low water led to the deflation from the lake floor and the deposition of pelletal clay lunettes. Evidence of unionid shell middens, artifacts and fireplaces in the lower Mungo unit points to an early human presence here.

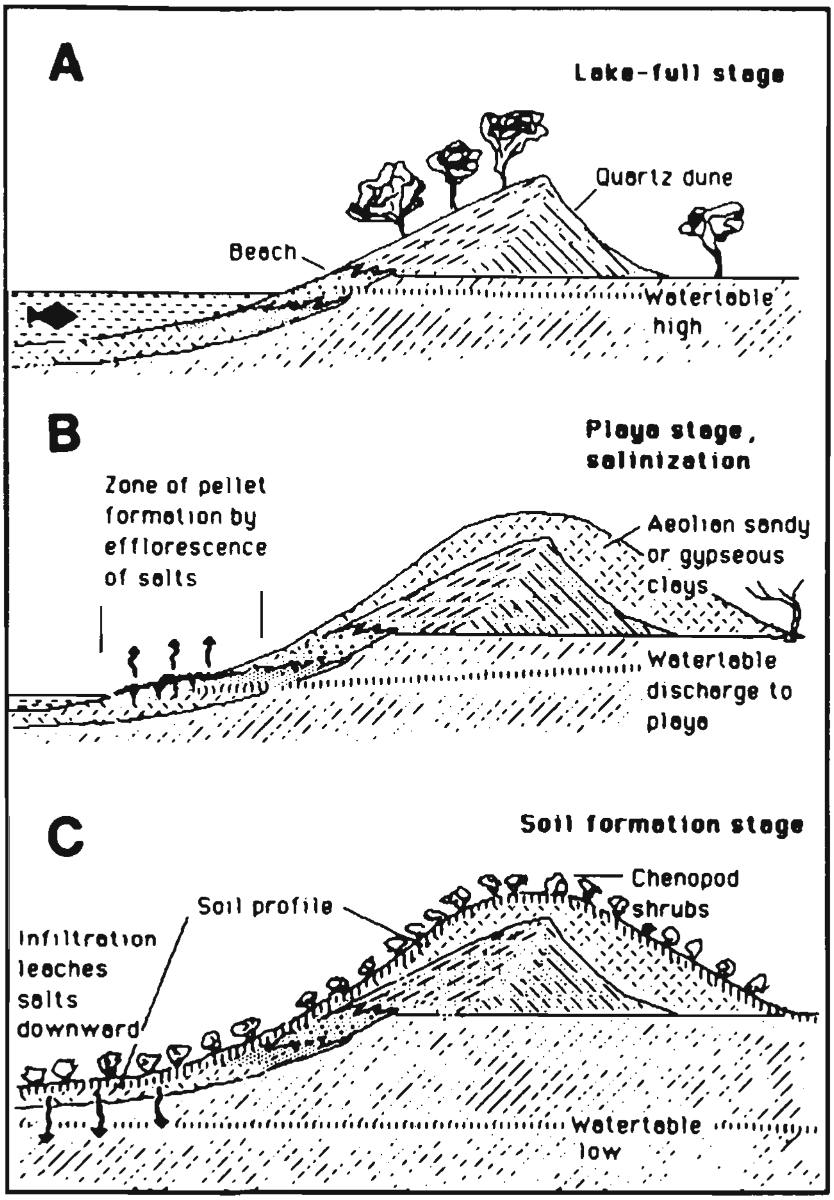


Fig. 3.2. Bowler's (1986a) model of lunette formation for lakes in southeastern Australia.

A Quartz foredune high water phase.

B Drying phase of oscillating saline waters and clay pellet dune formation.

C Stable phase of deep groundwater and soil formation on dune.

Water levels at Lake Mungo rose again by 32 ka* and remained comparatively high until about 25 ka* when another major oscillation heralded the final drying trend which culminated in the deposition of the thick Zanci clay pellet dunes between 18 and 16 ka*. Additional radiocarbon dates for lunettes at Lakes Albacutya, Tyrrell, Frome and Victoria, and even in southwestern Western Australia, point to the synchronous and large scale development of clay and gypseous clay dunes at this time (Bowler, 1983). Aridity at the Last Glacial Maximum (LGM) is also supported by extensive activation of Australia's continental dunes at this time (Wasson,1989). Apart from a brief return of water to the upper lakes at 15 ka* the Willandra Lakes have subsequently remained dry with groundwater tables well below the surface.

The lunette deposits of Lake Mungo and other Murray basin lakes have yielded some of the best preserved evidence of the early human occupation of southern Australia. In the Lake Mungo lunette, Bowler et al. (1970;1972) and Thorne (1971) discovered human remains including a cremated woman at a site dated at 26 ka*, and a man at a site dated at 30 ka*. The oldest occupation sites dated are at least 32 ka* and human habitation probably extends back to at least 40 ka* (Mulvaney and Golson, 1971). The lunettes have also preserved the remains of the marsupial fauna of the time, aboriginal hearths, stone artifacts and the discarded remains of charred mussel shells and fish bones.

CHAPTER 4

THERMOLUMINESCENCE DATING

GENERAL PRINCIPLES

A major aim of the present study was to establish an absolute chronology of Late Quaternary sedimentation on the Riverine Plain. By the 1960s it had become apparent that many of the large palaeochannel systems on the Plain had become defunct before the period that can be successfully dated by radiocarbon (Pels, 1964a; 1969). Even where charcoal and wood fragments from younger systems postdating the Cadell Fault were dated by Bowler (1978) doubt remained about possible contamination of samples by percolating groundwater.

Daniels et al. (1953) first proposed that thermoluminescence (TL) could be used to date fired archaeological materials. The technique has recently been extended with considerable success to other types of sample that enable it to reach back well beyond the limit of radiocarbon (Aitken, 1990). Following successful application to burnt flint and stalagmite calcite, Shelkoplyas and Morozov in 1965 (Forman, 1989) recognised that it was possible to also date certain wind and water borne sediments. This latter development has been of particular importance to studies of the Late Quaternary where TL is beginning to challenge radiocarbon as the most popular method of dating terrestrial deposits. Recent comparisons with corroborative dating methods (Readhead,1984, 1988; Short et al., 1989; Shepherd and Price, 1990; Roberts et al., 1990) support the accuracy of the TL dating methods outlined below.

Sedimentary TL dating is based upon the acquisition of TL energy by crystalline minerals buried within a sedimentary unit. The method requires that, during transport and before burial, most of the previously accumulated TL energy is removed by exposure to the ultraviolet component of solar radiation. Following burial the TL energy once again builds up as a result of the cumulative effect of prolonged exposure to the weak flux of nuclear radiation emitted by long-lived isotopes of uranium, thorium and potassium in the surrounding sediment and from cosmic radiation. Flux from rubidium plays a lesser but contributary role. Exposure of crystalline minerals to radiation produces free, or 'ionised', electrons by detaching them from their

parent nuclei. These electrons may become trapped within defects (lattice-charge disequilibrium sites) called electron traps in the crystalline lattice of ions (Aitken, 1990). Over periods of thousands of years the number of traps remains constant but the number of electrons in them increases with time. Once in a trap an electron remains there until being released by the vibrations of the crystal lattice. As the temperature is raised these vibrations get stronger, and the probability of eviction increases so rapidly that within a narrow temperature range the situation changes from that of the electrons being firmly trapped to that of being free to diffuse about the crystal. Exposure of sediments to light also causes vibration of the mineral lattice and eviction of electrons from traps. Some of the released electrons may be conducted to luminescence centres (defects in the crystal lattice usually due to impurities such as silver or manganese atoms) causing photons to be emitted as light. In most TL dating procedures the ultraviolet (UV) or blue regions of the emitted light are selected for analysis.

The time period since the last exposure to sunlight is determined by the total amount of TL energy absorbed since deposition [the palaeodose, P], and the rate at which the energy was acquired [the annual dose, AD].

TL Age = P/AD

TL METHODOLOGY

All TL dating in the present study was carried out by David Price in the TL Dating Laboratory at the University of Wollongong. The method used is essentially the combined regenerative additive quartz coarse-grain technique as modified by Readhead (1985), described by Nanson et al. (1991) and summarised in the following sections.

Palaeodose evaluation

The 90 to 125 μm quartz fraction of each sample was separated by sieving and then cleansed in HCl to remove carbonates and etched in HF to remove oxidised grain coatings and the outer layer of diffused silica. This etching also removes most of the TL produced by short-range alpha particle radiation. Subsequent heavy liquid separation produced a >99 per cent pure quartz sample that was divided into two portions. The first was bleached

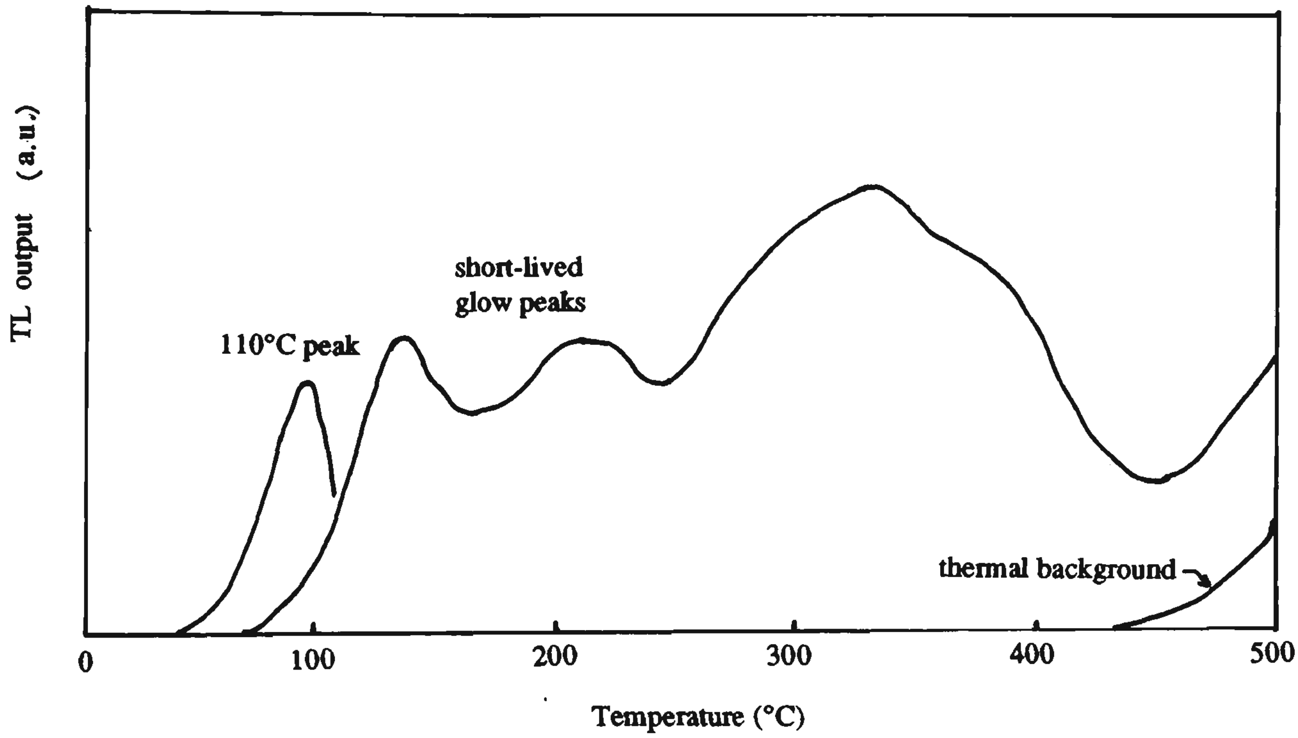
under a Philips MLU300 UV lamp for at least 24 hours to reduce stored TL to a minimum. Aliquots of this material were deposited as a monolayer onto 14 aluminium discs which were incrementally and serially irradiated to different levels using a calibrated ^{90}Sr plaque source. These discs were stored for a minimum of 12 hours and then heated to a temperature of 500°C at 5°C/sec in a high purity nitrogen atmosphere. The TL output emitted during heating was detected by an E.M.I. 9635QB photomultiplier tube fitted with a Chance Pilkington heat filter and a Corning 7-57 blue transmitting filter. Photon counting was achieved with Ortec NIM modules. The laboratory-induced TL levels were recorded as glow curves showing the relationship between TL output and temperature (Fig. 4.1a).

Eight sample aliquots consisting of treated unbleached quartz were glowed out as described above, resulting in a series of natural TL glowcurves (Fig.4.1b). The TL output of all aliquots was normalised using a second glow procedure in order to correct for any disc to disc variation. From this series of natural glowcurves mean TL levels were established at 25°C intervals. These values were compared with that exhibited by a pair of bleached laboratory irradiated samples selected to give a TL ratio of about unity. If the natural and the regenerated TL glow curves are the same shape, then the ratio of one to the other is constant and can be plotted as a temperature plateau region which is indicative of electron trap stability. In practice this was found to lie between 300°C and 500°C (Fig. 4.2a) with prominent glow peaks occurring at 325°C, 375°C and 480°C (Spooner et al., 1988). An analysis temperature of 375°C was most commonly used in the Wollongong Laboratory. This stable glow peak is usually the dominant one in the plateau region and provides the most reliable measurements of TL output. However, it is not always the most prominent peak as demonstrated by sample W751 whose maximum TL output occurred in the 325°C region (Fig. 4.1b). In the final TL computation it can be demonstrated that the sample palaeodose, and consequently the specimen age, follows this plateau characteristic (Nanson et al., 1991). Therefore, if the ratio of the natural TL to the laboratory-induced TL remains constant the TL age will also remain constant. The TL age uncertainty level may be reduced by taking the group mean of the TL ages determined across the temperature plateau.

Following establishment of an analysis temperature as above, a TL growth curve was prepared from the discs irradiated in the laboratory (Fig. 4.2b).

This related TL and radiation dose, generally in the form of a second or third order polynomial. The mean value of the TL output as measured from the discs containing unirradiated and unbleached material was fitted to the TL growth curve at the analysis temperature and the equivalent radiation dose (ED_N) received by the specimen was determined. The TL outputs measured from a series of natural TL plus beta irradiated discs were plotted on the TL growth curve with reference to the mean N value only. If there has been no change in TL sensitivity due to the different bleaching methods (sunlight and UV lamp) of the two portions of the sample, these values should coincide with the growth curve constructed using laboratory bleached and irradiated sample material. In this case an ED_N value computed from the N and $N + \beta$ should agree with that computed from the fitting of N to the regenerated TL growth curve (Fig. 4.2b). Essentially this is a combination of both the regenerative and the additive TL test methods (Aitken, 1985). In the age determinations on Riverine Plain samples the errors in the palaeodose computed using the N and $N + \beta$ data encompassed the palaeodose value determined from the regenerative growth curve. Therefore, no detectable TL sensitivity change was detected.

In general, it is desirable to estimate the starting point or surface residual TL at the time of burial by comparing the palaeodose with that contained in a specimen collected from immediately below the surface of the present day surface in a similar type of deposit that was recently implaced. Because aeolian and wave deposited sediments are usually well-bleached by light exposure (Wintle, 1982; Nanson et al., 1992b) lunette shoreline sediment assemblages in inland Australia are particularly well-suited to TL dating. However, water deposited sediments are considered to possess a higher residual signal because water attenuates UV and also because turbidity shifts the penetrating spectrum to the blue-green region (Forman, 1989). Although this cautions against the use of TL dating for fluvial deposits a recent systematic study of residual TL by Nanson et al. (1991) in modern near-surface samples on the Gilbert fan delta in northern Queensland showed that sands in muddy floodplain and shallow channel sediments were very thoroughly bleached. Given that the 375°C peak is only bleached by wavelengths less than 400 nm (UV) it follows that these sediments must be exposed at the surface periodically during transport before final incorporation into the deposit.



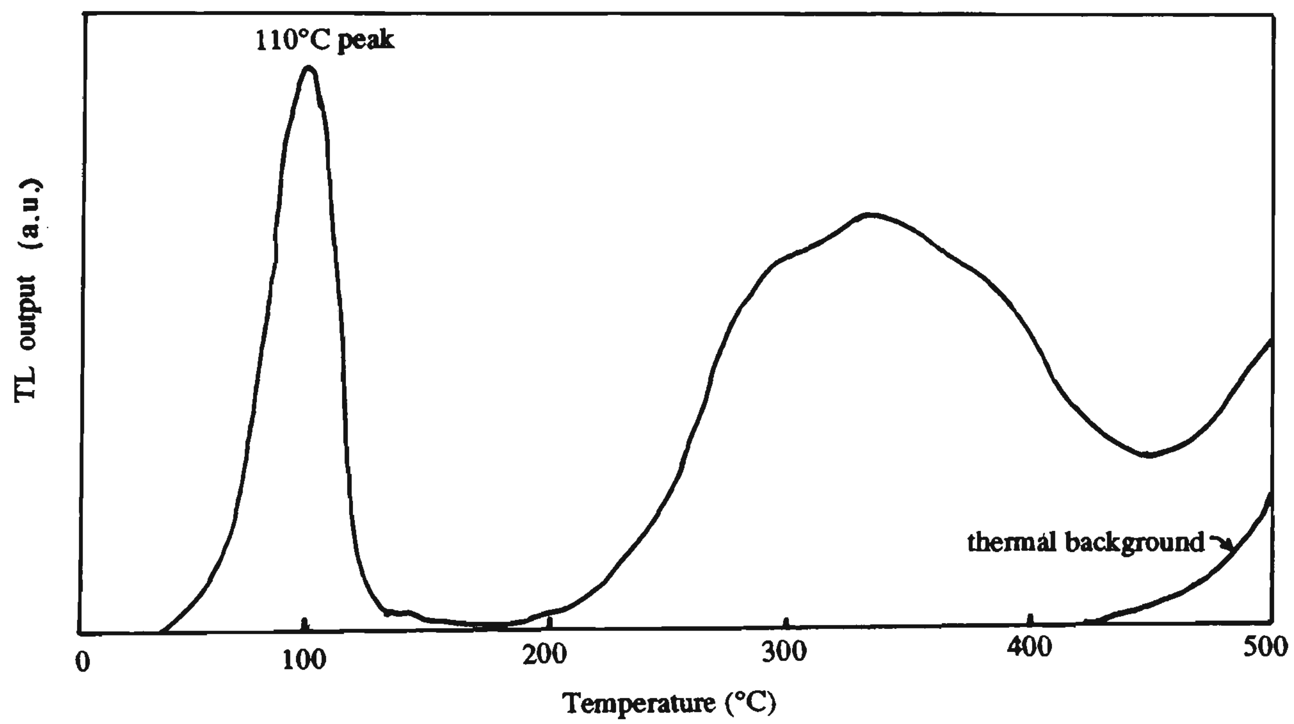
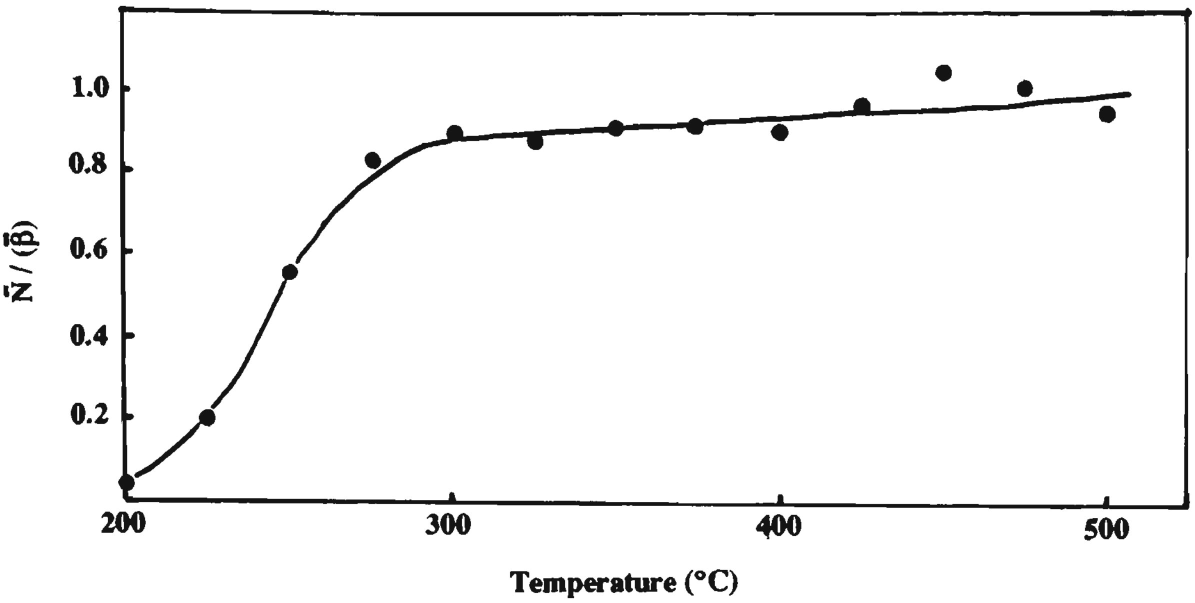


Fig. 4.1. Top: Regenerated TL glow curve for a laboratory bleached subsample of W751 irradiated to a level of 112.0 Grays. Bottom: Natural TL glow curve for Riverine Plain palaeochannel sample W751 showing TL output and temperature.



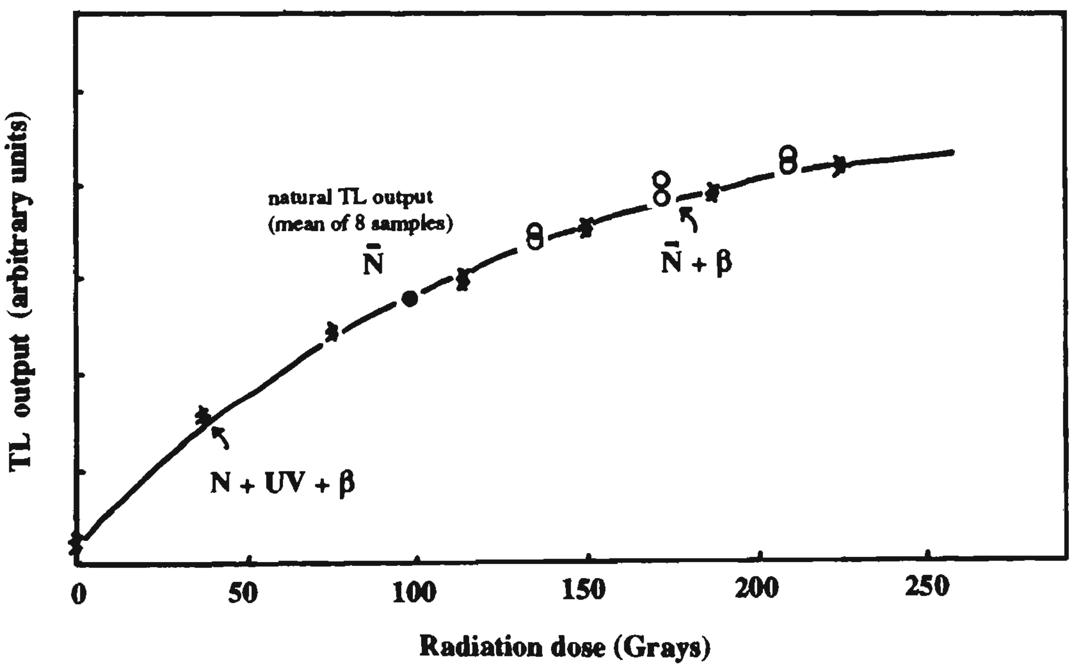


Fig. 4.2. Top: Plateau comparison showing showing relationship between natural and regenerated TL output with temperature for palaeochannel sample W751. Bottom: TL growth curve at 375°C for palaeochannel sample W751.

In the absence of any suitable modern Riverine Plain channel analogues, the palaeochannels dates in the present study were not corrected for residual TL. Almost all of the samples dated were collected from cross and trough sand beds indicative of the migration of small dunes (< 25 cm amplitude) in shallow water (Leeder, 1982). These sedimentary environments are considered similar to those in the shallow Gilbert River channels where bed sediments are often exposed during periods of low flow and where sediments are deposited and reworked many times before final deposition. Evidence of periodic exposure of Riverine Plain palaeochannel beds is provided by the common occurrence of aeolian sand dunes at the channel margins.

Annual dose evaluation

The radiation dose which accumulates TL within the quartz grains is derived from radioactive elements within the sample and from a sphere of 30 cm radius around it. Therefore it is desirable to sample from a homogeneous layer with no dissimilar material within a 30 cm radius. In sampling from the quartz sand palaeochannels and marginal dunes of the Riverine Plain this criterion was readily met. All samples were collected either from freshly exposed pit faces using metal tubing or from auger holes that were extended at least 30 cm beyond sample depth to detect possible inhomogeneities. Each sample was immediately sealed to preserve the environmental moisture content and avoid exposure to light. In the Lake Urana lunette some sampling difficulties were encountered in the older clay-rich units which included thin alternate sand and clay loam laminae. Dose rate estimates here in these somewhat variable deposits are probably less reliable than those determined in other deposits on the Riverine Plain.

Annual dose rate and field moisture content were measured in the laboratory. The K content was determined by means of XRF and AES and the Rb levels assigned. Combined U and Th activity levels were determined by calibrated thick source alpha counting assuming secular equilibrium in the U and Th decay chains. Independent laboratory checks suggested that the decay chains were within acceptable limits of experimental error and therefore close to equilibrium. Comparisons of thick source alpha counting with gamma spectroscopy assessment of dose rates indicate slightly younger dates (mean difference of 5 per cent) by alpha counting. This discrepancy is well

documented but not yet understood (Nanson et al., 1991). The cosmic ray contribution to AD was assumed to be 150 ± 50 μGy/yr.

Errors

TL dates express statistical and experimental uncertainties to one standard deviation and include estimates of environmental uncertainties that result from variations in dosimetry and moisture. The latter occurs in the sediment interstices and is a source of error because of its ability to absorb part of the radiation that would otherwise reach the mineral grains and build TL. If this effect is ignored there can be an appreciable underestimate of the sample age. Nott and Price (1991) showed that each 1 per cent error in moisture content produced approximately a 1 per cent age error. Therefore, a TL date based on zero moisture content might underestimate the age by about 20 per cent which is approximately the maximum water content (by weight) of a saturated quartz sand (Duff, 1993). For this reason environmental moisture content is measured in the laboratory and factored into the dose rate estimate. Of course, there can be no guarantee that moisture content has not varied over time. As long as the sample does not lie close to the water table and therefore fluctuate wildly in moisture content over time the error from moisture variation is not expected to exceed ± 5 per cent. In terms of moisture content sand dunes probably exhibit the least variation because of their superior drainage compared to river sands.

It should be noted that errors given for TL dates are much greater than those usually given for radiocarbon because they attempt to address the total experimental, environmental and statistical uncertainty assigned to each TL parameter, not just the statistical counting uncertainty assigned to radiocarbon dates.

Although TL is considered to be a reliable and accurate method of dating terrestrial sediments, it is not a high precision method for most of the dating range (Aitken, 1990). In most cases the error at one standard deviation is approximately 10 per cent. For dates of 50 ka, for example, the typical error of ± 5 ka means that we can place the date with reasonable confidence in a 10 ka age bracket. In a series of dates on a given formation ranging from, for example, 50 to 40 ka, it is invalid to attempt to use individual dates to

elucidate the details of events within that time period. Statistically, the dates cannot be differentiated.

COMPARISONS OF TL AND OTHER DATING METHODS

Although agreement with radiocarbon dates is often sought to validate TL, it is well documented that radiocarbon years are not equivalent to calendar years because of changes in the atmospheric $^{14}C/^{12}C$ reference level. Dendrochronological studies and U/Th dating of corals show that radiocarbon ages consistently underestimate calendar years over the past 30 ka with a maximum difference of about 3.5 ka at about 20 ka (Bard et al., 1990). Other studies based on variations in Earth's magnetic field suggest that radiocarbon ages of around 40 ka may underestimate calendar ages by between 4 and 5 ka (Barbetti, 1980; Barbetti and Flude, 1979). In this dissertation calendar years (which are assumed to correspond to U/Th and TL years) are reported as ka. Radiocarbon ages are reported as ka*.

Apart from the calibrated difference between radiocarbon and TL ages to 30 ka, other factors such as the method of AD assessment (alpha counting or gamma spectrometry) and the magnitude of the residual signal, make it difficult to correlate ages precisely by the two methods. Recent evidence supporting the veracity of TL includes comparisons with corroborative dating methods including U/Th, duplicate dating and the high degree of stratigraphic consistency of TL dates in a range of fluvial and aeolian settings (Readhead, 1988; Nanson et al., 1991; Nanson et al., 1992a; Nott and Price, 1991; Page et al., 1991).

CHECKS ON TL DATING OF RIVERINE PLAIN SEDIMENTS

Additional checks on the accuracy of fluvial TL dates were provided by the dating of marginal sand dunes produced by deflation from exposed river beds and comparisons with radiocarbon dates on Murray Basin palaeochannels that were active after about 20 ka. In the latter, problems of contamination by modern ^{14}C are generally much less severe than those associated with samples older than 30 ka and therefore approaching the radiocarbon dating limit (Polach, 1975). Another check on TL dates is provided by U/Th dating of indurated pedogenic pisoliths that have developed within the host deposit after deposition. In the Gilbert fan delta Nanson et al. (1991) compared U/Th

dates on secondary minerals such as calcite and iron oxide with TL dates from the host sediments and found that 12 paired dates lay within the range of acceptable values where the secondary minerals are younger than the host deposit except for two samples. In the present study U/Th dates were determined on carbonate pisoliths in soils overlying palaeochannel deposits of varying age.

An additional check on TL dates on fluvial sediments was provided by assessment of the TL output plateau in the region of the 325°C glow peak. Although this peak is less stable than the 375°C peak and somewhat affected by adjacent peaks in the low temperature region, it is very readily bleached by UV depleted natural sunlight such as that encountered when sedimentation occurs under water and is thus considered more reliable for dating certain fluvial sediments (Spooner et al., 1988). The correspondence of dates from the 325°C and 375°C plateau regions would provide support for the effective bleaching of the 375°C peak.

Evidence for the veracity of TL dating methods used here is presented in Chapter 6 along with results obtained from dating fluvial and aeolian sediments.

URANIUM-THORIUM DATING

Uranium-thorium dating was used in the present study to determine the age of pedogenic carbonate pisoliths in soil horizons overlying coarse sandy channel infills at three sites of widely varying palaeochannel ages. The dating was carried out by S.A. Short at the Australian Nuclear Science and Technology Organisation, Sydney.

In simple terms (see Nanson et al., 1991 for a fuller account), this method is dependent upon the very high solubility of Uranium (^{234}U) in oxidising groundwater and the very low solubility of Thorium (^{230}Th). Uranium occurs principally as carbonate and phosphate complexes of the uranyl ion (UO_2^{2+}) which may be precipitated with secondary minerals such as calcite in the form of dense pisoliths. If these pisoliths then form closed systems with respect to further uptake and leaching of uranium, they may be dated by means of measuring ingrowth of ^{230}Th which is the daughter isotope of ^{234}U.

The ingrowth technique employed in this study is essentially the pseudo-isochron method of Rosholt (1976) and Szabo and Sterr (1978) but includes a correction for the detrital (nonradiogenic) component of ^{230}Th (Ku and Liang, 1984). This technique has already been used with some success on impure carbonates in arid and semi-arid regions similar to the Riverine Plain (Ku et al., 1979; Szabo et al., 1981; Szabo and O'Malley, 1985).

Pedogenic carbonate samples collected on the Riverine Plain were hard dense pisoliths of the type favoured by Ku et al. (1979) being visually non porous and showing no signs of spalling. Because the pisoliths occurred in soil units overlying clean quartz river sands it is highly probable that the carbonate was derived from a non riverine source. Aeolian dust accession from the west (Butler, 1956; Dare-Edwards, in preparation), rather than groundwater concentration appeared to be the most likely source in these slightly elevated, well-drained locations. Clearly, it was anticipated that the U/Th dates on the carbonate pisoliths would post date both the underlying fluvial sands and the period of aeolian accession. If the last period of pisolith formation occurred sychronously over the Riverine Plain then this would be a strong circumstantial indication of a preceding synchronous phase of aeolian accession.

CHAPTER 5

PALAEOCHANNELS OF THE CADELL FAULT REGION

INTRODUCTION

In the southern region of the Riverine Plain, near Echuca, the Murray River swings sharply south along a fault line and is joined by its major south bank tributary, the Goulburn, on the floor of the large circular Kanyapella Depression (Fig. 5.1). The Late Quaternary evolution of rivers and associated landforms in this area was studied in considerable detail during the 1960s by Pels (1964b, 1966, 1969, 1971), Bowler and Harford (1966) and Bowler (1967, 1978). The majority of radiocarbon dates on Riverine Plain fluvial deposits were carried out on samples collected during this work.

An important feature in the region of the Murray-Goulburn confluence was the Late Quaternary disruption of stream courses by tectonic movements along the north-south oriented Cadell Fault between Deniliquin and Echuca (Fig. 5.1). Pels (1964b) used the fault to separate three episodes of ancestral river activity. Initially, the ancestral Murray and Goulburn flowed across the Cadell Block along the paths of the well-preserved Green Gully and Goulburn tributary channels. This was Pels' (1964b) Coonambidgal 1 phase.

Following faulting and uplift of land to the west, the ancestral Murray was diverted north through the present site of Deniliquin. The Goulburn was dammed and produced a large lake (Kanyapella) with an associated beach and lunette sand dune along its northeastern shoreline. Finely laminated silts on the floor of the lake also attest its existence (Bowler, 1978). The lake subsequently drained, presumably as the result of incision at its overflow point, and the Goulburn maintained a course south of the Cadell Block through the present site of Echuca. Only in comparatively recent times did the Murray divert to the south and establish its present course through a low point in the Barmah Sandhills and across the floor of the Kanyapella Depression (Bowler, 1978). Pels (1964b) found that the post-faulting drainage could be subdivided into separate Coonambidgal 2 and 3 phases on the basis of minor course changes and such features as the presence or absence of source-bordering sand dunes and scroll-

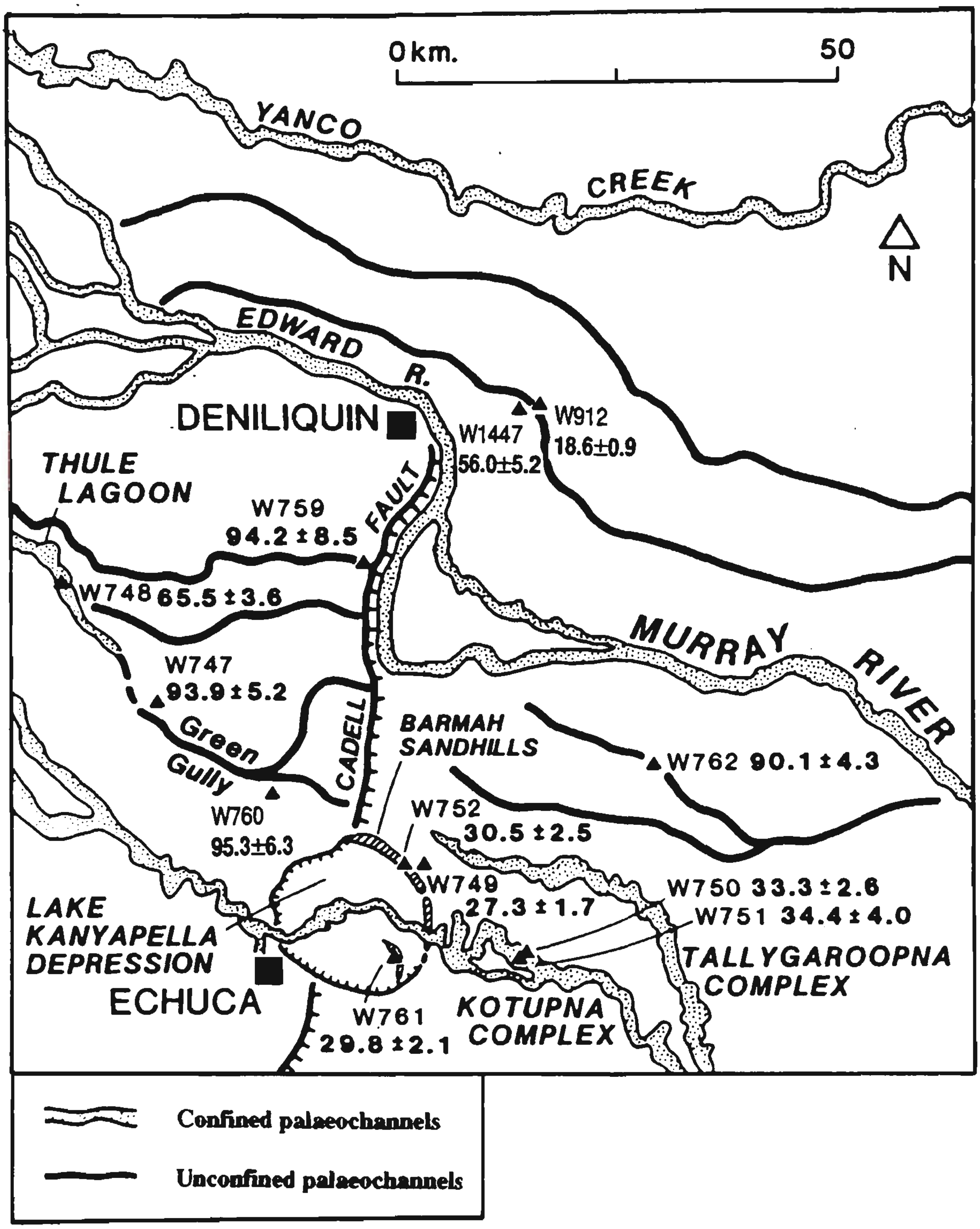


Fig. 5.1. TL dating sites on the Murray-Goulburn confluence region of the Riverine Plain. Note Cadell Fault and Kanyapella Depression. Terms confined and unconfined palaeochannels from Butler et al., 1973.

patterned floodplains. Pels (1969) believed that the Coonambidgal phases were cyclical, each controlled by climatic change with incision during humid episodes and aggradation during arid episodes. Large channel remnants of the Coonambidgal 1 and 2 phases suggest that channel forming discharges were considerably in excess of those associated with the present rivers (Fig. 5.2).

Pels (1964a) established that even the youngest prior streams to the north of the Murrumbidgee River were beyond the range of radiocarbon dating, as were the channel infills of the first ancestral system (Coonambidgal 1) on the Cadell Block (Pels, 1969). However, the sediments of the Murray deposited after its diversion northwards around the Block (Coonambidgal 2) yielded an age of approximately 24 ka* (radiocarbon years) and accordingly Pels (1969) suggested an age of around 30 ka* for movement along the Cadell axis.

Bowler (1967, 1978) also worked on the tectonically disturbed palaeochannels of the southern region of the Plain, concentrating on the Goulburn System. He confirmed the existence of large sinuous channels and associated floodplains of lateral accretion in the period straddling faulting but was not able to support Pels' (1969) model of cyclical incision and aggradation. Although Bowler (1978) was reluctant to put a precise figure on the magnitude of the ancient channel forming discharges, he considered that the Murray and Goulburn palaeochannels and their deposits provided evidence of a greatly increased discharge of both water and coarse bedload sediment throughout the region. He radiocarbon dated this phase as extending from before 30 ka* until ~13 ka*, coinciding with the period enclosing the climax of the last glaciation.

Mindful of inconsistencies between Pels' (1964b) use of the term Coonambidgal and Butler's (1958) definition, Bowler (1978) proposed local geographic names such as Tallygaroopna (Coonambidgal 1) and Kotupna (Coonambidgal 2) to identify the different phases of stream activity in the lower Goulburn Valley. More importantly, Bowler (1978) also questioned the classification of ancient channels into two exclusive types. He noted that both prior and ancestral attributes sometimes occur in different reaches of the same channel, as for example, along Green Gully on the Cadell Block. In addition, he noted that the ancestral channels carried appreciable quantities of sand and gravel and in this respect resembled prior streams. On the Cadell Block the ancestral channel

Fig. 5.2. Air photographs of Green Gully Thule Lagoon Reach (top) and modern Murray River (bottom) at same drainage area and scale.

deposits were also mantled by well-developed red-brown earth soil profiles with abundant pisolitic carbonate in the sub-soil. In the face of these typical prior stream characters, Bowler (1978) concluded that Pels' (1971) separation of ancestral stream activity into a genetically different category from that of the supposedly earlier prior streams was unwarrented.

Although Bowler's (1967) radiocarbon dates for pre- and post- diversion channels of the Goulburn agreed in broad terms with those of Pels (1969), some important differences were apparent. Bowler's pre-diversion (Tallygaroopna) fluvial sediments were younger, falling within the range of radiocarbon with four dates ranging from about 30 to 20 ka*. The first episode of diverted channels (Kotupna) persisted until about 13 ka* and the onset of the modern discharge and sediment regime was considered to have taken place thereafter. All five dates on post-Kotupna age channels yielded ages of less than 10 ka*. Taken at face value, Bowler's (1967) dates place the time of faulting at around 20 ka* and clearly place the Tallygaroopna phase within the range of radiocarbon dating. Bowler (1978) does, however, stress the special contamination risks associated with sand and gravel deposits which provide aquifers for groundwaters bearing organic compounds and he cautions against the acceptance of his 1967 radiocarbon dates as indicating anything more than estimates of minimum age.

TL DATING OF SOUTHERN PALAEOCHANNELS

In the face of an obvious need to resolve questions about the chronology and nomenclature of palaeochannels on the Riverine Plain, TL dating was initially concentrated in the southern region of the Plain in the vicinity of the Cadell Fault (Page et al., 1991). Here, the potential existed both for direct comparison of radiocarbon dates with those determined by TL and also the extension of the dating period well beyond 30 ka.

Samples were collected at existing sand and gravel quarries from fluvial deposits pre-dating the fault and from fluvial and aeolian deposits of the post-faulting Kotupna system. Most of the samples were collected in metal tubes from fresh pit faces where sediment homogeneity could be readily assessed visually although a few were carefully obtained by augering beneath the surface.

Table 5.1. TL dates and technical data - Murray Sector of Riverine Plain.

Sample Number	Section and Formation	Temp Plateau Region (°C)	Anal. Temp (° C)	Palaeo-dose (Grays)	K Cont. (%)	Moisture Content (% by wt)	U + TH Specific Activity (Bq/kg)	Annual Radiation Dose (µ Grays)	TL Age (ka)
W747	Green Gully Terrace	275-500	375	203±9	1.43	1.5	24.1±4	2163±76	93.9±5.2
W759	Cadell Block Palaeochannel	300-500	375	293±26	2.17	7.7	43.1±4	3115±71	94.2±8.5
W760	Green Gully-Goulburn Trib	275-500	375	241±19	1.65	0.5	24.0±4	2424±77	95.3±6.3
W762	Strathmerton Palaeochannel	325-500	375	211±7	1.58	1.2	24.4±4	2338±76	90.1±4.3
W748	Green Gully Point Bar	300-500	375	190±9	1.93	1.6	35.4±4	2921±76	65.1±3.6
W1447	Moonie Rd Pit Palaeochannel	275-500	375	160±14	1.6	3.5	52.1±4	2848±74	56.0±5.2
W749	Barmah Sandhills	275-500	375	62.8±3.3	1.16	4.3	49.0±4	2300±74	27.3±1.7
W761	Little Kanyapella Lunette	300-500	375	77.4±5.0	1.48	1.2	42.5±4	2596±76	29.8±2.1
W752	Barmah Sandhills	275-500	375	77.8±5.4	1.37	2.5	47.9±4	2548±75	30.5±2.3
W750	Kotupna Dune	275-500	375	97.6±7.2	1.60	2.3	55.3±4	2945±75	33.1±2.6
W751	McCoy Pit Kotupna Channel	275-500	375	96.9±11.	1.79	2.7	39.3±4	2819±75	34.4±4.0
W910	Deniliquin Dune	275-500	375	67.4±2.8	3.48	2.3	36.3±4	4544±75	14.8±0.7
W912	Moonie Rd Dune	300-500	375	86.8±4.1	3.12	5.3	69.8±4	4679±73	18.6±0.9

Notes:

1. Assumed rubidium levels (100 ppm), potassium content by AES and XRF.
2. Annual radiation values indicated assume a cosmic contribution of 150 µGy/yr.
3. U and Th specific activity levels were determined by calibrated thick source alpha counting and assume secular equilibrium.
4. Uncertainty values shown represent one standard deviation.

Subsequent dating of sediments from the Murrumbidgee sector of the Plain permitted regional correlation of palaeochannel chronologies. Table 5.1 provides ages of 13 dated samples from the Cadell Fault region and includes supporting technical data for estimated dose rates and equivalent total doses. Site locations and details are given in Figure 5.1 and Appendix 1.

The TL results reveal a consistent pattern of ages for the pre- and post-diversion channels. Pels' (1969) conclusion that prior stream deposits lie wholly within the Late Pleistocene and beyond the then limits of radiocarbon technology is supported by the TL results. To the east and north of the Cadell Fault and on the Cadell Block itself, dates on channels identified as being of prior stream type ranged in age from 56.0 ± 5.2 ka (W1447) to 94.2 ± 8.2 ka (W759). These ages broadly agree with dates subsequently found on the Murrumbidgee system to the north (Page et al., 1991).

TL determinations on sediments associated with Pels' (1964b) first phase of ancestral stream activity were of unexpected antiquity. Coarse sandy cross-beds underlying terraces adjacent to Green Gully have prior stream characteristics and yielded ages of 93.9 ± 5.2 ka (W747) and 95.3 ± 6.3 ka (W760), indistinguishable from ages of prior streams elsewhere. In the Thule Lagoon reach of Green Gully (Fig. 5.2), which has the ancestral stream characteristic of high sinuosity, the upper surface of a point bar dated at 65.5 ± 3.6 ka (W748). If this channel was abandoned due to movement along the Cadell Fault, then it appears that initial drainage disruption occurred at ~60 ka. A date of 56.0 ± 5.2 ka (W1447) on a large dune-bordered and apparently fault affected channel to the east of Deniliquin (Fig. 5.1) is also consistent with an earlier than previously thought onset of tectonic movement in this area. Bowler's (1978) radiocarbon dates of between 30 ka* and 20 ka* for Tallygaroopna deposits east of the fault, but apparently contiguous with those of Green Gully, are not supported by the TL evidence presented here. This is consistent with Pels' (1969) evidence that Green Gully was beyond the reach of radiocarbon technology. The terraces of Green Gully and the Goulburn Tributary were apparently active simultaneously with a number of major Murray and Murrumbidgee prior streams (Chapter 6). The large ancestral-type meanders and cutoffs that occupy the downstream part of the Green Gully trench are of limited extent and appear to have ceased their activity by 60 ka. The prior and

ancestral characteristics exhibited by different reaches of Green Gully call into question the usefulness of this morphological distinction, particularly in the vicinity of the Cadell Fault where tectonism may have affected channel planform.

At McCoy Pit fluvial sands of the Kotupna Complex (Bowler, 1978) dated at 34.4 ± 4.0 ka (W751). Fine well-bedded sands from deep within a source bordering dune a short distance to the north (Fig. 5.1) and clearly derived from the Kotupna alluvium, yielded an age of 33.3 ± 2.6 ka (W750). Three lunette dates associated with fault-dammed Lake Kanyapella yielded statistically indistinguishable ages of between 27.3 ± 1.7 ka (W749) and 30.5 ± 2.5 ka (W752). A date of 29.8 ± 2.1 ka (W761) for the inner lunette suggests that the lake was relatively short-lived. The temporary nature of the lake is further indicated by lacustrine deposits, supplied by the entire load of the Goulburn River, of generally less than 0.3 m over most of the lake floor. It seems clear that Lake Kanyapella formed about 30 ka, well after the period of initial tectonism and that the drainage disruption that caused the abandonment of Green Gully occurred by about 60 ka. TL dates on the Kotupna channels that fed Lake Kanyapella greatly exceed the radiocarbon ages reported by Bowler (1978) and confirm his suspicion of sample contamination with younger carbon. However, the TL dates do not indicate the termination age of the Kotupna system. Following the drainage of Lake Kanyapella the Kotupna system formed a new floodplain of lateral accretion up to 1 km wide across the exposed lake floor before the transition to present channel and floodplain morphology occurred. These Kotupna deposits clearly post-date 30 ka but have not yet been TL dated. Bowler's (1978) radiocarbon date of 13 ka* on charcoal remains of an *in situ* fire in fine sands and silts remains the only date currently available. Bowler (pers. comm., 1993) considers that this sample was free of gross contamination and of high reliability compared to, for example, his radiocarbon sample at McCoy Pit.

CONCLUSION

TL dating of the southern region of the Riverine Plain has provided a stratigraphically consistent set of ages on a sequence of palaeochannels associated with the Cadell Fault. For the first time, the great antiquity of the early channels has now been demonstrated and ages assigned to both the pre- and post- faulting phases of fluvial and lacustrine activity. However, movement of the

Cadell Fault has both clarified and obscured the nature of fluvial change along the Murray River (Schumm, 1968). Preservation of Green Gully has been of value in geographically separating different phases of channel activity, but the disruption of the drainage system upstream of the fault confuses the interpretation of climatic riverine response because of undoubted tectonic adjustment in the system. Pels' (1971) model of an early phase of prior streams followed by ancestral streams of markedly different character is clearly in need of revision.

To gain further insight into the evolution of palaeochannel systems on the Riverine Plain it was decided to concentrate sampling and stratigraphic work on the Murrumbidgee sector of the Plain where the sequence of channel development has not been significantly affected by tectonic disruption. Here undated palaeochannels occur both as continuous reaches on the surface of the Plain and also as remnants preserved along the margins of the modern, slightly incised, floodplains.

CHAPTER 6

THERMOLUMINESCENCE CHRONOLOGY OF MURRUMBIDGEE PALAEOCHANNELS

INTRODUCTION

The first clear evidence of the antiquity of the surface palaeochannels on the Riverine Plain was provided by TL dating in the Murray - Goulburn confluence region near the Cadell Fault (Page et al., 1991). This work, which is summarised in the previous chapter, showed a major fluvial episode before about 80 ka and also revealed that the Green Gully ancestral system was significantly older than some of the prior streams mapped on the Murrumbidgee sector of the Plain. The TL dates in this study strongly vindicated Bowler's (1978) reluctance to wholeheartedly endorse Pels' (1971) model of channel evolution and pointed to the need to develop a new stratigraphic model for the Riverine Plain freed from the rigid distinction between prior and ancestral streams.

Palaeohydrologic interpretation of the TL dates on the Murray - Goulburn channels is complicated by the role of movement along the Cadell Fault. In an attempt to unravel the relationship between channel behaviour and hydrologic regime in a less complex environment a program of stratigraphic investigation and dating was carried out on the tectonically stable Murrumbidgee sector of the Plain (Schumm, 1968; Page et al., 1991). The principal objectives of this program were as follow:

1. To map the major Murrumbidgee palaeochannel systems and establish their sequential development at channel intersections.

2. To TL date the major phases of palaeochannel activity.

3. To investigate the channel and floodplain stratigraphy of the palaeochannels by means of fieldwork at existing exposures (chiefly roadside pits), augering and an examination of NSW Department of Water Resources bore log records.

4 To construct a new sedimentological and hydrological model of palaeochannel activity on the Riverine Plain consistent with the TL chronology, observed stratigraphy and the emerging broad pattern of Australian and global climatic change since the last interglacial at 125 ka (Chappell and Shackleton, 1986; Nanson et al.,1992a; Kershaw and Nanson, 1993).

The present chapter considers the first two objectives. The third objective is treated in Chapter 7 and the fourth in Chapter 8.

PALAEOCHANNEL SYSTEMS OF THE MURRUMBIDGEE

Existing maps of the palaeochannels

During the early period of research on the Riverine Plain maps showing the locations of Murrumbidgee palaeochannels were produced by Langford-Smith (1958), Pels (1964a; 1964b), Pels et al. (1966) and Schumm (1968). Although many of the maps covered relatively small areas in considerable detail, only Langford-Smith (1958) showed all of the major systems in the complete Murrumbidgee sector of the Plain. Unfortunately, Langford-Smith's doctoral thesis map was not published in the widely available scientific literature. The first comprehensive geomorphic map of the Riverine Plain was produced by Butler et al. (1973). This map clearly demonstrates the complexity of an apparently almost featureless landscape but is limited as a research tool in the study of palaeochannel chronology because it does not indicate the relative ages of channels, even at points of intersection, and fails to distinguish adequately between major and minor streams. For example, Schumm's (1968) major Northern, Central and Southern Prior Streams are not clearly distinguished from the myriad smaller channels on the Plain. A further limitation of the Butler et al. (1973) map results from its compilation from uncontrolled air photographs and photomosaics. Features such as streams and dunes are imprecisely located relative to the Australian Map Grid with errors at road crossings (for example, Schumm's (1968) Central Prior Stream relative to the Coleambally - Jerilderie Road) and other measured points often in excess of 1 km.

GIS based map of palaeochannels

In order to provide an accurate base map for field site locations and the delineation of major channel systems a new map was prepared on a base provided by existing 1:50 000 topographic maps, many of which were completed since 1973 when the Geomorphic Map of the Riverine Plain was published (Butler et al.,1973). The palaeochannels were first mapped on the old (1950s and 1960s) air photograph mosaics, which generally permit easy identification of channel locations, and then transferred to the accurate topographic sheets. Relative palaeochannel ages were determined, where possible, at intersections. Locations of all major, and some minor, palaeochannels as well as those of the modern drainage were plotted on 30 topographic maps (Table 6.1) and then digitised into a Genamap Geographic Information System (GIS) covering Australian Map Zones 54 and 55. Because the base map straddled two map zones, data digitised from topographic maps constructed on a Universal Transverse Mercator projection were transposed onto an Albers Conical Area map projection to permit a seamless coverage of the mapping area (Page and Louis, in preparation).

Four major palaeochannel systems were identified on the basis of channel morphology and position in the landscape (Fig. 6.1). The sequence of relative ages was initially based on channel intersections and subsequently verified by TL dating. For the purpose of mapping, major and distinctive palaeochannel networks are referred to as *systems*, subsets of which are called *arms*. For convenience in referring to smaller lengths of channel the arms are sometimes further subdivided into *reaches*. All systems, arms and reaches referred to in the present study are shown on Figure 6.1. Locations of sampling sites and other features referred to are shown on larger scale sub-maps of the complete GIS area in Figures. 6.2 and 6.3. The latter show more detail of channel geometry and demonstrate the flexibility of GIS based mapping.

Coleambally Palaeochannel System

The Coleambally System is so named because of its association with the Coleambally Irrigation Area in the eastern Riverine Plain. This system, which is the oldest palaeochannel system mapped, consists of two main arms that

Table 6.1. Topographic maps used in production of GIS

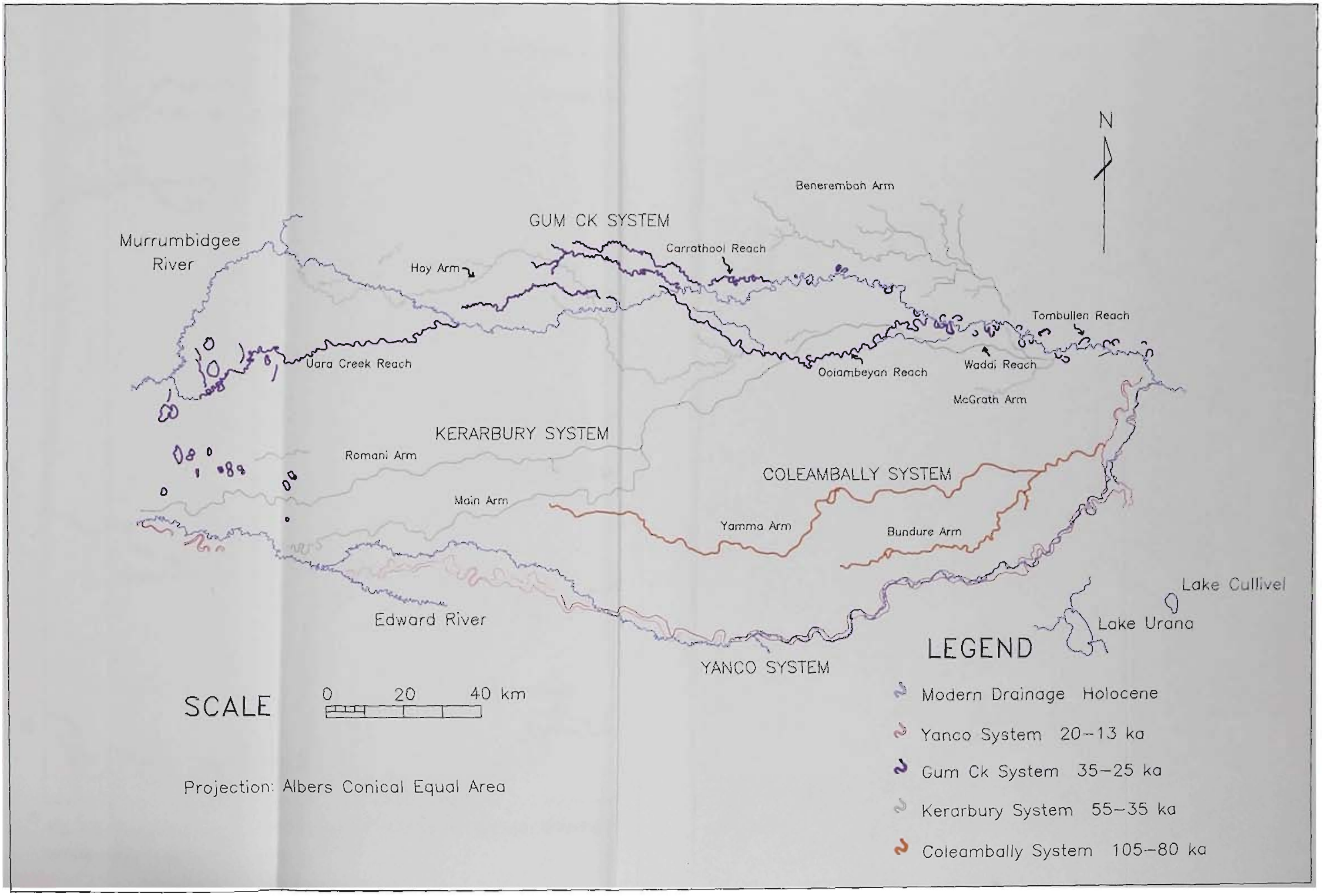
ZONE 54 ZONE 55

Paika 7639	Paika 7629	Maude 7729	Illilawa 7829	Carrathool 7929	Benerembah 8029		34°30'S
Weimby 7528	Balranald 7628	Toogimbie 7728	Hay 7828	Oolambeyan 7928	Darl Point 8028	Gog Weir 8128	
Kyalite 7528	Perekerton 7628	Tchelery 7728	Booroorban 7828	Epsom Downs 7928	Coleambally 8028	Corobimilla 8128	35°00'S
	Cunninyeuk 7627	Moulamein 7727	Wanganella 7827	Steam Plains 7927	Wilson 8027	Coonong 8127	
		Wakool 7727	Morago 7827	Conargo 7927	Jerilderie 8027	Urana 8127	35°30'S

144°E 145°E

Note: All maps 1:50,000 topographic except Paika 1:100,000 photo index series

FIG 6.1 MURRUMBIDGEE PALAEOCHANNELS – RIVERINE PLAIN



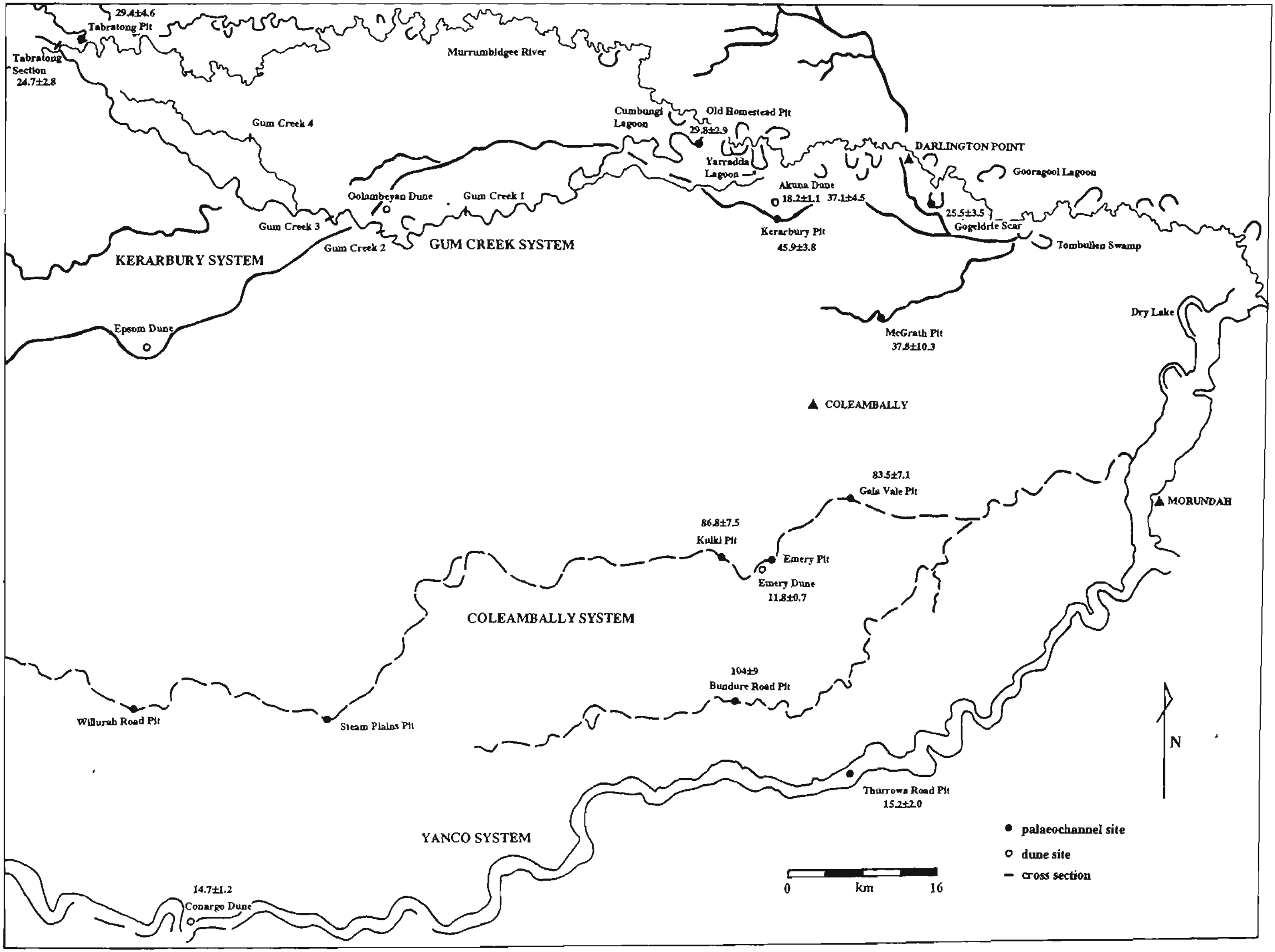


Fig. 6.2. Murrumbidgee eastern palaeochannel and dune field sites showing TL ages in ka. Site details are given in Appendix 1. Refer to Figure 6.1 for differentiation of palaeochannel systems.

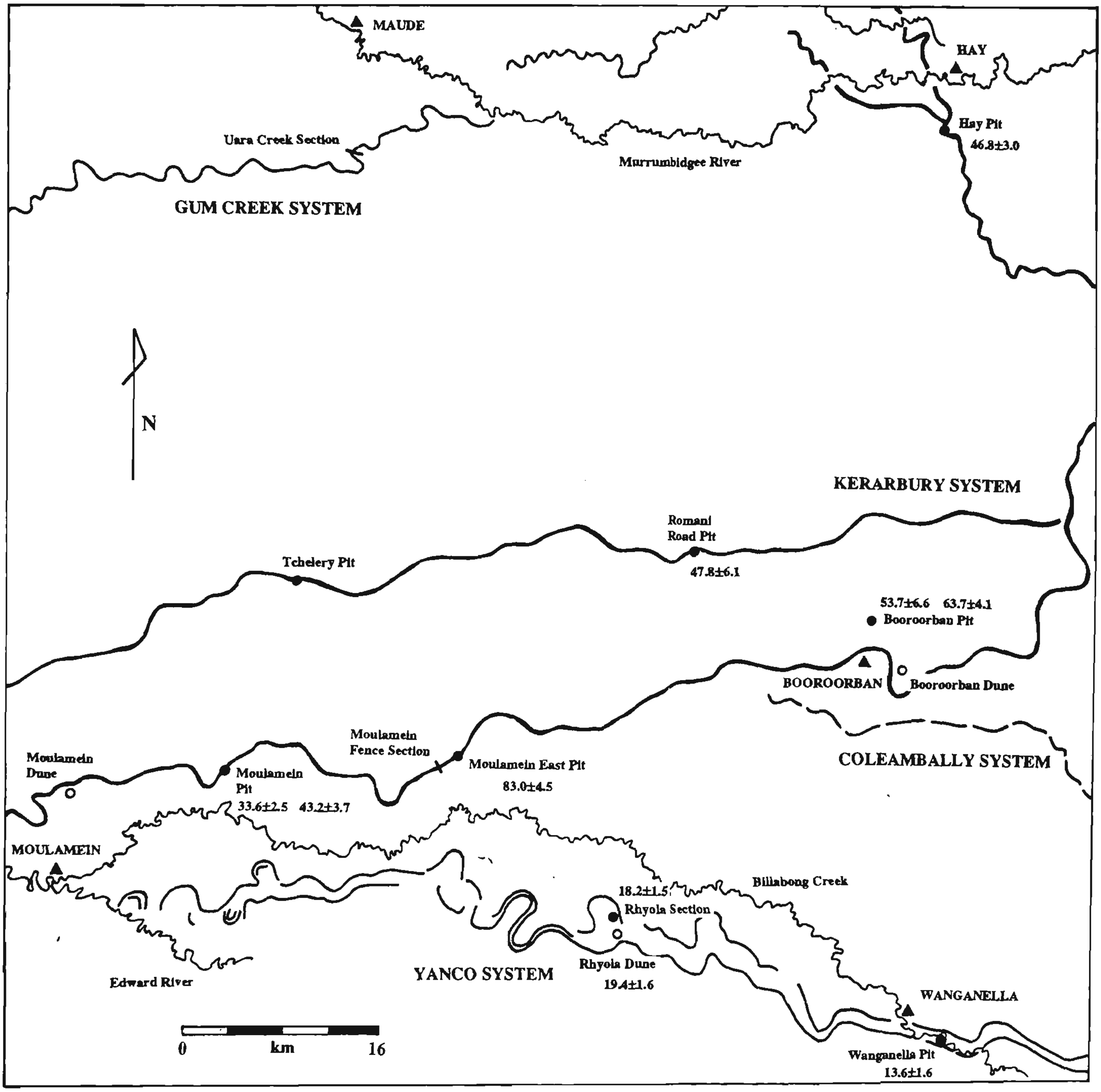
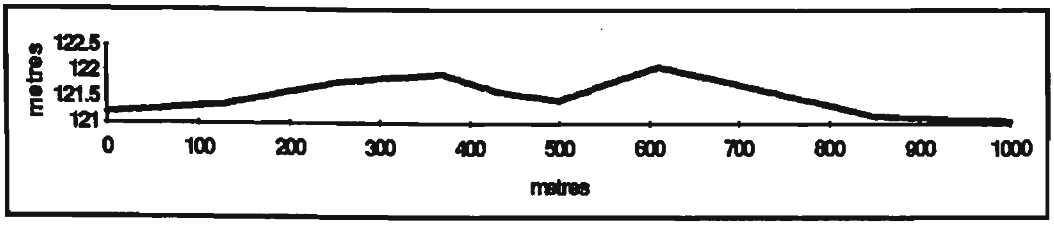
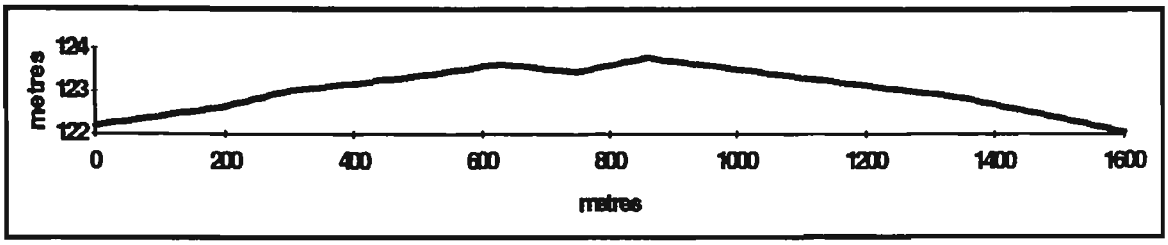


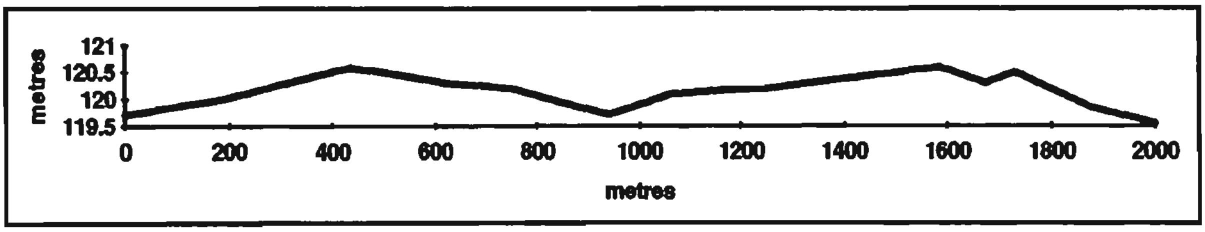
Fig. 6.3. Murrumbidgee western palaeochannel and dune field sites showing TL ages in ka. Legend as for Figure 6.2. Site details are given in Appendix 1. Refer to Figure 6.1 for differentiation of palaeochannel systems.



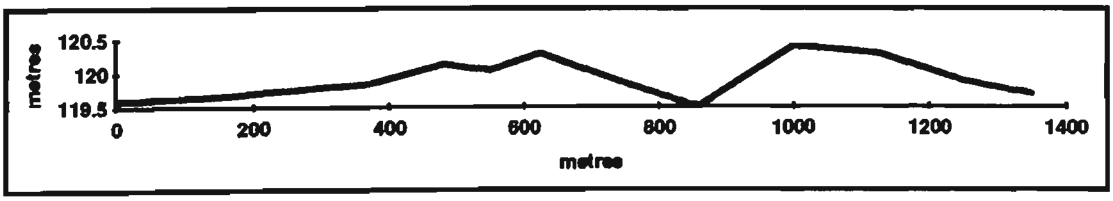
Coleambally System - Bundure Arm Section Y



Coleambally System - Bundure Arm Section R



Coleambally System - Yamma Arm Section A



Coleambally System - Yamma Arm Section B

Fig. 6.4. Water Resources Department cross sections of Bundure and Yamma Arm palaeochannels of the Coleambally System showing central channel and adjacent low levees. Section locations are shown in Chapter 7, Figure 7.8. All sections looking upstream.

correspond the Schumm's (1968) Central and Southern Prior Streams and the Yamma and Bundure Streams respectively of NSW Department of Water Resources surveys. The two main channels can be traced back to a single palaeochannel that emerges from the western margin of the modern Yanco Creek floodplain north of Morundah (Fig. 6.2). Downstream of the Yamma-Bundure bifurcation, which is partly obscured by vegetated sand dunes, the Bundure channel trends south then west before losing definition some 15 km east of the Carrathool - Conargo Road. The Yamma channel can be traced generally west towards Booroorban where it is obscured by younger deposits and channels of the Kerarbury System.

Both arms of the Coleambally System present classical prior stream surface morphology (Pels, 1971) being of low sinuosity and occurring as slightly elevated levee bordered depressions in the landscape (Fig. 6.4). Source bordering or marginal dunes are prominent to the east and north of the Yamma channel, particularly in its upstream reaches but are absent along the Bundure channel. This difference suggests that the two channels were not contemporaneously active. The slightly better surface preservation of the Yamma palaeochannel and the migration of marginal dunes across the Bundure bifurcation suggest that the Bundure channel is older.

Kerarbury Palaeochannel System

This complex distributary system includes Schumm's (1968) Northern Prior Stream and channels southwest of Griffith mapped by Pels (1964a). Its trunk stream includes the NSW Water Resources Department Waddi Stream which, despite being cut in several places by the younger Gum Creek System, can be traced from Tombullen Lagoon in the northeast to Moulamein in the southwest where the channel is finally obscured by modern channels and floodplains of the Edward River (Fig. 6.1). It is clear that the Kerarbury channel exited the Riverine Plain as a significant river. Although the Kerarbury System cuts across and clearly postdates the Coleambally System near Booroorban (Fig. 6.1) it is likely that it follows the same general course west as the earlier Coleambally System rivers in this region.

The major distributaries of the Kerarbury System include the McGrath, Benerembah, Hay and Romani Arms which successively bifurcate from the

main channel downstream of Tombullen Lagoon (Fig. 6.1). The McGrath channel branches south immediately west of Tombullen Swamp and cuts several older and deeper palaeochannels before dissipating on the Plain to the northwest of Coleambally. This relatively small channel appears to represent a terminal phase of the Kerarbury System.

Approximately 10 km west of Tombullen Swamp the Benerembah Arm branches north and is cut by the present Murrumbidgee River at Darlington Point. To the north of the Murrumbidgee this system forms a spectacular set of distributaries of decreasing size (Figs. 6.2 and 6.5) that were mapped by Pels (1964a). Further west the Hay distributary branches from the northern margin of the main channel and trends generally west and northwest to be cut by the present Murrumbidgee River at Hay and Maude before disappearing in the Lowbidgee area of modern flooding. North of Hay this distributary is also cut by channels of the Gum Creek System which is clearly younger.

The final significant Kerarbury distributary, the Romani Arm, bifurcates from the main channel to the northeast of Booroorban. It then trends parallel to the main palaeochannel before disappearing beneath the Mallee dunefield at the western margin of the Plain. At the area of bifurcation it is clear that the Romani Arm is the older of the two channels. Kerarbury System channels generally show typical prior stream characters including low sinuosity, well developed levees with scalded surfaces in the southwestern region, a tendency to form distributaries and the presence of large sand dunes at the eastern and northern margins of the major streams. The best developed and most continuous dunes occur along the trunk stream rising to more than 10 m above the adjacent Plain near Darlington Point (Fig. 6.6) but persisting as significant landscape features even along the Booroorban - Moulamein reach in the southwest. The dunes are invariably found at northern and eastern channel margins and are therefore presumed to have been formed by winds emanating predominantly from the southwest. Dunes are poorly developed or absent along the McGrath and Hay Arms of the Kerarbury System.

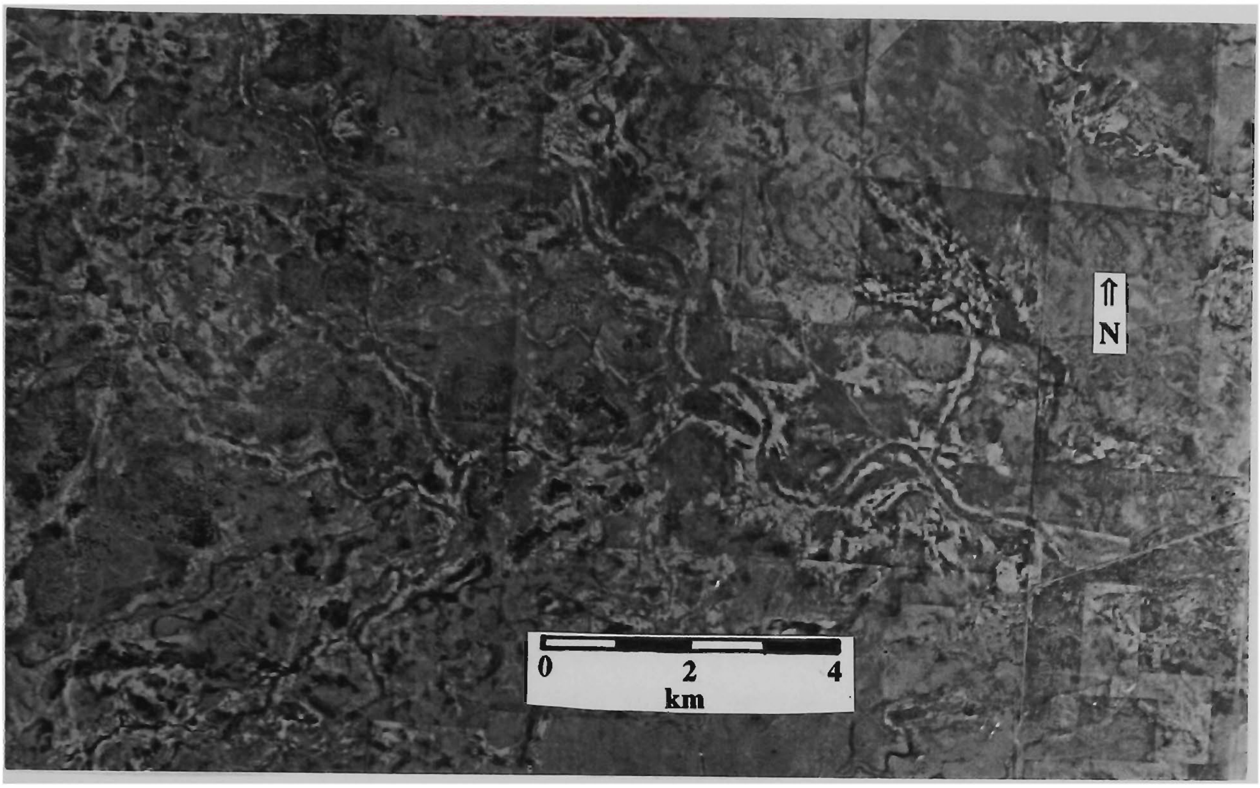
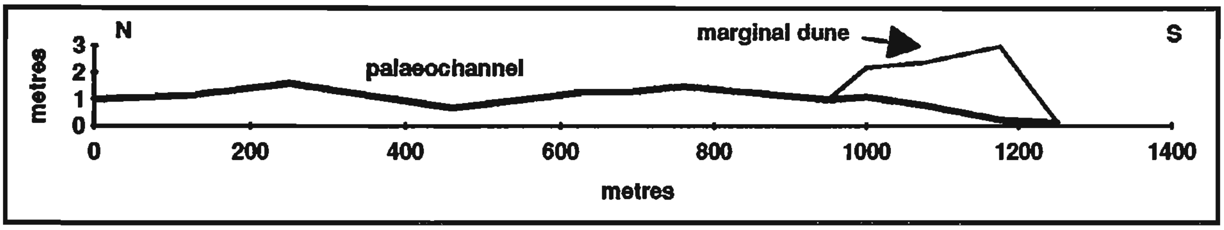
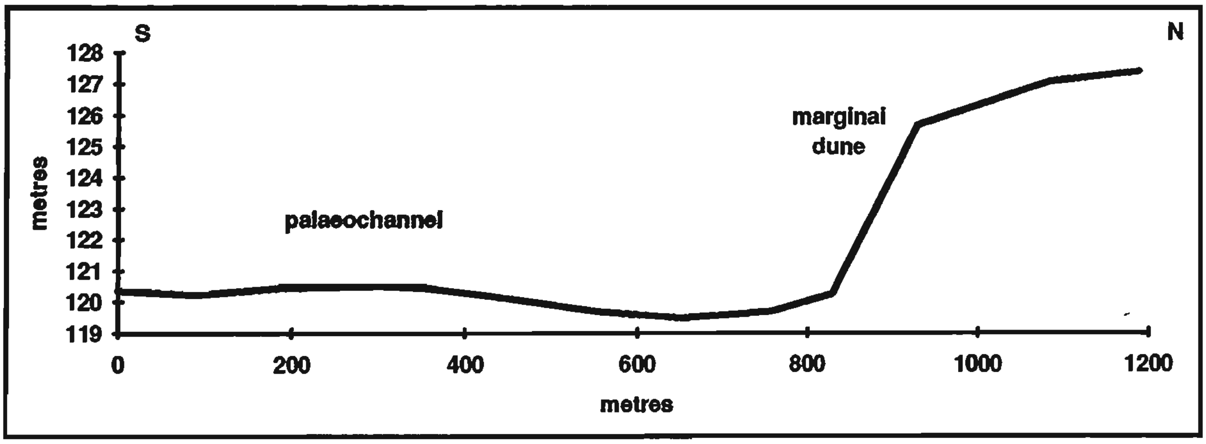


Fig. 6.5. Air photograph of Benerembah Arm, Kerarbury System, showing multiple distributaries and scalded levees. Palaeoflow to the west.



Kerarbury System - Moulamein Fence Section



Kerarbury System - Waddi Reach (Section 108)

Fig. 6.6. Surveyed sections across Kerarbury System palaeochannels in the southwestern region of the Plain and on Waddi Reach. Section locations shown on Figures 6.3 and 7.12 respectively.

Gum Creek Palaeochannel System

The Gum Creek Palaeochannel System corresponds to the ancestral Murrumbidgee system described by Schumm (1968). In the region upstream of Yarradda Lagoon it exists as a meander belt incised 1 to 3 m below the surface of the adjacent Plain and controls the course of the present Murrumbidgee River (Fig. 6.2). Meander wavelengths along the Gum Creek System greatly exceed those of the present Murrumbidgee River but display a similar tendency to decrease in size downstream (Fig. 6.7). Although ancestral systems of the Murray and Goulburn were studied in detail by Pels (1964b, 1966,1969) and Bowler (1967, 1978) comparatively little work has been done on the Murrumbidgee ancestral channels. Schumm (1968) described the ancestral Murrumbidgee reach between Narrandera and Yarradda Lagoon and, on the basis of channel morphology and limited Department of Water Resources stratigraphic data, estimated its bankfull discharge to have been approximately five times that of the present river. However, Schumm (1968) failed to discuss some puzzling downstream peculiarities of this system. The latter include the physical separation of the ancestral and modern channels downstream of Carrathool (Fig. 6.1), distributary prior stream style elements in the vicinity of Hay and a series of terminal lunette bordered relict lakes to the east of Balranald. In order to further examine these features the Gum Creek System has been subdivided into reaches as shown on Figure 6.1.

Tombullen Reach

Upstream of Yarradda Lagoon the *Tombullen Reach* of the Gum Creek System generally follows the line of the present drainage. Between Collingullie, to the west of Wagga Wagga, and Carrathool, palaeochannel remnants occur as large meander scars and scroll-patterned surfaces preserved along the northern and southern margins of the present floodplain (Fig. 6.8). Because many of these remnants accurately preserve channel geometry they are particularly useful in palaeohydrologic studies (Schumm, 1968). Meander wavelength measured at 23 palaeochannel scars between Collingullie and Yarradda Lagoon averaged 2920 m compared to 750 m for the present river (Fig. 6.7). Channel width estimated at 9 well-preserved palaeochannel sections ranged from 150 to 250 m compared to 60 to 80 m for the present river. These comparisons clearly support enhanced fluvial activity during the Gum Creek phase.

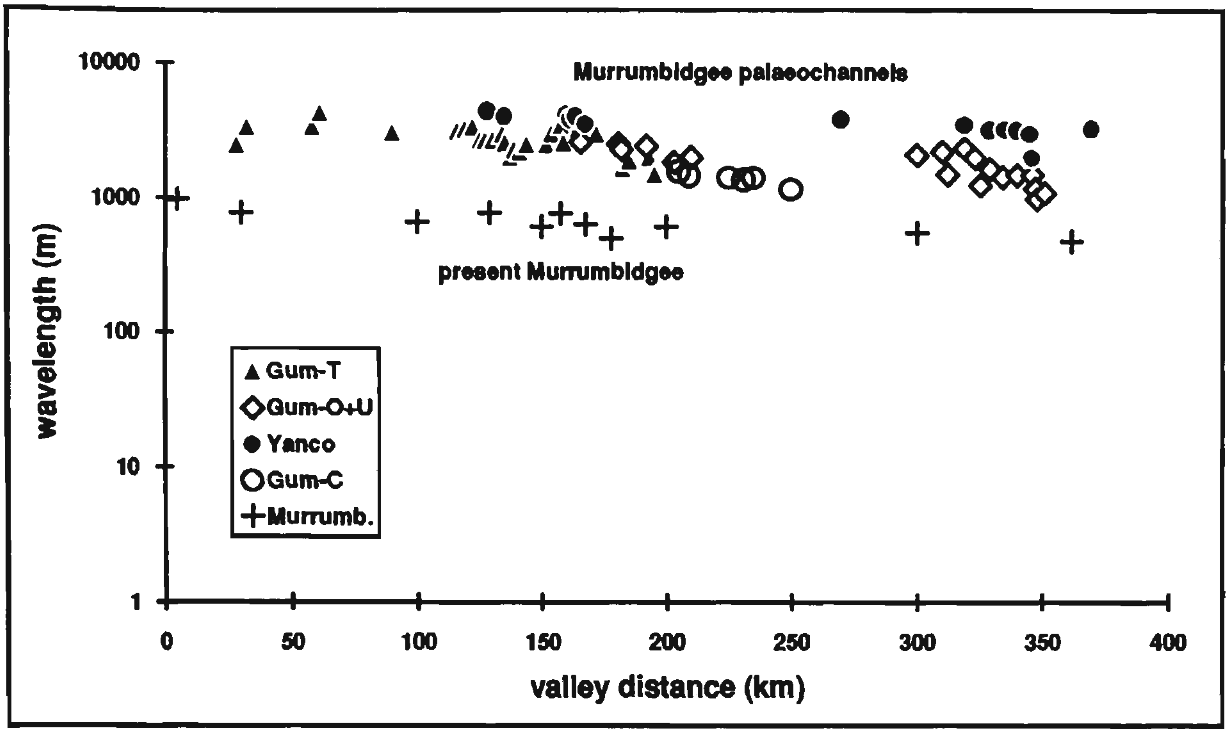
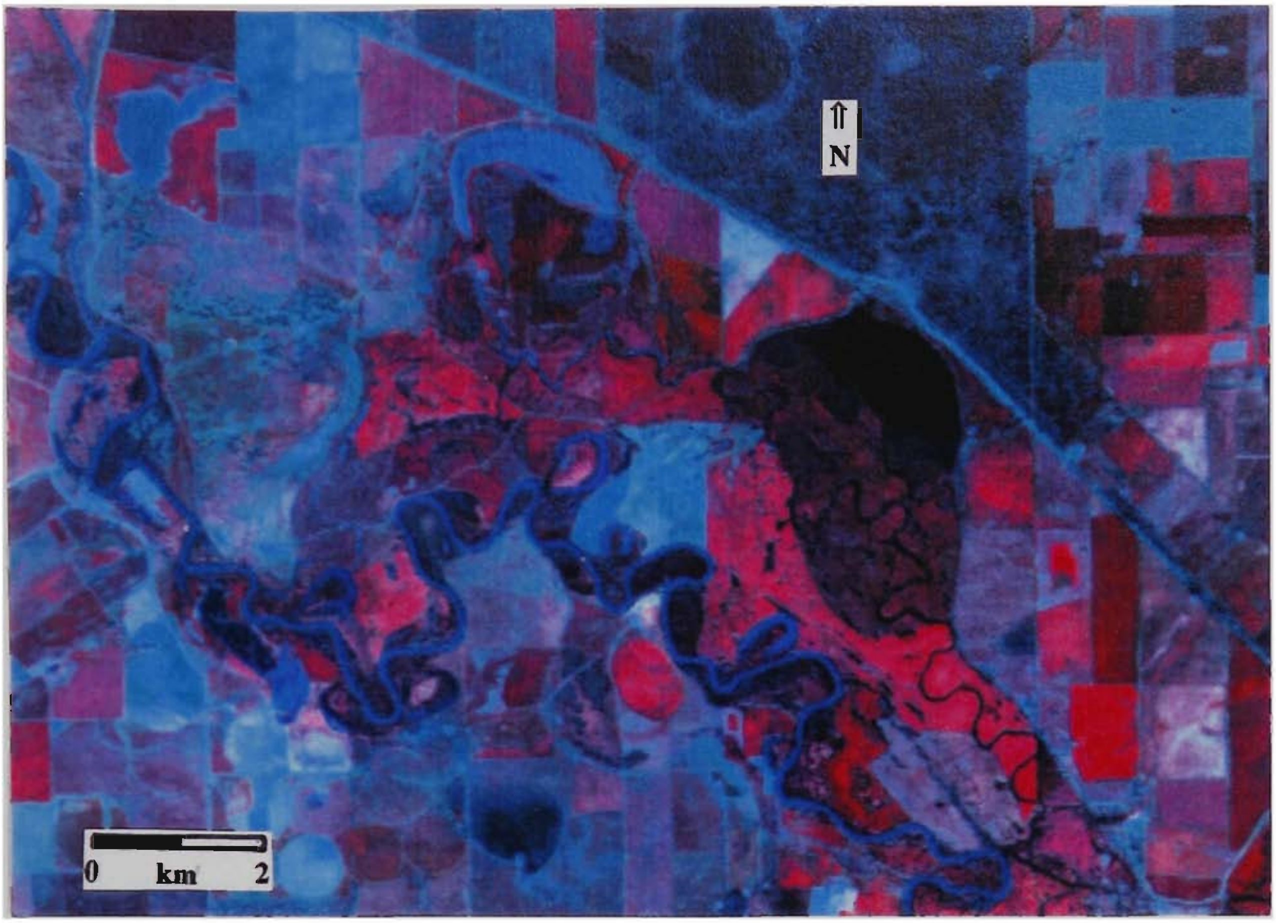


Fig. 6.7. Relationship between meander wavelength and valley distance downstream of Wagga Wagga for Gum Creek and Yanco System palaeochannels and present Murrumbidgee River. Separate Gum Creek reaches are indicated T, Tombullen; O+U, Oolambeyan and Uara; and C, Carrathool.

Oolambeyan and Carrathool Reaches

Downstream of Yarradda Lagoon the Gum Creek palaeochannels form an anabranching-distributary system. The first major distributary (*Oolambeyan Reach*) occurs as a large sinuous channel at the southern margin of the Murrumbidgee floodplain and trends southwest, cutting the older Kerarbury System at several locations (Figs. 6.1 and 6. 9). Meander wavelengths on this reach are consistent with those found along the Murrumbidgee floodplain upstream (Fig. 6.7) but show downstream decline possibly consistent with the reduction of discharge downstream of an anabranch. For much its length the Oolambeyan palaeochannel is followed by a modern suspended load channel that carries excess bed load deficient flood flows and directed irrigation water. This small muddy channel, itself called Gum Creek, supports mixed *E camaldulensis - E largiflorens* riparian woodland vegetation and is clearly visible on air photographs (Fig. 6.9).



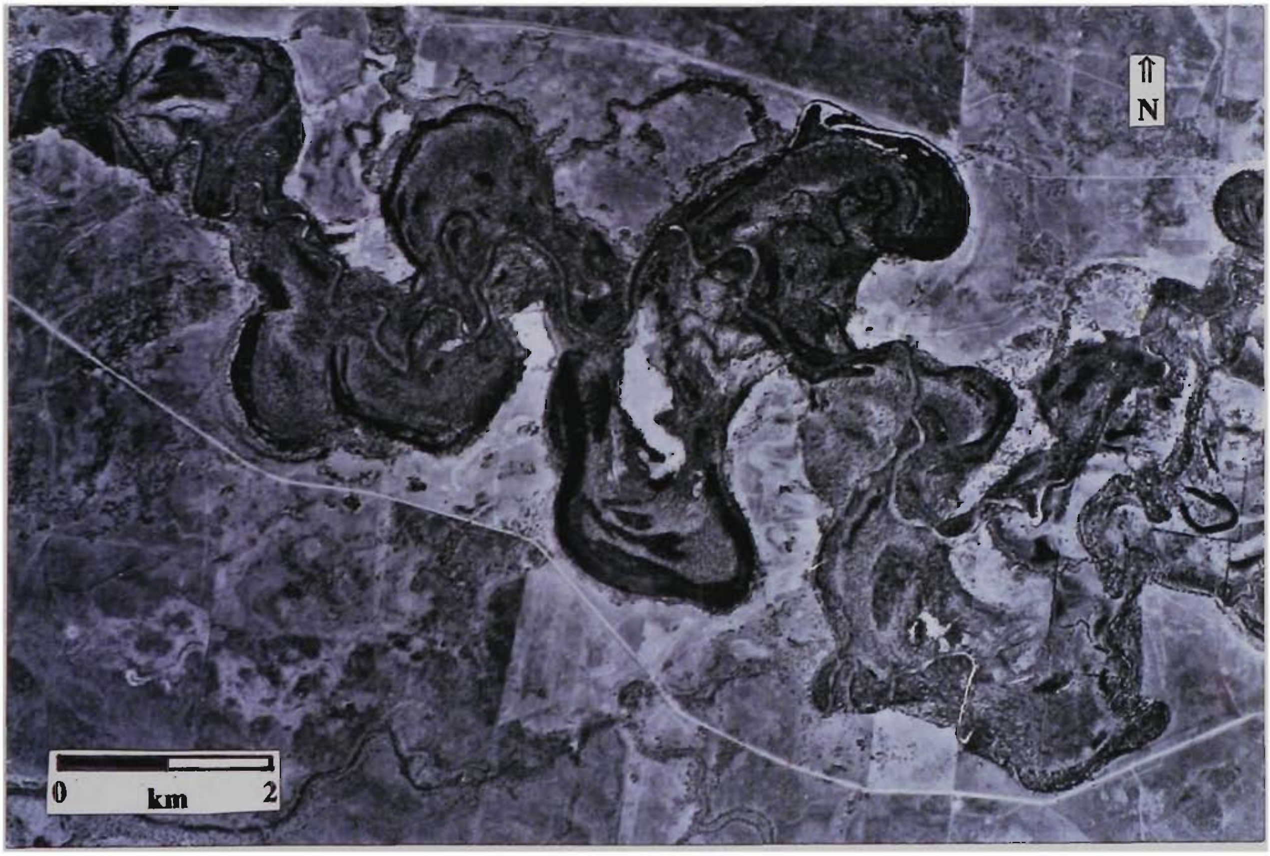


Fig. 6.8. Large meander scars along the present Murrumbidgee floodplain between Wagga Wagga and Narrandera (top) and Narrandera and Darlington Point (bottom). Flow is to the west.

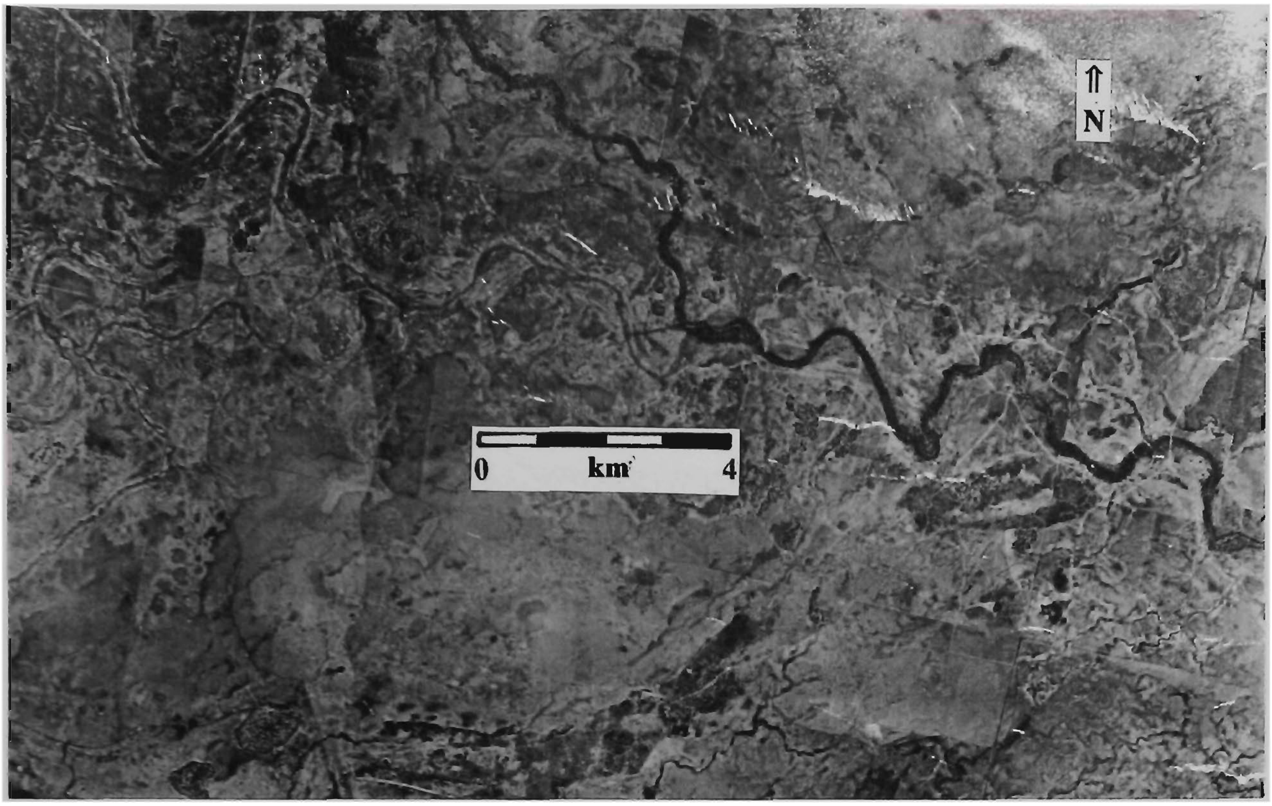


Fig. 6.9. Tree-lined modern Gum Creek following Oolambeyan Reach and cutting Kerarbury System palaeochannels south of Carrathool (Fig. 6.1). Flow is to the west.

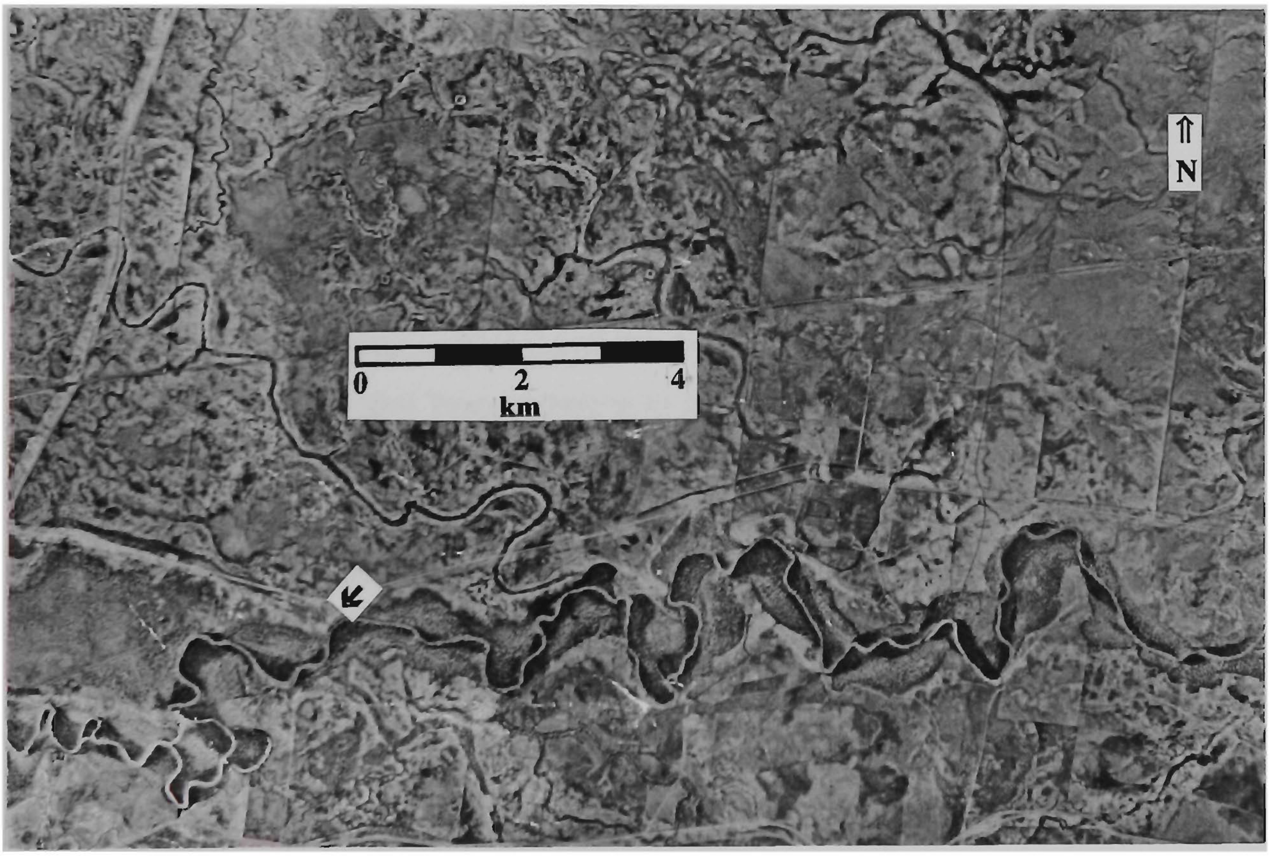


Fig. 6.10. Murrumbidgee River and tree-lined floodplain cutting Oolambeyan Reach of Gum Creek System (arrow) east of Hay. Prominent Carrathool Reach palaeochannels lie to the north. Flow is to the west.

After cutting the Kerarbury System for the last time the Oolambeyan palaeochannel trends northwest towards the Murrumbidgee becoming less sinuous and more like a prior stream in planform. About 15 km upstream of Hay the palaeochannel is cut by the Murrumbidgee (Fig. 6.10) and presents an excellent north bank sediment exposure. This low sinuosity channel can be traced a further 10 km west but then becomes obscured in a maze of channels of varying but generally younger age near Hay (Fig. 6.3).

In the reach downstream of the Oolambeyan palaeochannel bifurcation, and despite their explicit denial by Schumm (1968), large meander scars of the Tombullen Reach persist along the Murrumbidgee floodplain margins as far as Carrathool where they abruptly cease. Downstream of here the Murrumbidgee floodplain narrows to a single meander belt of width consistent with the dimensions of the present river. Although no further palaeochannel scars occur along the modern floodplain the sudden appearance of a sinuous palaeochannel on the northern margin of the Murrumbidgee almost certainly represents the downstream continuation of the palaeochannel (Figs. 6.1 and 6.11) and is mapped here as the *Carrathool Reach*. This sinuous channel and well-preserved floodplain has dimensions similar to those found along the reach upstream although meander wavelength is somewhat reduced and declines downstream (Fig. 6.7). It is likely that the Carrathool and Oolambeyan Reaches operated simulataneously and together carried the total discharge from the Tombullen Reach upstream of Yarradda Lagoon.

After paralleling the present floodplain for 30 km the Carrathool Reach is cut by the Murrumbidgee and then appears to branch into three separate distributaries near Hay (Fig. 6.3). Two of these distributaries cut the Kerarbury System (Hay Arm) northwest of Hay before forming further distributaries and losing surface expression in the Lowbidgee region where present flooding combines with the deposition of fine grained sediments and dense lignum vegetation (*Meuhlenbeckia cunninghamii*) to obscure many of the palaeochannel remnants.

Uara Reach

A little further west, near Maude (Fig. 6.3), air photographs show an obvious palaeochannel that branches away from the southern side of the Murrumbidgee (Fig. 6.1) and follows a generally southwesterly course

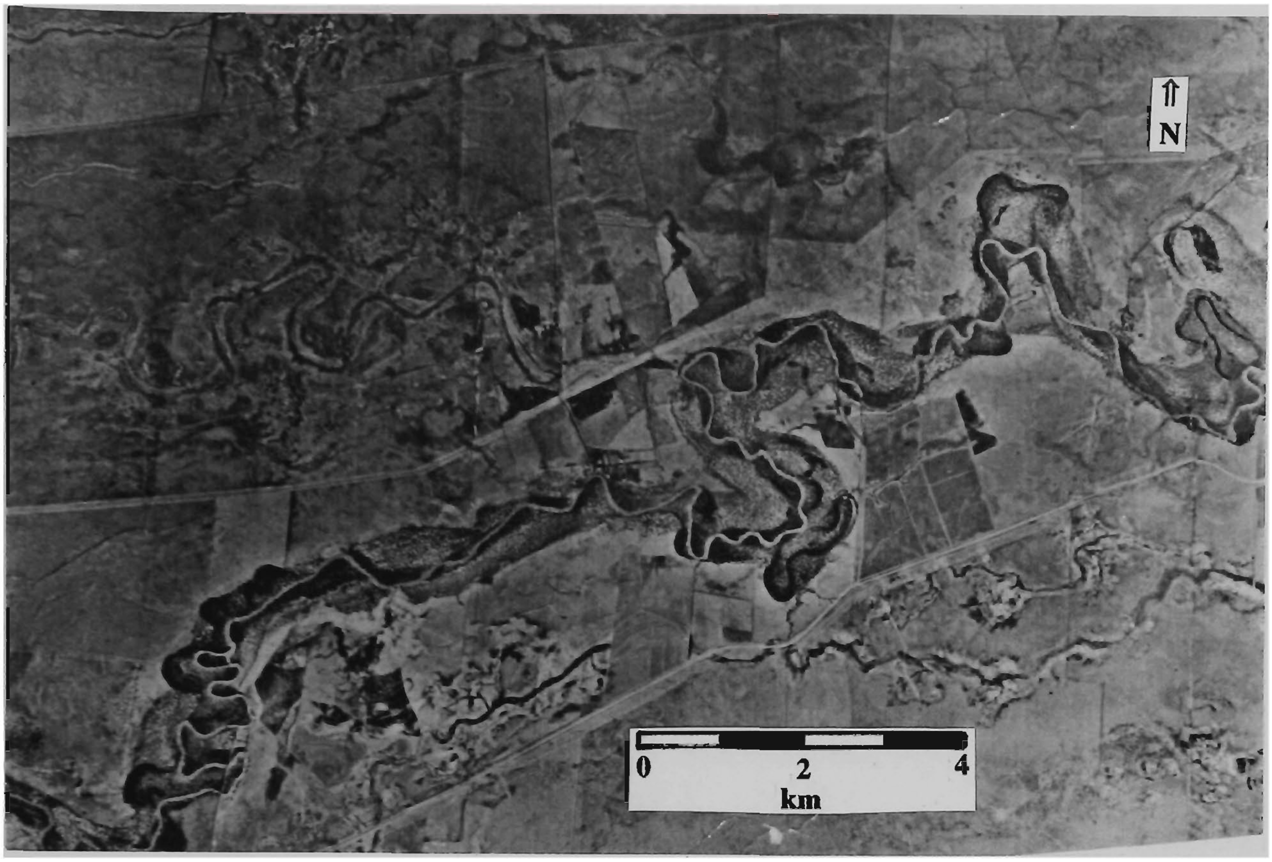


Fig. 6.11. Carrathool Reach of Gum Creek System branching to the north of the Murrumbidgee floodplain west of Carrathool. Flow is to the west.

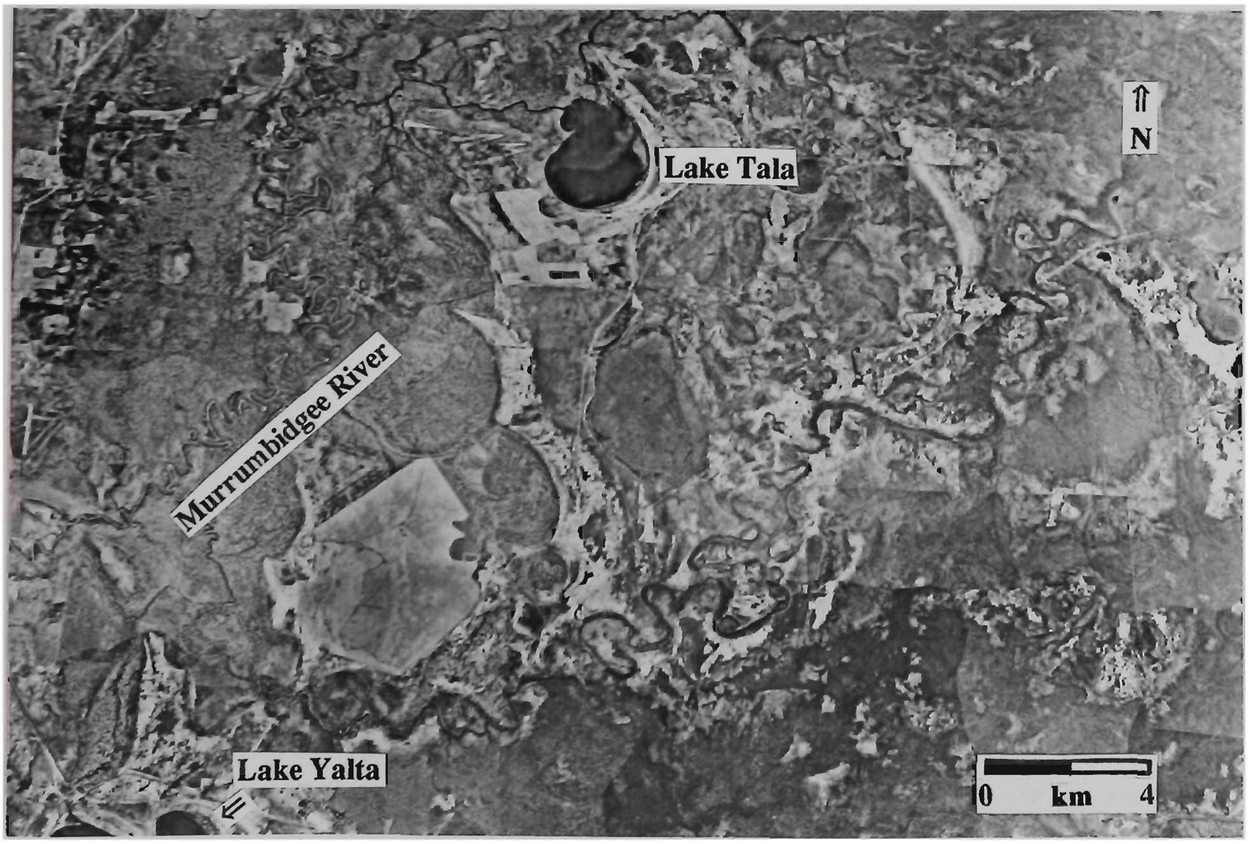


Fig. 6.12. Uara Creek Reach of Gum Creek System near the western margin of the Riverine Plain. Numerous lunette bordered relict lakes and the modern Murrumbidgee channel are also visible. Flow is to the west.

towards Balranald. The sinuous channel of the *Uara Creek Reach* follows a low ridge in the landscape one to two metres above the adjacent lignum swamps, which are inundated when major floods move along the lower Murrumbidgee, and terminates in a complex array of relict lunette bordered lakes including Lakes Tala and Yalta which are presently used as off-river irrigation storages (Fig. 6.12). Meander wavelengths along the reach are highly variable but are generally consistent with those measured on the Gum and Carrathool Creek palaeochannels upstream and certainly exceed those of the present Murrumbidgee River in this western region of the Plain (Fig. 6.7 and 6.12). It is not unexpected that meander wavelength should decline westwards just as it does on the present Murrumbidgee, presumably in response to declining flood peaks downstream (Page, 1988). Whether the Uara channel carried the full downstream discharge of the palaeo-Murrumbidgee is unclear. Under the present regime a small suspended load channel follows Uara Creek palaeochannel but flows only as a result of major flooding of the lower Murrumbidgee Valley.

Yanco System

The Yanco Palaeochannel System branches south from the present Murrumbidgee floodplain about 15 km west of Narrandera and trends generally southwest and west across the Plain towards Moulamein where it terminates abruptly at the edge of the modern Edward River floodplain. In its upstream region the Yanco System is incised about two metres below the general level of the Plain and is followed by the present channels and floodplains of Yanco and Billabong Creeks (Fig. 6.1). Although large meander scars can be identified throughout the length of the Yanco System, it is best expressed downstream of Conargo where it is geographically separated from the present channels of Yanco and Billabong Creeks. In this reach large sinuous channel remnants and floodplains of lateral accretion including scroll bar topography and cut-offs are well preserved (Fig. 6.13). Channel width averages 225 m and meander wavelength 3000 m compared to 60 m and 550 m, respectively, on the present Murrumbidgee downstream of Hay. Both wavelength and channel width show little tendency to decline downstream (Fig. 6.7). There can be little doubt that the palaeo-Billabong Creek left the Plain as a relatively powerful river similar in many respects to channels of Kotupna age on the Goulburn (Bowler, 1978) and those of Acres Billabong on the Darling (Bowler et al., 1978).

Although Pels (1971) and Schumm (1968) considered the Gum Creek and Yanco Systems to be part of a single ancestral phase sandwiched between the prior and modern rivers, no dating evidence was presented to support this assertion. Certainly, the two Systems are geographically widely separated and are sufficiently distinct on the basis of morphology and sediments to be warrant differentiation. In particular, the Yanco System persists across the Plain as a continuous large channel without anabranches or aggraded distributary elements. Also in contrast to the Gum Creek System, is the presence throughout its length of well-developed sand dunes to the east and north.

The absence of any published research on Yanco Creek and in particular the reach between Conargo and Moulamein is surprising given the excellent preservation of features here (Fig. 6.3) and also its geographical separation from the small modern rivers in this region (Brown and Stephenson, 1991).

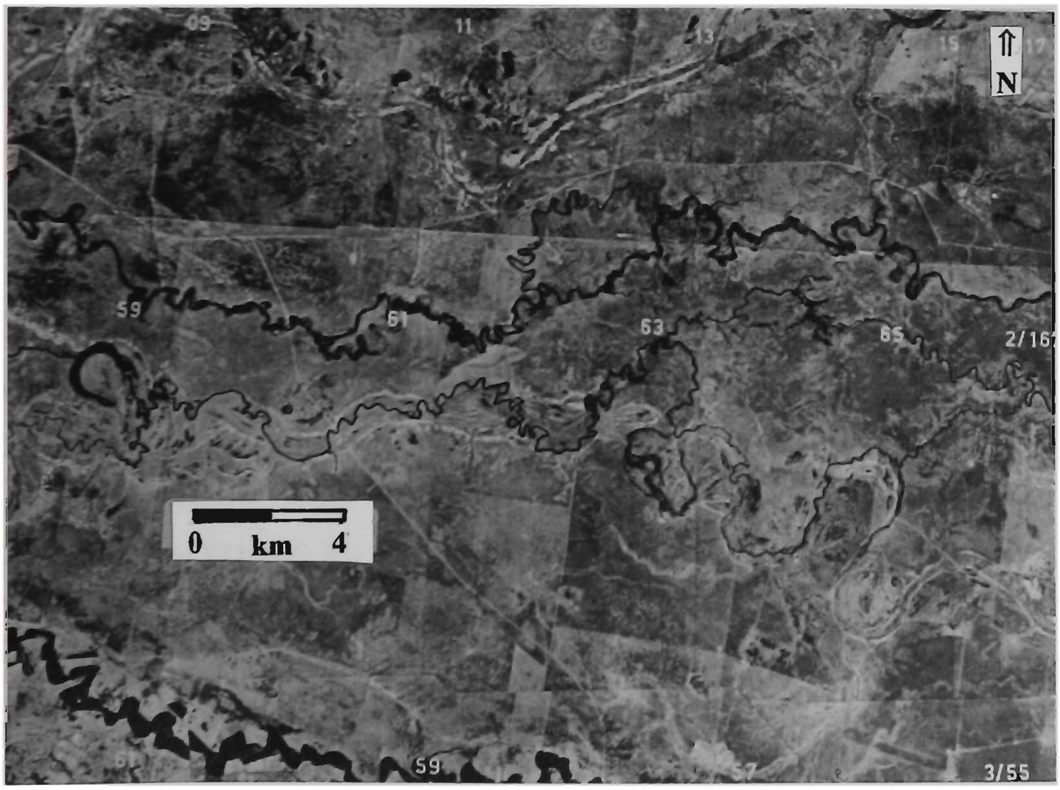


Fig. 6.13. Yanco System palaeochannels and floodplain remnants east of Moulamein. The western end of the Kerarbury System palaeochannel is visible to the north. Flow is to the west.

TL DATING OF PALAEOCHANNEL SYSTEMS AND MARGINAL DUNES

Introduction

TL ages and supporting technical data for Murrumbidgee palaeochannel and marginal dune samples are given in Table 6.2. Locations of dating sites are shown in Figures 6.2 and 6.3 and field descriptions of the sites are provided in Appendix 1. All samples were collected from pit exposures or auger holes. The fluvial samples were all from pebbly coarse sand channel infills except on the Yanco (Billabong Creek) System where two samples were collected from pits exposing cross-bedded lateral migration deposits. Infill dates should approximate the age of channel demise. Samples taken from pit faces were collected in sediments that showed acceptable homogeneity over at least a 0.6 m thickness although individual beds rarely exceeded 0.3 m thickness. Dune trough and cross sets of these dimensions are indicative of flow depths not exceeding approximately 2.8 m (Leeder, 1982). All aeolian dune samples in the Murrumbidgee sector of the Plain were collected from auger holes. To the north of Kerarbury Pit a large dune was sampled at depths of 2m and 7m to test for possible reworking of surface layers.

Palaeochannels

Within the limits of error (usually not exceeding approximately 10%) all of the palaeochannel dates were stratigraphically consistent with no overlap between successive systems (Fig. 6.14). Four dates on the oldest (Coleambally) palaeochannels ranged from 83.0 ± 4.5 ka to 104.0 ± 9.0 ka with the oldest date coming from Bundure Arm. Sample W1446 was extracted by auger from deeper sands beneath the Kerarbury Palaeochannel southwest of Booroorban. The deeper deposits here resemble those exposed at Moulamein Pit and probably represent the downstream continuation of the Yamma Arm of the Coleambally System. Dates on the Coleambally channel sediments correspond to the earliest set of dates on Murray-Goulburn palaeochannels in the vicinity of the Cadell Fault in the southern region of the Plain (Chapter 5). All dates lie within Oxygen Isotope Stage 5 (Chappell and Shackleton, 1986) and therefore agree well with dates reported by Nanson et al. (1992a) for a phase of greatly enhanced activity by Australia's northern and inland river systems.

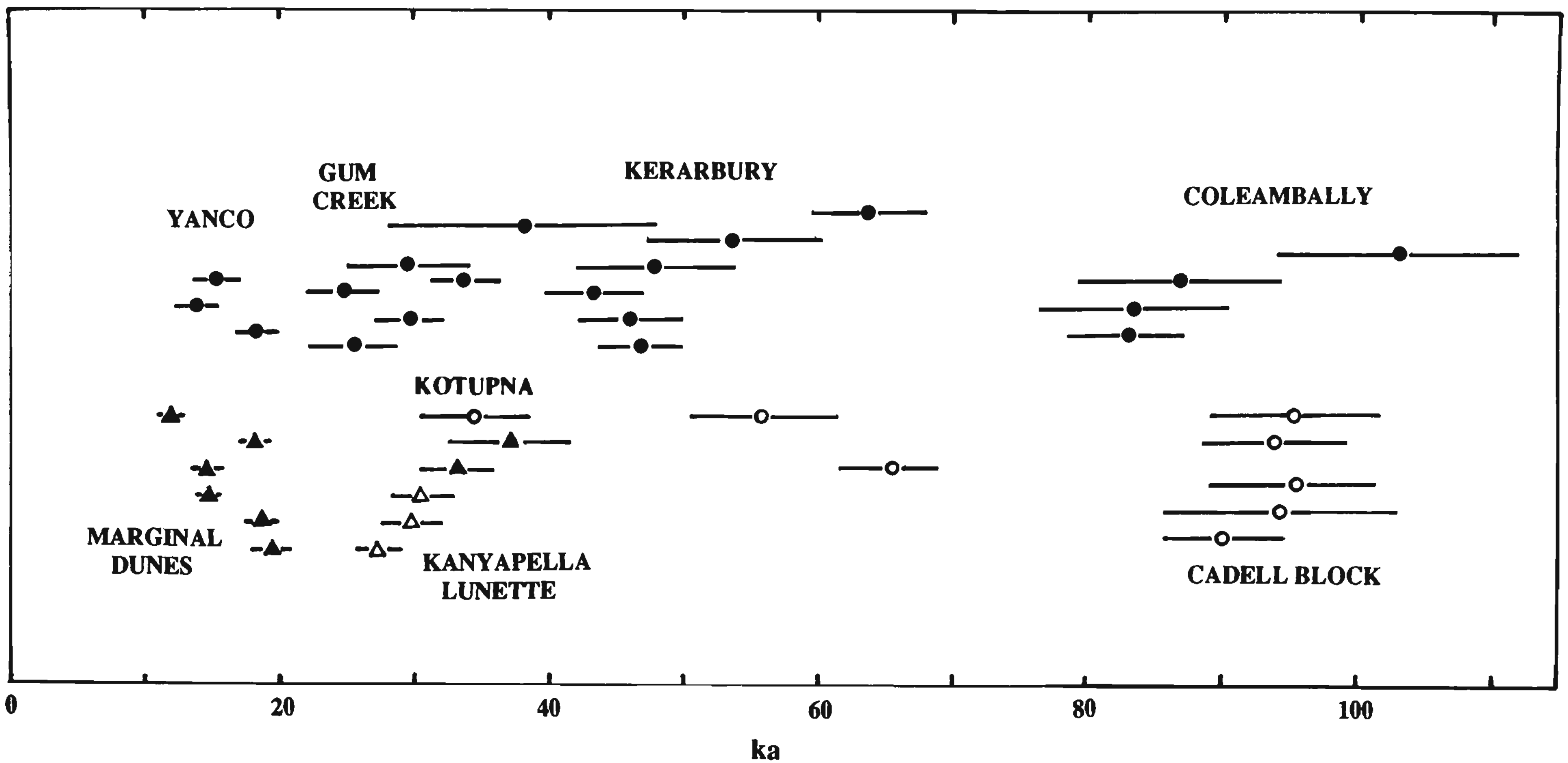


Fig. 6.14. TL dates and errors for fluvial and aeolian sediments on the Murrumbidgee and Murray-Goulburn sectors of the Riverine Plain. Solid circles Murrumbidgee palaeochannels, open circles Murray palaeochannels, solid triangles marginal dunes and open triangles Kanyapella lunette.

Because the Coleambally System TL samples were collected from channel infills they mark the termination of fluvial activity. Therefore, the earliest Coleambally (Bundure) channels probably date from before 100 ka. Given the limited lateral extent of the Bundure deposits it is unlikely that this stream was active before about 110 ka and thus, it post-dates Oxygen Isotope Stage 5e (Chappell and Shackleton, 1986).

No TL samples on the Riverine Plain yielded dates in the 80 to 70 ka age range, and only three (W748, W1445 and W1447) dated between 70 and 55 ka. Thus, it seems likely that the period 80 to 55 ka was one of reduced fluvial activity. This interval includes Oxygen Isotope Stage 4 and correlates with a major dust peak in the Vostok ice core (Petit et al., 1990).

The Kerarbury palaeochannels yielded eight dates ranging from 33.6 ± 2.5 to 63.7 ± 4.1 ka with a mean of 46.6 ka. Paired dates of 53.7 ± 6.6 and 63.7 ± 4.1 ka, and 33.6 ± 2.5 ka and 43.2 ± 6.1 ka on the Kerarbury System at Booroorban Pit and Moulamein Pit respectively indicated acceptable dating consistency. Although both pairs differ internally by 10 ka and point to the moderate precision of TL dating, they overlap at two standard errors. Given the 10 per cent errors associated with TL dates it is difficult to distinguish ages within the Kerarbury group. Nevertheless, dates from two clearly older Kerarbury channels north of Booroorban dated at > 47 ka while the apparently younger McGrath channel dated at 37.8 ± 10.3 ka.

Like the Coleambally samples, those from the Kerarbury System were all collected from sandy infills marking the terminal phase of channel activity. Extensive lateral migration floodplain deposits of the Kerarbury described below (Chapter 7) suggest that this system operated from before 50 ka and probably from about 55 ka. This period corresponds to Oxygen Isotope Stage 3 (Chappell and Shackleton, 1986) regarded by Nanson et al. (1992a) as being an important sub-pluvial phase of enhanced river activity in inland and southern Australia. However, this phase is not well dated on the Murray-Goulburn System to the south where only one date, on an aggraded dune-bordered palaeochannel to the east of Deniliquin (Fig. 5.1), yielded an age of 56.0 ± 5.2 ka. An older date of 65.1 ± 3.6 ka on a point bar of Green Gully is puzzling but little can be made of a single marginally discrepant date.

Very interesting dates are those on the Gum Creek and Yanco Murrumbidgee Palaeochannel Systems. On Gum Creek System four dates on channel infills ranged from 29.8 ± 2.9 to 24.7 ± 2.8 ka (Fig. 6.2). As with the majority of earlier system dates these ages mark the terminal phases of channel activity. Given the extensive marginal floodplain deposits associated with the meandering Gum Creek System, it seems likely that these channels date from about 35 ka to 25 ka and thus correspond with a cluster of 5 dates between 35 and 27 ka on the Kotupna-Kanyapella deposits of the Murray-Goulburn to the south. Taken together these dates provide a strong indication of enhanced fluvial activity at this time.

The Yanco System was dated at three locations including one channel infill and two lateral floodplain deposits (Figs. 6.2 and 6.3). Ages ranged from 18.2 ± 1.5 to 13.6 ± 1.6 ka. These dates indicate that the large and impressively preserved Yanco System was functioning in the period following the LGM at ~22 ka. The preserved channels and floodplains along this reach closely resemble similar features on the Kotupna System in Victoria (Bowler, 1978) and along the Darling River in western NSW (Bowler et al., 1978). Although the Yanco System dates are younger than the single 34 ka TL date on Kotupna channel sediments at McCoy Pit, they do agree closely with radiocarbon dates from the Kotupna channels from 16 to 13 ka* (Bowler, 1978) and also those from Acres Billabong on the Darling from 19 to 11 ka* (Bowler et al., 1978). Clearly, questions raised about possible contamination of *all* of the Kotupna radiocarbon samples by Bowler (1978) and Page et al. (1991) need re-assessment. In particular, the agreement of a late Kotupna radiocarbon date of 13 ka* on the floor of Lake Kanyapella with the remarkably consistent TL dates on the Murrumbidgee Yanco palaeochannels argues strongly for its validity.

Table 6.2 TL dates and technical data - Murrumbidgee Sector of Riverine Plain.

Sample Number	Section and Formation	Temp Plateau Region (°C)	Anal. Temp (° C)	Palaeo-dose (Grays)	K Cont. (%)	Moisture Content (% by wt)	U + TH Specific Activity (Bq/kg)	Annual Radiation Dose (µ Grays)	TL Age (kyr)
W905	Emery Dune Coleambally	275-450	375	39.7±2.4	2.40	4.5	38.9±4	3377±74	11.8±0.7
W745	Kulki Pit Coleambally	300-500	375	192±15	1.38	1.3	29.1±4	2214±76	86.8±7.5
W758	Gala Vale Pit Coleambally	275-500	375	171±13	1.25	2.4	29.4±4	2054±75	83.5±7.1
W904	Bundure Pit Coleambally	275-500	375	296±23	2.03	0.4	24.5±4	2849±77	104±9
W1557	Thurrowa Rd Pit Yanco	300-500	375	37.9±4.7	1.40	3.0	44.2±4	2497±74	15.2±2.0
W1559	Rhyola Section Yanco	300-500	375	41.8±4	1.25	2.3	41.8±4	2296±74	18.2±1.5
W1365	Rhyola Dune Yanco	275-500	375	35.9±2.6	1.05	1.0	27.7±4	1846±76	19.4±1.6
W1558	Wanganella Pit Yanco	325-500	375	31.3±3.5	1.15	3.8	48.2±4	2295±74	13.6±1.6
W1362	Romani Rd Pit Kerarbury	300-500	375	160±20	2.25	1.8	39.9±4	3344±75	47.8±6.1
W996	Old Homest Pit Gum Creek	325-450	375	76.9±7.2	1.85	2.2	23.6±4	2583±75	29.8±2.9
W907	Kerarbury Dune Kerarbury	300-500	375	82.3±5.0	3.49	4.8	41.3±4	4527±73	18.2±1.1
W1364	Kerarbury Dune Kerarbury	300-500	375	136±16	2.35	2.5	51.8±4	3659±75	37.1±4.5
W906	Kerarbury Pit Kerarbury	300-500	375	169±14	2.57	3.0	42.4±4	3683±75	45.9±3.8
W997	Tabratong Sect Gum Creek	325-500	375	81.0±9.0	2.435	4.1	31.5±4	3282±73	24.7±2.8
W998	Tabratong Pit Gum Creek	325-500	375	79.3±12.2	1.925	2.9	26.4±4	2695±74	29.4±4.6
W746	Hay Pit Kerarbury	300-500	375	141±8	2.05	2.1	34.2±4	3008±76	46.8±3.0
W1360	Moulamein Pit Kerarbury	300-500	375	140±10	3.2	8.9	48.2±4	4172±70	33.6±2.5
W1363	Moulamein Pit Kerarbury	300-500	375	120±10	1.9	4.4	34.7±4	2785±73	43.2±3.7
W1361	Booroorban Pit Kerarbury	325-500	375	164±20	2.0	4.5	42.8±4	3043±73	53.7±6.6
W1445	Booroorban Pit Kerarbury	300-500	375	154±9	1.15	2.3	52.3±4	2416±75	63.7±4.1
W995	Gogeldrie Scar Gum Creek	300-450	375	80.5±11	2.4	10.9	54.1±4	3159±63	25.5±3.5
W909	Conargo Dune Yanco	275-425	375	58.6±4.8	2.91	1.4	36.3±4	3988±76	14.7±1.2

Sample Number	Section and Formation	Temp Plateau Region (°C)	Anal. Temp (° C)	Palaeo-dose (Grays)	K Cont. (%)	Moisture Content (% by wt)	U + TH Specific Activity (Bq/kg)	Annual Radiation Dose (μ Grays)	TL Age (kyr)
W1371	Pioneer Pit -1.1 m	300-500	375	52.7±4.0	1.15	18.8	45.3±4	1914±63	27.5±2.3
W1560	Pioneer Pit -12.3 m	300-500	400	≥217±98	1.05	23.4	39.1±4	1645±60	≥132±60
W1556	Pioneer Pit -8 m	325-500	375	≥187±22	1.15	24.8	38.3±4	1700±60	≥110±14
W1446	Moulamein East Pit Coleambally	325-475	375	143±5	0.85	2.5	33.4±4	1719±75	83.0±4.5
W938	McGrath Pit Kerarbury	275-500	375	136±37	2.71	4.0	32.9±4	3593±74	37.8±10.3

Notes:
1. Assumed rubidium levels (100 ppm), potassium content by AES and XRF.
2. Annual radiation values indicated assume a cosmic contribution of 150 μGy/yr.
3. U and Th specific activity levels were determined by calibrated thick source alpha counting and assume secular equilibrium.
4. Uncertainty values shown represent one standard deviation.

TL dates on basal gravels of the Murrumbidgee River in its confined valley reach upstream at Wagga Wagga also provide a useful check on the Riverine Plain ages. At Pioneer Pit, some 5 km west of Wagga Wagga, a large pit has been excavated into basal gravels underlying approximately 7 m of fine grained alluvium associated with the modern flow regime. The pit bottom is presently (August, 1993) 14 m below local river gauge zero and has to be constantly pumped to remove inflowing groundwater. The generalised pit stratigraphy is shown in Figure 6.15. Beneath the contemporary scroll-patterned floodplain surface is a unit of sand, silt and clay. These fine-grained sediments rest upon a 6 m unit of gravels (maximum diameter 40 mm) with occasional sand lenses, one of which was TL dated at 27.5 ± 2.3 ka (W1371). An 8 m unit of coarser gravels (maximum diameter 80 mm) containing large tree fragments then continues to the pit bottom. Two TL dates from sandy lenses within this unit yielded ages of ≥114 ± 14 ka (W1556) at a depth of 8 m below gauge zero and ≥132 ± 60 ka (W1560) at a depth of 12 m. Both of the deep samples yielded poor TL plateau characteristics (D Price, pers. comm.) and are regarded as unreliable. However, the two dates do suggest that the coarse basal gravels are older than any of the palaeochannel deposits TL dated on the Riverine Plain and support Woolley (1972) who considered these deep gravels near Wagga Wagga to be of mid-Pleistocene age. The upper date, on finer gravels, is considered reliable and correlates with the Gum Creek palaeochannel phase.

Reliability of TL dates

The strong stratigraphic consistency of TL dates on Murrumbidgee palaeochannels argues for their reliability. Additional support for the validity of the dates is provided by corroborative dating of marginal dunes, correlation with radiocarbon dates and comparisons of dates calculated from the 375°C and 325°C TL plateau regions respectively.

<u>Marginal dunes</u>

Five TL samples were collected from marginal sand dunes of the Coleambally, Kerarbury and Yanco Systems. Ages ranged from 37.1 ± 4.5 to 11.8 ± 0.7 ka . Two samples from the Yanco System agreed closely with dates on nearby alluvial samples as did the deeper sample on the Kerarbury System (W1364). A shallow sample from the Kerarbury dune dated at 18.2 ± 1.1 ka (W907) and a low dune west of Emery Pit on the Yamma Arm of the

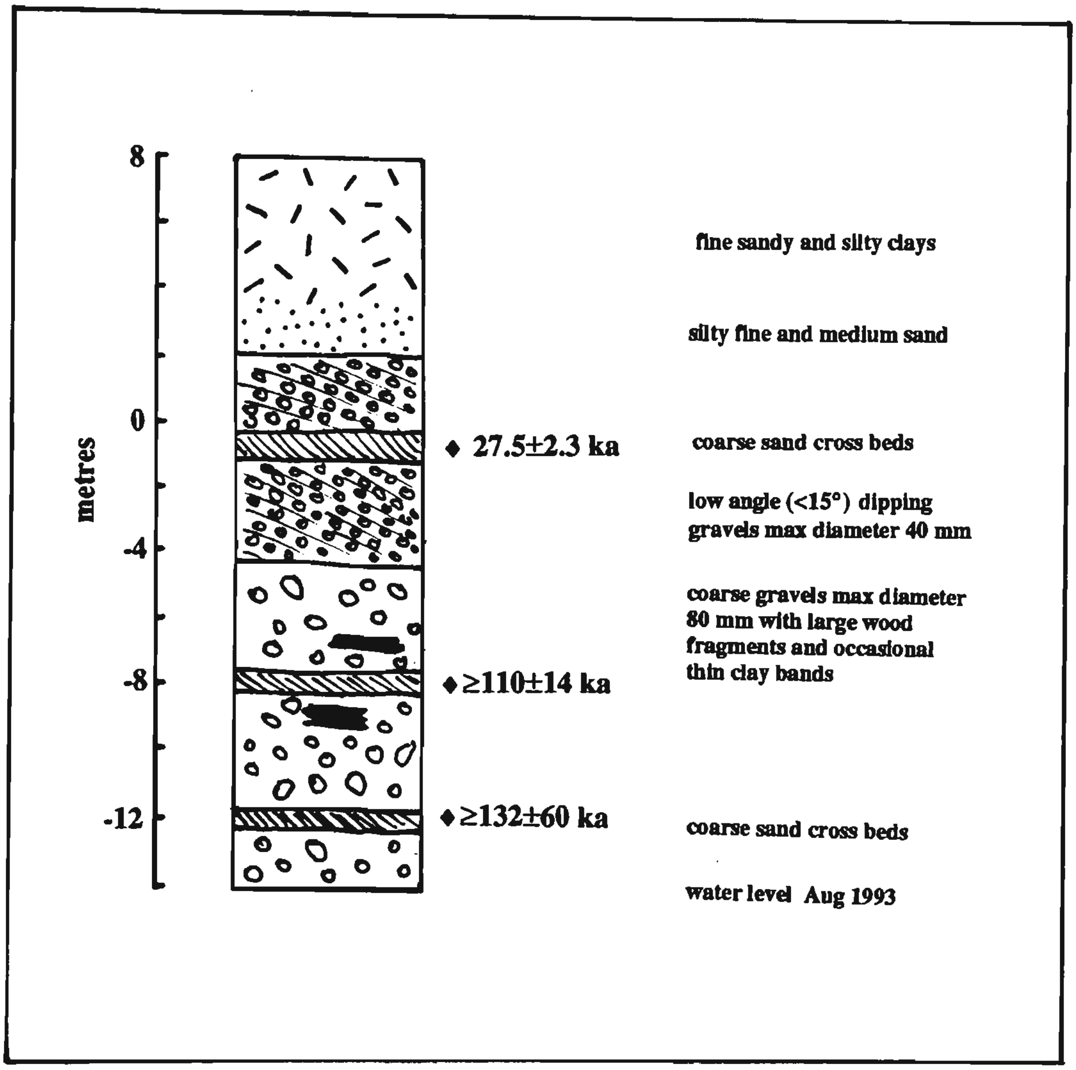


Fig. 6.15. Generalised Holocene and Late Pleistocene stratigraphy of Pioneer Pit near Wagga Wagga showing TL dating sites.

Coleambally System provided the youngest date of all at 11.8 ± 0.7 ka (W905).

The wide age spread of the marginal dune dates is not surprising. Clearly, marginal sand dunes are originally sourced from adjacent channels by deflation from the exposed bed at times of low flow and cannot pre-date the river channel from which they were derived. Of course, persistent channel activity might give rise to dune formation in an early period but not during subsequent phases of stream activity. Once formed a dune might be subsequently re-activated by some combination of aridity, vegetation stress and wind regime. Given that marginal dunes between Wanganella and Moulamein have active crests at present, possibly because of recent overgrazing and rabbit burrowing, it is likely that they would have been mobile during the well-documented phase of enhanced aeolian activity straddling the LGM (Wasson, 1989).

It is provisionally assumed here that TL dates on marginal dunes should not, within the limits of error, exceed ages of sediments in the supplying channel. However, if the dunes were re-activated, TL ages younger than those of the adjacent channel deposits could occur. Figure 6.16 shows a graph of paired TL dates from adjacent river and dune sites on the Murrumbidgee and Murray sectors of the Plain. All dates lie within the zone of acceptable values and hence support the veracity of the TL technique. The group of dates between 20 and 12 ka also supports the previously established peak of aeolian activity at, and following, the LGM (Wasson, 1989; Petit et al., 1990).

Correlation with radiocarbon dating

Direct correlation of TL with radiocarbon was not possible because of the almost total lack of suitable organic material in the dunes and palaeochannels being studied here. Such a comparison remains a priority but must await the location of suitable sites. Radiocarbon dates on the youngest palaeochannel deposits of the Darling River at 19 to 11 ka* (Bowler et al., 1978) and the Goulburn River at 16 to 13 ka* (Bowler, 1978) correlate closely with TL dates on the Murrumbidgee Yanco System from 18 to 13 ka. On the modern rivers floodplain deposits date to approximately 10 ka* (Pels, 1969; Urquhart, 1973; Bowler, 1978) and thus provide a minimum age for the most recent palaeochannels. Attempts to TL date the modern floodplains proved

unsatisfactory because of the large amount of residual TL remaining in these Holocene-age samples. Testing for residual TL in sand on modern point bars on the Murrumbidgee River showed that this deep narrow tree-lined channel results in poor bleaching of the sand fraction and consequently poor-quality and inaccurate TL plateaux. In contrast, the wide shallow palaeochannels offered excellent exposure to sunlight resulting in excellent TL characteristics. The modern floodplain radiocarbon dates also show that a large residual TL component has not inflated the calculated ages of the Yanco System sediments which cannot be younger than 10 ka.

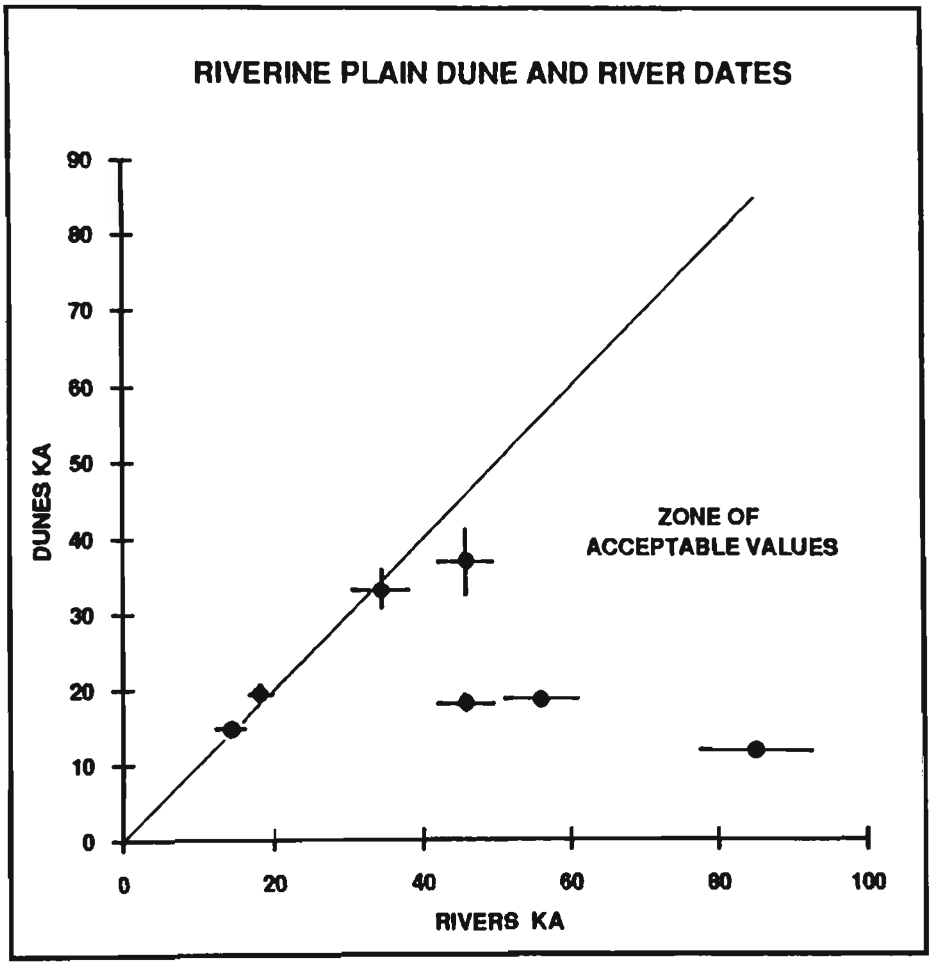


Fig. 6.16. Comparison of TL dates on fluvial and aeolian sands at adjacent sites on the Riverine Plain (includes Murrumbidgee and Murray-Goulburn data).

Comparison of 325°C and 375°C glow peaks

The problem of possible significant residual unbleached TL in fluvial samples dated in the 375°C plateau region has been discussed by Spooner et al. (1988) and Forman (1989). The 375°C glow peak is bleached only by wavelengths < 400 nm (UV) which have very poor penetrating ability in water. As a result fluvial deposits may contain a significant unbleached component upon burial unless they have been exposed at the surface during transport. Although such exposure is considered likely in the wide shallow Late Quaternary palaeochannel environments on the Riverine Plain it cannot be guaranteed. A possible check on the 375°C dates is provided by dates estimated at the 325°C plateau region. The latter glow peak is very readily bleached by exposure to UV depleted sunlight (Spooner et al., 1988) such as is likely to be encountered by sediments being transported in a shallow bed load stream. Despite the disadvantages of the 325°C glow peak outlined in Chapter 4, a subset of 16 of the Murrumbidgee dates was selected and ages were re-calculated using the 325°C plateau. It was predicted that any significant residual TL in the deep 375°C electron traps would result in greater calculated ages than those based upon the readily bleached 325°C plateau region.

Table 6.3 and Figure 6.17 show that dates obtained at the two temperatures are generally very similar (mean 375°C age 42.1 ka compared to mean 325°C age 42.4 ka) and, perhaps more importantly, that the 325°C dates are equally likely to be greater than or less than the 375°C dates. The agreement between the 375°C and the 325°C ages provides confidence that these sediments have been effectively TL minimised prior to deposition. It also supports the idea that well defined temperature plateaux provide reliable TL ages.

Table 6.3. Comparison of TL dates using the 375°C and 325°C glow peaks.

SAMPLE	375°C TL AGE ka	ERROR ka	325°C TL AGE ka	ERROR ka
W1360	33.6	2.5	34.2	3.8
W1362	47.8	6.1	47.7	4.5
W1363	43.2	3.7	41.0	7.2
W1557	15.2	2.0	16.8	1.7
W1558	13.6	1.6	9.8	1.0
W1560	18.2	1.5	19.1	1.9
W906	45.9	3.8	47.0	3.5
W995	25.5	3.5	19.7	3.9
W996	29.8	2.9	26.5	2.8
W997	24.7	2.8	21.2	2.4
W998	29.4	4.6	23.7	5.0
W745	86.8	7.5	106.0	21.0
W746	46.8	3.0	49.5	5.6
W751	34.4	4.0	33.2	6.8
W760	95.3	6.3	99.4	8.6
W758	83.5	7.1	83.8	7.1

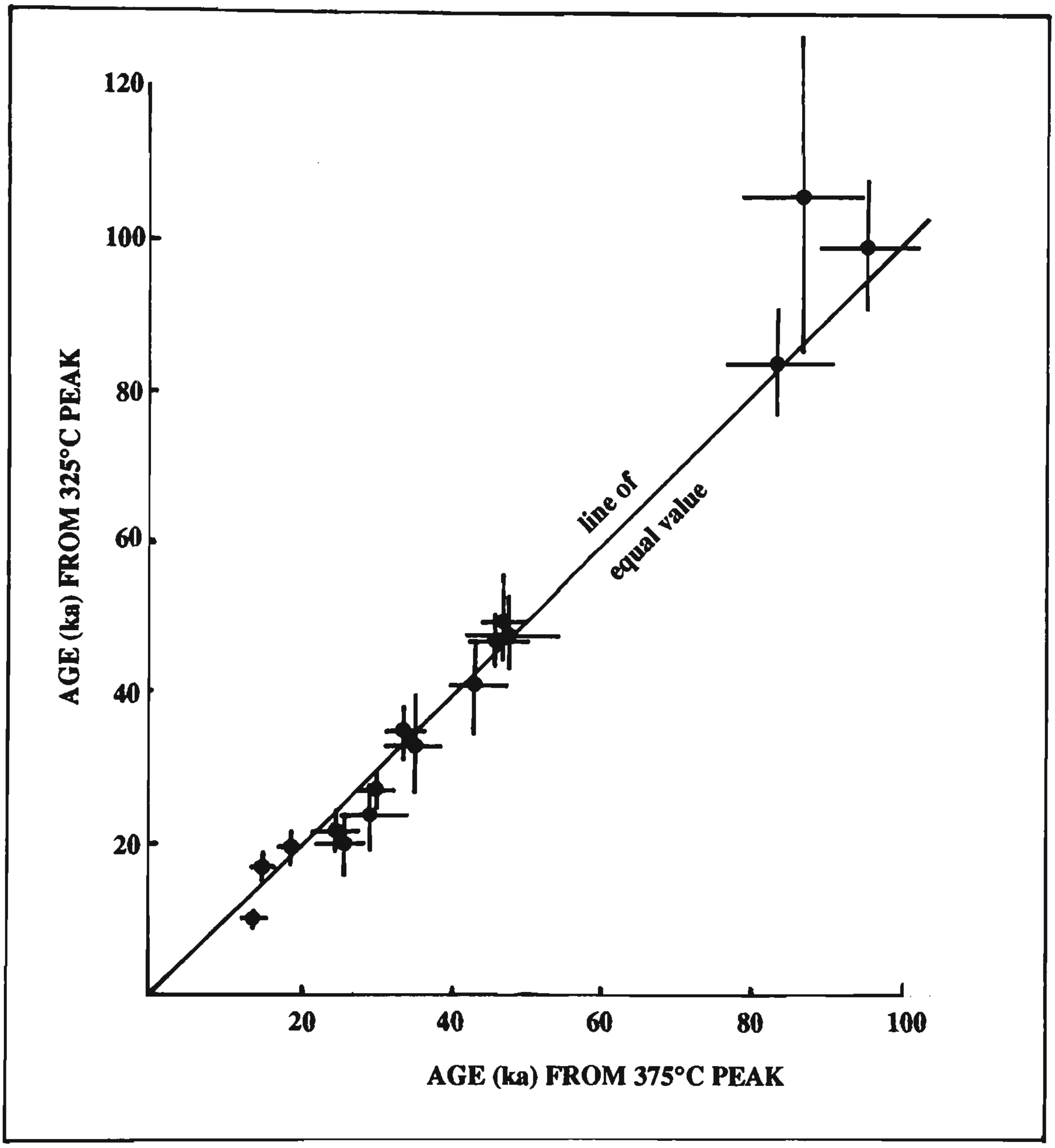


Fig. 6.17. Comparison of TL dates on fluvial sands calculated from 325°C and 375°C plateaux. Errors plotted to one standard deviation.

CHAPTER 7

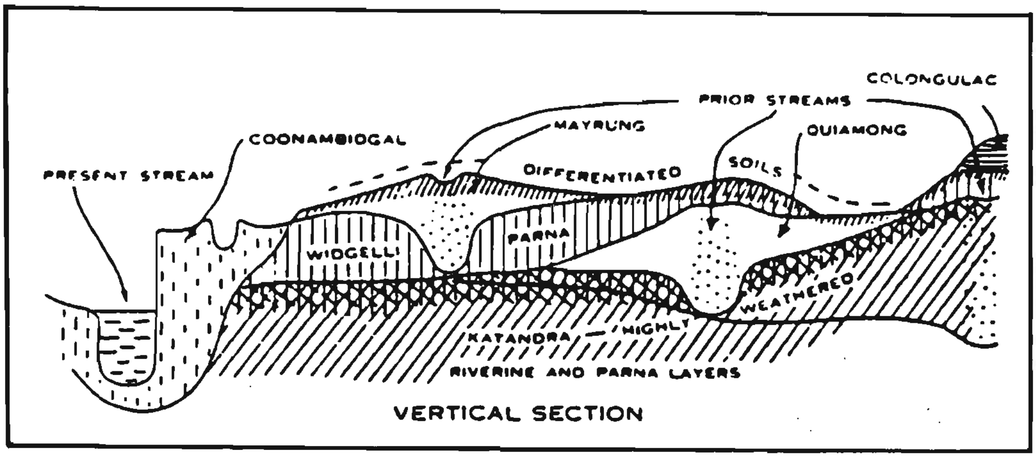
PALAEOCHANNEL STRATIGRAPHY

EXISTING STRATIGRAPHIC MODELS OF PALAEOCHANNEL DEPOSITS

Early models of prior stream stratigraphy were based predominantly upon soil surveys and exposures at roadside pits sunk into the palaeochannels to extract road aggregate. Butler's (1958) idealised section (Fig. 7.1) showed lenses of gravelly sand confined to infills of incised channels. Adjacent to the channels were low levees and laterally tapering wedges of overbank alluvium increasing in clay content with distance from the channel. Schumm's (1968) version of this diagram (Fig. 7.1) emphasised the 'shoestring' nature of the channel fills (and has been adopted by Brown and Stephenson, 1991) but dispensed with overbank sediment wedges in favour of a simple arroyo style cut and fill sequence. Windblown calcareous clay (parna) is a prominent component of Butler's (1958) palaeochannel model. An extensive blanket of Widgelli Parna is shown sandwiched between the earlier Quiamong and later Mayrung Prior Stream phases. The parna was considered by Butler to represent a period of maximum landscape aridity between semi-arid phases of stream deposition.

An interesting feature of both Butler's (1958) and Schumm's (1968) models is the absence of any stratigraphic record of the incised channels associated with postulated humid conditions on the Plain. Given that the incised channels were formed in cohesive sediments and dominated by suspended sediment loads, Schumm's (1963a, 1963b,1969) own research in North America suggests that they were sinuous and subject to, at least modest, lateral migration. Therefore, a stratigraphic record of these channels should exist and include some combination of point bar, oblique, counter point and abandoned channel deposits (Nanson and Croke, 1992). Although gravel pits in prior stream deposits did not often provide exposures of sediments marginal to the aggraded channel, Pels' (1964a) auger hole section across a large Type A prior stream shows a 1300 m wide basal sand unit considerably in excess of the estimated channel width (200 to 300 m). Lateral channel movement before the phase of channel aggradation is implied.

Stratigraphic details of ancestral channel deposits in the vicinity of the Cadell Fault were provided by Pels (1964b) and Bowler (1978). Pels' sections of



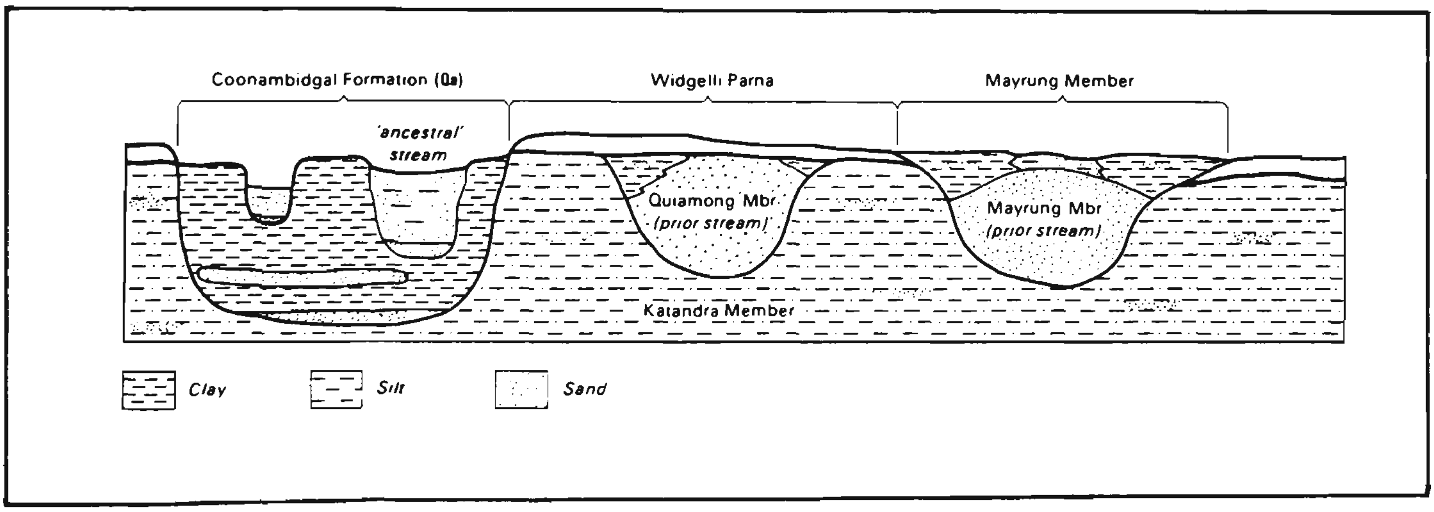


Fig. 7.1. Riverine Plain stratigraphic palaeochannel models of Butler (1958) showing deposits and groundsurfaces (top) and Schumm (1968) showing prior and ancestral deposits (bottom).

ancestral Wakool River and Cochran Creek (Fig. 7.2) revealed 9 m thick units of basal sand and gravel overlain by approximately 3 m of medium and heavy clay. These 2 km wide upward fining units were interpreted as the deposits of streams whose discharge waned during increasingly arid climates (Pels, 1969). Because Pels identified three sequential episodes of ancestral stream activity his model of Late Quaternary hydrologic change closely resembled Butler's (1958) prior stream model in that it required repeated shifts from channel incision during humid phases to channel aggradation during arid phases.

However, upward fining sediment facies do not demand waning stream discharge. Bowler's (1978) Tallygaroopna and Kotupna deposits also include thick gravel and sand beds overlain by sandy loams and clays (Fig. 7.2). These were interpreted as the deposits of large laterally migrating mixed load streams. The preservation of scroll bar topography over these deposits clinches the case for lateral migration and led Bowler (1978) to reject Pels' (1969) oscillating climate model in favour one including a prolonged period of relatively high discharge and stream energy during Tallygaroopna and Kotupna time followed by a shift to the present lower discharge and suspended load dominated rivers.

Bowler (1978) also found scant support for the rigid distinction between prior and ancestral stream periods and modes of activity. He noted that the so-called ancestral deposits of the Goulburn River contain cross bedded pebbly sands and are mantled by well-developed red-brown earths containing pisolitic carbonate. Thus, they strongly resemble classical prior stream deposits found elsewhere on the Plain. His Kotupna channels are also, like many prior streams, flanked by sand dunes produced by deflation of the exposed river bed (Bowler, 1978). Statistically indistinguishable TL dates of 34.4±4.0 ka (W751) and 33.1±2.6 ka (W750) respectively on cross bedded Kotupna fluvial sands and a nearby marginal dune strongly support their contemporaneous formation.

Bowler's (1978) doubts about the classical prior-ancestral stream model have now been confirmed by TL dating which shows that the ancestral Green Gully system on the Cadell Block co-existed with prior streams elsewhere on the Plain and pre-dated the Murrumbidgee Kerarbury System (Page et al., 1991). The need for the development of a new palaeochannel stratigraphic model is

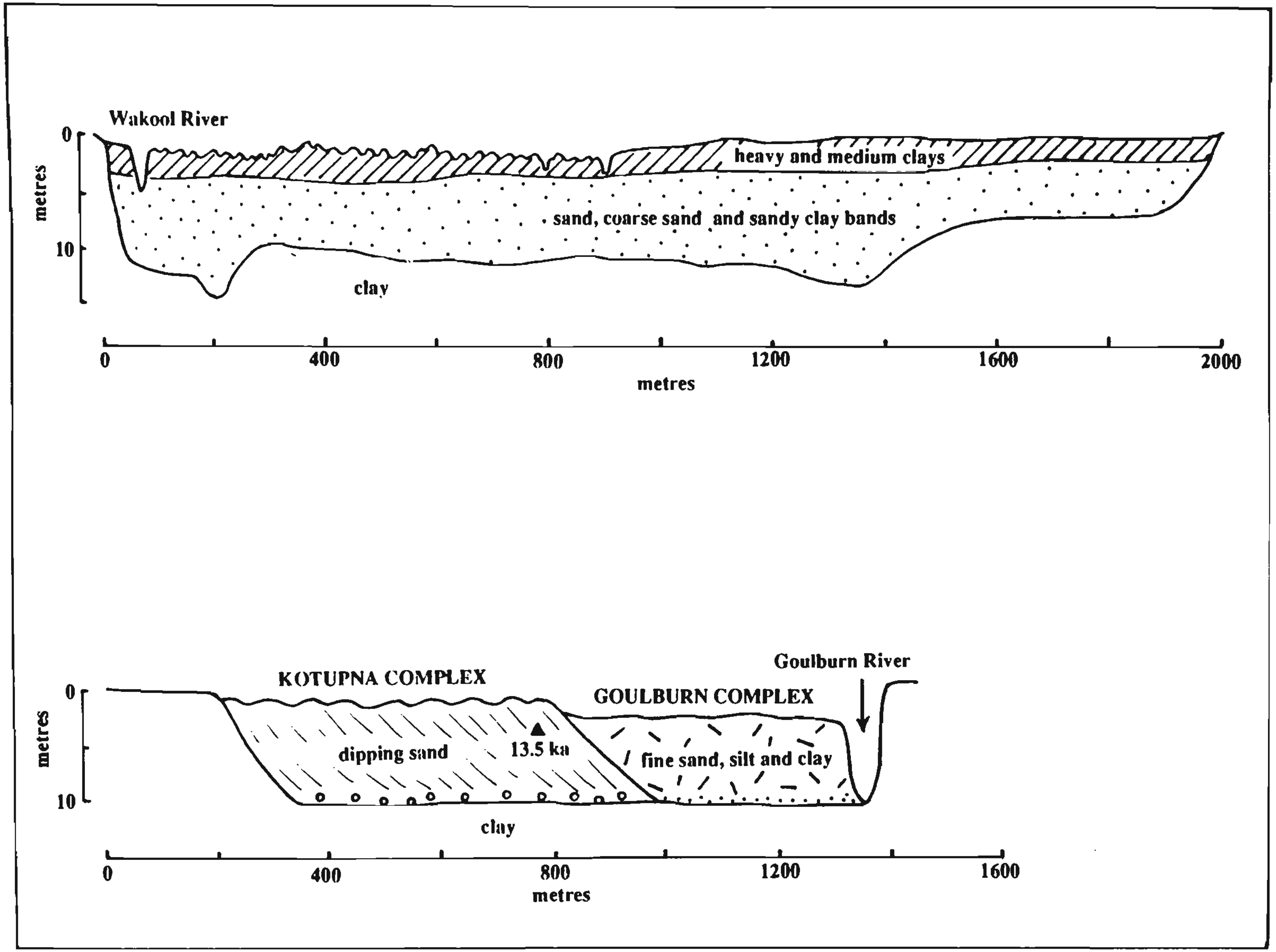


Fig. 7.2. Riverine Plain palaeochannel and floodplain stratigraphy as described by (top) Pels (1966) and (bottom) Bowler (1978).

clear. The Murrumbidgee palaeochannels have not been complicated by the effects of local tectonics and are described by a wealth of stratigraphic data from roadside pits and bore hole sections logged by the NSW Department of Water Resources during their extensive surveys of proposed new irrigation areas in the 1960s. Almost none of the survey data has been published. Taken together with the TL dates, it provides a basis for the development of an entirely new, chronologically calibrated, stratigraphic model.

FIELD STRATIGRAPHY AT PIT EXPOSURES

The surface of the Riverine Plain is dotted with small quarries (borrow pits) which have been opened to exploit the coarse bedload sediments of the palaeochannels for road base and other uses. Because of the 'shoe-string' nature of the channel infills the pits are generally less than 100m wide but may extend for several hundred metres along the channel axis as at Kerarbury, Emery and Hay Pits (Figs. 6.2 and 6.3). At many of the deeper pits the coarse bedload material has been excavated to the maximum depth of channel incision where heavily weathered mottled clays are commonly encountered. These correspond to Butler's (1958) Katandra sediments but are of unknown age. Where working pit faces exist good exposures of the infill sediments and their flow structures are displayed (Fig. 7.5). These faces also provide excellent sites for the collection of TL dating samples because uniform layers of at least 0.6 m thickness can be readily identified. The restricted lateral extent of the pits precludes accurate determination of maximum channel width but typically the thickness of the fine grained overburden increases away from the channel thalweg. Figure 7.3 shows surveyed pit sections on all four of the palaeochannel systems. Details include local ground surface elevation, overburden thickness and the depth of the boundary between the bedload sands and the clay basement. Median grain sizes for the channel infill sediments downstream and across the Plain are summarised in Figure 7.4 (a more complete description of grain size parameters is given in Appendix 2). No attempt was made to carry out an exhaustive statistical survey of palaeochannel infill grain size parameters but the general pattern of median and maximum sizes reveals little variation, either from east to west across the Plain, or from one system to another.

Pit exposures reveal the final bedload aggradational phase of the palaeochannel and therefore provide useful information about channel

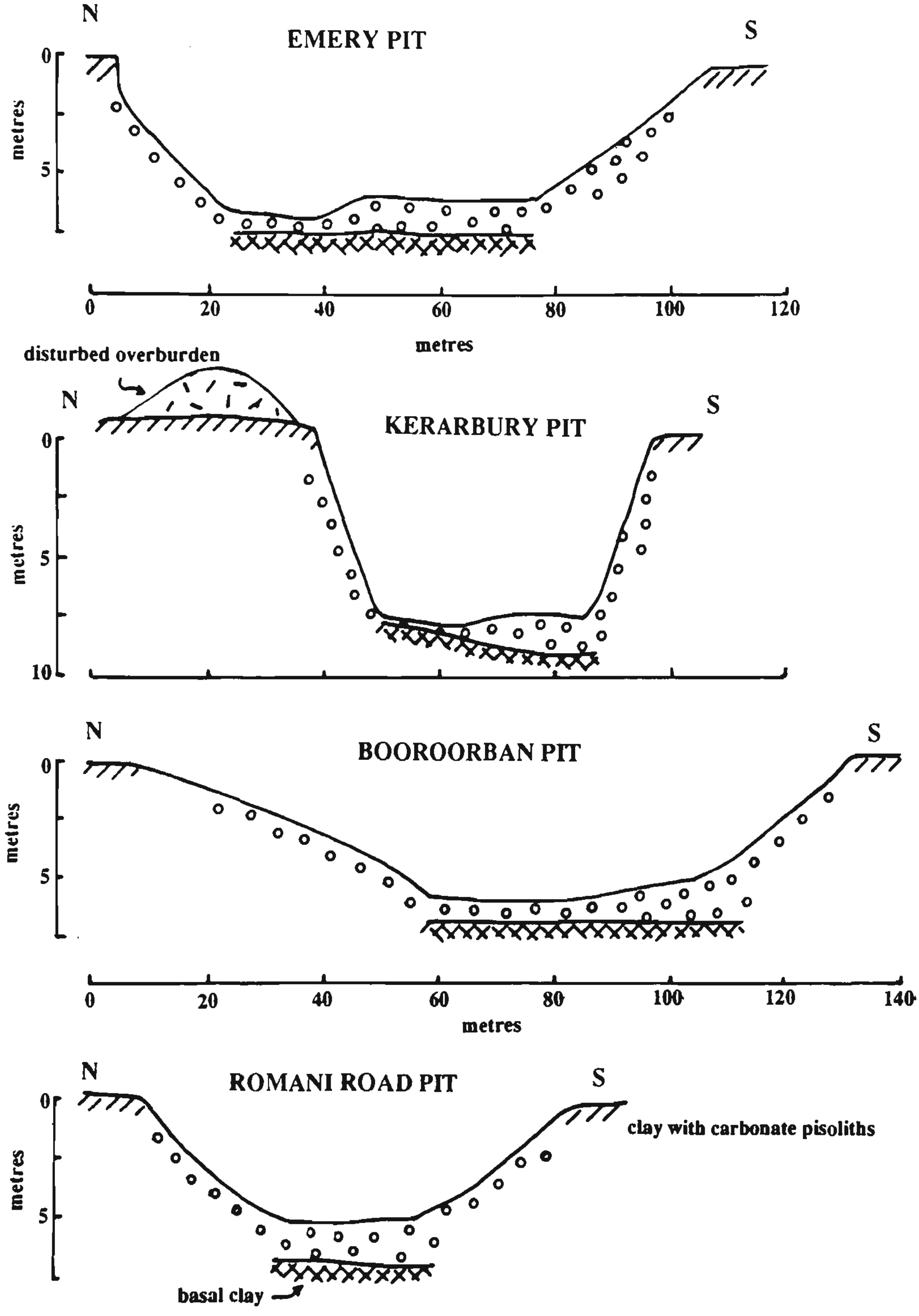


Fig. 7.3a. Surveyed sections at Emery Pit (Coleambally System) and Kerarbury, Booroorban and Romani Road Pits (Kerarbury System) showing surface soil, coarse sandy channel infill and basal clay.

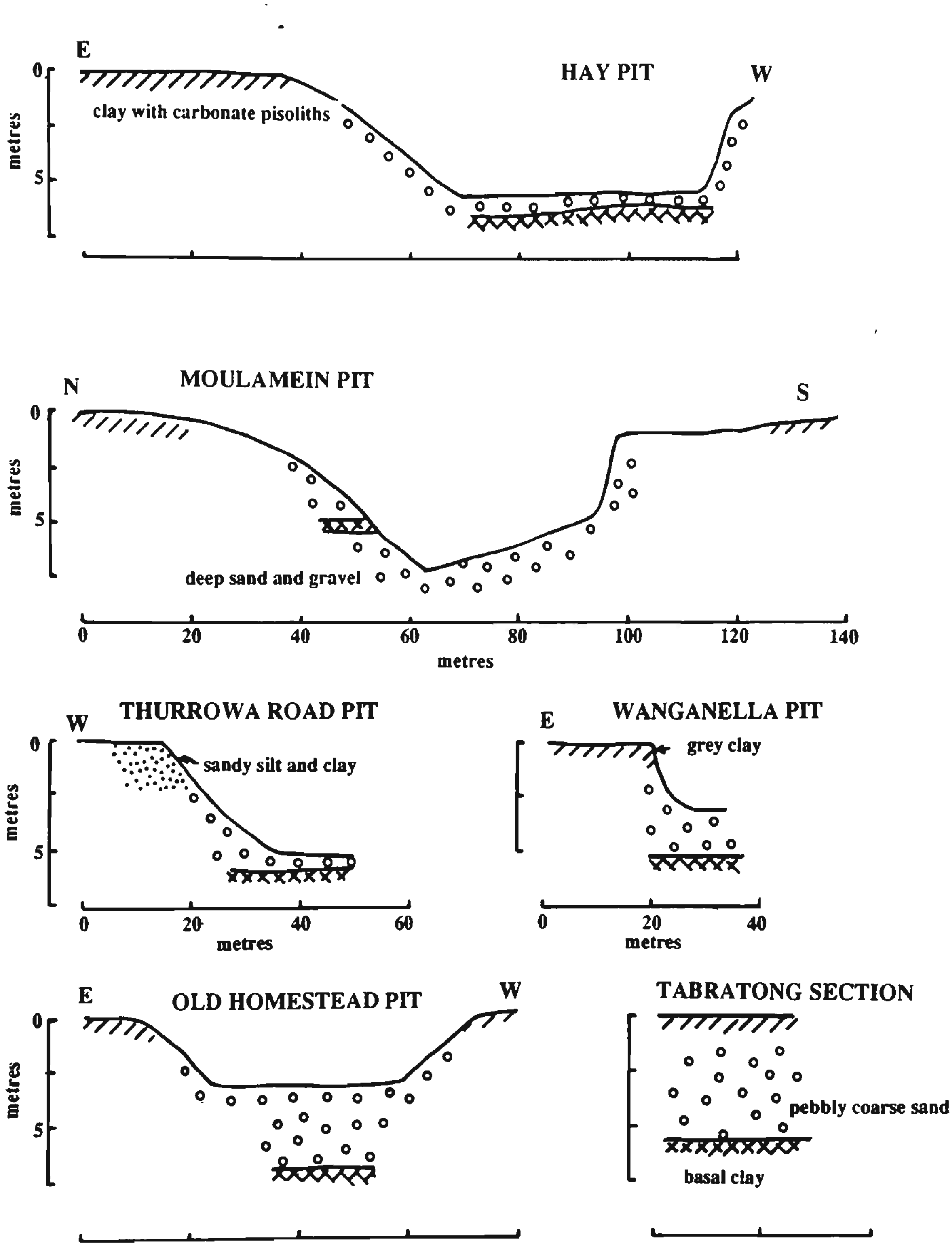


Fig. 7.3b. Surveyed sections at Hay and Moulamein Pits (Kerarbury System) Old Homestead Pit and Tabratong Section Gum Creek System) and Thurrowa Road and Wanganella Pits (Yanco System) showing surface soil, coarse sandy channel infill and basal clay.

conditions at the time. Median grain diameters determined by sieving range from 0.5 to 2.0 mm (coarse to very coarse sand) with minimal variation either vertically at any one section or downstream (Fig. 7.4). However, maximum grain diameters do decrease westwards from 16 - 25 mm at Emery Pit and 8 -16 mm at Kerarbury Pit, to 4 - 8 mm in the central and western regions of the Plain. At Kerarbury Pit maximum grain size also decreased upwards from 8 - 16 mm in the lower 4 m of the fill to 4 - 8 mm in the next 3 m with few grains larger than 4 mm in the sediments up to 2.5 m below the present ground surface. Although not many deep pits occur along the Gum Creek and Yanco Palaeochannel Systems, available exposures reveal a similar pattern of grain sizes with maximum diameters at Thurrowa Road, Wanganella Station, Old Homestead and Tabratong Pits, all being in the 4 - 8 mm range.

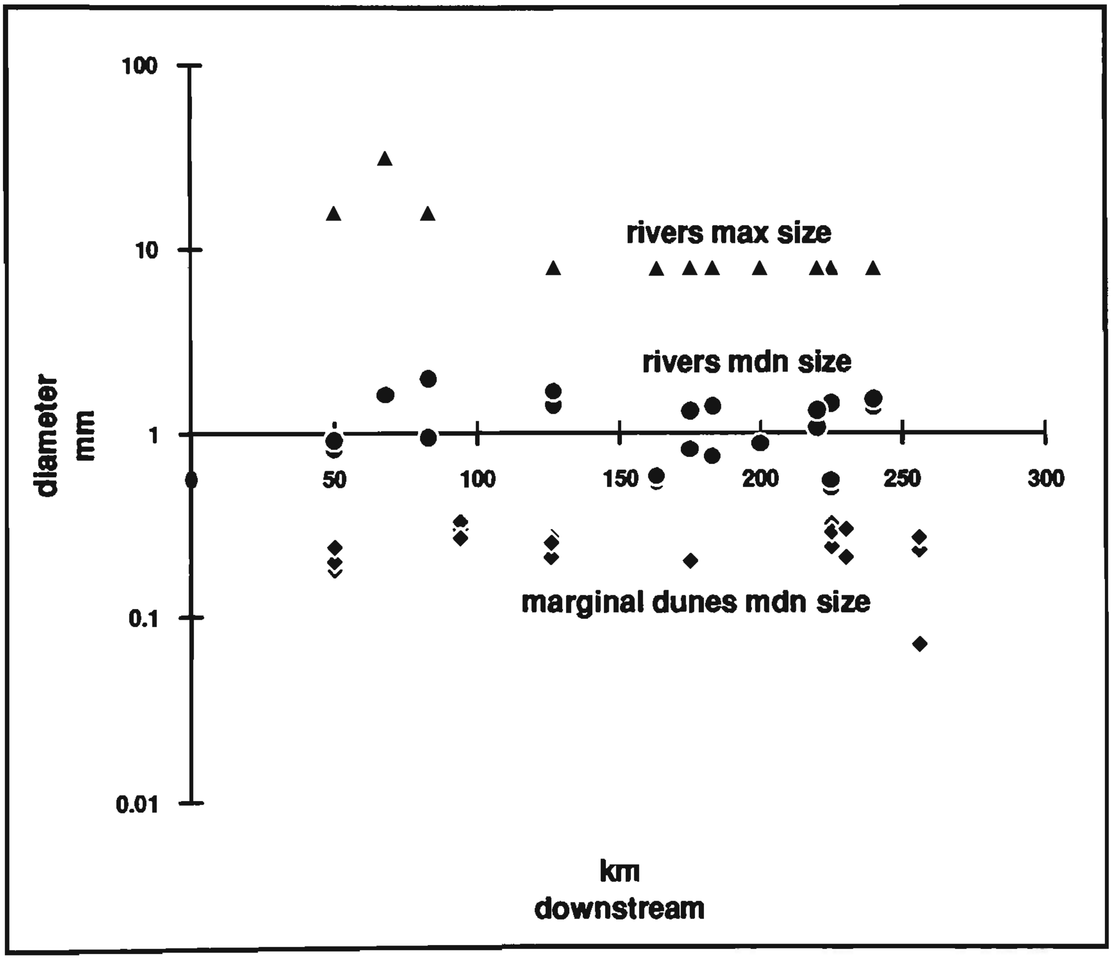


Fig. 7.4. Palaeochannel and marginal dune grain diameters from east to west in the Murrumbidgee sector of the Riverine Plain.

Bedding structures at Kerarbury, Emery and Hay Pits.

Detailed descriptions of sediment bedding structures were carried out at Kerarbury, Emery and Hay Pits where excellent exposures both parallel and normal to the mean flow direction occur in the pit walls (Figs. 7.5 and 7.6) Sedimentary structures in the channel fills are dominated by cross and trough cosets (Pi-cross-stratification) with concave upwards foresets and tangential lower boundaries formed by the downstream migration of curved crested river dunes generally ranging from 0.10 to 0.30 m in height (Allen, 1970b; Collinson and Thompson, 1982; Leeder, 1982; Miall, 1990). Maximum bed amplitude measured was 0.50 m with only rare examples greater than 0.30 m. On the basis of Allen's (1970) data relating dune dimensions to flow depth, these amplitudes indicate formation in flow depths of less than 4 m and mostly less than 3 m. This is not surprising since Leeder's (1982) data show that for grains of 1 mm mean diameter dune forms occur in a range of bed shear stresses from 1 - 7.5 Nm^{-2} with the transition to an upper stage plane bed occurring between bed shear stresses of 7.5 and 14 Nm^{-2}. At shear stresses above 14 Nm^{-2} dunes do not occur. Estimates based on the eastern palaeochannel infills (Kerarbury, Emery and Kulki Pits) indicate that flow depths of less than 0.4 m are sufficient to produce shear stresses of 1 Nm^{-2} and that depths of 3.6 and 5 m result in shear stresses of 7.5 and 14 Nm^{-2} respectively (see Chapter 8 for details).

Ripple cross lamination was not observed at any of the pit faces, but this is not unexpected given that ripples do not normally form in sediments whose mean diameter is < 0.6 mm (Leeder, 1982). Where complete vertical infill sequences are exposed, as at Kerarbury Pit, cross bed thicknesses tend to decrease towards the surface (Fig. 7.6) with maximum values of 0.30 to 0.40 m in the basal 3 m, then 0.20 m in the middle units, and less than 0.15 m in the uppermost 2 to 3 m. This trend is not accompanied by a significant variation in median grain size but maximum grain size does decline sympathetically. These trends are consistent with decreasing flow depths in the aggrading channel. Even at depths of 2 m available shear stresses would have been sufficient to move the full range of grain sizes present (Komar, 1987).

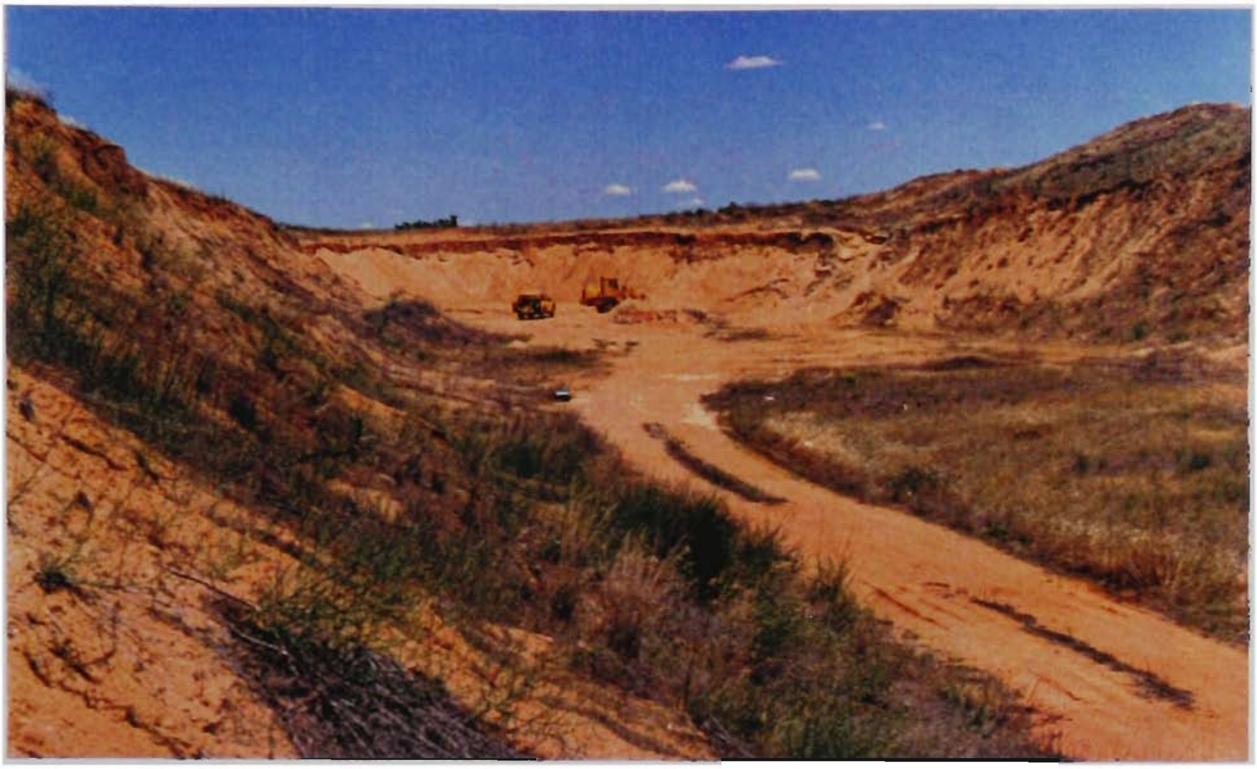
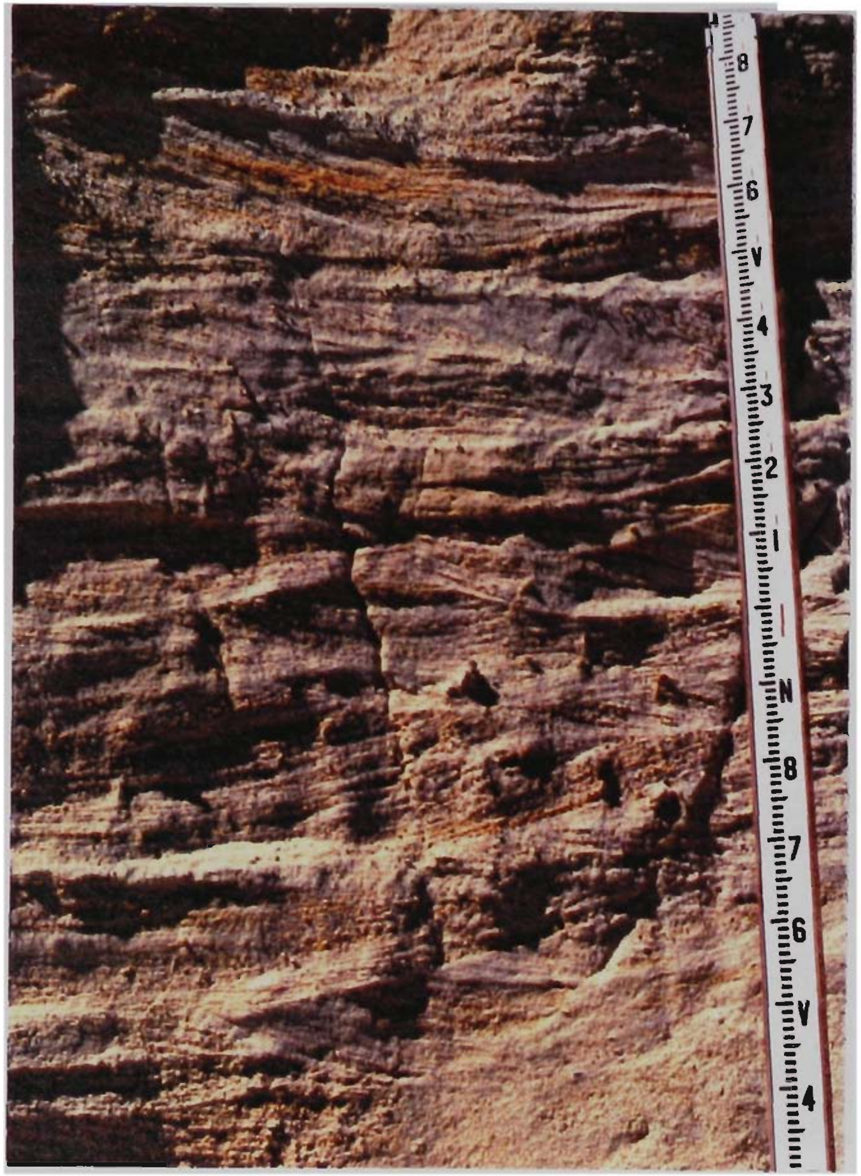


Fig. 7.5a. Photographs of Kerarbury Pit looking west along the palaeochannel (top) and large tabular cross bed set (tape marked in cm) in western pit face 1 m above basal clay (bottom).



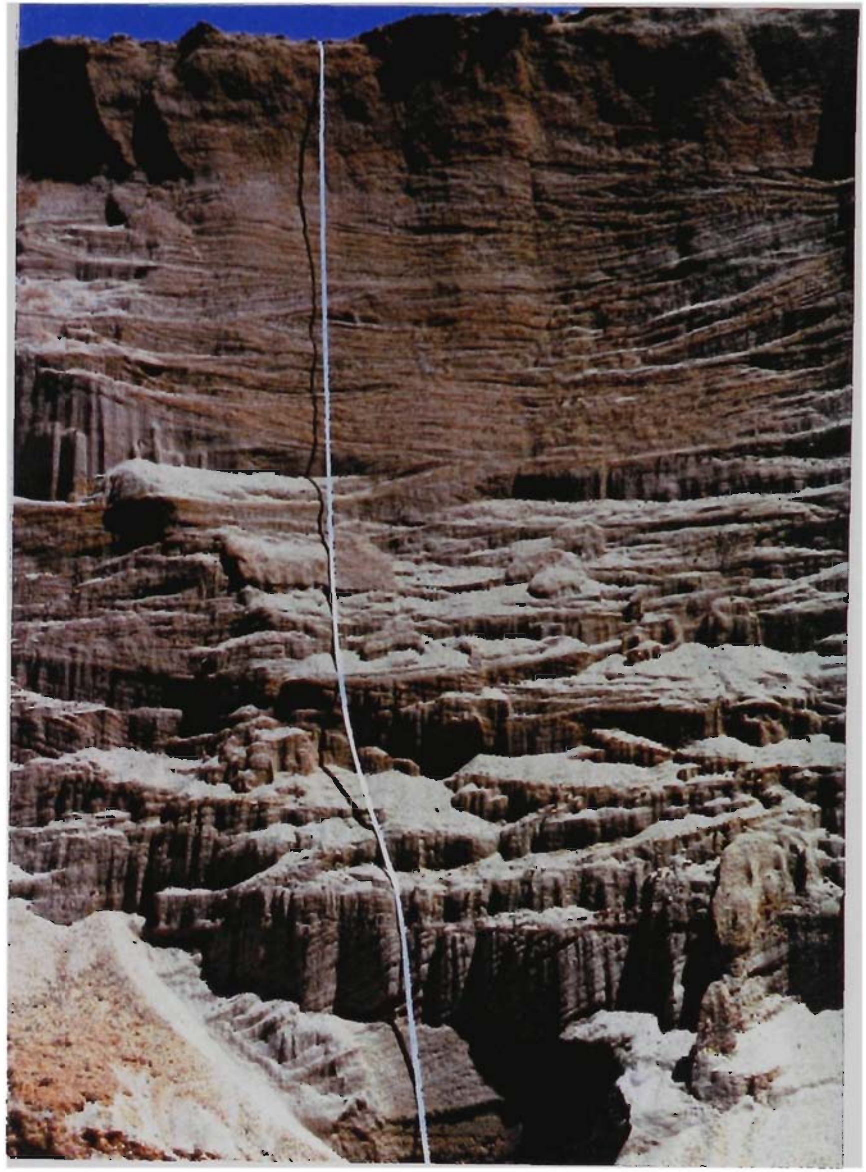


Fig. 7.5b. Cosets of trough beds at Hay Pit (left) and Kerarbury Pit (right).
Note cross beds from Figure 7.5a near base of Kerarbury section.

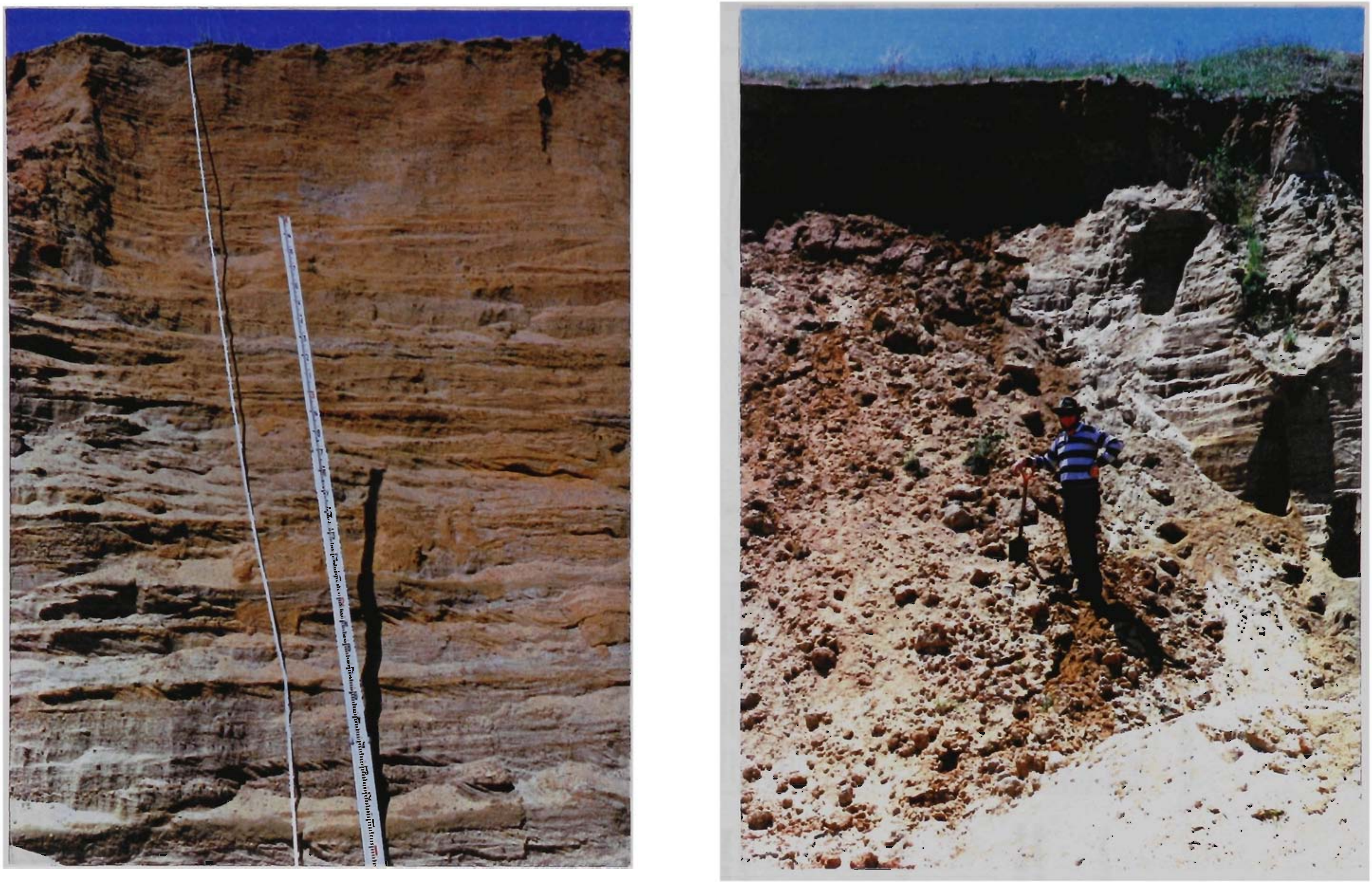


Fig. 7.5c. Tabular cosets of cross beds at Kerarbury Pit in southern face (flow left to right) with metric staff (left) and northern face showing surface red-brown earth soil profile in shadow near top of section.

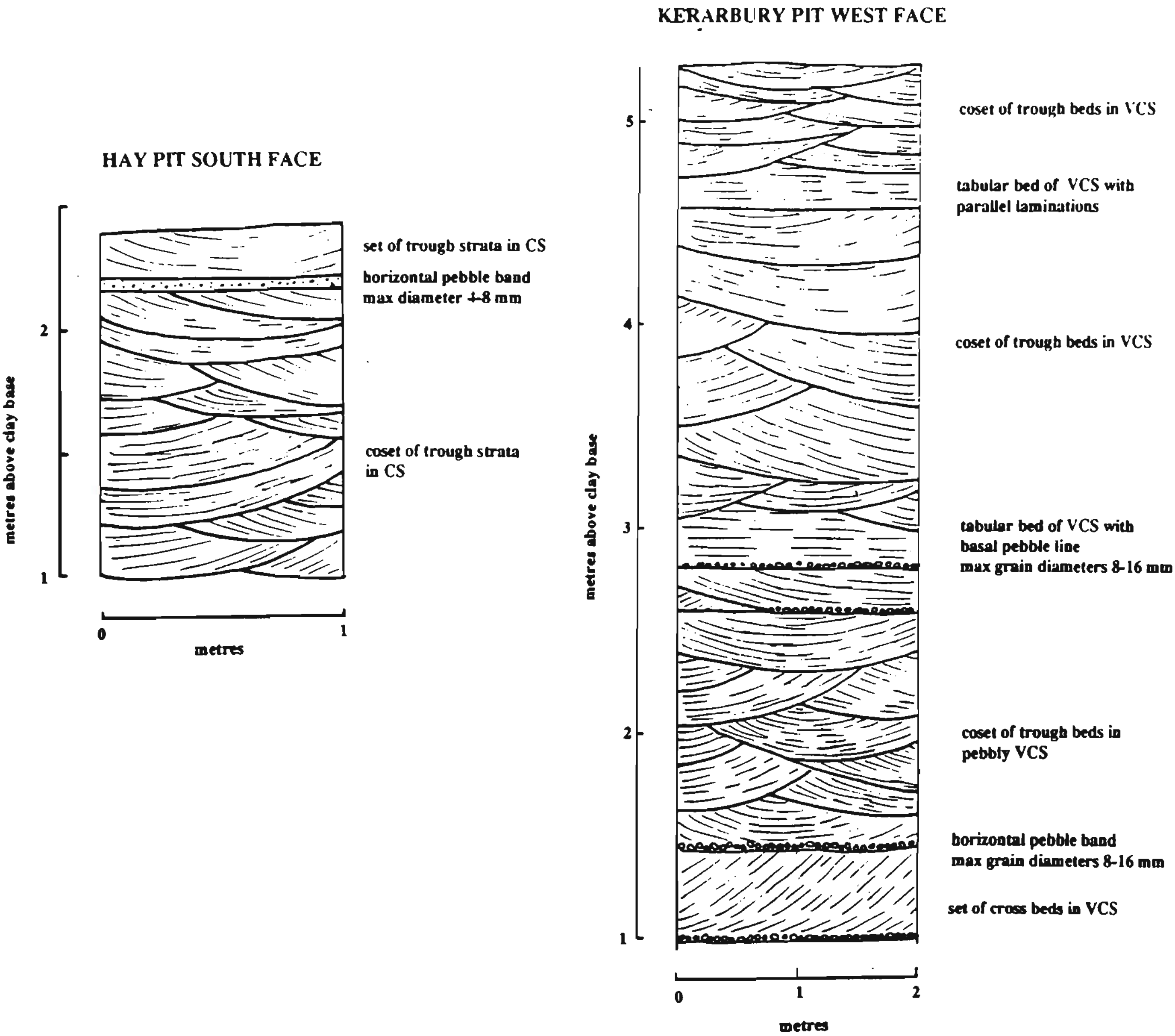
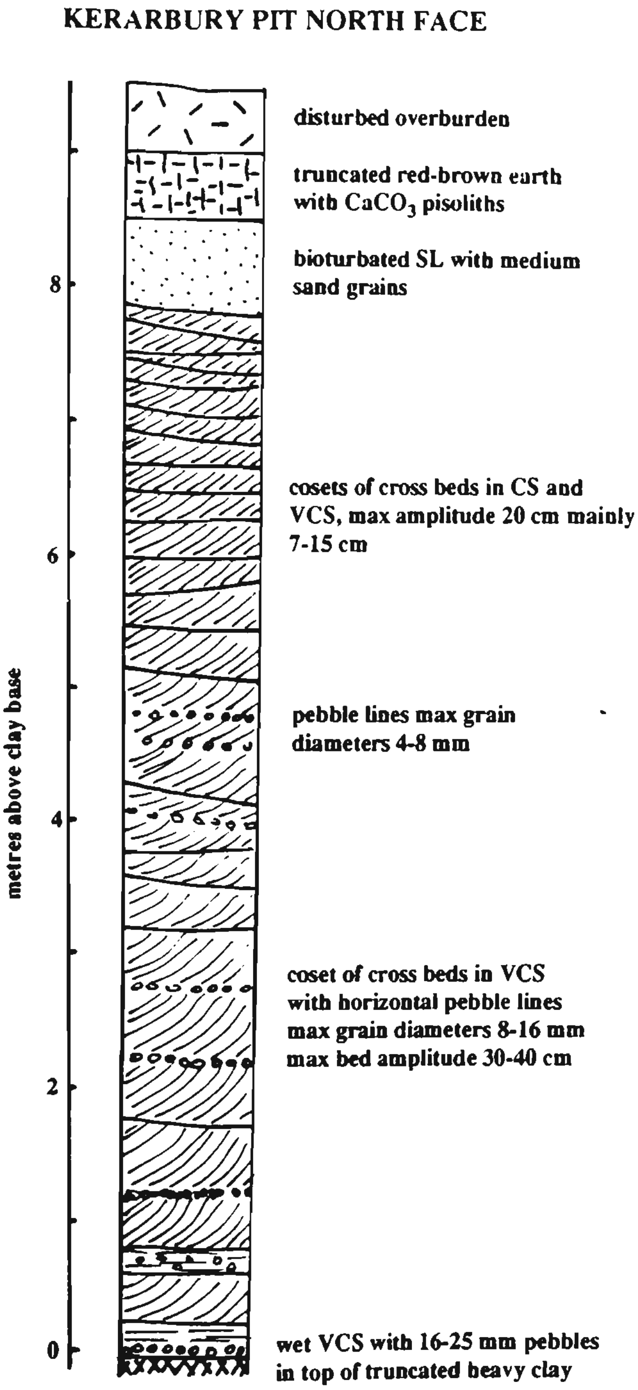


Fig. 7.6a. Details of bedding structures at Hay Pit (left) and Kerarbury Pit (right). See photographs in Figure 7.5b.



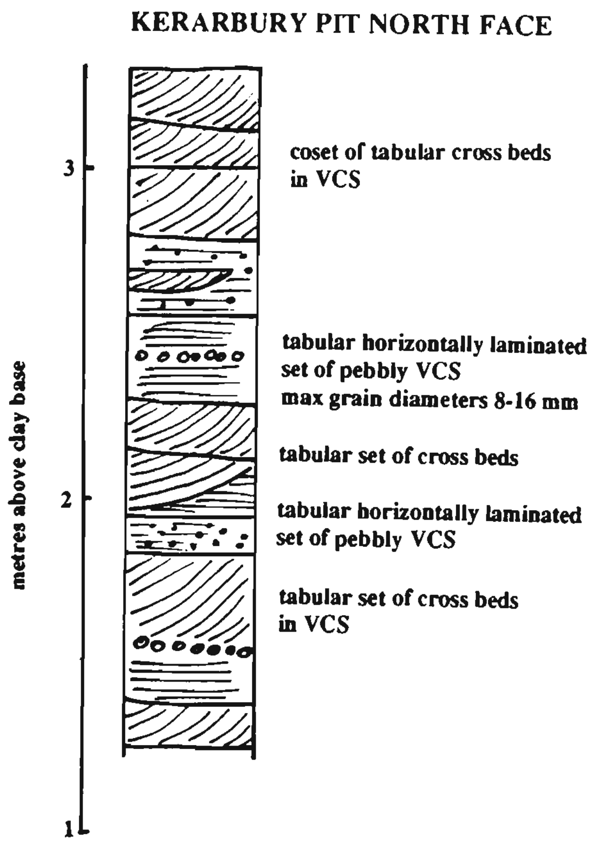


Fig. 7.6b. Details of bedding structures at Kerarbury Pit north face exposure. See Figure 7.5c for photograph of this section.

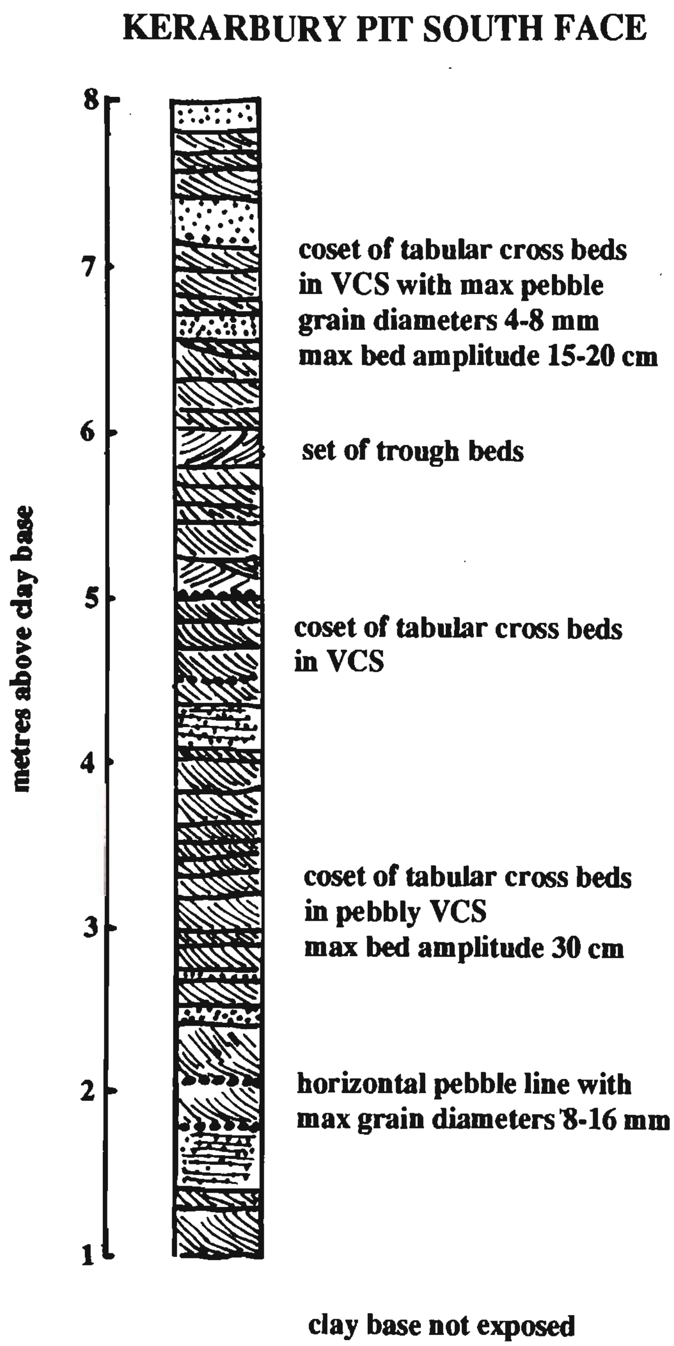


Fig. 7.6c. Details of bedding structures at Kerarbury Pit south face. See Figure 7.5c for photograph of this section.

Surface sediments and soils

At the majority of pits, clean bedload coarse sands extend to within 2 m of the ground surface at the channel thalweg. Above here there is usually a sharp transition to sandy clays which probably include both fluvial and aeolian components. Surface soil profiles are well-developed along the Coleambally and Kerarbury Systems, particularly at slightly elevated levee sites where superior drainage gives rise to bright red duplex profiles, strong pedality and calcareous sub-soil horizons (Table 7.1). Scalding has often removed the lighter textured surface horizons from these soils to leave extensive areas of bare ground that strongly reflect sunlight and show up clearly on air photographs and large scale satellite imagery. The relative ease of recognition of palaeochannels on air photographs compared to their obscurity at ground level is largely the result of the distinctive light reflecting properties of the vegetation that colonises the channels and their adjacent levees.

TABLE 7.1. Profile characters of soils developed on palaeochannel levees.

Coleambally System - Yamma Arm (Kulki Pit)

0-30 cm	Overburden 5yr 3/4	Fine aeolian sand pH 6
30-65 cm	B_{21} 5YR 4/8	Medium clay with coarse sand pH 8 sub-angular blocky peds with abundant cutans and pedotubules
65-105 cm	B_{2Ca} 7.5YR 4/4	Medium clay pH 9 abundant hard $CaCO_3$ pisoliths to 3 cm diameter
105 cm+	C 10YR 5/4	Light medium clay with medium sand grains grading to iron oxide stained coarse river sands

Kerarbury System - Hay Arm (Hay Pit)

0-35 cm	B_{21} 5YR 4/6	Heavy clay pH 7.5-8 angular blocky peds, abundant cutans
35-75 cm	B_{2Ca} 10YR 4/6	Light medium clay pH 8.5 hard $CaCO_3$ pisoliths to 2 cm diameter
75 cm+	C 10YR 5/4	Sandy loam grading to clean medium to coarse river sands

Sub-soil carbonate pisoliths are common in the red-brown earth levee soils of the Coleambally and Kerarbury Systems but also occur in soils of the Gum Creek System which are not subject to present river flooding. Good examples occur on palaeochannels southwest of Yarradda Lagoon (Old Homestead Pit) and north of the Murrumbidgee River between Carrathool and Hay (Tabratong Section and Tabratong Pit).

The carbonate pisoliths are found in well-drained duplex soils and are thus thought unlikely to be the products of groundwater precipitation. A more likely explanation of the carbonate is aeolian dust accession from a westerly source region in the Mallee where calcareous sediments are common. Pedogenic translocation of the carbonate to the sub-soil results in pisolith formation (Butler, 1956; Beattie, 1971). U/Th dates on carbonate pisoliths in soils overlying palaeochannels of different age are consistent with the aeolian accession hypothesis. Palaeochannels TL dated at 37.8 ± 10.3 ka (W938), 56.0 ± 5.2 ka (W1447) and 104.0 ± 9 ka (W904) yielded U/Th soil pisolith ages of 9.8 +1.2 or -1.1 ka (LH0938), 9.0 ±1.5 ka (LH0939) and 10.5 ±1.6 ka (LH0937) respectively. Technical details for the U/Th dates as provided by S A Short (ANSTO) are given in Table 7.2. The statistically indistinguishable U/Th ages approximate the last phase of pisolith formation and are consistent with the well-documented period of Australian continental dune mobilisation

Table 7.2. Uranium-thorium dates and technical data.

ANSTO ID number	Map reference Sample site	$^{234}U/^{238}U$ Corrected[1]	$^{230}Th/^{234}U$ Corrected[2]	Age ka	TL Age[3] ka
LH0937	390400-6116900	1.22±0.10	0.0922±0.0139	10.5±1.6	100.3±9
LH0938	405100-6157200	1.25±0.09	0.0868±0.0101	9.8+1.2,-1.1	37.8±10.3
LH0939	430700-6168500	1.15±0.08	0.0794±0.0129	9.0±1.5	56.0±5.2

Note:
1. $^{230}Th/^{232}Th$ activity ratios for the dilute acid ($CaCO_3$-selective) leach for LH0937, LH0938 and LH0939 were 1.24±0.06, 2.05±0.11 and 1.09±0.06 respectively. Thus it may be concluded that LH0938 is the purest calcrete and gives the most accurate age for calcrete formation. However, all three determinations are clearly highly satisfactory.
2. $^{234}U/^{238}U$ activity ratios (corrected) for the $CaCO_3$ component are the same within error (mean 1.21±0.05) indicating the same regional source of uranium-bearing water.
3. TL dates are for the underlying palaeochannel sands at each site.

(Bowler, 1986a; Wasson, 1989) and dust accession during Oxygen Isotope Stage 2 (Petit et al., 1990; Alloway et al., 1992). The U/Th dates do not support Butler's (1958) view that the major period of parna deposition on the Riverine Plain separated the last two, Quiamong and Mayrung, palaeochannel phases which are probably equivalent to the Coleambally and Kerarbury phases identified in the present study.

Taken alone, the pit exposures are consistent with Schumm's (1968) cyclic arroyo palaeochannel model of alternate incision and aggradation. Maximum incision depth decreases generally to the west from greater than 10 m near Narrandera to only 5 m near Moulamein (Fig. 7.7). This trend is consistent with a decline in the magnitude of flood peak dicharges across the Plain. At present, for example, the mean annual flood peak on the Murrumbidgee River declines from 434 m^3/s at Narrandera to 127 m^3/s at Balranald, largely in response to channel and floodplain storage rather than to a significant loss of total flow (Page, 1988). At most pit sections it appears that maximum channel incision was followed by aggradation until bed levels were less than 2 m below the adjacent levees. During floods these shallow channels would have been particularly prone to levee crevassing and distributary formation (Pels, 1964a).

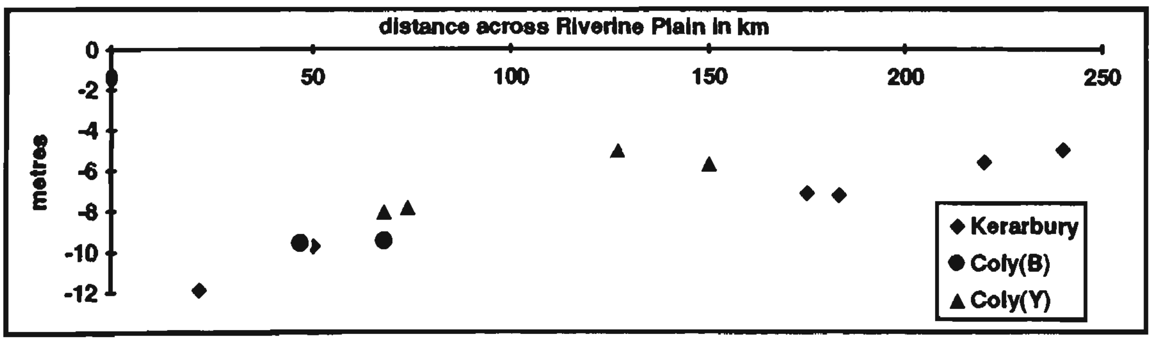


Fig. 7.7. Maximum incision depth of Coleambally and Kerarbury palaeochannels at pit exposures on the Riverine Plain.

WATER RESOURCES DEPARTMENT STRATIGRAPHIC SECTIONS

During the 1960s the NSW Water Resources Department (WRD) carried out extensive topographic and soil surveys of areas intended for future irrigation developments in the eastern Murrumbidgee region of the Riverine Plain. Detailed augering of reaches along all three major palaeochannel systems was carried out at this time. Although sub-surface surveys carried out before 1964 were incorporated into the work of Pels (1964a), Stannard (1962) and Schumm (1968), surveys of the Bundure (Coleambally System), Waddi (Kerarbury System) and Tombullen (Gum Creek System) deposits undertaken since 1964 have not been reported in the wider scientific literature. These detailed high quality data, which were drawn to my attention by Mr Per Gunn (Coleambally Office, WRD), form the basis of the stratigraphic models developed in the present study.

Coleambally Palaeochannel System

The Coleambally Palaeochannel System is the oldest yet to be TL dated and ranges from 105 - 80 ka. It contains one major bifurcation whose arms correspond to Schumm's (1968) Southern and Central Prior Streams. These were respectively named the Bundure and Yamma Streams by the WRD.

Bundure Arm

In November 1967 M. Stannard presented an in-house report to the WRD on a 20 km reach of the Bundure Arm downstream of its bifurcation with the Yamma Arm (Fig. 6.1). This reach is characterised by low sinuosity (1.3) and has typical prior stream features including low levees. Twenty cross sections, each between 600 and 1000 m long, were surveyed relative to Australian Height Datum (AHD) along the reach (Fig. 7.8). At each section, bore holes from 2 to 20 m deep and spaced 80 to 100 m apart were logged for soil colour and Northcote (1979) field textures. Other characters such as the presence of carbonate and manganese and the maximum diameters of coarse grained sediments were also noted. The survey reach was approximately 20 km upstream of Bundure Pit where channel infill sediments were dated at 104.0 ± 9.0 ka.

Profiles of ground surface and basal clay elevation along the reach indicate a mean slope of 0.00026 (Fig. 7.9). Figure 7.10 shows stratigraphic details at

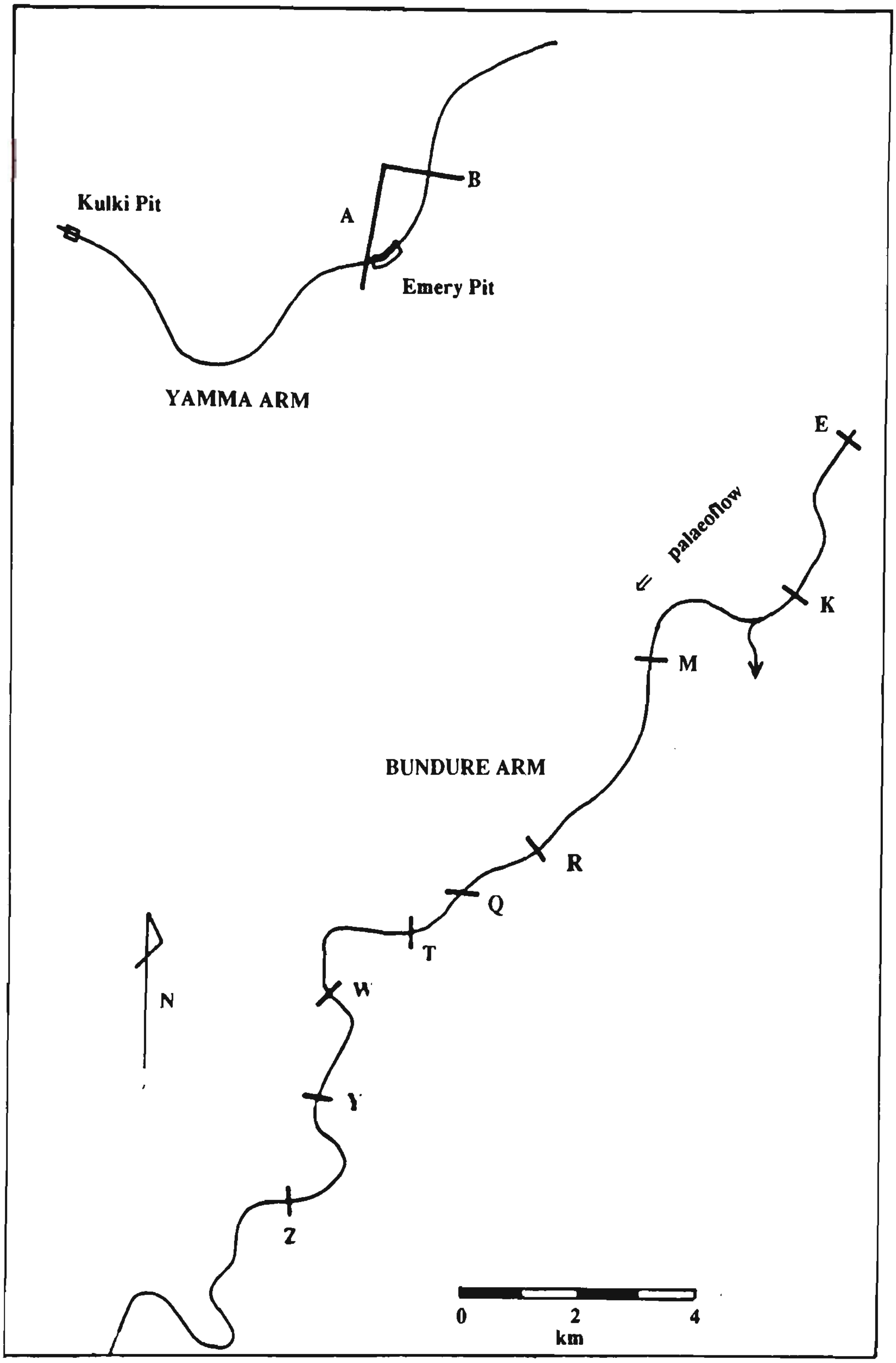


Fig. 7.8. Map showing locations of selected WRD auger hole sections on Yamma and Bundure Arms of Coleambally System.

Stannard's Sections Q, T, W and Z. which are all located on bends of the Bundure channel and therefore present the best potential for the preservation of floodplain deposits formed by lateral channel migration. All sections show characters consistent with those observed at pit exposures. Directly beneath the surface expression of the palaeochannel, classical vertical sediment sequences of 6 to 8 m of pebbly coarse sands (maximum diameters 10 to 16 mm) overlain by 2 to 3 m of fine grained sediment rest unconformably upon a heavily weathered and mottled clay basement similar to Butler's (1958) Katandra surface. Exceptions to this pattern occur only where the Bundure channel intersects the deeper sands of earlier palaeochannels which may extend to depths of more than 20 m below the present ground surface. Such locations are significant agriculturally because of potential losses of irrigation waters to deep aquifers.

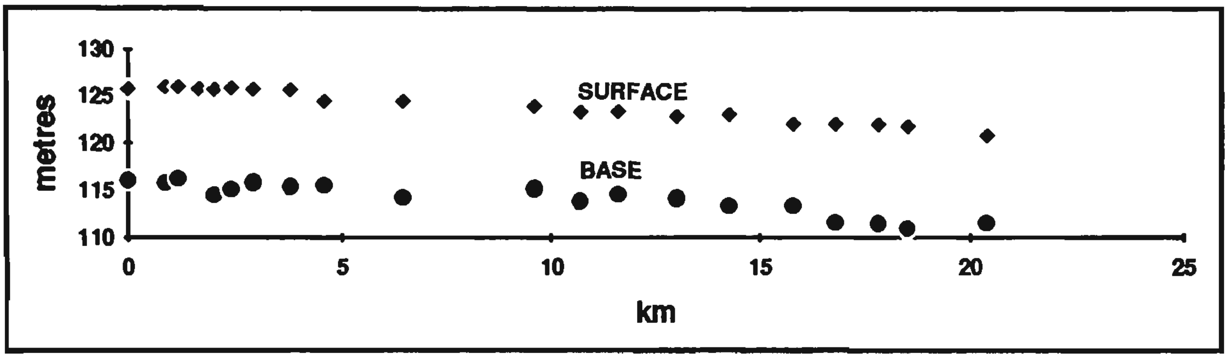


Fig. 7.9. Longitudinal profile of Coleambally (Bundure Arm) palaeochannel at WRD Sections.

At Sections Q and T the complete Bundure sequence of deposition is revealed. Floodplain deposits up to 600 m wide include approximately 400 m of upward fining sediment bordering 200 m wide sections of vertical accretion. The floodplain units include 1 to 4 m of pebbly coarse sand overlain by 4 to 6 m of clay loams and then clays with strong pedogenic characters comprising the uppermost metre. Section T is complicated by a shallow sand-filled channel which is clearly visible on air photographs and probably formed as a crevasse splay through the levee. Although the horizontal sequence is incomplete, Sections W and Z reveal similar patterns to those found at Q and T. Although mean auger hole spacing of about 90 m on the Bundure sections makes it difficult to estimate pre-aggradation channel width with

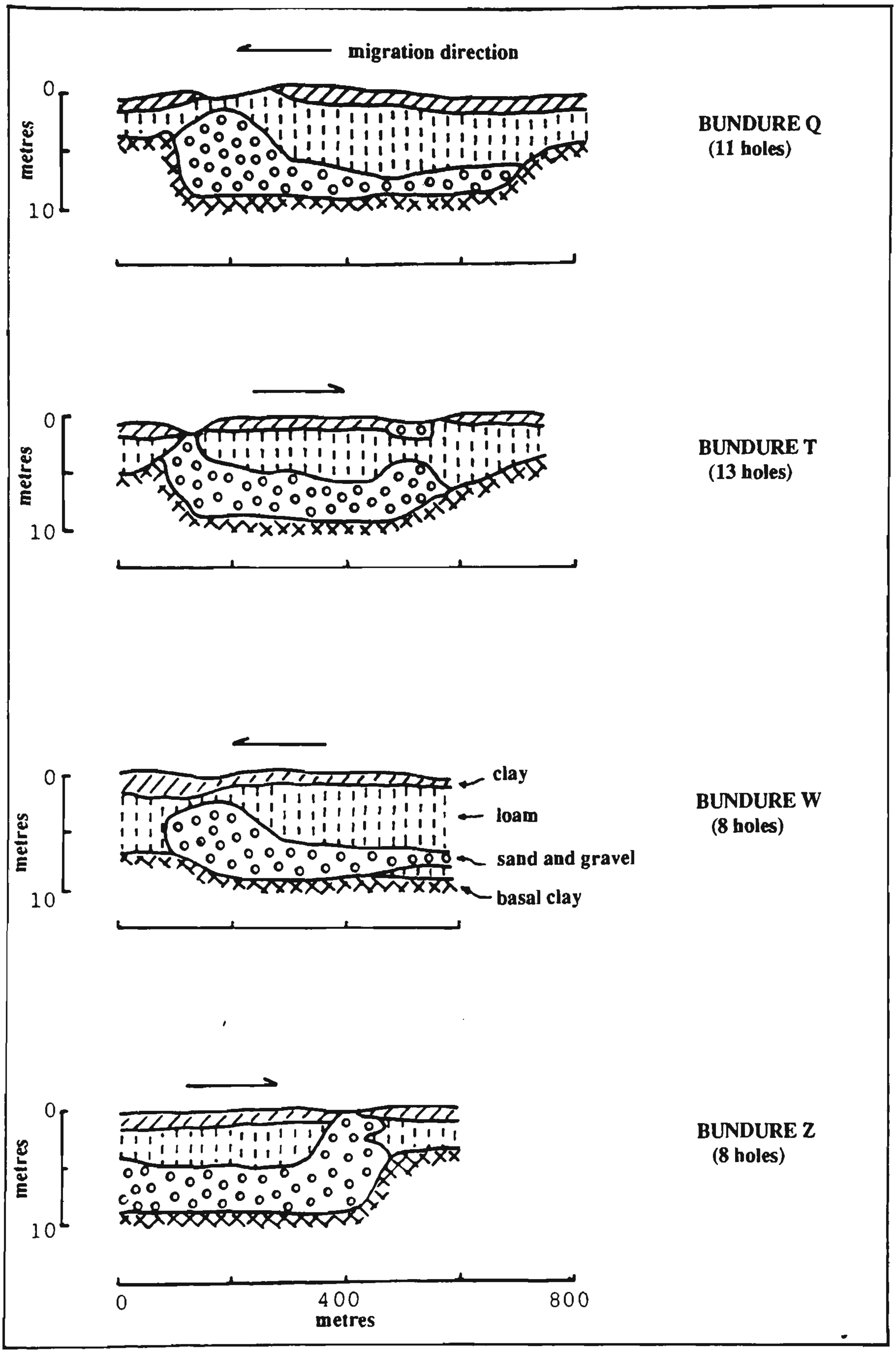


Fig. 7.10. Palaeochannel stratigraphy at Sections Q, T, W and Z on the Bundure Arm of the Coleambally System. Channel migration direction determined from air photographs. All section viewed from downstream.

precision, on the basis of the width of the vertically aggraded channel fill at Sections Q, W and Z, a value of between 150 and 200 m is considered likely.

The sequence of Bundure channel development is interpreted as follows:

1. The channel incised to a depth of 8 m to 9 m below the general level of the Plain.

2. Limited lateral channel migration by a mixed-load river produced a trailing sequence of upward fining sediments at the insides of bends immediately before ~100 ka. These vertical sediment sequences are consistent with basal channel and point bar deposits overlain by oblique upper bank and overbank deposits (Nanson and Croke, 1992).

3. The channels aggraded by coarse sandy bedload deposition to within 2 m of the Plain surface. Low levees were deposited during the vertical accretion phase with a final channel depth about 2 m below the levees which themselves rose 0.5 to 1.0 m above the backplain. These shallow aggrading channels were prone to avulsion through levee crevasses such as that at Section T. Source bordering dunes did not develop during this phase of channel aggradation.

4. Abandonment of the Bundure channel occurred by avulsion upstream at about 100 to 90 ka to form the Yamma Arm. Post abandonment activity has been restricted to the accession of calcareous dust and prolonged pedogenesis with the last period of carbonate pisolith formation occurring at about 10 ka. Minor erosion of levee soils by scalding, perhaps as the result of the advent of livestock grazing in the period of European settlement, is apparent along the Bundure channel.

Yamma Arm

The Yamma Arm of the Coleambally Palaeochannel System can be traced west from its bifurcation with Bundure Arm to Booroorban (Fig. 6.1) where it is obscured by younger Kerarbury System deposits. The reach surveyed by the WRD in 1962 has a sinuosity of 1.1, a maximum depth to basal clay of about 8 m and a channel slope of 0.0003. The latter value was determined on 1:50000 topographic maps because WRD surveys across channel sections

were not related to a common datum. Maximum bed load sediment grain diameters noted in auger holes ranged from 16 to 25 mm consistent with those examined in Emery and Kulki Pits.

Of several sections surveyed by the WRD on this reach only Sections A and B, located downstream and upstream respectively of Emery Pit, on an open bend (Fig. 7.8), provide sufficient stratigraphic information at depth to permit the confident interpretation of floodplain deposits. Auger hole depths and spacings here were similar to those reported for the Bundure sections.

Section A, which extends for a horizontal distance of nearly 1300 m, indicates alternate phases of lateral migration and vertical aggradation over at least that distance (Fig. 7.11) during a lengthy period before ~85 ka. At the northern 400 m of this section a 1 m unit of basal coarse sand is overlain by 6 to 7 m of loam and clay. Following lateral migration to the south the channel encountered older deep palaeochannel sands and, perhaps because of the additional sand supply, aggraded to within 3 m of the surface. However, channel activity did not terminate with an avulsion but continued with renewed lateral migration over a distance of 550 m and the deposition of a 2 to 3 m basal unit of coarse sand overlain by about 5 m of loam and clay in an upward fining sequence. Finally, the channel aggraded to produce a lenticular coarse sand body 5.5 m thick and mantled by only 2 m of fine grained sediment probably containing some calcareous aeolian dust. Channel activity then ceased, pehaps because of an upstream avulsion, but this is obscured by the more recent activity of the Yanco System.

Section B extends for only 600 m at depth but reveals a similar pattern of sediment variation to the equivalent part of Section A (Fig. 7.11). Lateral migration deposits comprise 2 to 2.5 m of coarse sand overlain by 5 m of loam and clay and extend for at least 400 m before passing horizontally into a 5.5 m lenticular sand unit beneath the Yamma palaeochannel.

Channel width immediately preceding the final aggradational phase is estimated on the basis of the lenticular infill geometry at 170 m at Section A and 200 m at Section B. TL dates on the infill indicate an age of between 90 and 80 ka for channel termination. Stratigraphic detail at the two Yamma Sections is broadly consistent with that found along the Bundure Arm and clearly shows that pit exposures alone do not provide a complete picture of

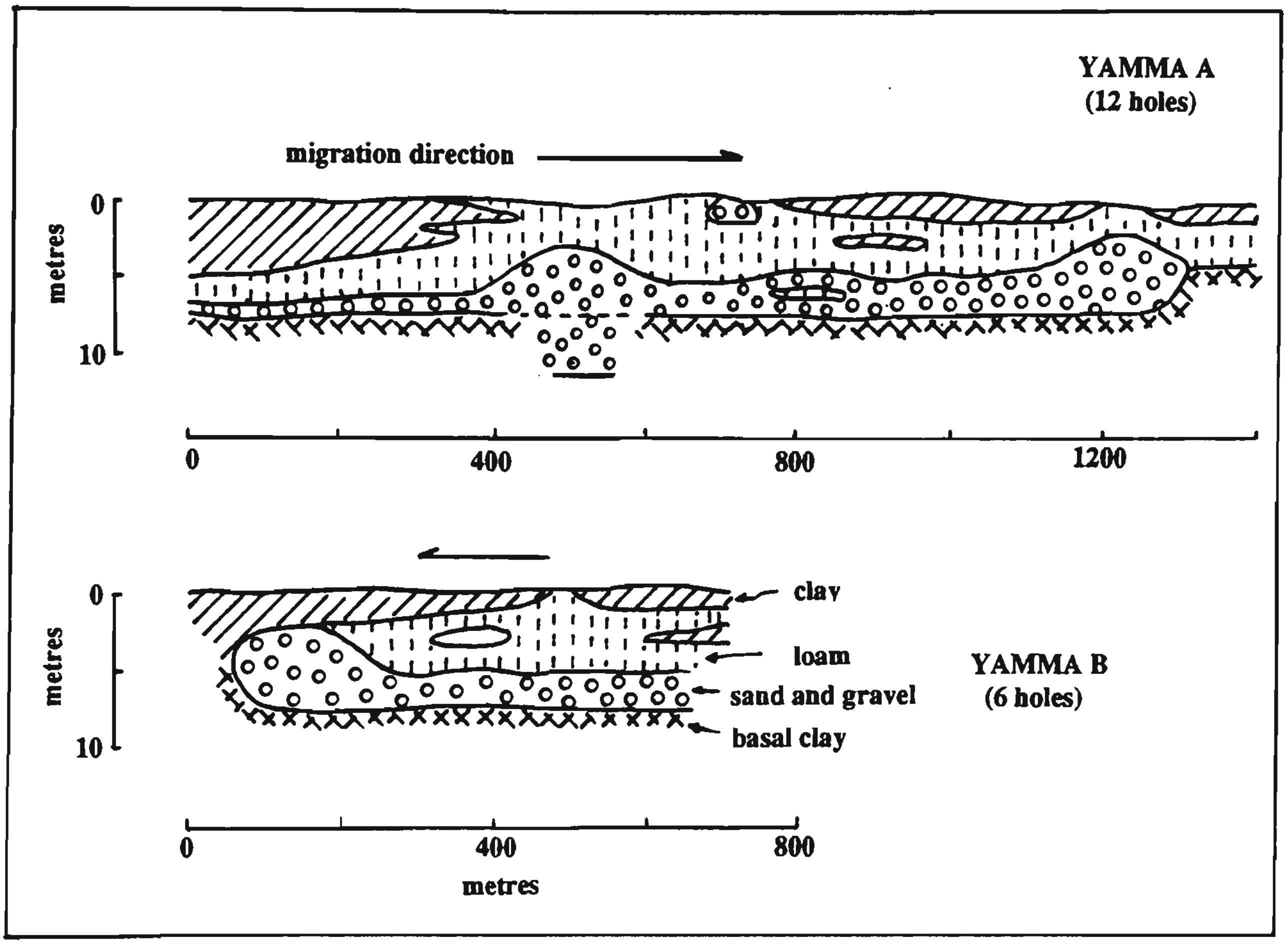


Fig. 7.11. Palaeochannel stratigraphy at Sections A and B on the Yamma Arm of the Coleambally System. Channel migration direction based on bend configuration (Fig. 7.8). Both sections viewed from downstream.

palaeochannel stratigraphy and sequential development. Although it is clear that the palaeochannels terminated in a phase of bedload aggradation (Pels, 1969), earlier phases of upward fining sedimentation point to the alternation of channel conditions between mixed-load stable and bedload aggrading. Bowler's (1978) suggestion that phases of prior stream activity might be preceded by phases of lateral migration by mixed-load streams is strongly supported by the WRD sections.

A total distance of lateral channel migration in excess of one km at Section A is consistent with a prolonged period of stream activity. Bowler (1978) and Bowler et al. (1978) estimated lateral migration rates of up to 20 cm/y on palaeochannels of the Goulburn and Darling Rivers. This rate, which is two to three times greater than those estimated on the present Murrumbidgee near Wagga Wagga (Owens, 1992), is consistent with over 5000 years of activity by the Yamma channel.

Trough and cross bedded coarse sands at pit exposures suggest that the Yamma Arm terminated as a wide, shallow (2 m deep) channel bordered by low levees and, in places, wind blown dunes to the north and east. Although the dunes become subdued to the west of Kulki Pit their presence here suggests that the Yamma and Bundure Arms were not simultaneously active. A small dune southwest of Emery Pit was TL dated at 11.8 ± 0.7 ka. Given that these marginal dunes were initially deflated from the exposed river bed, this young date is consistent with remobilisation of the dune in the period following the LGM when widespread aeolian activity occurred in continental Australia (Wasson, 1989).

Kerarbury Palaeochannel System

The Kerarbury Palaeochannel System dates from about 55 to 35 ka and is equivalent to Schumm's (1968) Northern Prior Stream and the WRD Waddi Stream. The trunk Kerarbury channel can be traced across the Plain from the western side of Tombullen Swamp to Moulamein (Fig. 6.1) where it is obscured by recent channels and floodplains of the Edward and Murray Rivers. In the northeastern region the Kerarbury channels are cut by both the modern Murrumbidgee and the Gum Creek System which clearly postdate it.

Although the Kerarbury System is similar in many respects to the older Coleambally System upon which it is superimposed in the southwest, it does exit the Plain as a major palaeochannel and clearly demonstrates that not all of the prior streams dissipated before reaching the Mallee region (Butler, 1958). Near Moulamein the Kerarbury channel is particularly well-developed occurring as a slightly elevated sinuous depression bordered by low scalded levees that are conspicuous on air photographs. Throughout its length the trunk channel is bordered by sand dunes to the north and east. Marginal sand dunes also occur along the Benerembah Arm (Pels, 1964a) and the Romani Arm northwest of Booroorban but are poorly expressed or absent on both the Hay and McGrath Arms. Clearly, marginal dune formation was not a continuous phenomenon during the Kerarbury phase.

Surveys of the Benerembah Arm by the WRD were described by Pels (1964a) who identified a hierarchy of distributary channels that he interpreted as indicating climatically forced cycles of channel incision and aggradation. Subsequently, in 1966-67, a 27 km reach of the Kerarbury trunk channel between Tombullen Swamp and Yarradda Lagoon was surveyed relative to Australian Height Datum and augered at 14 cross sections up to 3.2 km long (Fig. 7.12). The sections were oriented north-south across the west trending channel and augered every 80 to 100 m. Sinuosity along this reach was 1.1 and mean slope 0.00032. A longitudinal profile of the reach shows that maximum depth to the basal clays ranged from 11.7 m below ground level in the east to 9.7 m in the west (Fig. 7.13). Maximum sediment grain sizes described in bore logs ranged from 8-16 mm. At several sections well-developed sand dunes occur at the northern and northeastern margins of the palaeochannel.

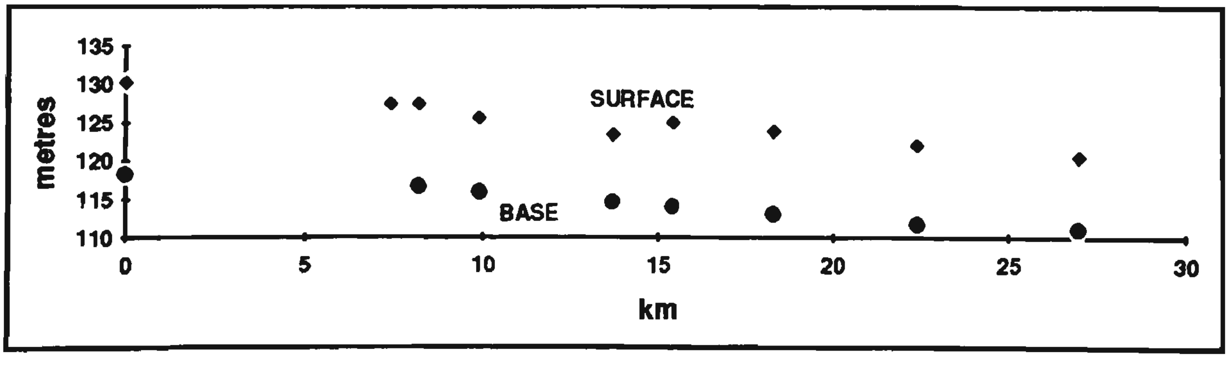


Fig. 7.13. Longitudinal profile of Kerarbury (Waddi Reach) palaeochannel using WRD sections near Darlington Point.

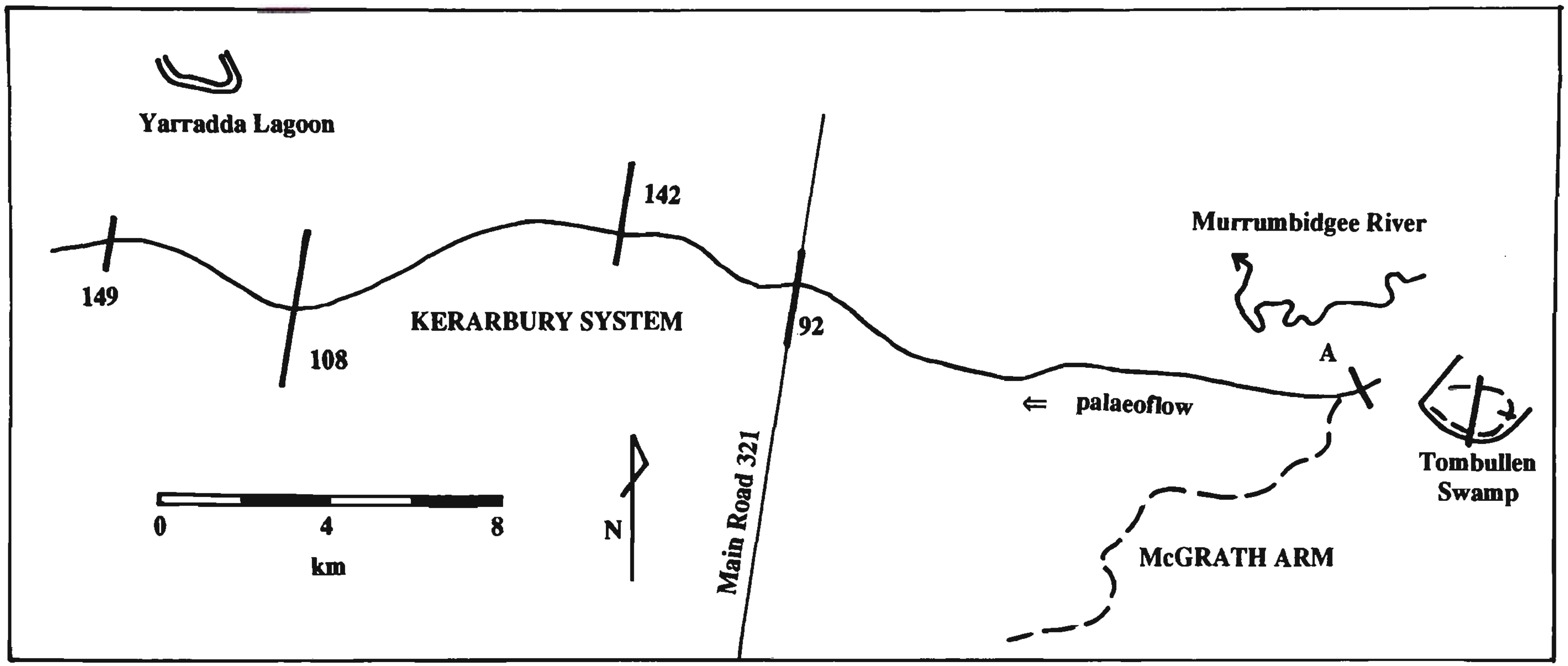


Fig. 7.12. Map showing locations of selected WRD auger hole sections on Waddi Reach of the Kerarbury System near Darlington Point. Note Tombullen Swamp and north-south section in east.

WRD Sections 92, 142, 108, and 149 (Fig. 7.14) provide the basis of the stratigraphic interpretation of the Kerarbury deposits in this area. At each section the final channel position is underlain by horizontally extensive lenticular sand units between 7 and 10 m thick and a thin (2 m) upper mantle of sandy loams, sandy clays and clays. As at the Coleambally sections, pedogenisis of these sediments at levee sites has produced red duplex profiles with abundant pisolitic carbonate. Flanking each channel infill are upward fining sequences of coarse sand, loam and clay above the truncated strongly weathered clay base which is generally horizontally disposed (± 1 m). These sequences provide unambiguous evidence for lateral channel migration in excess of 1000 m, probably by a stable mixed-load channel. Variations in the thickness of the basal coarse sand unit from 1 to 5 m probably reflect differences in point bar configuration relative to the bend axis, channel curvature and rate of lateral channel migration (Hickin and Nanson, 1984), but at Section 149, and to a lesser extent at Section 142, brief periods of vertical accretion between longer episodes of lateral migration appear to be indicated. In any event, all sections clearly reveal the final phase of channel aggradation at 50 to 40 ka. At Sections 108 and 92 channel migration both to the north and south of the final channel position is indicated. A TL date of 45.9 ± 3.8 ka on channel infill sediments at Kerarbury Pit (Fig. 6.2) lies close to the average of all Kerarbury channel dates and suggests that the trunk channel was defunct by 40 ka.

Large sand dunes are well-developed along the northern margins of the surveyed reach. The onlapping of the base of the large dune at Section 108 (Fig. 7.14) by fine grained alluvium shows that the dune had developed before the final phase of channel activity. A TL date of 37.5 ± 4.5 ka deep within this dune agrees acceptably with the adjacent channel date of 45.9 ± 3.8 ka. A near surface TL date of 18.2 ± 1.1 ka further supports the proposed instability of dune crests at about the time of the LGM.

McGrath Distributary Arm

The McGrath Arm of the Kerarbury System branches southwest from the trunk channel at the western end of Tombullen Swamp (Fig. 6.1). Approximately 10 km south of Waddi Section 92, Main Road 321 between Darlington Point and Coleambally intersects the McGrath distributary at a broad north swinging bend. A WRD bore hole section here (Fig. 7.15)

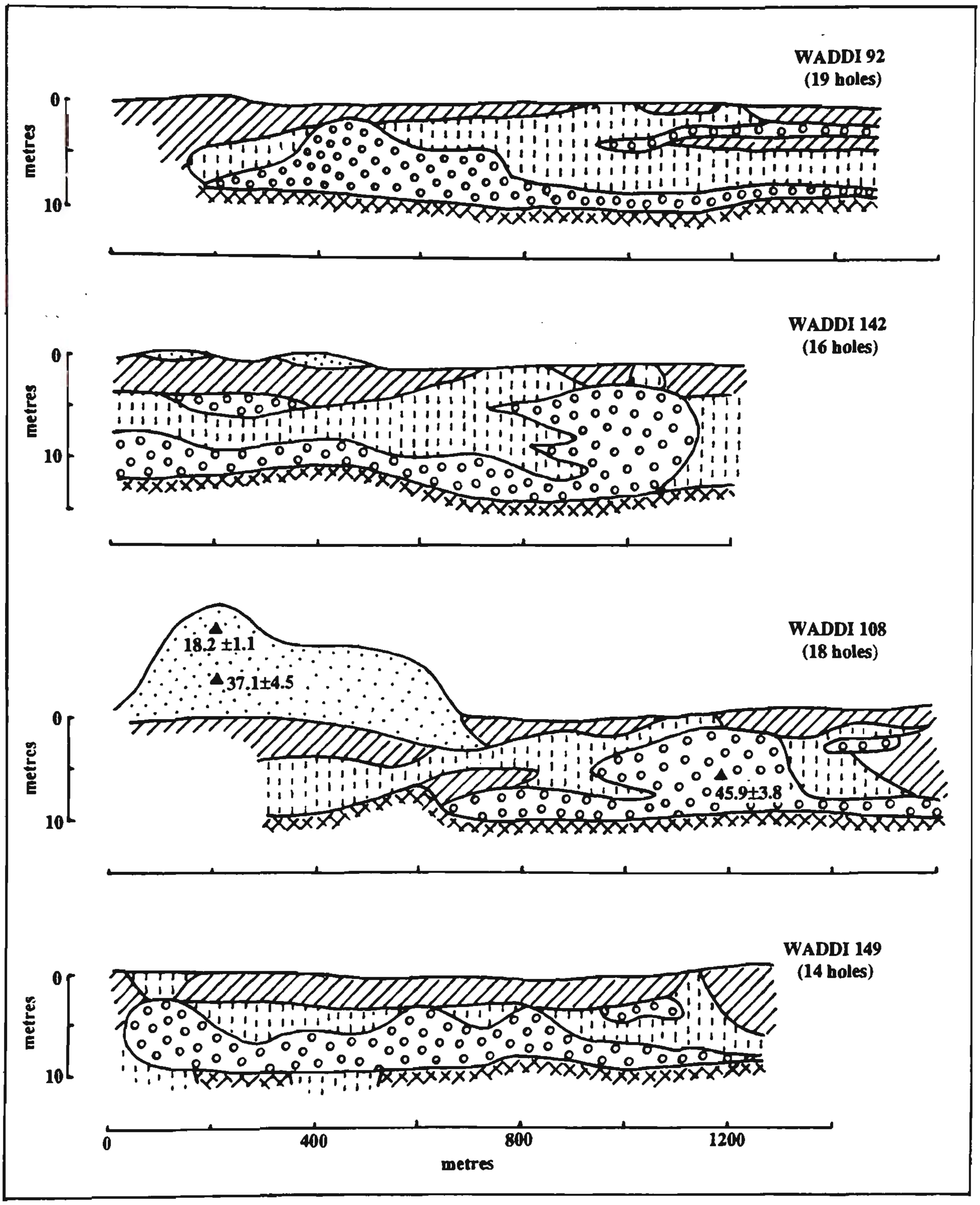


Fig. 7.14. Palaeochannel stratigraphy at Sections 92, 142, 108 and 149 on the Waddi Reach of the Kerarbury System. All sections viewed from downstream.

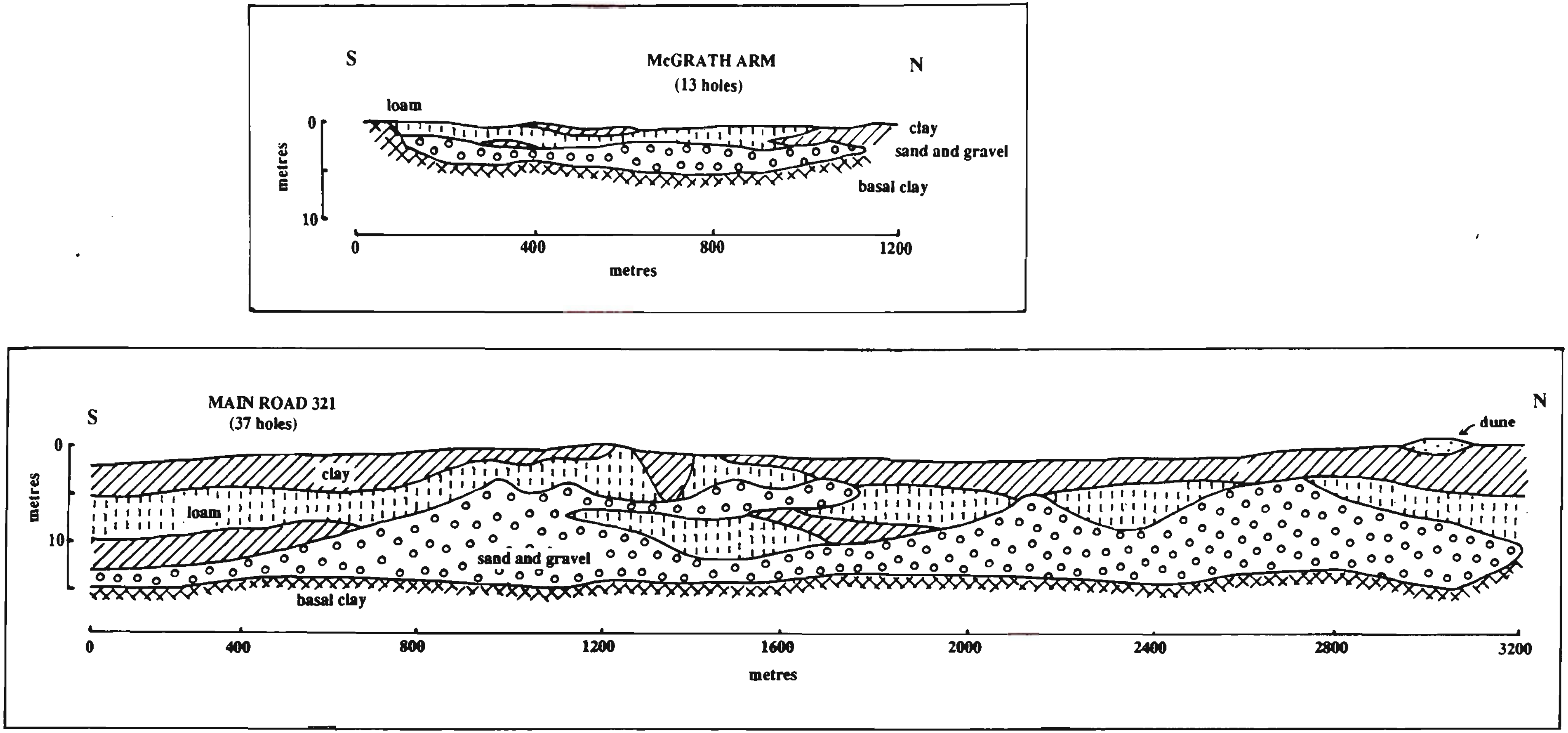


Fig. 7.15. Palaeochannel stratigraphy at McGrath Arm Section (top) and Main Road 321 Section between Darlington Point and Coleambally (bottom). Both sections run from south to north.

reveals 1.5 to 2.0 m of surficial loam and clay and then 2.0 to 3.5 m of pebbly coarse sand resting on a heavily weathered clay palaeosol 4 to 5 m below the local ground surface.

Given that this north-south section runs along a well-defined bend axis it is clear that the upward fining sediment sequence was deposited by a shallow north migrating channel. The thickest sand unit at this section occurs beneath the floodplain at the maximum depth of incision and not beneath the defunct channel. The northernmost 200 m of the section shows a general decrease in the depth of maximum incision from 5 m to only 3 m below the surface and probably indicates waning fluvial energy. Approximately 10 km west of Main Road 321 the surface expression of the McGrath palaeochannel disappears probably indicating that the channel dissipated in this region. A TL date of 37.8 ± 10.3 ka on coarse sands at McGrath Pit is consistent with this channel's operation late in the Kerarbury phase but the high error band cautions against confident acceptance of this interpretation.

Pedogenic carbonate pisoliths at McGrath Pit yielded a U/Th age of 9.8 + 1.2 or - 1.1 ka. This date appears to confirm that even the last of Butler's (1958) prior stream phases had suffered aeolian dust accession after 40 ka and before 10 ka, probably soon after the LGM in Oxygen Isotope Stage 2.

Older palaeochannels

Between Waddi Section 92 and McGrath Pit on Main Road 321 a 3.2 km DWR section with boreholes every 100 m traverses an extensive west trending older and deeper palaeochannel system that has poor surface expression apart from a string of marginal sand dunes. This system is shown by Pels et al. (1968) to consist of channels that enter the Riverine Plain at the western side of Dry Lake (Fig. 6.2), a large meander cutoff on the Yanco Palaeochannel System, and then trend almost due west before being cut by the McGrath distributary 6 km east of Main Road 321. From here the older channels continue west beneath beneath Main Road 321 before heading west and then southwest across the Plain.

The WRD Main Road 321 section reveals typical palaeochannel stratigraphy with a nearly horizontal truncated clay palaeosol overlain by upward fining sequences of pebbly sand, loam and clay (Fig. 7.15). Here the basement lies

14 to 15 m below the ground surface and can be traced laterally for 3.2 km. Bore holes indicate that the coarse sand unit is continuous (it occurs in all deeper holes) but varies in thickness from less than 2 m to more than 10 m. Again, alternate periods of mixed-load lateral channel migration and bedload aggradation, similar to those inferred on the Coleambally and Kerarbury Systems, are indicated. These similarities suggest that this deeper system formed under generally similar hydrologic conditions to those associated with its subsequent counterparts. Although the older system has not been dated it may have been active during the penultimate glacial cycle, i.e., before 130 ka (Chappell and Shackleton, 1986).

Gum Creek Palaeochannel System

The Gum Creek Palaeochannel System dates from 35 to 25 ka and forms a complex anabranching-distributary pattern along, and to the north and south of, the present Murrumbidgee floodplain. Although the stratigraphy of equivalent aged units on the Goulburn and Murray Rivers has been described in some detail (Pels, 1966; Bowler, 1978) comparatively little is known about the stratigraphy of the Murrumbidgee deposits.

Narrandera to Yarradda Lagoon

Upstream of Yarradda Lagoon the palaeochannel remnants occur as large meander scars at the margins of the present floodplain. Scroll-patterned floodplains enclosed by these bends (e.g., Gooragool, Yarradda and Cumbungi Lagoons) provide compelling evidence of lateral channel migration over distances exceeding 1 km (Fig. 6.8).

Schumm's (1968) conclusions about the ancestral Murrumbidgee River were based largely upon his observations of this reach and limited stratigraphic data provided by WRD bore holes at Tombullen Swamp and Whitton Weir site. On the basis of this information Schumm (1968) estimated ancestral channel width at 140 m, mean depth at 10.5 to 14.5 m below the adjacent Riverine Plain surface and hence, a width depth ratio of between 10 and 13. On the basis of a statistical relationship between w/d and perimeter sediment Schumm (1960) concluded that the ancestral channel contained approximately 16 per cent silt-clay in its perimeter and was, like the present Murrumbidgee, a river strongly dominated by suspended sediment load. He

also estimated the bankfull discharge of the Tombullen channel to have been about five times greater than that of the present Murrumbidgee.

However, Schumm's calculations at Tombullen Swamp were based upon Stocklin's (1963) report on a bore hole section across the neck of the meander scar (Fig. 7.12) where the ancestral channel is superimposed upon sediments deposited during the much older Kerarbury palaeochannel phase. Marginal dunes nearby also appear to be associated with the Kerarbury channel. At the neck section the boundary between the two channels is difficult to determine. A subsequent survey some 800 m to the east (Fig. 7.12) provides less ambiguous data because the channel here does not overlie the Kerarbury sands. Stocklin's (1964) north-south section traverses two channel widths and an intervening 1200 m of floodplain. Supplementary bore holes at the bend axis and elsewhere provide useful additional information.

The section shows that the Gum Creek floodplain at Tombullen Swamp lies approximately 3 m below the general level of the adjacent Riverine Plain. Maximum channel depth relative to the floodplain is only about 6 m. Mean channel width determined from air photographs and the bore hole section, is about 220 m. If mean depth is 5 m a w/d ratio of 44 implies a silt-clay percentage of about 6 (Schumm, 1968, Table 5) and hence, a mixed-load or marginal bedload system.

Bore holes through the palaeochannel sediments at Tombullen Swamp provide a detailed record of floodplain stratigraphy (Fig. 7.16). A truncated heavy clay basement 5-6 m below the surface is overlain by 0.5-1.5 m of coarse sand which grades upwards to sandy clays and then a surficial 1.5-2.0 m unit of heavy grey clay. These clays are thickest at the preserved channel cross sections where they appear to comprise meander cutoff sediment plugs. The upward fining floodplain sediments are typical of laterally migrating mixed-load streams and closely resemble the lateral migration facies of the earlier Coleambally and Kerarbury Systems although the thickness of the basal sand unit is somewhat less. A TL date of 25.5 ± 3.5 ka on bedload sands in a meander cutoff west of Tombullen Swamp (Fig. 6.2) approximates the age of channel activity.

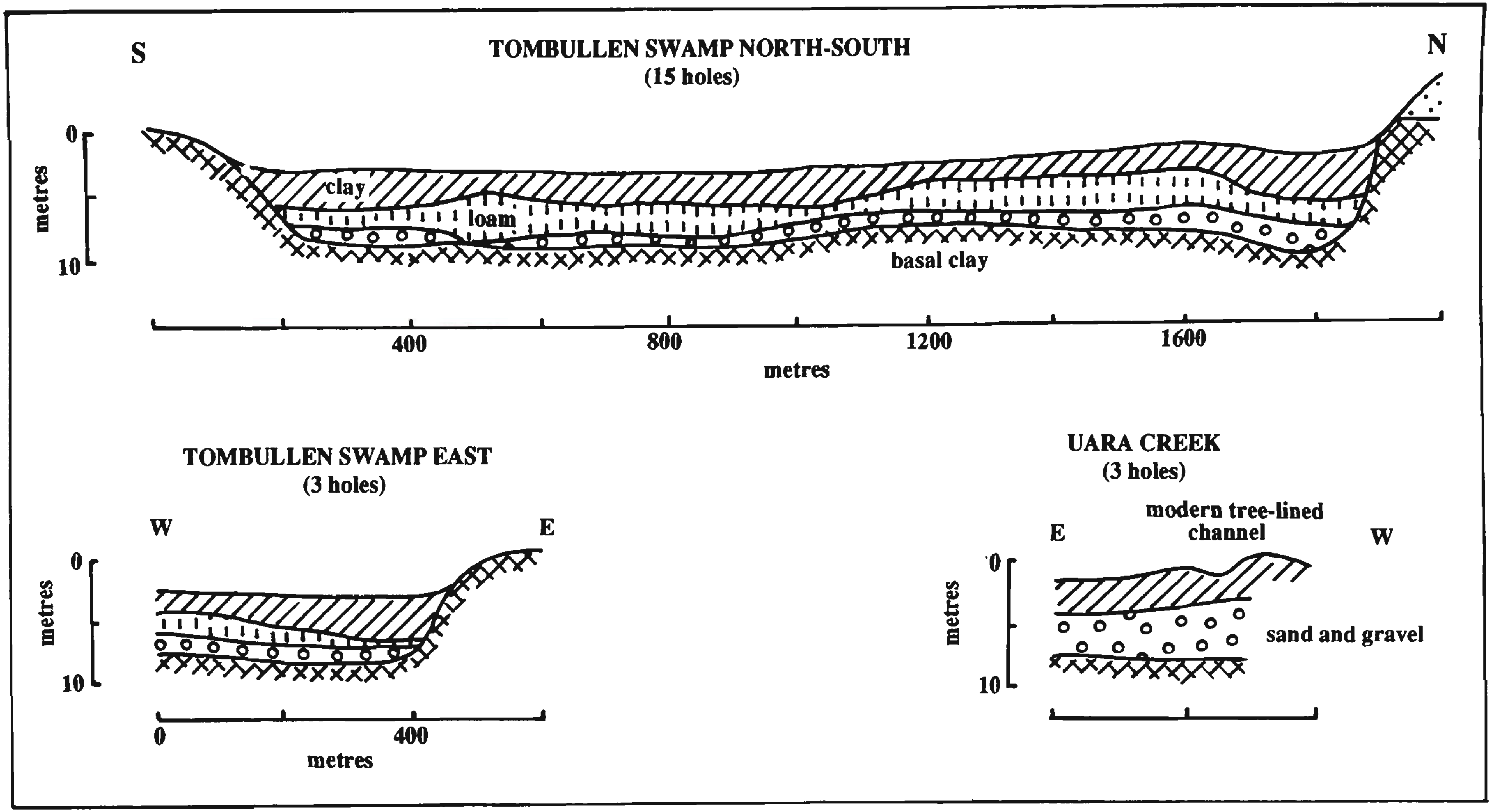


Fig. 7.16. Palaeochannel stratigraphy at Tombullen Swamp and Uara Creek on the Gum Creek System.

Yarradda Lagoon to Hay

To the west of Yarradda Lagoon a large sinuous palaeochannel (Oolambeyan Reach) with coarse sandy infill sediments dated at 29.8 ± 2.9 ka diverges from the southern margin of the Murrumbidgee floodplain and is followed in part by the small muddy modern channel of Gum Creek which receives water from the Murrumbidgee during floods and has a well-defined tree-lined course. At first the Oolambeyan palaeochannel is highly sinuous and has a clearly defined infilled cross section whose surface lies 2.5-3.0 m below that of the adjacent Riverine Plain. Auger holes into this channel at four sections (Fig. 6.2) revealed 2.5-5.0 m of fine grained sediment overlying 1-4 m of coarse sand. The maximum depth of channel incision varied from approximately 7.5 m below the Plain in the east to only 5.5 m some 70 km downstream (Fig. 7.17). For the next 50 km downstream until it is cut by the modern Murrumbidgee some 20 km east of Hay, the palaeochannel is characterised by decreasing sinuosity and the presence of several minor distributary channels that dissipate on the adjacent Riverine Plain. At its intersection with the Murrumbidgee an excellent north bank exposure reveals classical prior stream characters with a mottled clay palaeosol base and a cross and trough bedded coarse sandy infill. Above these sands are fine grained pedogenically altered sediments containing carbonate pisoliths. The bed of the modern river here is incised at least 4 m below the base of the palaeochannel. Despite the obvious prior stream characters of this palaeochannel its infill sediments yielded a TL age of 24.7 ± 2.8 ka. Clearly, prior stream characters are not restricted to the older palaeochannel systems on the Plain.

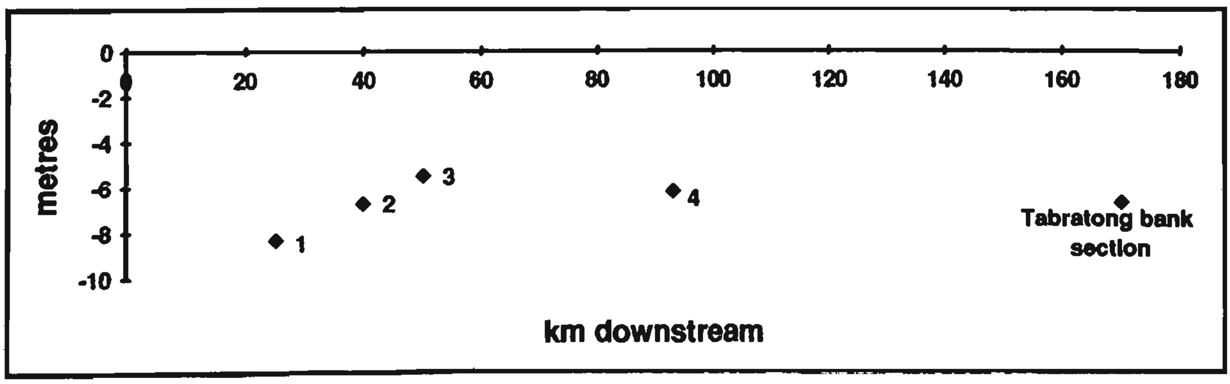


Fig. 7.17. Maximum depth of incision of Gum Creek palaeochannel below adjacent Riverine Plain surface. Surveyed sections are numbered 1 - 4.

Although large meander scars continue to occur at the margins of the Murrumbidgee floodplain downstream of Yarradda Lagoon [despite Schumm's (1968) assertion that they do not] they do cease abruptly immediately to the west of Carrathool (Fig. 6.1). The downstream continuation of these channels appears as the well-preserved sinuous Carrathool Reach to the north of the present river. At Tabratong Station a series of shallow auger holes showed that both the channel and its adjacent floodplain deposits contain coarse sands only 2 to 3 m below the surface. The base of these sands was more than 4 m below the surface but collapse of the auger holes prevented a determination of the maximum depth of incision. A TL date of 29.4 ± 4.6 ka on the Tabratong Station infill sands confirms its similar age to other reaches of the Gum Creek palaeochannel.

Hay to Balranald

To the north and west of Hay the Gum Creek palaeochannels form a complex branching system that cuts the Kerarbury (Hay Arm) System. Some of the channels appear to peter out and others merge with the modern depositional environments of the Lowbidgee and associated swamps. To the west of Hay and about 15 km east of Maude an obvious palaeochannel emerges from the southern margin of the Murrumbidgee floodplain and can be traced via a sinuous course with occasional meander cutoffs to a system of lunette bordered relict lakes to the east of Balranald (Fig. 6.1).

Like the Oolambeyan Reach, the Uara Palaeochannel Reach south of Maude is followed for most of its length by a small modern muddy channel here called Uara Creek. This channel appears to carry almost no bedload at present but receives water from the Murrumbidgee during floods and is utilised as an irrigation supply channel. A bore hole section across Uara Creek next to the Maude-Moulamein Road revealed that the grey muds of the modern Uara Creek channel were underlain by coarse sands extending to 6.5 m below the present groundsurface. These upward fining sandy deposits, which could also be traced laterally beneath the floodplain over a distance of at least 200 m (Fig. 7.17), confirm lateral migration by a mixed-load channel very different in character to the modern Uara Creek.

Yanco Palaeochannel System

The Yanco Palaeochannel System can be traced from west of Narrandera to Moulamein as a slightly trenched floodplain belt between 1 and 3 m below the general surface of the Riverine Plain. Upstream of Morundah the trench attains its maximum width of 5 km and contains several large meander scars including Dry Lake (Fig. 6.2). Downstream of Morundah trench width decreases to generally less than 2 km but channel and floodplain remnants are well-preserved, particularly downstream of Conargo where the palaeochannels and modern drainage of Billabong Creek are geographically separate.

Despite its impressive dimensions, as noted by Brown and Stephenson (1991), and continuity across the Plain, the Yanco palaeochannels have not been described in any detail in the scientific literature. Superficially, with their scroll-patterned floodplains and large sinuous channels, they closely resemble Bowler's (1978) Kotupna Complex in northern Victoria and the deposits of Acres Billabong and Talyawalka Creek on the Darling (Bowler et al., 1978). Three TL dates on the Billabong Creek palaeochannel deposits ranging in age from 13.6 ± 1.6 to 18.2 ± 1.5 ka confirm that the three systems were indeed, simultaneously active.

Investigations of channel geometry and floodplain stratigraphy on the Yanco palaeochannel were carried out at two pits and three auger sections. Existing floodplain pits at Thurrowa Road and Wanganella Station (Figs. 6.2 and 6.3) revealed thin fine grained alluvial deposits of the modern Yanco and Billabong Creeks overlying sandy clays and coarse sands of the Yanco Palaeochannel System. Upstream, at Thurrowa Road (Fig. 7.3), fine grained surface alluvium with friable pedogenic carbonate (not pisoliths) overlay approximately 4 m of yellow-brown and grey coarse sand with maximum grain sizes in the 2 - 4 mm diameter range. At the pit base was a truncated mottled clay. At Wanganella Station the pit section (Fig. 7.3) was located about 50 m west of the tree-lined shallow muddy channel of the modern Billabong Creek. Here a grey clay surface unit graded to brown sandy clays at 0.7 m and then coarse sand at about 1.5 m. The sands continued to an eroded mottled clay at 5.4 m. Maximum grain diameters ranged from 2 - 5 mm.

Drill hole sections were carried out with a truck mounted Gemco 210 rig at Dry Lake and near Rhyola Station (Figs. 6.2 and 6.3). Four auger holes were drilled at Dry Lake across an unusually wide channel at the axis of a meander cutoff . The maximum depth attained was 22 m. Although the dimensions of the clay infill plug could be defined readily, maximum channel depths were difficult to determine because of the poorly defined boundary between the upper channel deposits and those of the deeper palaeochannel deposits that can be traced west to Main Road 321. On the basis of the clay plug channel depth was estimated to be 5.5 m below bankfull stage. The 600 m wide channel here was abnormally large but probably is consistent with natural inter-section variation. Air photographs show that channel width on the Dry Lake cutoff varies from 250 m at the upstream bend limb to over 600 m at the bend axis.

The downstream reach of the Yanco palaeochannel between Wanganella and Moulamein contains well-preserved cross sections with widths of 200-250 m. Survey and drilling of a meander scar section west of Rhyola Station (Fig. 6.3) revealed a 250 m wide channel partly infilled with 3 m of coarse sand and a surface 1 m unit of light to heavy clay. Maximum channel depth here was 6 m and mean depth approximately 5 m. A survey of a section at the downstream region of the bend duplicated these figures.

Two 400 m long bore hole sections across the Yanco System floodplain near Rhyola Station (Fig. 7.18) confirmed the presence of upward fining alluvium with basal coarse sands from 2.0-3.5 m thick overlain by about 2 m of sandy loam and sandy clay. Air photographs show that scroll-patterned floodplains at the inside bend margins in this reach typically extend for distances of 1.5-2.0 km. They are consistent with a lengthy period of floodplain formation.

Marginal dunes of fine sand are well-developed along the Yanco System. At Rhyola West one of these attains a thickness of almost 6 m and directly overlies lateral accretion deposits. A TL deep sample in a marginal dune south of Rhyola Station yielded an age of 19.4 ± 1.6 ka in close agreement with a nearby fluvial sample date of 18.2 ± 1.5 ka (Fig. 6.3). The absence of comparable dunes along Gum Creek Arm suggests that the peak of dune formation occurred in the Yanco phase after the LGM.

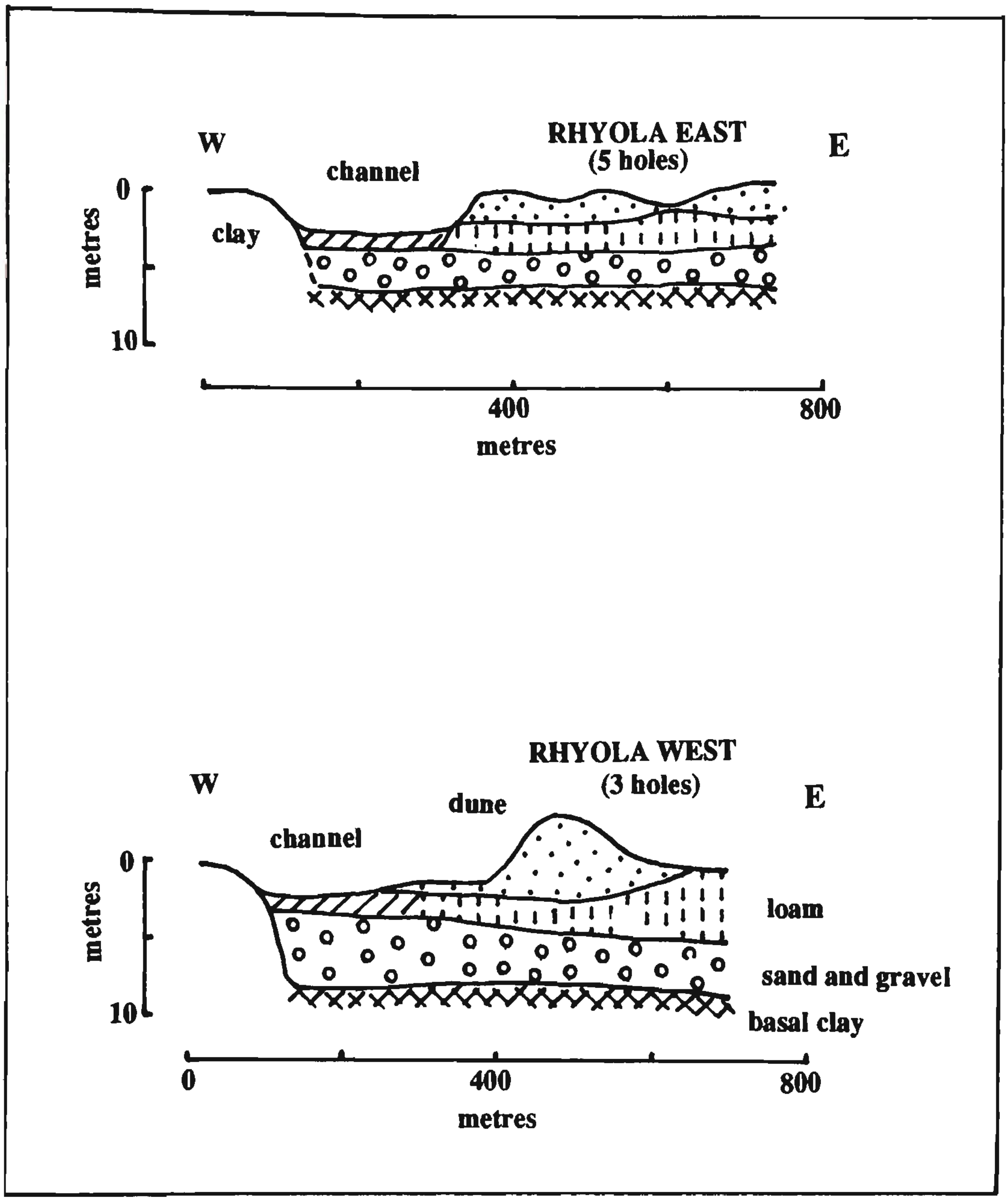


Fig. 7.18. Palaeochannel stratigraphy at Rhyola East and West sections on the Yanco System near Moulamein.

CONCLUSION

A combination of data from pits, river bank exposures, auger holes and DWR surveys has revealed that during the last glacial cycle since about 100 ka the Murrumbidgee River has alternated between stable sinuous mixed-load and aggrading low sinuosity bedload modes of activity. Although these modes can be roughly equated with Pels' (1971) ancestral and prior stream types, his simple model of an early phase of prior streams followed by a later phase of ancestral streams is not supported by the present findings. In addition, the view that ancestral streams were simply larger versions of the modern suspended load rivers on the Riverine Plain is also flawed. The mixed-load phases of channel activity were generally associated with greater volumes of bedload transport than the modern rivers and substantially larger components of coarse grained floodplain sedimentation (Bowler, 1978). As a result these channels possessed higher width-depth ratios and very large meander wavelengths compared to the present rivers. Although the final (Yanco) palaeochannel phase did not experience a major terminal episode of aggradation and channel straightening sufficient to obliterate slightly incised sinuous channel and scrolled floodplain remnants, downstream reaches of the Gum Creek System did aggrade and straighten to produce classical prior stream characters. On the basis of TL dating of the Yanco Palaeochannel System it appears that the transition to the present channels on the Riverine Plain took place between 15 and 10 ka or close to the Oxygen Isotope Stage 2/1 boundary (Chappell and Shackleton, 1986), well after the LGM.

CHAPTER 8

INTERPRETATION OF MURRUMBIDGEE PALAEOCHANNELS

INTRODUCTION

Three major phases of palaeochannel activity on the Murrumbidgee sector of the Riverine Plain have been identified by means of field mapping and air photograph interpretation. Previous studies (Schumm, 1968; Bowler, 1978) have suggested that the peak palaeochannel phases were associated with larger discharges, and that they carried considerably more bedload than the modern rivers which are highly sinuous, deep and dominated by suspended load .

TL dates show that the palaeochannels existed from at least 100 ka to about 13 ka and therefore spanned most of the last glacial cycle from the latter part of Oxygen Isotope Stage 5 until the end of Stage 2 (Nanson et al., 1992a; Kershaw and Nanson, 1993). Palaeochannels on the Plain in this period appear to have been characterised by repeated shifts from laterally migrating mixed-load systems to vertically aggrading levee bordered bedload systems. Distributary formation was common, particularly during the terminal phases of channel activity when the shallowing channels were prone to levee crevassing. On occasions the distributary channels also experienced alternate phases of incision and aggradation before themselves forming successively smaller distributaries that petered out on the Plain. Pels' (1964a) sections across the Kerarbury Benerembah Arm distributary system southwest of Griffith show laterally confined sand infills in a hierarchy of channels of decreasing size. The stratigraphy here, which is consistent with sequential cut and fill and minimal lateral channel migration, conforms to Schumm's (1968) arroyo model. It follows that these channels were probably short-lived features.

Stratigraphic sections on both the Coleambally and Kerarbury Palaeochannel Systems reveal early phases of mixed-load deposition and bedload aggradation during terminal channel phases. However, even the laterally migrating mixed-load phases appear to have been sometimes punctuated by shorter episodes of bed aggradation and occasionally, the formation of major distributaries such as the Bundure-Yamma bifurcation on the Coleambally

palaeochannel and the Benerembah, Hay and Romani branches on the Kerarbury palaeochannel. Although the mixed-load and bedload dominated phases correspond broadly to ancestral and prior style channels (Pels, 1966), it is clear that the simple model of an early phase of prior streams followed by a later phase of ancestral channels needs drastic revision. Indeed, each major phase of channel activity appears to have been characterised by early ancestral style channels and later prior style channels during system decline as suggested by Bowler (1978). Also consistent with Bowler's view of channel development is evidence that the major ancestral style channels generally carried considerably more bedload than the modern rivers which are true suspended load systems.

Although the early Murrumbidgee palaeochannel phases from 105 to 85 ka and 55 to 35 ka respectively show broad agreement with accepted models of fluvial activity (Nanson et al., 1992a) and climatic change in other parts of Australia (Bowler, 1986a; Kershaw and Nanson, 1993) and the rest of the world, the activity of the large Yanco channels after the LGM until at least 15 ka departs dramatically from existing climate models which generally demand aridity, enhanced aeolian and reduced fluvial and lacustrine activity at this time (Wasson, 1989; Petit et al., 1990; Colhoun, 1991).

Models of channel evolution

Clearly, an acceptable model of channel evolution on the Riverine Plain should be consistent with:

- the observed stratigraphy and TL chronology of the Murrumbidgee palaeochannels,
- established models of stream-channel evolution, and
- the generally accepted pattern of global and regional Late Quaternary climatic change.

Channel equilibrium model

Changes in channel morphology, both along a given river, and over time, have been the subject of intense interest by geomorphologists since the 1960s when the concept of channel equilibrium became entrenched in the scientific literature. At its simplest the equilibrium concept states that a river will establish a stable combination of morphological elements for a given discharge of water and sediment (Hickin, 1983). From this premise it followed that changes in stream discharge would lead to an adjustment of channel morphology until a new stable condition was achieved. One manifestation of the equilibrium tendency was the more or less regular downstream increase in channel width, depth and meander wavelength noted on many North American rivers (Leopold and Maddock, 1953; Leopold and Wolman, 1957). Subsequent studies verified the general nature of these relationships and emphasised the special significance of bankfull or dominant discharge in the development of channel morphology (Wolman and Leopold, 1957; Dury, 1961; Woodyer, 1969; Page, 1988). Despite doubts about the universal applicability of any given frequency of bankfull discharge (Lewin and Manton,1975; Pickup and Warner, 1976; Williams, 1978) the concept of channel adjustment to hydrologic regime is well-accepted. Therefore, it is not surprising that many geomorphologists have sought to fit patterns of channel evolution into the known pattern of Late Quaternary climatic and hydrologic change as evidenced by ice advance and retreat, sea level change, the oxygen isotope stratigraphy based on Greenland and Antarctic ice cores and deep ocean calcareous muds, and the huge volume of work on environmental change in continental locations (Nanson et al., 1992a; Kershaw and Nanson, 1993).

Dury (1965) in particular, sought to exploit the established empirical relationship between bankfull discharge and meander wavelength to reconstruct discharges and climatic regimes of the late Pleistocene in Europe and North America. On the basis of large palaeomeander wavelengths he argued for increased bankfull discharges by a factor of 20 to 80 and a doubling of precipitation. It has remained a moot point whether meander wavelength is capable of yielding estimates of sufficient precision to justify these conclusions (Hack, 1965; Schumm, 1968; Hickin, 1983). Apart from the difficulty of defining mean meander wavelength and uncertainty about the adoption of a single summary discharge index to characterise the formative

flow (Hickin, 1983), there was concern about the influence of boundary materials on channel morphology (Hack, 1965). If meander wavelength is scaled principally to channel width (Wolman and Leopold, 1957), and only indirectly to discharge, it is clear that meander wavelength is strongly influenced by the nature of the channel boundary, with coarser sediments being associated with larger wavelengths for a given discharge than finer sediments. Although boundary sediment variation is usually statistically trivial in relationships between wavelength and discharge over several orders of magnitude it becomes increasingly important as the discharge range contracts. Where evidence exists for a change in the nature of sediment load, and hence boundary sediments, between a palaeochannel and its modern counterpart, as is the case on the Riverine Plain, systematic errors in discharge estimates are likely to occur and result in inaccurate as well as imprecise reconstructions of discharge. Rotnicki (1983) notes that because all data sets (for example; Carlston, 1965; Dury, 1965; Schumm, 1968) contain a large amount of scatter, discharge estimates based on meander wavelength lack precision. Indeed, Dury's (1965) data show that the range of wavelengths at a given discharge may exceed an order of magnitude. Rotnicki (1983) compared measured values of bankfull discharge on the Prosna River in Poland with meander wavelength based estimates from 14 equations in the literature. For a measured value of bankfull discharge of 22.5 m^3/s estimates ranged from 0.2-34.1 m^3/s, or more than two orders of magnitude. The frequently used equations of Dury (1965) and Carlston (1965) gave errors of 36% and 78% respectively.

Schumm's (1968) proposed solution to this problem was to specify the nature of the statistical relationship between discharge, boundary sediments and meander wavelength. His relationship,

$$\lambda = 438\ Q_b^{0.43} / M^{0.47}$$

where λ is meander wavelength in feet, Q_b is bankfull discharge in cfs and M is weighted mean per cent of silt-clay in the channel perimeter, was considered to significantly improve the statistical resolution of the wavelength-discharge relationship and permit improved discharge reconstruction. However, notwithstanding theoretical objections to the M parameter (Melton, 1961; Riley, 1975), Schumm's (1968) equation was based on a geographically restricted data set including 28 mid-western United States

rivers and six Australian river sections with a modest range of discharges. Riley (1975) showed that Schumm's equations did not apply to the Namoi-Gwyder system of Australia and Bowler (1978) found that none of the relationships between discharge and meander wavelength in the literature could successfully predict discharges on the present Murray and Goulburn Rivers in southern Australia. The concensus appears to be that palaeo-meander wavelength provides only a first indication of discharge scale and should not be used if better than moderate precision is required.

An apparently superior approach to discharge estimation is provided by the study of well-preserved neck cutoffs on meandering rivers (Rotnicki, 1983). Cutoffs are formed during the process of lateral migration on a meandering river when bends are shortcircuited, usually during major floods. Because they do not occur in flume channels formed in uniform materials (Friedkin, 1945) it is suspected that cutoffs are often produced by meander train distortions arising from floodplain sediment inhomogeneities. Such cutoffs are commonly initiated across the neck of a bend (neck cutoff) or through the swale of a point bar complex removed from the existing course (chute cutoff). Sedimentation in the abandoned channel is rapid and, with closure of at least one end of a neck cutoff, the pools of the abandoned river become ponded, forming oxbow lakes (Erskine and Melville, 1982). In the low energy environment of the cutoff lake, fine-grained sediments from suspension begin to form a drape over the old river bed. These infill sediments form a cast that very effectively preserves the cross section of the channel and provides potentially valuable information about the flow regime of the abandoned channel (Rotnicki, 1983). Augering of the sediment infills permits the reconstruction of the former channel cross-section and, when combined with slope data and estimates of hydraulic roughness, permits reliable estimates of former channel forming discharge. This method was used by Rotnicki (1983) to estimate the discharge of the Prosna River with an error of less than 10 per cent (20.6 m^3/s compared to a measured value of 22.5 m^3/s).

Excavations of cutoffs on the Murrumbidgee River near Wagga Wagga reproduced the precision of Rotniki's results. Three neck cutoffs were augered near the bend axis. At each section heavy clay infills rested directly on top of gravels of the abandoned armoured river bed (Fig. 8.1). Discharge estimates at the three sections (Table 8.1) yielded an average value of 526

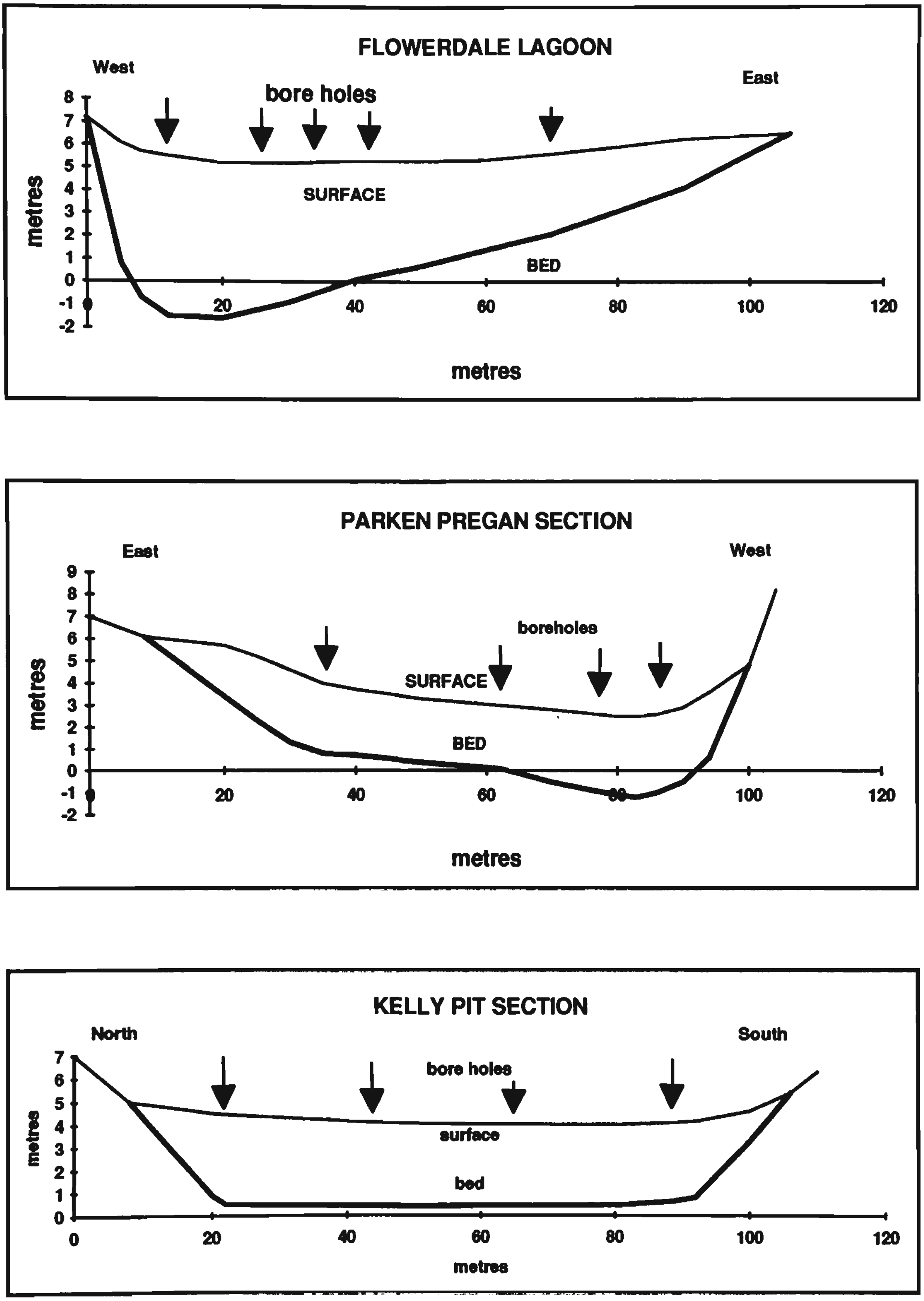


Fig. 8.1. Surveyed sections at three meander cutoffs on the Murrumbidgee River near Wagga Wagga showing infill sediments and the geometry of the pre-cutoff channel.

m^3/s compared to 480 m^3/s as measured at the Water Resources Department Hampden Bridge gauge. This mean error of 10 per cent provided an encouraging indication of the potential application of similar discharge estimates to the palaeochannels of the Riverine Plain.

Table 8.1. Discharge estimates at Murrumbidgee meander cutoffs near Wagga Wagga.

	FLOWERDALE	PARKEN PREGAN	KELLY PIT
WIDTH (m)	87	89	104
AREA (m^2)	430	412	480
DEPTH (m)	4.94	4.63	4.61
SLOPE	0.00025	0.00025	0.00025
'n'	0.0375	0.0375	0.0375
VELOCITY (m/s)	1.23	1.18	1.17
DISCHARGE (m^3/s)	**529**	**486**	**561**

MEAN BANKFULL DISCHARGE = 526 m^3/s
MEASURED BANKFULL DISCHARGE = 480 m^3/s

MEAN ERROR = 10 %

Geomorphic threshold model

Somewhat paradoxically, just as the details of Late Quaternary climate change are becoming increasingly well-understood as the result of dramatically improved dating and interpretive techniques, there has been increasing criticism of the tendency to ascribe all forms of channel and broad landscape evolution to long-term climatic change. Underlying this criticism has been the recognition of what Hickin (1983) describes as non-linearities in system adjustment. Schumm (1973) proposed that geomorphic systems could undergo dramatic episodic changes when critical erosive thresholds were exceeded. Threshold response implied that distinctly different equilibria could exist on either side of a defined boundary condition (Schumm, 1977).

An often quoted example of this kind of change in channel morphology is that occurring in response to a small increase in slope for a given stream discharge. Observations by Lane (1957), Leopold and Wolman (1957) and Ackers and Charlton (1971) suggest that as channel slope is slowly increased, straight channels will give way to meandering and ultimately braided channels. The transitions from one pattern to another are often abrupt. At the limits of the stable channel pattern domains, very small changes in slope can result in a sudden shift from, for example, meandering to braided. Schumm and Beathard (1976) pointed out that the identification of channels poised at thresholds can be of great significance in river management because these channels are the most susceptible to dramatic change.

Channel changes across a threshold can be effected by factors that are either extrinsic or intrinsic to the reach considered. An example of extrinsic threshold exceedence is channel change in response to a large flood or series of larger than average floods. Schumm and Lichty (1963), for example, showed that a large flood on the Cimarron River in 1914 severely eroded the floodplain, destroyed bank vegetation and caused an influx of coarse sediment that resulted in channel straightening, steepening and widening until 1942. On NSW coastal rivers Erskine (1986), Erskine and Warner (1988) and Nanson and Erskine (1988) have shown that significant channel changes can be related to alternate periods of higher than average rainfall and flooding (Flood Dominated Regimes or FDRs) and lower than average rainfall and flooding (Drought Dominated Regimes or DDRs) with

each period persisting for 30-50 years. During FDRs channel width generally increases but sinuosity and depth decrease. During DDRs these trends are reversed. Therefore, the channel oscillates between two equilibria and does not reach a stable equilibrium related to some long-term climatic average (Nanson and Erskine, 1988).

Truly catastrophic floods can also provide the external stimulus required for threshold exceedence and resultant wholesale channel adjustment. Nanson and Erskine (1988) define a catastrophic flood as one that might occur on average less than about once every 200 years. The geomorphic effects of such extreme events can exhibit great persistence as, for example, on Wollombi Brook in eastern NSW following a major flood in June 1949 (Erskine, 1986). Here the downstream 89 km of a 130 km reach widened by 100 per cent and locally aggraded by up to 4 m. The downstream movement of coarse sediment slugs through channel reaches can also produce rapid changes in channel morphology arising from the influx of bedload sediment (Page, 1972; Erskine, 1986). These changes include channel widening, shallowing and straightening. Recently, Friend (1993) has pointed out that channel changes may result directly from changes in the availability of bedload rather than any change in water flow variables. In particular, sudden inputs of coarse bedload, from hillslope failure, volcanic eruptions or changed landuse, are likely to result in shifts to higher channel width/depth ratio and lower sinuosity.

Not all threshold exceedences are externally triggered. Schumm and Beathard (1976), Nanson (1986), Brizga and Finlayson (1990) and Shu and Finlayson (1993) have shown that sudden channel morphology shifts may be inherent or intrinsic to the natural development of the system. In particular, rivers with well-developed levees are prone to the formation of new channels by crevassing and subsequent avulsion. Carson (1984) noted that because localised overbank flow initially carries little or no bedload, it is highly aggresive and will quickly scour a deep channel. As this new channel becomes established it will also begin to convey available bedload and possibly convert to an aggrading channel as the supply of sediment increases. This alternation between incision and aggradation is not unlike the reconstructed channel sequence along Pels' (1964a) distributary system near Griffith on the Riverine Plain.

Perhaps the most extreme examples of avulsion and the formation of new river courses are provided by the Yellow River in China (Shu and Finlayson, 1993). Rapid sedimentation along the lower reaches of the Yellow River has raised its bed some 10 m above the adjacent floodplain. Present management policy is to continually raise the levee banks along the river to keep pace with bed aggradation. There is clearly a limit to how long this process can continue before a major breach and avulsion occurs. Historical records indicate that the Yellow River has broken its levees 1593 times with 26 major changes in course during the past 2550 years, or an average of one major course change per century.

Often a newly avulsed channel flows along a steeper gradient on a lower part of the floodplain and, as a result, differs sharply in morphology from the pre-avulsion channel. Brizga and Finlayson (1990) showed that differences in channel capacity, slope and meander wavelength between a pre- and post-avulsion channel of the Thomson River in Victoria were not associated with any change in catchment hydrology or climate but arose directly from channel avulsion. On certain non-migrating reaches of the Clyde and Manning Rivers of coastal NSW, floodplains are formed gradually by vertical accretion and are destroyed catastrophically by large floods. Nanson (1986) noted that the vertical growth of these floodplains brings about their own destruction. As steep levees gain height they confine larger and larger flows to the main channel and to steep gradient backchannels on the narrow floodplains. Eventually, an erosional threshold is exceeded and wholesale floodplain destruction results. The floodplain then gradually recovers until the next episode of devastation. This pattern results in an essentially disequilibrium condition with the channel and floodplain never in any stable equilibrium condition (Nanson, 1986; Nanson and Erskine, 1988).

Climates of the last glacial cycle in Australia

Apart from the relatively brief period containing the LGM at around 18.5 ka* or 22 ka (Bard et al., 1990), the Murrumbidgee palaeochannels operated during what Porter (1989) has described as average Quaternary glacial conditions when snowlines were depressed approximately 500 m below those of the present and sea levels were reduced by about 50 m. Presumably, mean air temperatures at these times were at a level intermediate between those of the LGM and the present interglacial.

During the last 20 years refinement of the oxygen isotope record in deep-sea sediments and Antarctic ice cores has provided a secure basis for Quaternary stratigraphic correlation (Jansen, 1989). Calibration of the oxygen isotope record against well-dated sequences of sea level change and orbital tuning (Chappell and Shackleton, 1986) has provided the primary basis of global correlation of climatic and environmental change. Five major oxygen isotope stages are recognised within the period extending back to, and including, the last interglacial at about 125 ka (Shackleton and Opdyke, 1973). Figure 1.1 shows the isotope record and stage boundaries during the last full glacial cycle for core V19-30 from the Panama Basin of the eastern equatorial Pacific. Jansen (1989) and Porter (1989) regard this core as probably the best benthic oxygen isotope record available for the last 350 ka.

Recently, Kershaw and Nanson (1993) have attempted to summarise patterns of climatic and hydrologic change during the last full glacial cycle in the Australian region. Sequences of fossil pollen, continental dune mobilisation, and fluvial and lacustrine activity are related to established records of broad regional and global significance including the ^{18}O deep sea record of Shackleton and Opdyke (1973), the Huon Peninsula sea level curve (Chappell and Shackleton, 1986) and the temperature (Jouzel et al., 1987) and dust particle (Petit et al., 1990) records derived from the Vostok Antarctic ice core.

Despite qualifications on matters of detail, Kershaw and Nanson (1993) demonstrate a remarkably consistent pattern of climatic conditions throughout the last full glacial cycle. In general, there is a positive relationship between global temperatures, sea levels and precipitation. However, the wettest conditions were apparently lagged somewhat behind the interglacial maximum. A major phase of fluvial activity in central and southeastern Australia dated from 110 to 80 ka (Nanson et al., 1992a) correlates with Stages 5a to 5c and not 5e. Within this pluvial phase there is some dating evidence for time transgression towards the southeast where activity declined at 70 ka in the Nepean catchment compared to 90 ka in the Eyre Basin of northern and central Australia. Although little dating evidence is available, Wasson (1989) speculated that the period between 100 and 70 ka in Isotope Stage 5 may have also been a time of high lake levels in Australia.

A second and apparently synchronous phase of enhanced fluvial activity occurred throughout northern central and southeastern Australia between 50 and 35 ka but with greater intensity in the south. The reason for stronger activity in the southeast is not known but it may have been associated with an equatorward compression of zonal pressure zones and weaker penetration of the northern summer monsoon or wet season at the time. In the south deeper northward penetration of winter frontal systems may have boosted precipitation (Bowler, 1986a). This sub-pluvial of Isotope Stage 3 (Nanson et al., 1992a) corresponds to the marked lacustral phase documented in the Willandra Lakes and elsewhere (Bowler,1986a; Bowler and Teller, 1986). Chappell and Grindrod (1983) believe that this period was cool and moist in Australia and produced enormous inland lakes full of freshwater aquatic life. Pollen records in southern Australia also point to cool moist conditions during Stage 3 (D'Costa, 1989; Kershaw, 1991). Recent TL dating of shorelines at Lakes Eyre (over 20 m above the present lake floor) and Frome indicates high lake levels in the period 60 to 40 ka (Nanson et al., 1992b).

The Stage 3 sub-pluvial appears to have come to an end in the period from 35 to 30 ka or at the Oxygen Isotope Stage 3/2 transition. The demise of major fluvial and lacustrine systems after about 35 ka points to a transition to aridity that is strongly supported by the record of continental dune activity and fossil pollen records (D'Costa, 1989). In the Pilliga Sandstone region of NSW tree pollen became scarce after about 25 ka and forest vegetation gave way to a treeless steppe formation indicative of arid or semi-arid conditions (Dodson and Wright, 1989). Wasson (1989) has produced impressive radiocarbon dating evidence for a major phase of dune building centred on 20 ka during the LGM in Isotope Stage 2 when northern hemisphere glaciers were at their greatest extent and Australian annual temperatures were lower by 6°C to 10°C (Chappell and Grindrod, 1983). This phase of dune building correlates well with evidence of enhanced loess accumulation in New Zealand (Alloway et al., 1992) and dust accumulation in the Vostok ice core (Petit et al., 1990). The LGM in southern inland Australia was also a time of widespread clay lunette formation when increasing aridity is thought to have lowered water levels and concentrated salts in groundwaters (Bowler, 1986b). As saline groundwaters discharged onto the lake floors they were responsible for salt crystallisation in, and pelletisation of, the lake muds. Westerly winds then blew the pellets into clay-rich lunettes at the eastern lake shoreline (Bowler and Wasson, 1984; Bowler, 1986b).

A less intense phase of Australian continental dune building, New Zealand loess accumulation and Antarctic ice dust concentrations occurred in Isotope Stage 4 (Wasson, 1989; Alloway et al., 1992; Kershaw and Nanson,1993). The relative absence of dates on fluvial sediments at this time is consistent with a period of greatly reduced fluvial activity (Nanson et al., 1992a).

In summary, the Australian continental evidence correlates well with the oxygen isotope record from the Pacific Ocean and Antarctica. It indicates predominantly pluvial conditions during Stages 3 and late Stage 5 and predominantly arid conditions during Stages 2 and, to a lesser extent, 4. Clearly, the two early phases of Murrumbidgee palaeochannel activity dated (Coleambally and Kerarbury) show good agreement with other data for Stages 3, 4 and 5. The two later palaeochannel phases from 35 to 25 ka and 20 to 13 ka do not conform to the generally accepted pattern of aridity associated with Stage 2.

MURRUMBIDGEE PALAEOCHANNEL DISCHARGES

The evidence of palaeochannel remnants, the stratigraphy of floodplain deposits and TL dating have provided a comprehensive picture of enhanced fluvial activity on the Riverine Plain for much of the period between 100 and 13 ka. Apart from the LGM which peaked at about 22ka during Oxygen Isotope Stage 2, this period was characterised by what Porter (1989) has recently described as average climatic conditions for the Late Quaternary. In the following section an attempt is made to estimate stream discharges on the Murrumbidgee sector of the Riverine Plain during the three dated palaeochannel phases.

Coleambally and Kerarbury Phases

Although terminal stage palaeochannel locations of the Coleambally and Kerarbury Systems are well-preserved on the Riverine Plain, these remnants are not particularly suited to discharge reconstruction. Because the aggrading bedload rivers were wide, shallow and of low sinuosity they did not form regular meander trains suitable for discharge estimation based upon wavelength or the reconstruction of meander cutoff channel sections. In addition, the aggraded terminal channels do not provide a reliable indication of peak discharges during preceding phases of lateral channel migration.

In order to make an assessment of discharges during the peak mixed-load, laterally migrating phases requires information about channel dimensions, slope and hydraulic roughness. These data can then be factored into a hydraulic equation such as that of Manning (Leopold et al., 1964) to approximate stream discharge. The best available data are provided at the WRD sections where slope and maximum depth of incision are reliably surveyed. Channel width before aggradation can be estimated from the basal width of the lenticular coarse sandy channel infills which often widen upwards, presumably reflecting increasing w/d ratios in the aggrading bed load channels.

Bundure and Yamma Arms - Coleambally System

Table 8.2 provides discharge estimates for the WRD surveyed reaches of Bundure and Yamma Arms of the Coleambally System. Because channel sinuosity immediately before aggradation can only be approximated, a probable range of discharges based on a range of possible channel slopes is given for each reach. Manning 'n' is estimated at 0.035 at each section as typical of wide sandy channels with few obstructions. Depths are based on the maximum incision of the channel below the adjacent plain discounted for the height of levees which were probably formed during the aggrading channel phase. Discharge estimates based on the Manning Equation ranged from 1414 to 1844 m^3/s with a mean of 1616 m^3/s or approximately 5 times the present bankfull discharge at Darlington Point. These values are of the some order as Schumm's (1968) estimates of 2180 and 1000 m^3/s for large and medium channels respectively at Kulki Pit.

Waddi Reach - Kerarbury Arm

Table 8.3 provides discharge estimates for the WRD surveyed Waddi Reach downstream of Tombullen Swamp. The method of estimating channel depth and width is the same as for the Coleambally channels. On the assumption that channel sinuosity before aggradation was greater than the final value of 1.1, values of 1.2 and 1.5 were used to estimate the likely discharge range. The mean discharge estimated from the Manning Equation was 2610 m^3/s or approximately 8 times the present bankfull discharge at Darlington Point. This value is close to Schumm's (1968) estimate of 2100 m^3/s for an

Table 8.2. Discharge estimates for Coleambally palaeochannels.

REACH	D (Max) metres	SLOPE	'n'	D(Mean) metres	WIDTH metres	VELOCITY m/s	DISCHARGE m^3/s
BUNDURE Sinuosity 1.3	7.75	0.00026	0.035	6.5	165	1.65	1844
BUNDURE Sinuosity 1.5	7.75	0.00023	0.035	6.5	165	1.52	1630
YAMMA Sinuosity 1.2	6.5	0.00030	0.035	5.5	185	1.55	1577
YAMMA Sinuosity 1.5	6.5	0.00024	0.035	5.5	185	1.39	1414

Table 8.3. Discharge estimates for Kerarbury palaeochannels

REACH	D(Max) metres	SLOPE	'n'	D(Mean) metres	WIDTH metres	VELOCITY m/s	DISCHARGE m^3/s
WADDI Sinuosity 1.2	8.5	0.00029	0.035	7	220	1.79	2757
WADDI Sinuosity 1.5	8.5	0.00023	0.035	7	220	1.60	2464
MOULAMN Sinuosity 1.3	5	0.00015	0.030	4	200	1.03	825

intermediate sized palaeochannel at Kerarbury Pit but falls well short of his estimate of 8200 m^3/s for the largest channel. A crude estimate of bankfull discharge on the Kerarbury channel near Moulamein at the southwest margin of the Plain was based upon survey and field augering at Moulamein Pit (Fig. 6.3). Estimated channel width here is essentially a guess based on the preserved levee configuration. The discharge estimate of 825 m^3/s is only 32 per cent of that at the Waddi Reach but is 6.5 times the present Murrumbidgee bankfull discharge at Balranald and thus suggests that the Kerarbury Palaeochannel, like the present river, also suffered marked reduction of flood peaks in a downstream direction.

Gum Creek and Yanco Phases

Because the degree of preservation of the Yanco System channels is generally very good, discharge estimates can be based upon more reliable measurements of channel morphology than were available on the Coleambally and Kerarbury Systems. Both channel width and meander wavelength are particularly well preserved along certain reaches of the Gum Creek and Yanco Systems. In places borings across meander loops and cutoffs permit the reconstruction of channel cross sections which can be combined with estimates of channel slope and hydraulic roughness to calculate mean velocity and hence, discharge.

<u>Gum Creek System</u>

The palaeochannel reach of Gum Creek between Narrandera and Carrathool contains more than 20 well-preserved meander scars and cutoffs (Fig. 6.2) with meander wavelengths ranging from 1700 m to 3500 m (Fig. 6.7) and channel widths from 150 m to 230 m (mean about 180 m). Although not as numerous, similar marginal floodplain scars also occur in the confined valley reach upstream to Wagga Wagga. The palaeochannel dimensions greatly exceed those of 450-650 m (meander wavelength) and 60-70 m (channel width) on the present river. On the downstream Uara Creek reach palaeochannel meander wavelength declines to about 1600 m but individual values vary widely (Fig. 6.7).

Meander wavelength based discharge estimate

The ratios of palaeo to modern wavelength of approximately 2400:550 or 4.4:1 in the eastern Riverine Plain and 1600:520 (3:1) in the west indicate a palaeochannel bankfull discharge to modern discharge ratio of between approximately 20:1 and 10:1 if the statistical relationship between meander wavelength(L) and bankfull discharge(Q_{bf}) takes the form,

$L = 30\ Q_{bf}^{0.5}$ (Dury, 1965)

However, as has been discussed, discharge estimates based on this equation lack precision and do not take account of boundary sediment variation. In this case, the difference between bankfull discharges is probably exaggerated.

Meander cutoff based discharge estimate

Although a number of well-preserved cutoffs occur along the upper Gum Creek System their bend axis regions have been frequently inundated during the period 1990 - 1993 and hand augering has not been possible. However, in 1967 the WRD carried out a detailed survey of Tombullen Swamp in preparation for its use as an off-canal storage for the soon to be completed Coleambally Main Supply Canal. As shown in Figure 7.12 the swamp is a large palaeochannel meander cutoff on the southern margin of the Murrumbidgee floodplain to the east of Darlington Point. The WRD survey included an augered section (15 holes over 2 km) across the bend from north to south, a shorter auger survey (3 holes over 400 m) at the bend axis and other individual test holes. The surveys and air photographs show that the palaeochannel is 200-230 m wide with an average bed level 5.5 m below the adjacent floodplain of lateral accretion which is itself inset some 3 m below the landscape of the surrounding Riverine Plain. Based on two sections, bankfull discharge of the palaeochannel is estimated at 1215 m^3/s (Table 8.4) or about 4 times the present value of approximately 310 m^3/s at Darlington Point. This estimate is less than Schumm's (1968) value of 1445 m^3/s at Yarrada Lagoon but is based on survey data that are more reliable. In any event, the two values are within 20 per cent of one another which is close to the limit of accuracy of discharge reconstruction by this method (Kotnicki, 1983).

Table 8.4. Discharge estimate for Tombullen Swamp channel.

WIDTH (m)	DEPTH (m)	SLOPE	'n'	VELOCITY (m/s)	DISCHARGE (m^3/s)
215	5	0.00018	0.035	1.13	1215

Yanco System

The Yanco System is the final palaeochannel phase dated on the Murrumbidgee sector of the Riverine Plain. Although several large meander scars of this system are apparent in the reach between Narrandera and Conargo (Fig. 6.2) the palaeochannels here have been partly obscured by recent deposition from the small modern suspended load channels and are not ideal for discharge reconstruction. However, downstream of Conargo, and particularly between Wanganella and Moulamein, the modern channels and the palaeochannels are geographically separated. In this reach the latter are particularly well-preserved with large meander loops and scroll-patterned floodplains of lateral accretion. The dimensions of the Yanco palaeochannels along this reach are all the more impressive for being at the western edge of the Plain. Clearly, this Yanco channel left the Riverine Plain as a powerful river.

Meander wavelength based discharge estimate

Meander wavelengths along the Yanco System average approximately 3000 m compared to around 550 m on the present Murrumbidgee. By Dury's (1965) reasoning this difference suggests a decrease in discharge by a factor of 30. However, the stratigraphic record of these channels and their clear association with numerous source bordering dunes strongly suggest that they carried large amounts of coarse sandy bedload and had relatively high width/depth ratios. A more reliable estimate of discharge should be provided by preserved channel cross sections at meander scars.

Meander cutoff based discharge estimate

To the west of Rhyola Station a large meander loop and well-preserved channel section with bedload sediments TL dated at 18.2 ± 1.5 ka was

surveyed and augered to provide details of the channel's cross sectional geometry (Fig. 7.18). The 250 m wide channel contained approximately 1 m of silt and clay overlying 2-3 m of bedload coarse sands and finally a truncated clay basement presumed to represent the maximum channel depth. Assuming a slope of 0.0001 and a Manning 'n' of 0.035 the channel section yielded a bankfull discharge estimate of 1240 m^3/s (Table 8.5) or about 4.4 times the present bankfull discharge of the Murrumbidgee River at Hay (280 m^3/s). The surveyed width depth ratio of this channel was approximately 45:1 and thus not in the typical suspended load channel range (Schumm, 1963b).

Table 8.5. Discharge estimate at Rhyola Cutoff.

WIDTH (m)	DEPTH (m)	SLOPE	'n'	VELOCITY (m/s)	DISCHARGE (m^3/s)
250	5.5	0.0001	0.035	0.9	1240

Discussion of discharges

Stratigraphic and dating evidence on the Riverine Plain indicate that much of the last glacial cycle from 100 ka until 13 ka was characterised by rivers very different from the narrow deep suspended load ones of today. During this long period of close to average late Pleistocene conditions the rivers on the Murrumbidgee sector of the Plain often carried bankfull discharges in the order of 4 to 8 times those of the present rivers and a greater amount of coarse bed load. A similar conclusion for the Murray - Goulburn sector was arrived at by Bowler (1978). Repeated shifts from stable laterally migrating mixed load to aggrading bedload channels are apparent in the stratigraphic record, as are terminal phases of levee crevassing and the formation of distributaries of successively decreasing size. Although the proposed increases in discharge are modest and consistent with known conditions in other Australian river and lake systems during Oxygen Isotope Stages 3 and 5, other aspects of Riverine Plain channel behaviour are atypical and require explanation. Most puzzling is the evidence for the persistence of large rivers throughout much of Oxygen Isotope Stage 2, although perhaps not at the peak of the LGM, when other studies indicate aridity in the Australian landscape. Also of interest are the repeated oscillations of channel

behaviour during the relatively stable climatic conditions of Oxygen Isotope Stages 3 and 5a to 5d.

Discharges of water and sediment in Oxygen Isotope Stages 3 and 5

Estimates of bankfull discharge for the Coleambally and Kerarbury phase palaeochannels range from 1500 to 2600 m^3/s in the upstream eastern reaches to 800 m^3/s in the southwest. These values exceed present discharges by a factor of between 4 and 8 but are consistent with a range of data from other studies which indicate enhanced fluvial activity, larger lakes and generally moister climates in Australia during Stages 3 and 5 (Bowler, 1986a; Nanson et al.,1992a; Kershaw and Nanson, 1993;) and correlate closely with global records provided by deep ocean cores and Antarctic ice cores (Jouzel et al., 1987; Porter, 1989; Petit et al., 1990).

Increased stream discharges do not imply higher precipitation during Stages 3 and 5 but they do indicate more effective precipitation as a result of reduced evaporation accompanying lower temperatures. Assuming a mean continental temperature reduction of between 3°C and 5°C (Chappell and Grindrod, 1983) even modestly reduced precipitation totals would be capable of yielding greater amounts of runoff (Schumm, 1968). Of course, mean discharges need not have increased by the same factor as peak flows which probably reflected more seasonal conditions associated with a larger winter snow pack and spring flooding. Although it is often asserted by locals that snowmelt produces late winter and spring floods on the present Murrumbidgee River, the proportion of its catchment above 1500 m is less than 2 per cent at Narrandera. Given an average 60 days per year duration of snow cover at 1500m (Slatyer et al., 1985) the contribution of snowmelt to flooding is usually minimal. However, with the temperature reductions of average glacial times the area retaining 60 days per year cover would have extended down to 1000 m and included 16 per cent of the catchment above Narrandera. A substantial impact on flow regime would have resulted with consistently higher spring flows and larger flood peaks in years of above average snowfall. The average glacial temperature reduction would also have lowered the treeline to about 1300-1400 m and significantly increased the area subject to enhanced mechanical weathering and associated periglacial hillslope processes (Galloway,1965; Colhoun, 1991). In the Kosciusko region the pollen record and radiocarbon dating show that alpine

vegetation did not become established on the Main Range until after 15 ka and probably between 12 and 10 ka (Martin, 1986). The increased quantity of coarse sediment delivered to the upper Murrumbidgee Valley from slopes unencumbered by trees during the Quaternary is demonstrated by the deep valley fills upstream of Narrandera at the eastern margin of the Riverine Plain. Between Gungagai and Narrandera a Plio-Pleistocene sequence in the Palaeozoic confined bedrock valley increases in thickness from 30 to 180 m (Woolley, 1972). At Narrandera the bedrock basement is below present sea level. The Quaternary component of the fill (the Cowra Formation) occupies the uppermost 15 m at Gundagai but thickens to 30 m at Wagga Wagga and nearly 40 m at Narrandera. Apart from surficial silt-clay dominated modern floodplain deposits, the Cowra Formation is dominated by very poorly sorted, mineralogically diverse, coarse sand and gravel. A TL date from near the top of the Cowra Formation gravels at Pioneer Pit in Wagga Wagga yielded an age of 27.5 ± 2.3 ka thereby confirming their Late Pleistocene age. Deeper gravels here TL dated at greater than 100 ka.

Discharges in Oxygen Isotope Stage 2 (30 to 13 ka)

The generally accepted model of Australian and global climates at the LGM invokes widespread aridity and increased windiness with greatly reduced fluvial activity, falling lake levels and a concomitant increase in continental dune activity. The LGM contrasted sharply with the cool moist conditions of the preceding period (the Stage 3 Sub-pluvial) which terminated at about 30 ka. Although there is now a great deal of evidence in support of the arid LGM model (Kershaw and Nanson, 1993) it remains axiomatic that unanimity of evidence about the climatic or hydrologic conditions in any past period is a rare commodity. The present program of field work and TL dating has shown that the large sinuous mixed-load channels and floodplains of the Gum Creek and Yanco Palaeochannel phases were active from 35 to 25 ka and 20 to 13 ka respectively. Five dates for rivers and marginal dunes on the Yanco System cluster between 13.6 ± 1.6 and 19.4 ± 1.6 ka. Evidence has been presented to suggest that bankfull stream discharges in this period were greater than those of today by a factor of 4. How can this finding be supported in the face of the weight of contrary evidence?

Previous studies of the late Quaternary evolution of the Riverine Plain used radiocarbon dating to establish a chronology of fluvial activity. Although no

dating of the Murrumbidgee Yanco System was carried out, Pels (1969) and Bowler (1967; 1978) published chronologies for the Coonambidgal II - Kotupna channels in the Murray - Goulburn sector of the Plain. The bedwidths, meander wavelengths and reconstructed cross-sectional areas of these channels considerably exceed those of the modern rivers and point to ancient discharges in excess of those of today (Bowler, 1978). Three radiocarbon dates on charcoal associated with sandy deposits of the Kotupna channels ranged from 16.2 ± 0.3 to 13.0 ± 0.3 ka*. One date of 13.5 ± 0.3 ka* on deposits on the floor of the Kanyapella Depression clearly postdates the lake-full phase when a sandy lunette TL dated at around 30 ka was constructed. Pels' (1969) single radiocarbon date of 24.0 ± 0.8 ka* on Coonambidgal II deposits near Deniliquin is consistent with the early Kotupna dates. Although Page et al. (1991) TL dated Kotupna deposits at McCoy Pit at 34.4 ± 4.0 ka, and questioned Bowler's (1978) radiocarbon dates because of possible groundwater contamination, it is possible that the Kotupna phase operated at least intermittently from before 34 ka until about 13 ka and that the dates are therefore internally consistent.

Bowler et al. (1978) dated palaeochannels of the Darling River along the Acres Billabong anabranch near Tilpa, NSW, where the Moomba to Sydney gas pipeline trench exposed sediments deposited by southerly channel migration. The contrast between the morphology of the modern Darling and large Acres Billabong channels pointed to a major change in hydrologic regime involving former increased discharges and bedloads. Three radiocarbon dates indicated that channel migration of Acres Billabong occurred between 19 and 11 ka* at a rate of 0.17 m to 0.20 m per year, a figure that corresponded closely with the channel migration rate established for the Kotupna phase of the Goulburn River (Bowler, 1978). The stratigraphic consistency of these dates strongly supports their validity. Comparisons of the dimensions of the Yanco, Kotupna and Acres Billabong channels show similar differences between the modern rivers and their respective palaeochannels (Table 8.6). Palaeochannel widths range from 2-3 times those of the modern rivers and meander wavelengths from 2-6 times those of the modern rivers. Similar, although undated, channel and floodplain remnants also occur in the Lachlan sector of the Riverine Plain along the Willandra Creek supply channel for the Willandra Lakes and Box, Umbrella and Moolbong Creeks (Bowler, 1986a).

Table 8.6. Comparison of morphological parameters of Gum Creek, Yanco, Acres Billabong and Kotupna channels dated between 35 and 10 ka.

SYSTEM	CHANNEL WIDTH (metres)	MEANDER WAVELENGTH (metres)
Gum Creek	150 - 220	3000 - 4000
Yanco	150 - 250	2000 - 3000
Murrumbidgee	50 - 70	450 - 750
Kotupna	122 - 137	3000
Goulburn	70	550
Acres Billabong	NA	2200
Darling	NA	1050

The well-dated lunette sequence at Lake Tandou (Hope et al., 1983) also supports the possibility of larger river discharges during Oxygen Isotope Stage 2. Although Lake Tandou is usually regarded as part of the Menindee Lakes, on the lower Darling River in western NSW, it is geographically isolated from the modern Darling being linked to Talyawalka Creek palaeochannel system which is, in turn, the downstream continuation of the Acres Billabong reach studied by Bowler et al. (1978). Eleven radiocarbon dates on shells of the freshwater mussel, *Velesunio ambiguus*, and three on soil carbonate in the sand dominated Bootingee unit of the Tandou lunette yielded ages ranging from 27 to 15 ka*. The combination of high quartz sand content and the presence of many aquatic faunal indicators such as mussels, fish, yabbies, frogs and platypus in archaeological sites in the Bootingee unit indicates that fresh water conditions may have persisted in the lake throughout the period represented by this unit (Hope et al., 1983). Although the youngest dates obtained from the Bootingee are about 15 ka*, the dated middens were well within the unit and thus do not coincide with the termination of dune formation which may have been several thousand years later.

When the previously published river and lunette dates for the Murray Basin are considered along with TL dates on the Yanco System and sand lunettes and beaches at Lakes Urana and Cullivel described below it becomes difficult

to unreservedly accept the present orthodoxy of extreme aridity during the period including the LGM and covering most of Oxygen Isotope Stage 2.

Although the evidence from lakes and rivers shows that high levels and enhanced activity occurred between 30 and 13 ka it remains possible that the glacial maximim itself at 22 ka (Bard et al., 1990) occupied a short arid interregnum of perhaps less than four to five thousand years between more humid conditions leading into and out of the maximum. Indeed, the large number of dates indicating clay lunette formation and dune activation at the LGM appears to be matched by an almost complete absence of dates indicating higher lake levels and enhanced river activity. The period 24 to 20 ka (20.5 to 17 ka*) is discussed further in Chapter 10.

OSCILLATING PALAEOCHANNEL BEHAVIOUR

Introduction

The stratigraphic record of Murrurnbidgee palaeochannels reveals evidence of repeated shifts from stable laterally migrating mixed load facies to aggrading bedload facies with the formation of cut and fill distributaries during some of the terminal channel phases. Given the frequency of these shifts during periods of relatively stable climates, such as Oxygen Isotope Stage 3, their explanation in terms of climatic forcing requires repeated hydrologic shifts in the Murrumbidgee catchment not apparent in the wider regional or global context. In short, channels responding to the major shifts in climate during the last glacial cycle were also exhibiting oscillating conditions of much greater frequency than those attributable to climate change.

A probable explanation for the high-frequency channel shifts can be sought in current models of channel response to threshold exceedence (Schumm, 1979; Nanson and Erskine, 1988; Brizga and Finlayson, 1990). Schumm and Beathard (1976) argued that the identification of rivers near to a threshold boundary, such as between braided and meandering, was of considerable management value because these rivers are the most prone to sudden changes in pattern. Clearly, the Murrumbidgee palaeochannels flow on slopes too gentle to promote braiding under the present flow regime. According to Leopold and Wolman (1957) a minimum slope of 0.009 would be required to produce a braided channel at Narrandera given the present

bankfull discharge of 14000 cfs. The actual channel slope is 0.0002. However, Lane (1957) produced a slope-discharge graph which distinguished three river pattern zones: highly braided, highly meandering and intermediate (Fig. 8.2). The intermediate zone included streams with spatial and temporal changes in channel pattern from low sinuosity braided to high sinuosity meandering, ie, streams poised between the two pattern types. Schumm and Beathard (1976) found that the Chippawa River in Wisconsin, which displayed both spatial and temporal channel pattern shifts, plotted in Lane's intermediate zone (Fig. 8.2). Present values of slope and mean discharge on the Murrumbidgee in the reach between Narrandera and Carrathool place the river in the highly meandering zone of the graph. Modest increases in mean discharge (by a factor of between 1.5 and 3) and slope (in response to decreased sinuosity) shift the palaeochannels into the intermediate zone in the same region as the Chippawa River. Thus, according to Lane's (1957) data set the estimated slope and discharge range of the eastern Riverine Plain palaeochannels places them, like the Chippewa, in the category that is susceptible to threshold shifts. The concept of a broad zone of channels prone to shift from one pattern to another is also favoured by Carson (1984) who found that Leopold and Wolman's (1957) simple slope discriminator between braided and meandering channels did not apply to rivers on the Canterbury Plains of New Zealand.

If it is assumed, on the basis of the stratigraphic evidence, that the Murrumbidgee palaeochannels were predominantly mixed-load laterally migrating types, then a likely trigger for threshold shift must be sought. Although intrinsic threshold exceedence (Brizga and Finlayson, 1990) associated with levee crevassing probably played a role in terminal phase distributary formation, it seems likely that the major shifts to low sinuosity aggrading channels were initiated by inputs of coarse sediment from the confined upstream valley (Woolley, 1972), probably as the result of major individual floods or periods of flood dominated regime (Erskine and Warner, 1988; Nanson and Erskine, 1988). An assessment of the nature of the coarse grained sediment component of the palaeochannels deposits suggests that the principal impetus for channel aggradation was increased sediment input from upstream rather than changed long term flow conditions (shear stress and flow velocity).

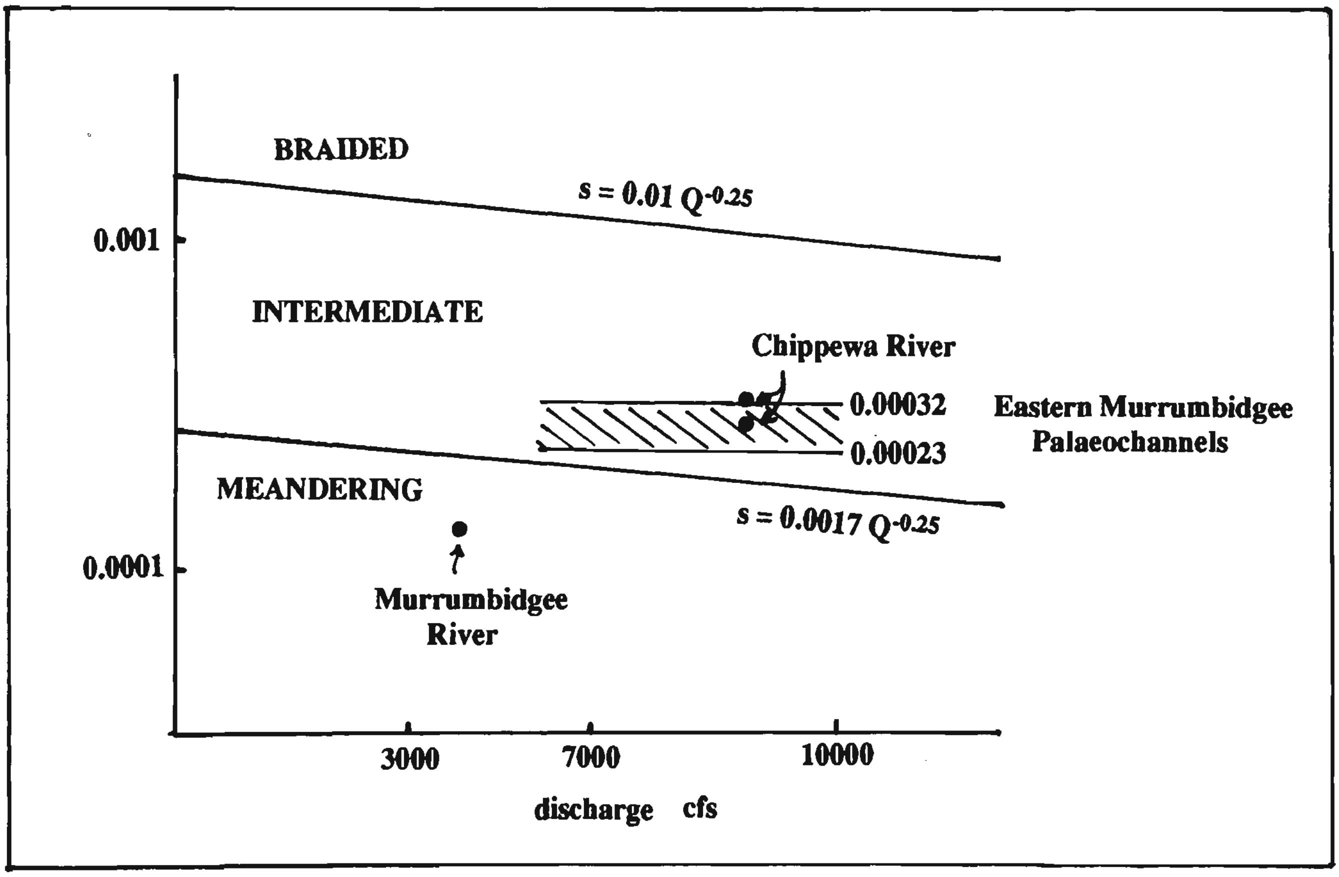


Fig. 8.2. Graph showing channel pattern in relation to slope and mean annual discharge. Zones defined by Lane (1957).

Channel change in response to sediment supply

Theory of sediment entrainment

The determination of the flow conditions required to move the bedload sediments of the Murrumbidgee palaeochannels was based on recent work by Komar (1987) who investigated the entrainment of mixed sediment size distributions. Early experimental studies of the initiation of sediment motion by fluid flow generally focused on essentially uniform grain sizes, for example, natural grains from a single size distribution or, in some cases, artificial glass spheres of uniform size. The material was placed in a flume and the flow strength increased until the first grain movement was observed. Empirical threshold curves developed in this way are now reasonably well-established (Miller et al., 1977).

However, most natural beds of sediment depart markedly from the assumed condition of essentially uniform grain sizes and densities. In applying the experimental curves to mixed size distributions, it has generally been assumed that the median grain size can be taken as representative of the sediment distribution as a whole. This approach ignores the potential for selective entrainment of grains of different sizes which is important in the development of such phenomena as bed armouring (Komar, 1987).

Recent work by Milhous (1973), Day (1980), Carling (1983) and Hammond et al. (1984) has concentrated on the entrainment of mixed grain size distributions. Komar (1987) summarises much of the work for sediment size distributions with median grain sizes ranging from 1.55 mm to 20 mm, and individual particles from 0.15 mm to 200 mm (Table 8.7).

Figure 8.3 from Komar (1987) compares the relationship between critical shear stress and grain diameter for mixed size distributions with the curve of Miller et al. (1977) for uniform size distributions. Each of the data sets shows that for selective entrainment from deposits of mixed sizes, the larger the grain diameter, the greater the shear stress required for entrainment. Each curve obliquely crosses the dashed line of Miller et al. (1977) for uniform

Table 8.7. Recent studies of grain entrainment in mixed size distributions.

STUDY	MEDIAN SIZE (mm)	RANGE OF SIZES (mm)
Milhous (1973)	20	8 - 117
Carling (1983)	20	10 - 200
Hammond et al. (1984)	7.5	5 - 40
Day (1980)	1.75	0.15 - 11.1
	1.55	0.15 - 4.1
	0.44	0.15 - 2
	0.42	0.15 - 2.9

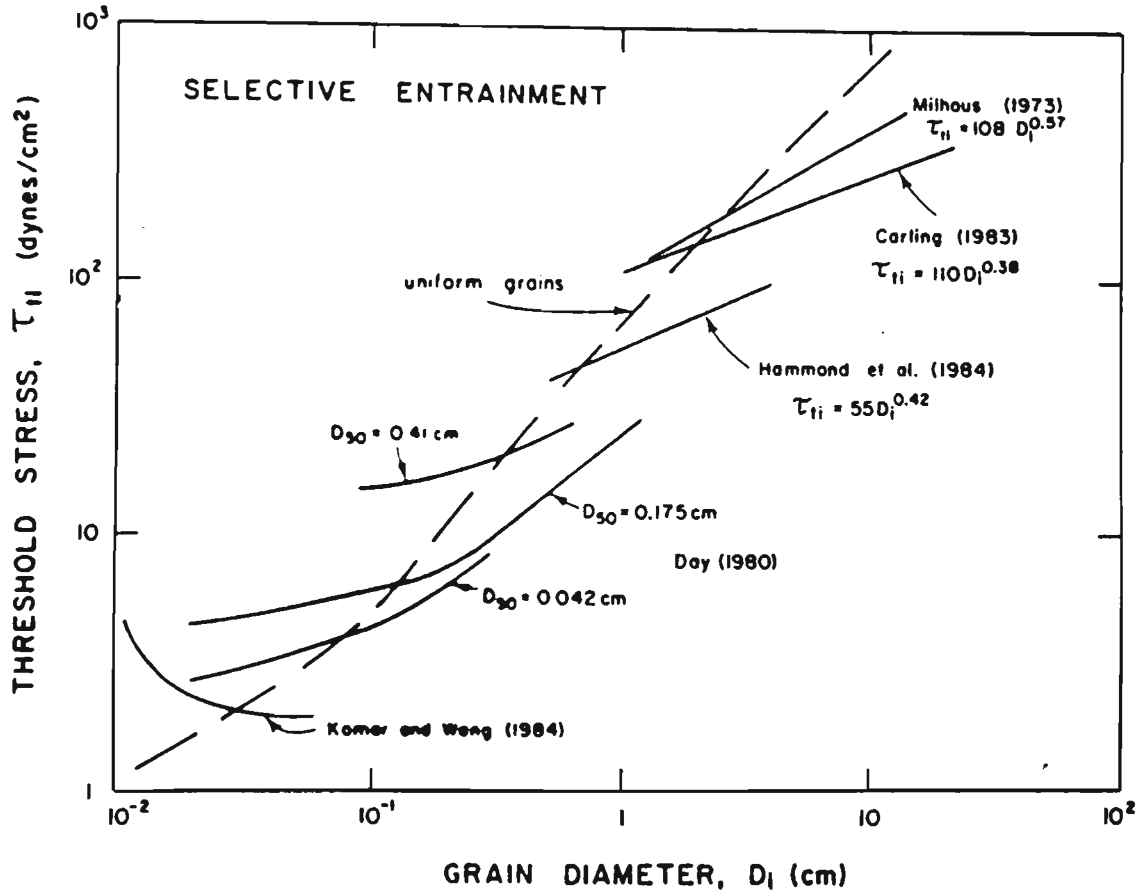


Fig. 8.3. Sediment entrainment curves from various studies of mixed grain sizes compared with the standard threshold curve (dashed) for uniform grains from Miller et al. (1977). Graph from Komar (1987).

sizes such that the coarser size fractions are entrained at lower flow stresses than they would if found in deposits of uniform size, while the finer size fractions require greater shear stresses than they would if found in uniform size distributions (Komar, 1987). In general the curve crossover points for the curves of Day (1980) approximate the median diameters.

Palaeochannel grain size distributions and critical shear stress

Upstream confined valley reach

Sediment samples from point bars and the upper unit of the basal gravels in the Murrumbidgee Valley near Wagga Wagga (Appendix 2) had an average median diameter of 5 to 10 mm, and a range of diameters from approximately 0.1 to 50 mm. These sediment distributions conform closely with those studied by Hammond et al. (1984) in terms of median and maximum diameter.

Critical values of shear stress to move grains in a mixed distribution of median size 7.5 mm can be determined from

$$\tau = 55\, d^{\,0.42}$$

where, τ is shear stress in dynes/cm^2, and d is diameter in cm (Hammond et al., 1984). Selected values of sediment size and shear stress are listed in Table 8.8.

Table 8.8. Grain diameters and entrainment shear stresses for mixed sediment distributions with median size 7.5 mm. Based on Hammond et al. (1984).

Diameter (mm)	Shear Stress (dynes/cm^2)
6	44.4
10	55
20	73.6
30	87.2
40	98
50	108

Flow depths and shear stresses for the modern Murrumbidgee River at Wagga Wagga are given in Table 8.9. At a flow depth of 6 m (bankfull stage), a shear stress of 105.8 dynes/cm^2 should be capable of moving grains up to almost 50 mm in a bed whose median size is 7.5 mm. However, should the bed be armoured such that the median grain size increases to 20 mm, then larger values of shear stress are required. Based on the data of Milhous (1973) and Carling (1980), who experimented on distributions with median diameters of 20 mm and particles up to over 100 mm diameter, the threshold shear stresses for grains of different size are shown in Table 8.10.

A depth of 6 m will not move the median diameter grains. Indeed, to move grains of 20 mm diameter will require a flow depth of between 8 m and 9 m. Grains of 40 mm diameter would not be moved under any conditions likely to occur in the modern Murrumbidgee. This conclusion is consistent with the observations of present gravel extractors on the river that little or no coarse gravel (ie, > 40 mm) moves under the present regime. Under a braided, low-sinuosity palaeo-regime, as suggested by pit exposures of the Pleistocene Cowra Formation, grains of 40 mm diameter on an armoured bed would be moved at flow depths of between 5 m and 6 m (Table 8.9). Those of 30 mm diameter would move at flow depths of between 4 and 5 m. These data suggest that the armoured bed of the present regime could readliy become mobile under a channel regime of reduced sinuosity and increased slope. Although bed armouring may have existed from time to time in the Late Quaternary, major floods would have readily disrupted the stable bed and delivered greatly increased amounts of coarse sediment to the Riverine Plain. Grain sizes, computed shear stresses and observations on the modern Murrumbidgee River suggest that Komar's (1987) equations for bedload transport can be applied with confidence to palaeo-environments on the Riverine Plain.

Table 8.9 Shear stresses and flow depths for modern and palaeo-Murrumbidgee River at Wagga Wagga.

	Modern river (slope = 0.00018)	Palaeo-river (slope 0.0004)
Depth (cm)	Shear stress (dynes/cm^2)	Shear stress (dynes/cm^2)
100	17.6	39.2
200	35.2	78.4
300	52.9	117.6
400	70.6	156.8
500	88.2	196.0
600	105.8	
700	123.5	
800	141	
900	159	
1000	176	

Table 8.10. Critical shear stresses for entrainment of grain sizes of a given diameter in a mixed sediment distribution of median size 20 mm according to Milhous (1973) and Carling (1980).

Diameter (mm)	Shear stress (Milhous, 1973)	Shear stress (Carling, 1980)
20	160	143
30	202	167
40	238	186
50	270	203
60	300	217

Riverine Plain reach

Samples of the bedload sediments of Murrumbidgee palaeochannels on the Riverine Plain were collected at a series of pits. Grain size parameters determined by sieving are summarised in Table 8.11 and Figure 7.4. (a more comprehensive data set is given in Appendix 2). Taken together the data display remarkable uniformity. Although maximum grain diameters decrease from east to west across the Plain, median sizes remain within the range 0.5 to 2.0 mm.

Table 8.11. Summary of grain sizes in Riverine Plain palaeochannel infills and the upper gravel unit at Wagga Wagga.

	RIVERINE PLAIN	PIONEER PIT	ARMOUR LAYER
Number samples	21	7	7
Median (mm)	1.1	5.8	9.1
Maximum (mm)	4 - 8	32 - 64	32 - 64

On the basis of these data, it was assumed that the experimental results of Day (1980) for mixed sediment distributions with median sizes of 1.55 mm and 1.75 mm reasonably approximate channel infill distributions on the Riverine Plain. If anything, shear stresses estimated from Day's (1980) curves might overestimate those required to move grains of the slightly smaller median sizes encountered on the Plain. Shear stresses required to initiate grain movement in sediment distributions of 1.75 mm median size are given in Table 8.12. Estimates of shear stresses in Riverine Plain palaeochannels are given in Table 8.13.

It is clear that even flow depths of 2m, which can be readily deduced from cross-beds in pit faces at sites all over the Plain (Chapter 7), would be sufficient to move the full range of grains where maximum size does not exceed 8 mm. Even at Emery Pit where grain diameters of up to 24 mm were present, flow depths of 2 m in low sinuosity channels would readily move these grains. In sinuous channels, flow depths of 4 m would be sufficient to

Table 8.12. Shear stresses and grain diameters based on Day (1980).

Diameter (mm)	Shear stress (dynes/cm^2)
2	7.4
4	11.6
8	20.5
16	35
24	53

Table 8.13. Shear stresses and flow depths in Riverine Plain palaeochannels. Slopes of 0.0003 (low sinuosity mode), 0.0002 (intermediate) and 0.00015 (high sinuosity mode) are assumed.

Depth (m)	Shear stress (s = 0.0003)	Shear stress (s = 0.0002)	Shear stress (s = 0.00015)
1	29.4	19.6	14.7
2	58.8	39.2	29.4
3	88.2	58.8	44.1
4	117.6	78.4	58.8
5	147	98.0	73.5

initiate movement. Therefore, it can be concluded that sediment transport on the Riverine Plain was not limited by the ability of the flow to move the grains (stream competence) but rather by sediment supply and discharge (Friend, 1993).

Bed aggradation of palaeochannels on the Riverine Plain

Discharge variation across the Plain

Throughout the Tertiary the Riverine Plain has been a sink for sediments derived from the Southeastern Highlands of Australia (Brown and Stephenson, 1991). Fluvial deposition in this region has been favoured by decreasing gradients and increasing catchment aridity to the west. The second factor, in particular, means that the present Murrumbidgee River receives minimal tributary input in the reach downstream of Narrandera. Indeed, mean discharge decreases downstream from around 100 m^3/s at Narrandera to only 77m^3/s at Balranald. Although irrigation losses contribute to this decrease in discharge, natural losses to distributary channels such as Gum Creek and Yanco Creek also occur. It is probable that the climatic gradient across the Plain existed throughout the Late Quaternary and that the palaeochannels of the Murrumbidgee also received minimal tributary input between the present location of Narrandera and its confluence with the Murray River. At times when Willandra Creek was active, the Lachlan River did not join the Murrumbidgee until near Wentworth in the Mallee region.

On the present Murrumbidgee River, the long reach across the Riverine Plain without tributary input is associated with marked downstream hydrograph attenuation during floods. In general, flood peaks decline sharply downstream of Wagga Wagga, while the duration of flood discharges tends to increase (Table 8.14). Between Narrandera and Balranald the mean annual flood, which approximates bankfull discharge (Page, 1988), declines from 434 to 127 m^3/s and the ten year flood declines from 1340 to 457 m^3/s (Page and McElroy, 1981). A summary of annual flood data at gauging stations along the Murrumbidgee Valley is given in Table 2.2. It is likely that similar downstream hydrograph attenuation occurred during the Late Pleistocene although its magnitude may have been somewhat reduced during the lower sinuosity channel phases when flow was more direct across the Plain.

Table 8.14. Mean flood peak reduction and duration increase downstream of Wagga Wagga on the Murrumbidgee River based on 31 floods. (After Julian, 1975)

RIVER GAUGE	DISTANCE DOWNSTREAM[3] (km)	PEAK[1] %	DURATION[2] DAYS
Wagga Wagga	0	100	4.6
Narrandera	96	68	8.4
Hay	278	39	25.2

Note: 1 Peak expressed as a percentage of Wagga Wagga maximum.
2 Duration expressed as days flow greater than 75% of peak.
3 Axial valley distance downstream in km.

Modelling of bedload transport on the Riverine Plain

In order to model the effects of flood hydrograph attenuation on the downstream movement of sandy bedload sediments, Colby's (1964a) relationships between mean velocity, flow depth and the discharge of sands were applied to hypothetical flood hydrographs for river cross sections at the eastern and western margins of the Riverine Plain. Aggradation or degradation of a sandy channel bed can be determined by a calculation of the difference between the quantity of sand entering and leaving a given river reach (Colby, 1964b). Where more sand enters than leaves a reach it will be stored in the channel and/or floodplain. If the sand is deposited wholly on the stream bed then the volume of sand can be averaged over the bed area to provide an estimate of net change in bed elevation.

The aim of the present study was to establish likely trends in bedload transport across the Riverine Plain by means of a simple model. The precise estimation of volumes or rates of sedimentation based on realistic data was not attempted. Although a number of simplifying assumptions were made they are not thought to seriously undermine the general validity of the conclusions reached.

Assumptions

1 Bedload sand discharge was not supply limited.
2 Reach length was 200 km.
3 For each hydrograph modelled it was assumed that the same amount of water would enter and leave the reach but that between the upstream (eastern) and downstream (western) sections the flood peak would be reduced by 50% and the flow duration would be increased by 100% at all flow levels. These factors are modest compared to present levels of hydrograph attenuation.
4 Channel slopes at the eastern section and western sections were 0.0003 and 0.0002 respectively.
5 At both sections the channel cross section was assumed to be a vertical walled flume 200m wide. This is a gross simplification that would clearly affect the quantum of sand moved. However, it should not affect the broad trends in sand discharge across the Plain.
6 In keeping with Colby's (1964a) approach a density of 1363 kg/m^3 for freshly deposited sand was assumed.

Calculations

Mean velocities at each section were estimated for a range of flow depths using the Manning Equation with a roughness coefficient ('n') of 0.03. Estimates of sand discharge for given flow depths and mean velocities were based upon Colby's (1964a) empirically determined Figure 19 which is based upon a water temperature of 15°C and a median grain diameter of 0.3 mm. The latter value is lower than the typical range of Riverine Plain channel infills (0.5 to 1.5 mm) but not sufficiently to alter the general pattern of sand discharge. For example, Colby's (1964a) data show that discharge trends for 0.8 mm median diameter sands very closely follow those of 0.3 mm diameter but that actual discharge rates are reduced by about 25%. Insufficient data were provided in Colby (1964a) to base estimates on the 0.8 mm sands.

Computed bed load storage on the Riverine Plain

Estimates of sand discharges at given depths and flow velocities permitted the establishment of a relationship between sand discharge and water discharge at each of the model cross sections (Table 8.15 and Fig. 8.4).

These data were then combined with model hydrographs for major (5800 m^3/s), large (2900 m^3/s) and medium (1500 m^3/s) floods at eastern cross sections to estimate the input of sand to the model reach. The calculations based on Colby's (1964) data show that input of sand exceeds output for each flood magnitude selected (Table 8.16). Details of hydrographs and calculated volumes of sand discharge are provided in Appendix 3.

Table 8.15. Sand bedload discharge of model Murrumbidgee palaeochannels of the eastern and western Riverine Plain. (After Colby, 1964a)

EASTERN SECTION				WESTERN SECTION			
slope .0003, width 200m, n 0.03				slope .0002, width 200m, n 0.03			
Depth m	Velocity m/s	Q m^3/s	QS tonnes/m/d	Depth m	Velocity m/s	Q m^3/s	QS tonnes/m/d
1	0.58	116	7	1	0.47	94	1
2	0.92	367	53	2	0.75	300	21
3	1.20	722	157	3	0.98	590	69
4	1.46	1168	292	4	1.19	955	161
5	1.70	1695	476	5	1.39	1386	243
6	1.92	2299	666	6	1.57	1878	410
7	2.12	2974	860	7	1.74	2430	557
8	2.33	3722	1031	8	1.90	3037	680
9	2.52	4533	1290				
10	2.70	5402	1500				

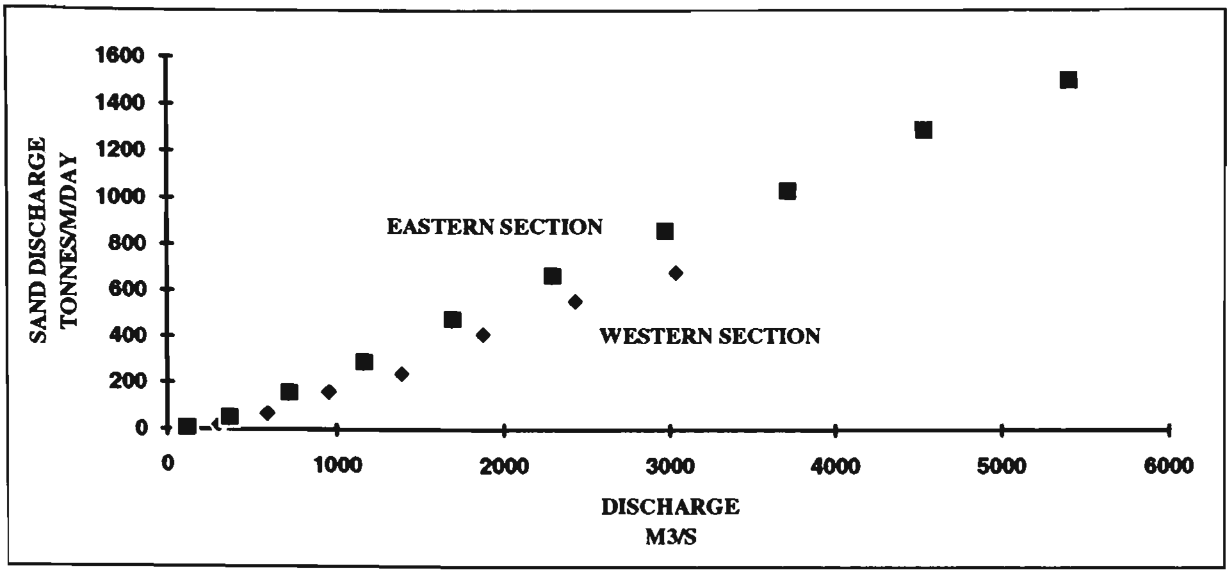


Fig. 8.4. Relationships between sand and water discharge for model Riverine Plain palaeochannels based on Colby (1964a).

Table 8.16. Bedload sand transport at eastern and western Riverine Plain sections.

	EASTERN SECTION			WESTERN SECTION			
FLOOD	Q max m^3/s	Q duration days	Q sand $m^3 \times 10^3$	Q max m^3/s	Q duration days	Q sand $m^3 \times 10^3$	**Net bed elevation change**
MAJOR	5800	40	4845	2900	80	3464	**+0.035 m**
LARGE	2900	30	1695	1450	60	953	**+0.019 m**
MEDIUM	1500	24	691	750	48	286	**+0.010 m**

Note: The major flood peak of 5800 m^3/s approximates the NSW Department of Water Resources (1988) estimate for the present 100 year flood at Wagga Wagga.

Although the data for net bed elevation change for each of the floods considered could be used to estimate possible rates of long term bed aggradation the underlying assumptions and data used severely limit the reliability and precision of any quantitative estimates. Nevertheless, the model does illustrate an important principle. If sediment discharge is not supply limited, the constraints of declining flood peaks and gradients across the Riverine Plain will ensure that not all of the bedload sediment entering the Plain during a flood event will leave the Plain. In bedload dominated streams the majority of this sediment will be stored on the river bed (Schumm, 1963b) and result in channel aggradation. Channel stability will occur only during periods of limited sediment supply when the amount of bedload sediment entering the Plain does not exceed the amount that can be transported from the Plain. During much of the Quaternary, sediment loads on the Riverine Plain appear to have been supply rather than transport-limited (Friend, 1993) and stable laterally migrating streams have resulted. However, during periods of abundant sediment supply from the upstream confined valley reach, probably triggered by single large floods or more prolonged periods of flood dominated regime, the Riverine Plain channels have aggraded and evolved prior stream characteristics. Repeated shifts from one style of channel pattern to the other are indicated by the stratigraphic record.

Cut and fill associated with levee crevasse distributary formation

In addition to the shifts from stable to aggrading channels described above there have been periods of distributary formation associated with the terminal phases of channel aggradation and levee formation when shallow (often < 2 m deep) sand bed streams flowed across the Plain. Complex patterns of distributaries apparent on air photographs and Pels' (1964a) stratigraphic sections near Griffith suggest that these progressively smaller channels were produced by frequent levee crevassing and ensuing short-lived cycles of cut and fill. The likely processes involved here resemble those described by Carson (1984) on braided rivers in New Zealand and Brizga and Finlayson (1990) in Victoria. When the levee crevasse first occurs the new channel flows down the levee backslope on a relatively steep gradient. Because this channel initially carries little bedload it is sediment-undersaturated (Friend, 1993) and scours along its course (Carson, 1984). As the new channel becomes dominant more bedload sand is fed into it and aggradation occurs,

rapidly resulting in the formation of a new distributary. Pels (1964a) noted that successive distributaries decreased in size and often petered out after only a short distance. These episodes of arroyo style cut and fill during periods of declining flow (Schumm, 1968) are significant in that they have produced many of the visible surface features of the Riverine Plain. However, they should not be confused with the major shifts from stable laterally migrating (ancestral style) channels to vertically aggrading (prior style) channels. The cut and fill distributaries of decreasing size form predominantly during the terminal phases of the aggrading channels.

Marginal dunes

One of the complications affecting the preceding estimates of sediment transport across the Riverine Plain is the loss of bedload sand to marginal dunes. The amount of bedload lost to dune storage is likely to have been relatively small given the limited extent and volume of the dunes and their construction from only the fine sand bed load fraction. Given the absence of any evidence of increasing median grain size in the palaeochannels in a downstream direction it appears that loss of sand to marginal dunes did not make a significant impact on downstream sediment flux. In this study losses of sand to dunes have not been factored into the bedload calculations.

Of course conditions of bed aggradation and channel shallowing would have been ideal for selective deflation and dune formation. Sediment samples were collected in auger holes at seven marginal dunes across the Murrumbidgee sector of the Riverine Plain (Figs. 6.2 and 6.3) revealed consistent median grain diameters close to the medium - fine sand boundary (0.25 mm) and always clearly finer than the coarse and very coarse fluvial sands from which they were derived (Fig. 7.4). The locations of the dunes and their grain size characters suggest that they were derived from deflation of nearby exposed sandy river beds by westerly to southwesterly winds.

The dunes closely border the northern and eastern margins of many palaeochannels and appear to have undergone minimal transgression despite the reworking of their crests subsequent to initial formation. Along the Murrumbidgee palaeochannels mapped and TL dated in the present study the dunes reach a maximum local elevation of a little over 10 m near Kerarbury Pit but typically do not exceed 5 m. Because they border all three

palaeochannel systems it appears that marginal dunes have formed intermittently throughout the last glacial cycle until about 10 ka when they appear to have become largely stabilised (Wasson, 1989). The dunes formed throughout the last glacial cycle and therefore, are not exclusively associated with aridity. Indeed, there is good reason to believe that the dunes formed initially during periods of channel aggradation and were reworked in more arid phases.

CONCLUSION

Palaeochannel morphology and floodplain stratigraphy on the Murrumbidgee sector of the Riverine Plain show that the period between 105 and 13 ka has been characterised by generally larger rivers that carried a greater proportion of bedload than the present rivers whose deposits are dominated by silt and clay (Schumm, 1968). The stratigraphic record indicates that channels during this period frequently oscillated between stable meandering mixed-load (ancestral) and aggrading low sinuosity bedload (prior) modes. A consideration of the bedload sediments and likely palaeoflow conditions on the Plain suggests that mode switches from stable to aggrading channels were probably initiated by threshold exceedence flow events which resulted in copious amounts of pebbly coarse sand being delivered from the confined valley upstream. Given that bedload discharge was not supply-limited the combination of decreasing slope and flood hydrograph attenuation westwards would have guaranteed the aggradation of channels on the Plain and accompanying shifts to lower sinuosity and higher width depth ratios. Between about 15 and 10 ka the final palaeochannel phase ended and the modern rivers with their reduced discharges and domination by suspended sediment loads became established.

CHAPTER 9

LATE QUATERNARY EVOLUTION OF LAKE URANA

INTRODUCTION

Relict inland lakes with associated crescentic transverse dunes (lunettes) are characteristic features of the western (Mallee) region of the Murray Basin of southeastern Australia (Bowler and Magee, 1978). They are also found scattered across the Riverine Plain, particularly in the area to the east of Balranald (Fig. 6.1) where the Uara Creek palaeochannel apparently fed a terminal lake complex. In the eastern Riverine Plain relict lakes are less common but several do exist including a large well-preserved example with a compound lunette some 4 km to the west of Urana (Fig. 9.1).

Although these inland lakes are typically dry under the present climatic regime, or at best contain surface water seasonally, their deposits point to previous episodes of profound hydrologic change. At times of water surplus the lakes experienced deep freshwater conditions when wave action led to the development of sandy beaches and foredunes at their eastern and northeastern margins in response to dominant west to southwesterly winds. Archaeological evidence suggests that lake full conditions were associated with thriving shoreline and aquatic life that supported human communities at varying times since about 40ka (Bowler, 1986a). On other occasions desiccation of the lakes under saline conditions led to the formation of clay-rich dunes by deflation from the exposed lake floor (Bowler, 1983). These dunes are characteristically aligned more directly north-south and hence are the product of a more westerly wind than their sandy counterparts. Radiocarbon chronologies at these lakes, particularly Lake Mungo in the Willandra chain (Bowler, 1971), have yielded a high quality record of landscape evolution and human occupance over the range of radiocarbon dating. At Lake Mungo, lunette construction came to an end at the LGM when lake drying and high saline groundwater tables combined to produce extensive clay-rich lunettes (Bowler, 1986a).

In its oval to kidney shape, shallow topography, northwest to southeast orientation and shoreline geomorphology, Lake Urana (Fig. 9.1) closely resembles other previously studied lakes of the Murray Basin. It is approximately the same size as Lake Albacutya in Victoria which was investigated by Bowler (1983). Because

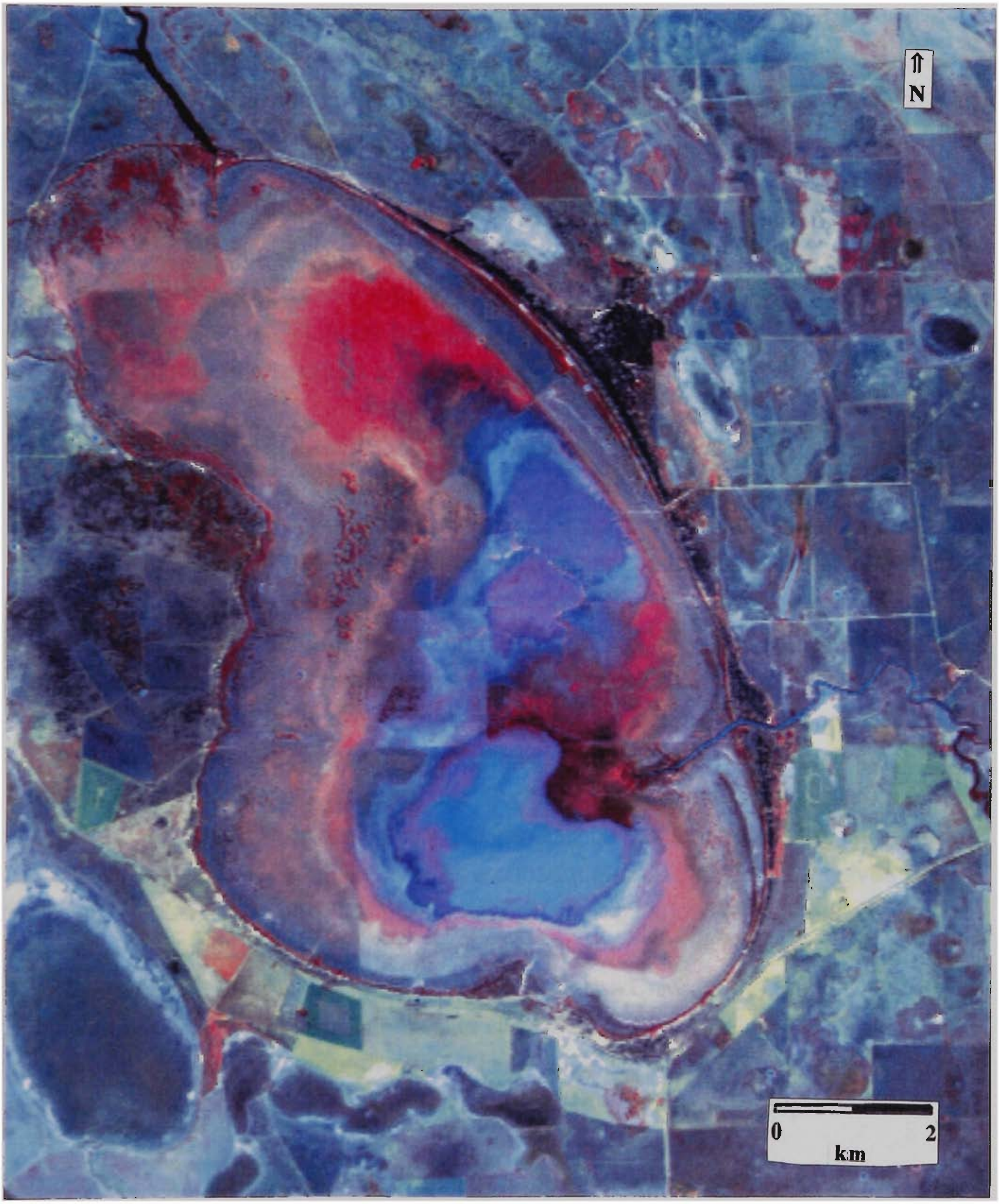


Fig. 9.1. Landsat Thematic Mapper false colour scene of Lake Urana showing shallow muddy water in claypans and flush of vegetation on the recently inundated lake floor.

of the excellent preservation of Lake Urana's shoreline features, particularly its large lunette and cambered beaches, it has generally been assumed to be a quite recent feature. However, the discovery of human remains in the Urana lunette in 1988 and their TL dating at more than 25 ka (Page et al., 1994b) demonstrated the antiquity of this system and presented an opportunity to compare the TL palaeochannel record of Late Quaternary hydrologic change with that contained in the Urana lunette. During the course of this work we also investigated Lake Cullivel, some 20 km to the northeast, where a similar, although smaller, lake and lunette system exists. All TL dates reported at Lakes Urana and Cullivel were collected from freshly exposed pit faces or auger holes into wave and wind deposited sediments of the eastern and southern lake margins. TL ages and supporting technical data for the Urana and Cullivel samples are presented in Table 9.1.

LAKE URANA - GENERAL GEOMORPHOLOGY

Lake Urana occupies a 65 km^2 depression lying approximately 10 m below the surrounding surface of the Riverine Plain. The major catchment for Lake Urana is provided by Urangeline Creek which drains 2400 km^2 of low undulating country to the east and includes the 900 km^2 catchment of Boree Creek and its terminal Lake Cullivel (Fig. 9.2). The detailed surface hydrology of the basin is quite complex. In wet years flood water from both Colombo Creek to the north and Billabong Creek to the south may flow across low catchment divides and enter the lake via Coonong Creek and Washpool Gully respectively. Furthermore, the lake's usual outlet, Cocketgedong Creek, has been known to experience flows back into the lake (pers. comm., Urana Shire Council, 1989). As a consequence, Lake Urana receives floodwaters derived, in part, from the southeastern highlands via the Murrumbidgee River and its distributary channel, Colombo Creek (Fig. 9.2). However, judging by the size of deltaic deposits, it appears that Urangeline Creek is the dominant contributory channel. In contrast to Lake Urana, Lake Cullivel's input is entirely locally derived. Present groundwater tables at Lake Urana lie 35 to 60 m below the surface and are highly saline (>20000 µs/cm) (CRA-Mitsubishi, 1989).

Although Lake Urana often holds shallow surface water in late winter and spring, particularly in the low-lying 'claypans' area (Fig. 9.1), it has filled to overflow level only a few times since records commenced in 1840, the last occasion being 1974 when it discharged through Cocketgedong Creek into the Colombo Creek - Yanco Creek system to the west. Under the present hydrologic regime of high annual

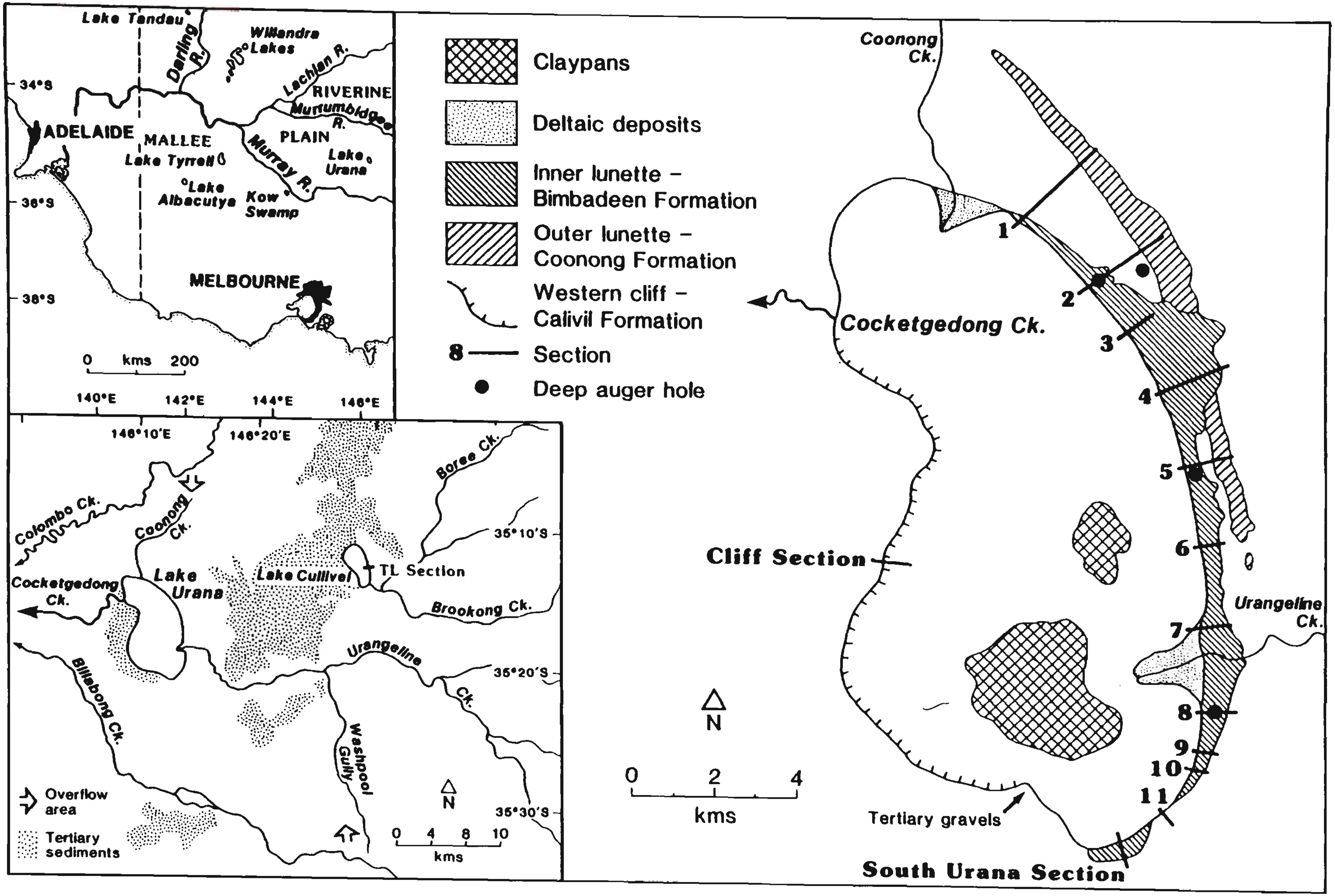


Fig. 9.2. The Lake Urana study area showing section and deep bore hole locations.

evaporation (1800 mm) and modest precipitation (420 mm) Lake Urana and Lake Cullivel are relics of former more humid conditions (Atlas of Australian Resources, 1986).

Lake Urana exhibits most of the characteristic morphological features of lunette bordered lakes of the Murray Basin. At its western margin an irregular cliffline up to 10 m high has been cut into a low ridge of highly weathered Pliocene sandstone (Calivil Formation) and Ordovician metasediments (Fig. 9.3). Calcareous red-brown earths mantled by pisolitic ironstone gravels are found along this ridge. Because the soil carbonate is unlikely to have been derived from the high energy fluvial sandstones of the underlying Calivil Formation it is thought to be the product of late Pleistocene aeolian accession, the last major phase of which probably occurred at about the time of the LGM. Evidence from the Mallee dunefield, (Bowler and McGee, 1978) lunettes and source bordering dunes on the Riverine Plain (Bowler, 1986a) and dust peaks in the Antarctic Vostok ice core (Petit et al., 1990), all point to a peak of aeolian activity at that time.

The north-south orientation of the Tertiary ridge was probably instrumental in blocking the westward flow of Urangeline Creek and may have combined with floodplain deposition along Colombo Creek to the north to initiate a lake basin in late Pleistocene times. Overflow of Lake Urana occurs via Cocketgedong Creek where a low area exists at the northern end of the Tertiary ridge. Wave erosion of the western cliffline is suggested by the presence of coarse sandy beach deposits here and also by evidence of substantial cliff retreat into the Calivil Formation (Fig. 9.3). Auger holes sunk into the lake floor up to 200 m from the cliff base revealed weathered Calivil sandstone beneath a thin (less than 1 m) layer of grey lacustrine mud. In contrast, lake sediments more than 12 m deep were encountered in a drill hole located between the inner and outer lunettes on the eastern side of the lake near Section 2 (Fig. 9.2). Substantial cliff retreat and thick lake floor sediments indicate a lake of great antiquity. The cliffline is not likely to be of recent tectonic origin for it is highly irregular in planform and there is an absence of faulting in the Calivil Formation elsewhere in this region (pers. comm., J Lea, CRA-Mitsubishi,1991).

Gravel beds are common in the Calivil Formation but their only exposure at Lake Urana occurs at the southern shoreline in an irrigation drain (Fig. 9.2). It is probable that these gravels provided the bulk of sediment for the distinctive coarse grained beach and dune deposits a short distance to the east.

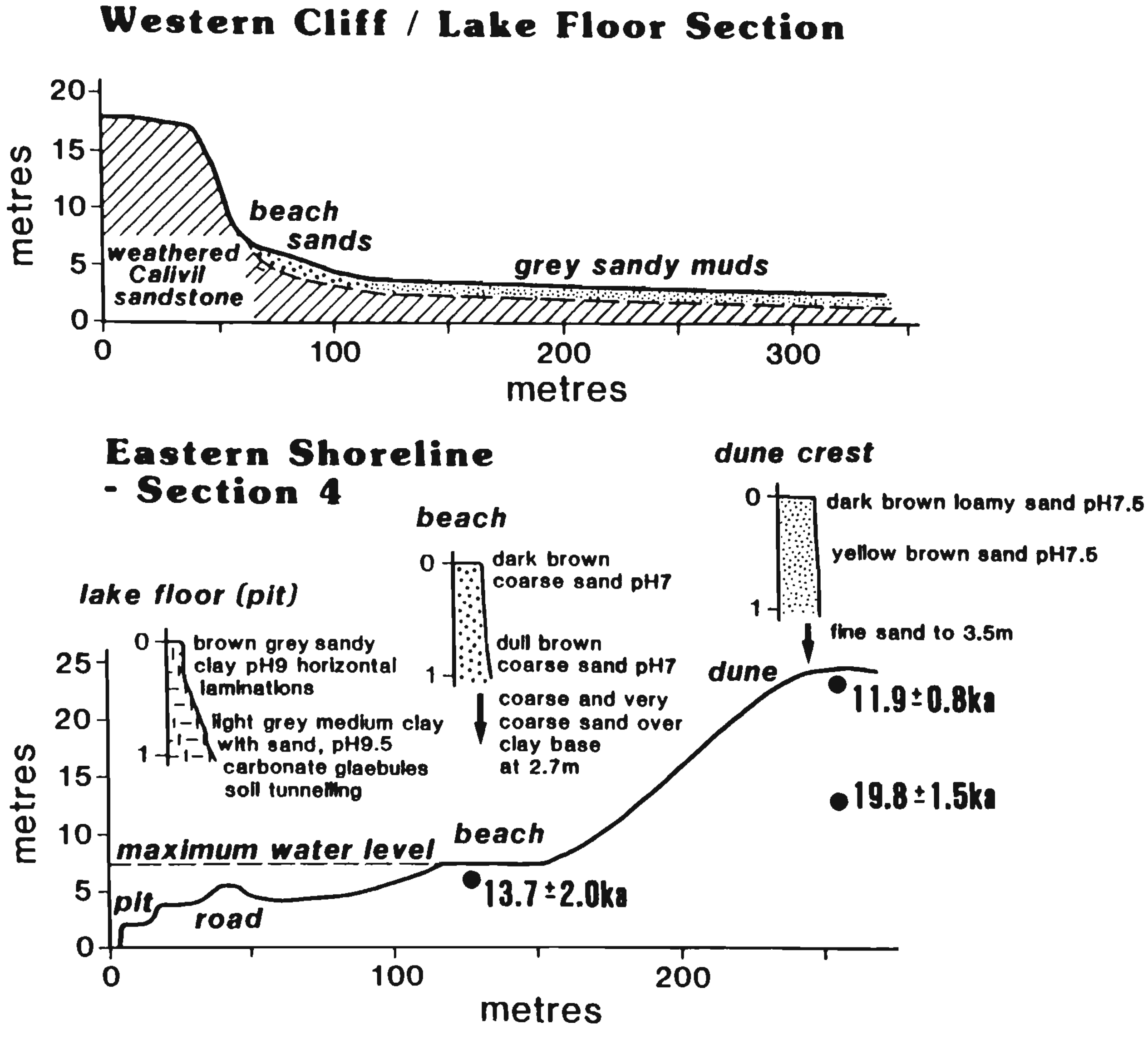


Fig. 9.3. Topographic and stratigraphic sections of the western and shoreline of Lake Urana. TL dates given in ka.

The lunette at Lake Urana attains its maximum development in the northeastern shoreline region where a dual ridge system exists (Figs. 9.2 and 9.4). The inner lunette has well developed beaches and foredunes and its sediments are dominated by quartz sand. The outer lunette has a more subdued topography (Fig. 9.4) and has sediments with a higher clay content and stronger pedogenic characters. The two ridges are clearly defined to the north of Urangeline Creek and diverge towards the north. South of Urangeline Creek it appears that the two northern lunettes are superimposed to form a compound lunette (Bowler, 1983) which declines rapidly in elevation to the south. A small isolated and irregular dunefield at the extreme southern end of the lake is significant because it contains evidence of human occupation before 20 ka (Page et al., in prep.). Beach deposits are also particularly well preserved here but their coarse textures strongly suggest derivation from the Tertiary gravel outcrop to the west.

INNER LUNETTE COMPLEX - BIMBADEEN FORMATION

To describe the characters of the inner lunette system twelve approximately equally spaced sections were selected for topographic survey and sediment sampling along the eastern shoreline of Lake Urana (Fig. 9.1). Four representative sections from north to south are shown in Figure 9.4. Additional information from soil pits and auger holes was collected at various sites including Section 4 where the inner dune approaches its greatest elevation. The orientation of the inner lunette is approximately 070° and indicates a dominant wind direction from the WSW at the time of formation (Bowler, 1983).

The inner lunette landform assemblage is particularly well developed in the north. Here coarse sandy beaches 2-3 m thick (Figs. 9.4 and 9.5) are characterised by steep faces and cambered berms which are up to 40 m wide, and rise 5-6 m above the lake floor. South of Urangeline Creek they are very weakly developed, rarely amounting to more than a 0.3 m thick lens of coarse sand overlying grey lacustrine muds. A pit in nearshore lake sediments at Section 4 (Fig. 9.3) revealed well laminated sodic (pH >9) grey sandy clays and medium clays with abundant nodular carbonate glaebules. The sodicity is possibly a relict of past conditions when saline groundwater tables were closer to the surface (Bowler, 1983).

Directly east of the beach is a steep transverse dune of fine sand which reaches a maximum elevation of 26 m above the lake floor at Section 3 (Fig. 9.5). The greatest vertical development of the dune coincides with its region of maximum

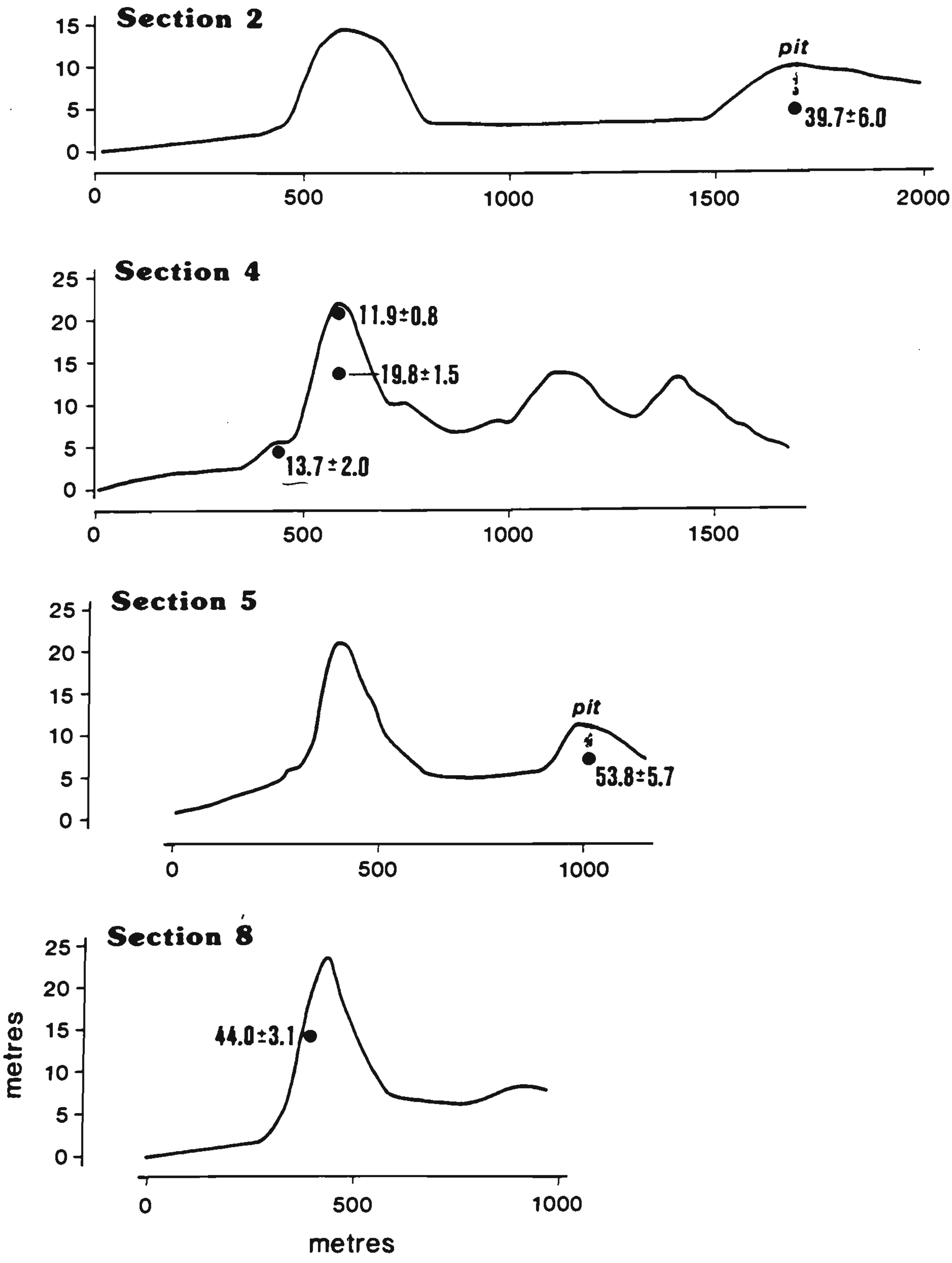


Fig. 9.4. Topographic sections of the lunette system. TL dates given in ka.

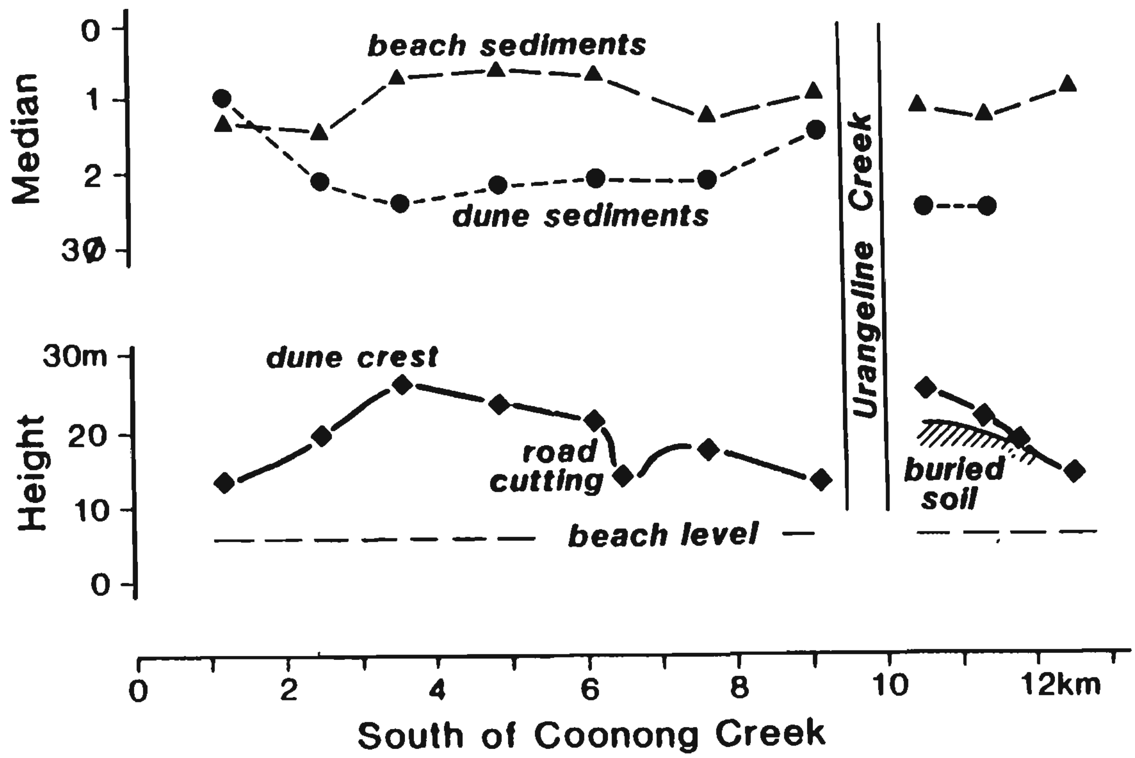


Fig. 9.5. The long (N-S) profile of the inner lunette crest and median grain size of near-surface sediment.

downwind westerly fetch across the lake. Between Sections 3 and 4 a hummocky transgressive sheet of sand up to two kilometres wide extends eastwards from the main dune and partly covers the outer lunette (Fig. 9.1 and Section 4, Fig. 9.4). Elsewhere the inner ridge occurs as a single symmetrical steep sided ridge with minimal downwind development. This suggests that the dune was well vegetated throughout much of its formation and did not suffer significant episodes of instability. Although the compound lunette rises 25 m above lake floor to the south of Urangeline Creek at Section 8, fieldwork here shows that the fine sand unit occurs only as a five metre capping over older dune sediments which are pedogenically altered and contain appreciable amounts of clay.

Beach and inner lunette sediments are moderately sorted and dominated by sand sized particles with <2% silt-clay. Where the inner lunette is best developed between Sections 3 and 5 the median size of beach sands ranged from 0.62 to 0.37 mm compared to 0.30 to 0.18 mm for dune sands (Table 9.3 and Fig. 9.5), consistent with the formation of the dune by deflation of the finer fraction of sand from beaches deposited by wave action. The vastly greater quantity of dune sand than beach sand (Fig. 9.4) suggests that the majority of shoreline sediment was in the easily transported medium to fine sand grades and readily deflated from the beach. Figure 9.5 summarises the relationships between shoreline location, dune height and medium grain size for the inner lunette. Very weak pedogenesis of the inner lunette complex, including an absence of podzolisation, suggests that low rainfall and minimal soil organic content have characterised the Holocene.

A TL date of 13.7 ± 2.0 ka (W817) was obtained in coarse sands 1.2 m below the crest of the beach berm at Section 4 and two TL samples from the dune at Section 4 at depths of 1.2 m and 12 m below the crest yielded ages of 11.9 ± 0.8 ka (W757) and 19.8 ± 1.5 ka (W756) respectively. Given that the dune here is almost 20 m thick these dates indicate that the beach and dune system developed from before 20 ka until around 12 ka. The low percentages of clay and absence of carbonate in the beach and upper dune sediments of the Bimbadeen Formation suggest that minimal aeolian clay accession has occurred here during the Holocene.

North of Urangeline Creek auger holes into the lunette reached basal clays at Sections 2 and 5 and beach sands at Section 7 but revealed no significant textural changes or buried soil horizons. The entire ridge appears to have been constructed during a period of relatively uniform depositional conditions. Short pauses in

Table 9.1. Thermoluminescence data and ages, Lakes Urana and Cullivel.

Sample No	Section and Formation	Temp Plateau Region (°C)	Analysis Temp (° C)	Palaeodose (Grays)	K Content (%)	Moisture Content (% by wt)	U + TH Specific Activity (Bq/kg)	Annual Radiation Dose (µ Grays)	TL Age (ka)
W829	Southern Sect Bimbadeen Fm	300-500	375	10.6 ± 2.1	NT[b]	3.1	12.9	400 ± 75	26.6 ± 7.3
W830	Southern Sect Bimbadeen Fm	300-400	350	9.8 ± 0.8	NT[b]	2.6	7.9	303 ± 75	32.4 ± 8.5
W831	Southern Sect Coonong Fm	300-500	375	32.4 ± 1.8	0.23[b]	4.8	26.8	900 ± 73	36.0 ± 3.5
W756	Sect 4 Bimbadeen Fm	275-500	375	33.5 ± 2.0	1.11[b]	0.9	17.3	1693 ± 77	19.8 ± 1.5
W757	Sect 4 Bimbadeen Fm	275-500	375	21.7 ± 1.1	1.10[b]	0.6	23.7	1819 ± 77	11.9 ± 0.8
W817	Sect 4 Bimbadeen Fm	300-400	350	7.8 ± 0.5	0.17[b]	1.0	11.8	570 ± 77	13.7 ± 2.0
W913	Sect 8 Coonong Fm	300-500	375	118 ± 8.0	1.81[a]	9.0	41.0	2680 ± 70	44.0 ± 3.1
W902	Cullivel Sect Bimbadeen Fm	275-450	375	16.0 ± 1.1	0.35[a]	0.2	20.4	948 ± 77	16.8 ± 1.8
W903	Cullivel Sect Coonong Fm	300-450	375	117 ± 10.0	1.53[a]	6.5	88.6	3382 ± 72	34.6 ± 3.1
W1357	Sect 2 Coonong Fm	325-500	375	130 ± 19.0	1.70[a]	12.2	84.3	3265 ± 67	39.7 ± 6.0
W1358	Sect 5 Coonong Fm	325-450	375	66.0 ± 5.6	0.70[a]	1.2	15.6	1226 ± 76	53.8 ± 5.7

Notes:

1. Assumed rubidium levels, K content by AES (a) and XRF (b).
2. Annual radiation values indicated assume a cosmic contribution of 150 µGy/yr.
3. U and Th specific activity levels were determined by calibrated thick source alpha counting and assume secular equilibrium.
4. Uncertainty values shown represent one standard deviation.

deposition would not have manifested themselves as palaeosols due to the region's slow pedogenesis in sandy sediments noted above.

South of Urangeline Creek a single 25 m high lunette declines rapidly to the south disappearing altogether between Sections 10 and 11. Beach deposits are poorly developed in this region and fine dune sands at Section 8 are restricted to a 5 m upper unit which thins to a 0.1 m veneer at Section 10. Beneath the sandy cap is a sharp break to a buried soil containing appreciable clay and pedogenic carbonate. This lower unit appears to be the southern continuation of the outer lunette of the northeastern quadrant.

The inner lunette system at Lake Urana has been designated the Bimbadeen Lunette Complex and its constituent sediments the Bimbadeen Formation (Page et al., in press). Its definitive characters are well preserved beach and dune topography, sandy textures with minimal clay and carbonate content and weak pedogenesis. These properties indicate formation during a continuous or intermittent series of high water levels extending from before 20 ka until approximately 12 ka. Because the Bimbadeen Formation attains its maximum expression in the northeastern shoreline region and the lunette is oriented to the ENE (070°) a controlling wind regime from the WSW (250°) is deduced. The strong development of the Bimbadeen Lunette Complex north of Urangeline Creek and its very weak development to the south indicate that the Creek, and not the western cliffline, provided the bulk of sediment. Given a predominantly WSW wind and wave regime, sediments would have been swept from south to north along the shoreline by longshore currents and beach drifting with deposition concentrated on the north-eastern shoreline.

OUTER LUNETTE COMPLEX - COONONG FORMATION

North of Urangeline Creek the inner lunette is backed by an older transverse dune which typically occurs as a discrete ridge separated from the Bimbadeen dune by the almost horizontal surface of the old lake floor. A bore hole here (Section 2, Fig. 9.2) revealed more than 12 m of lacustrine mud dominated by calcareous and gypsiferous clays.

Because the outer lunette is aligned more to the north-south (076° orientation) than its inner counterpart the two ridges diverge to the north such that the inter-dune spacing of about 300 m at Section 5 increases to 1500 m at Section 1 (Fig. 9.4).

Between Sections 3 and 4/5 the outer dune is draped with the transgressive sediments of the Bimbadeen Formation. Between Section 6 and Urangeline Creek the outer lunette is absent and presumed to have been removed by the lateral movement of the Creek whose palaeochannels are evident in this area.

The topography of the outer lunette is much more subdued than that of the inner dune with local relief not exceeding six metres except to the south of Urangeline Creek. In cross section it is more asymmetric having relatively steep upwind and gentle downwind sides (Fig. 9.4), typical of other Australian clay lunettes (Bowler, 1983). Bright red and brown pedogenically altered clayey sands are found in the outer lunette to the north and south and suggest that, despite excision on Urana Creek and superimposition by the Bimbadeen complex in the southern area, the outer lunette was formed as a single ridge. The outer lunette and its southern continuation have been designated the Coonong Lunette Complex and its sediments the Coonong Formation (Page et al., in press).

The stratigraphy of the Coonong Formation is not complex. A core of sandy sediment is overlain by a clay rich layer with a well developed surface soil. Although the clay content of the Coonong soil varies, its other characters are remarkably consistent along the dune. These included reddish and yellow brown colours, moderate pedality, weak to strongly subplastic soil bolus behaviour (Northcote, 1979), high pH (8 to 9.5) and the presence of subsoil fine earth carbonate (FEC) and soft carbonate glaebules (Fig. 9.6). The Coonong clay unit varies from 5 m thick in the north at Section 1 to <2 m at Sections 8 and 10. The north-south decrease in thickness of the Coonong upper clay unit and the concomitant increase in thickness of the underlying sand unit is shown in Figure 9.7. Deflocculated samples of the Coonong clay are characterised by bimodal sediments with appreciable sand and clay but only 4-6% silt (Table 9.2). Bimodality and subplasticity is typical of Australian parna and clay dune deposts (Dare-Edwards, 1984) and is consistent with the presence of sand-sized clay aggregates seen in thin sections in the primary deposit. At Section 8 alternate sandy clay loam and loamy sand layers between 0.1 m and 0.3 m thick and gently dipping (5 to 7 degrees) back into the dune core (Fig. 9.6) suggest oscillating lake environments at the time of deposition; some truncation of the dune has occurred with its topographic axis shifting eastwards. A similar, although more complex, pattern was identified by Bowler (1971) at Lake Mungo.

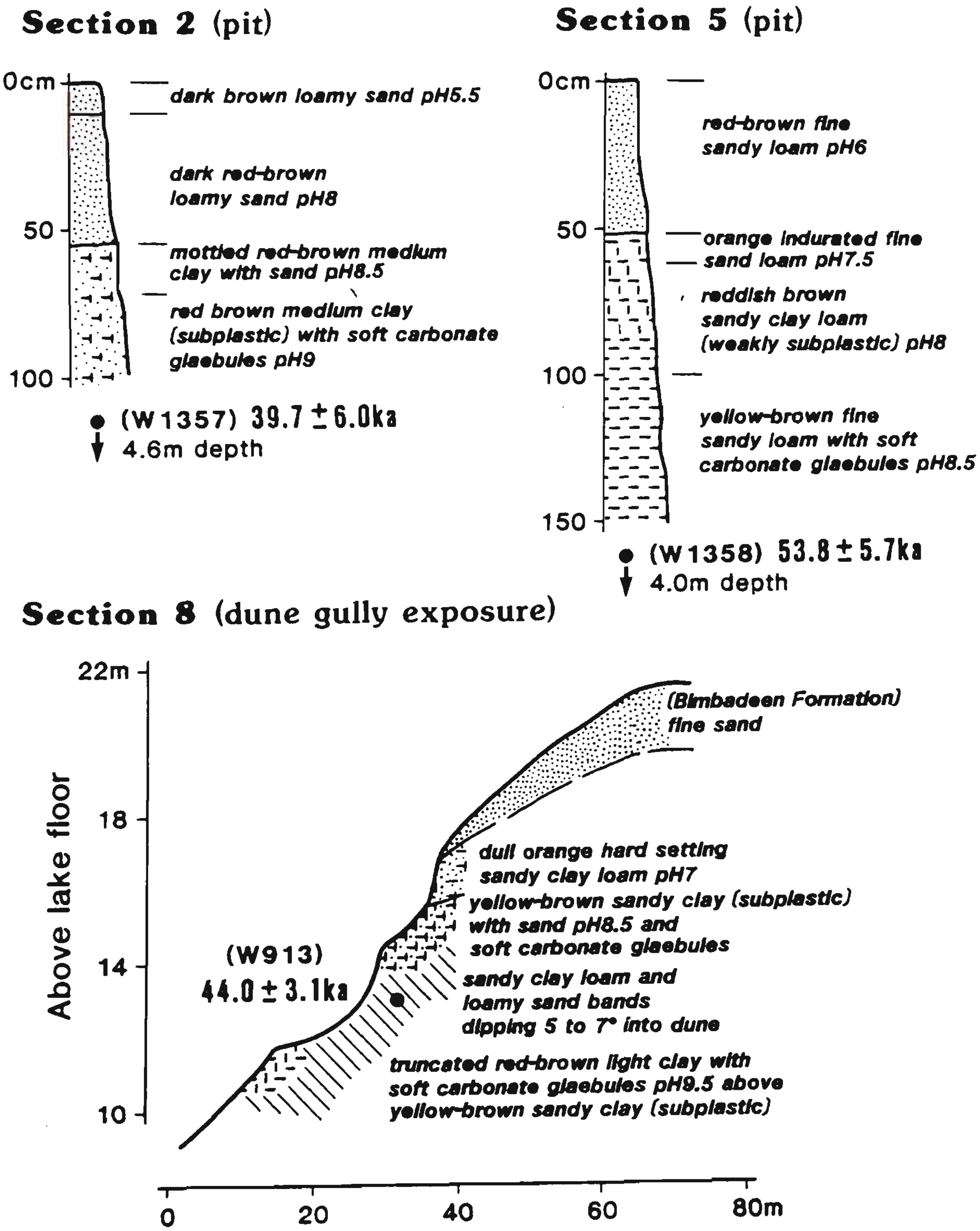


Fig. 9.6. Stratigraphy of the Coonong Formation at Sections 2, 5 and 8.

TL samples from deep within the sandy core of the Coonong Formation at Sections 2 and 5 yielded ages of 39.7 ± 6.0 ka (W1357) and 53.8 ± 5.7 ka (W1358) respectively (Fig. 9.4). At Section 8 a sample only 1 m below the base of the Coonong soil gave an age of 44.0 ± 3.1 ka (W913) (Fig. 9.4). These apparent stratigraphic discrepancies probably result from the difficulty of accurately assessing TL dose rates in the rather variable loamy sands of the Coonong Formation. However, the dates are all clearly older than those on the Bimbadeen Formation and, taken together, they indicate that the Coonong Formation was probably deposited in the interval from about 55 ka to as young as 35 ka (the latter young age accommodates a TL date obtained in the Southern Dune, below).

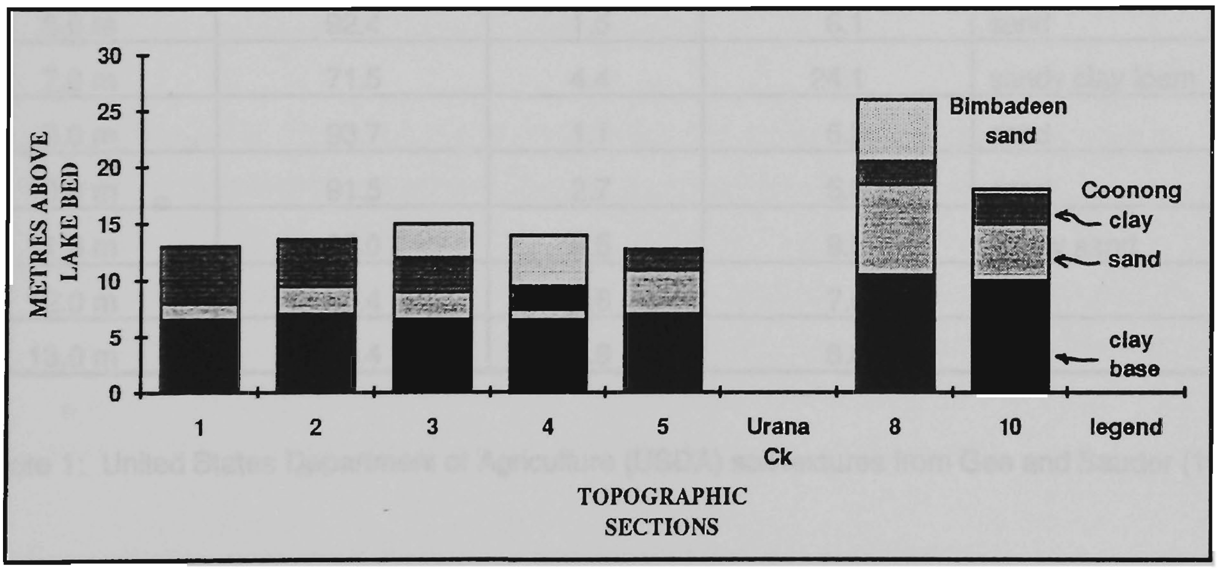


Fig. 9.7. North-south variation in thickness of sediment units in Coonong Formation.

Table 9.2. Hydrometer grain size fractions for Coonong Formation on the outer lunette. Locations of auger holes are shown in Figure 9.2.

Sample	% sand (>50 µm)	% silt	% clay (> 2µm)	USDA texture
Section 2				
1.8 m	49.8	15.0	35.2	sandy clay
2.9 m	32.1	5.7	62.2	clay
3.8 m	27.4	9.4	63.2	clay
4.8 m	86.8	0.3	12.8	loamy sand
6.1 m	44.4	6.8	48.8	clay
Section 5				
1.3 m	83.1	3.0	13.9	sandy loam
1.8 m	87.5	6.1	6.5	loamy sand
2.8 m	88.5	5.8	5.7	sand
4.0 m	96.8	0.3	2.9	sand
5.5 m	63.6	3.5	32.9	sandy clay loam
Section 8				
6.0 m	92.4	1.5	6.1	sand
7.0 m	71.5	4.4	24.1	sandy clay loam
9.0 m	93.7	1.1	5.2	sand
10.0 m	91.5	2.7	5.8	sand
11.0 m	85.0	6.5	8.5	loamy sand
12.0 m	90.4	2.6	7.0	sand
13.0 m	89.4	1.8	8.8	sand

Note 1: United States Department of Agriculture (USDA) soil textures from Gee and Bauder (1986).

Table 9.3. Textural characters of Lake Urana's eastern and southern shoreline deposits.

	Eastern shoreline		Southern shoreline	
Texture parameter	Beach	Dune	Beach	Dune
Median diameter (mm)	0.49	0.24	1.17	0.59
% Gravel (>2 mm)	3.0	0.0	20.6	0.0

SOUTHERN DUNE

At the southern end of Lake Urana (Fig. 9.2 - South Urana Section) a small isolated hummocky dune rises 14 m above the lake floor and 8 m above an impressive beach deposit at its northern margin. Both beach and dune sediments here are clearly coarser than those found in the eastern lunette system (Table 9.3). The southern beach sediments contain pebbles >20 mm that appear to have been derived from Tertiary gravels a little to the west (Fig. 9.2).

From exposures in two Urana Shire Council quarries at the site and an auger hole which was sunk to the basal deposits at the centre of the southern dune, two stratigraphic units were identified (Fig. 9.8). An upper layer of quartz sand has a well-developed bright brown siliceous sand surface soil profile which grades to clean medium sands with a thin carbonate pan about 2.4 m below the surface. The carbonate layer occurs along the top of a 2 m thick unit of subhorizontally laminated sand (Fig. 9.8). Individual layers dip gently toward the lake and were probably deposited on the stoss side of the dune along a saltation ramp (Collinson and Thompson, 1982). The well preserved internal dune bedding suggests rapid accretion and minimal pedogenic modification.

Outcropping on the floor of the quarry about 5 m below the dune crest was a truncated reddish-brown unit with crude sedimentary bedding and weak pedogenic characters (Fig. 9.8). The sediments of the buried soil grade vertically down into medium aeolian sands and then pebbly beach deposits with individual clasts to 40 mm. Where exposed in quarry faces these beach deposits show crude internal cross strata dipping at approximately 15 degrees north towards the lake. The beach sediments rest unconformably on a grey medium clay basement.

From the upper unit at 1.5 and 1.9 m below the dune surface (Fig. 9.8) TL ages of 26.6 ± 7.3 ka (W827) and 32.4 ± 8.5 ka (W830) respectively are in the correct stratigraphic order but are statistically indistinguishable. The high errors associated with each date reflect the very low dose rates in these sands (Table 9.1). Because the instrumental limit of accuracy remains constant, the percentage error involved in the measurement of the radiation dose increases as the radiation dose itself declines.

This unit appears to have been deposited between 30 and 25 ka, probably early during the Bimbadeen phase. An earlier termination of deposition here than on the

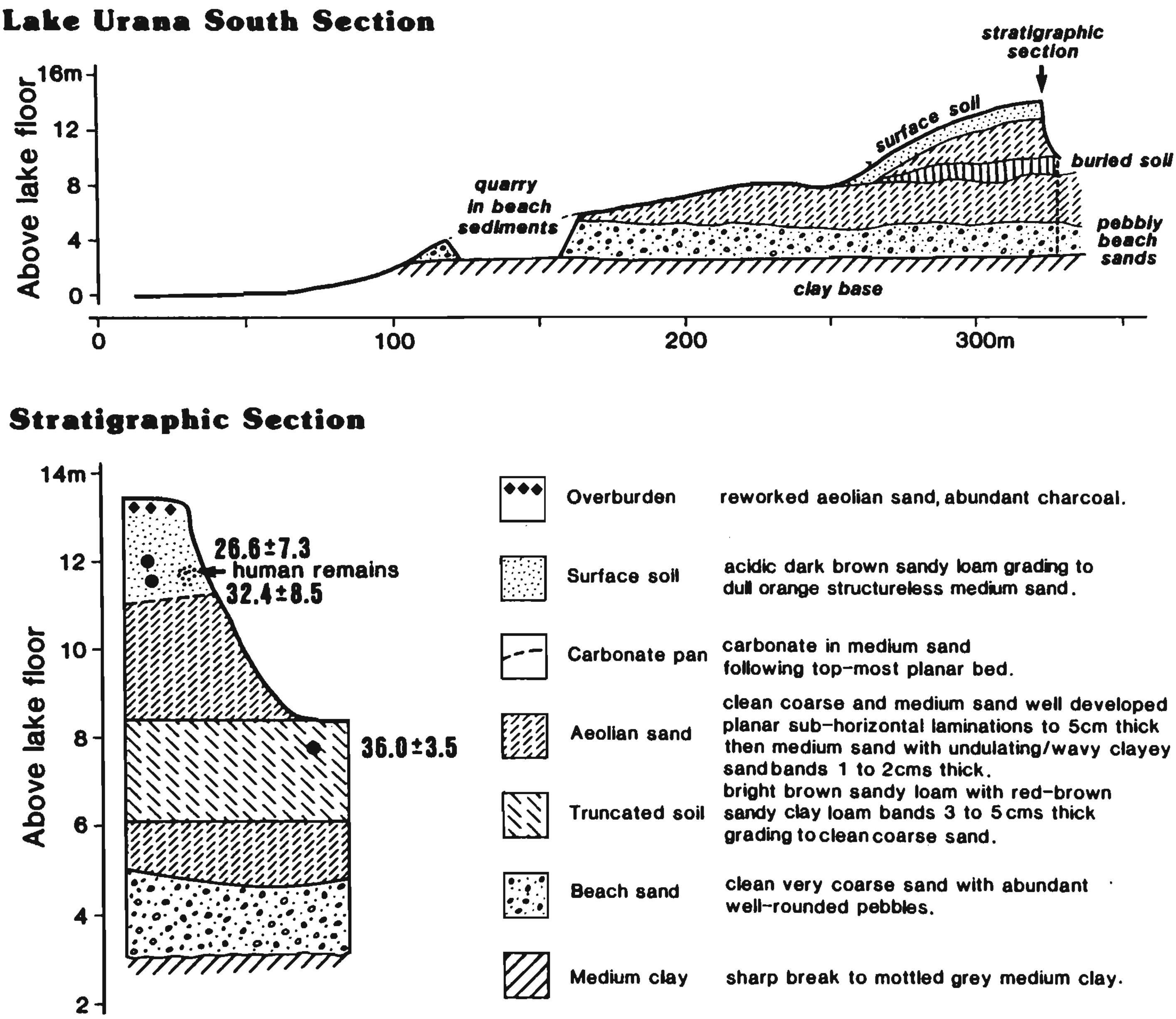


Fig. 9.8. Stratigraphic section of the southern dune (Fig. 9.2). TL dates given in ka.

inner lunette further north is supported both by the TL dates and the stronger pedogenic characters of the surficial soil. It appears that the Tertiary gravels to the west ceased to yield sediment for longshore movement and aeolian reworking by about 25 ka. At present these gravels carry a 0.5 m veneer of lacustrine mud and are exposed only in a drainage ditch.

A single date of 36.0 ± 3.5 ka (W831) on loamy sands located 6 m below the dune surface and in the upper metre of the buried soil is not statistically distinguishable from the dates above, but in combination with the palaeosol it suggests that this lower unit is contemporaneous with the Coonong Formation. The presence of pebbly beach sands below the truncated soil (Fig. 9.8) indicates a high water phase before 36 ka.

Although the southern dune is quite small it is important because it contains artefacts and skeletal remains of human occupation in this area before 25 ka. In December 1988 part of a female skeleton, including an almost complete cranium, was discovered in the working face of the quarry between 1.8 m and 2.0 m below the upper soil profile. The skeletal remains were of great gracility and hence are similar in many respects to those of the Lake Mungo 1 female radiocarbon dated at 26 ka* (Bowler and Thorne, 1976). Details of the skeletal remains and their significance are provided below.

HUMAN OCCUPATION AT LAKE URANA

During routine stratigraphic investigations at the southern Urana dune with Tony Dare-Edwards of Charles Sturt University in December 1988, human skeletal remains were discovered in a working pit face approximately 2 m below the local ground surface. TL dating of sands associated with the remains indicates that their age corresponds with middens and burials radiocarbon dated between 32 and 27 ka at Lake Mungo and their gracile Aboriginal morphology is also similar to the Mungo remains (Bowler, 1971; Bowler and Thorne, 1976). The Urana site provides the first corroboration of a human presence at this time in western New South Wales. Although TL dating of archaeological sites in Australia is quite new, recent work by Roberts et al. (1990a and 1990b) has successfully used TL to demonstrate the human occupation of Arnhem Land before 50 ka.

Description of human remains

The skeletal remains were discovered in the working face of a Urana Shire Council quarry in the southern Urana dune (Fig. 9.8). They were enclosed beneath a well-developed siliceous sand soil profile which had clearly not been disturbed by an inhumation burial. The remains were apparently human and, given their likely age, probably Aboriginal. Only part of the skeleton was present, the rest having been destroyed by quarrying. Rather than risk destruction of the remains in this vulnerable sand face it was decided to excavate them before seeking expert identification and advice about proper means of preservation or, if appropriate, disposal. Sediment samples for thermoluminescence (TL) dating were collected from the materials adjacent to the bone and approximately 25 cm above them. The bones were carefully exposed by use of trowel and brush and collected in labelled bags. Finally, the cranium was exposed, removed and laid in a solid box on a bed of sand.

Preliminary stratigraphic descriptions and sample collection at the time of the original find were supplemented by detailed survey at the site during the summer of 1988-1989. Additional archaeological materials recovered at the site included two large grindstones and numerous amorphous quartzite artefacts. The skeletal remains from the dune were briefly examined by Alan Thorne and Steve Webb of the Department of Prehistory, Australian National University, in Wagga Wagga on 17 March 1989 and some observations recorded. These observations provided the anatomical details documented in the following sections.

The bones were partially broken up, friable and fragile but with surfaces generally in a good state of preservation. They varied in colour from light brown to dull white with patches of blue black manganese spotting and thin carbonate encrustation. Portions of both femoral and humeral shafts were preserved but broken or eroded fragments of all major skeletal elements were present. The cranium, which was filled with light brown sand, was damaged, with the base and facial portions broken away (Fig. 9.9). Post mortem deformation of the cranium had resulted in the sides of the vault being forced together. There was fragmentary preservation of the maxillae and mandible sections. Several teeth were present. There was no duplication of parts and it was clear the remains belong to a single individual. Due to the warped state of the cranium a restricted number of measurements (in millimetres) were taken (Table 9.4). No pathology or trauma was observed.

Ethnicity

The characters of the cranium left no doubt of the Aboriginality of the remains. The fragmentary dental arcade showed pronounced molar roll and helicoidal wear. The vault was long and relatively low and the zygomatic and maxillary fragments showed typical detailed Aboriginal features.

Sex

The skeletal remains were clearly those of a woman with both the postcranial fragments and preserved teeth supporting this conclusion. The postcranial skeleton was generally very delicate and thin-walled, especially given its aboriginality. There was barely sufficient difference between the humeri to establish handedness. The preserved cranial parts were thin and delicate also, with evidence of a pronounced occipital bulge or bun. The Larnach and Freedman (1964) sexing technique gave values of either 7 or 8 on the 7 to 21 scale (Table 9.5). This is below the male-female overlap and strongly indicated that the cranium is female.

Age

The individual was clearly adult. Despite erosion of the proximal and distal long bone shaft ends, epiphysial fusion lines on a femur and both humeri indicate cessation of growth consistent with adulthood. External fusion had commenced cranially on the posterior third of the sagittal suture with few areas of complete obliteration. The two available maxillary third molars were in full occulsion and worn to stage III (Campbell, 1925). Given the sex of the skeleton its personal age was estimated at between 35 and 40 years.

Table 9.4. Cranial measurements (mm) of Lake Urana skeleton.

Glabella-Opisthocranion	186
Glabella-Bregma	108
Glabella-Bregma projection	22 (61 from Bregma)
Bi-Zygion (at suture)	110
Minimum frontal breadth	86
Bregma-Lambda	112

Table 9.5. Larnach and Freedman (1964) cranial values of Lake Urana skeleton.

Glabella prominence	1
Supercilliary ridges	1
Zygomatic trigone	1
Malar tuborosity	1
Occipital markings	1
Mastoid size	1 (tip broken but clearly small)
Palate size	1 or 2
TOTAL	**7 or 8**

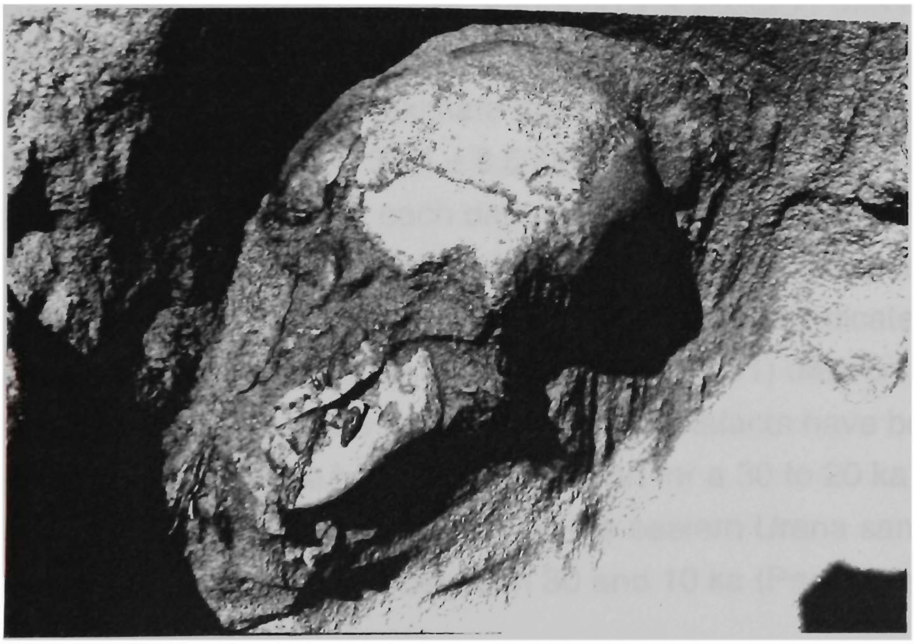


Fig. 9.9. Photograph of partly exposed cranium in southern dune.

Disposal of the remains

Once the skeleton had been positively identified by Thorne and Webb as Aboriginal in origin the regional office of the National Parks and Wildlife Service was contacted for advice and guidance. The remains were then presented to the Wiradjuri Regional Land Council which arranged for their reburial on the floor of Lake Urana.

TL dating of the site

The bones were found in the Bimbadeen Formation between 1.8 m and 2.0 m below the surface in the lower part of a siliceous sand profile and 0.4 m above a thin carbonate pan. The soil unit formed a continuous unit over the skeleton and clearly postdates placement of the body on the dune. In the absence of any evidence of grave excavation we believe that the remains were probably laid in a shallow surface depression on the dune and covered with not more than a thin scraping of sand.

In the absence of suitable charcoal deposits within the units described, and given the difficulties inherent in the interpretation of radiocarbon dates on bone and soil carbonate the chronology of the site was established by means of thermoluminescence (TL) dating. Although the skeleton was not dated directly, two TL dates on samples (W829 and W830) collected from the stratum containing the remains are thought to approximate the age since death of the individual. The two dates of 26.6 ± 8.5 ka and 32.4 ± 8.5 ka are statistically indistinguishable given the high errors associated with each date (compared to W831) . Assuming that the dune sediments 25 cm above the skeletal remains were deposited at approximately the time of death a minimum age in excess of 20 ka is indicated. A maximum age of around 30 ka is suggested by the 36 ± 3.5 ka (W831) date on the buried soil sediments some 4 m below the skeleton. No artefacts have been found in units below the surface of the buried soil. Support for a 30 to 20 ka age range for the burial site is also given by five dates on the eastern Urana sand lunette which indicate that this unit formed between 30 and 10 ka (Page et al. in press.).

Significance of the human remains

Skeletal remains of this antiquity are important for a variety of reasons but in particular the light they might shed on the derivation of Aboriginal morphology. The few measurements made on the Urana skeleton show that it is similar to the gracile

Lake Mungo I female dated to approximately the same period (Thorne, 1976). Although the Urana cranium is larger, it is at the female end of the Larnach and Freedman (1964) sexing scale and is of delicate structure. The fragmentary cranial remains were similarly delicate and thin walled. The finding of fully modern human remains of this age at Lake Urana is given added significance because of the rarity of Pleistocene human remains in this part of the Riverine Plain. There is no other example of such an ancient site within the Wiradjuri country of Australia.

TL dates on beach and lunette deposits at Lake Urana show that the period between about 30 and 25 ka was associated with a full freshwater lake providing resources capable of supporting human occupation and similar to those that existed during the Mungo lacustral period at the Willandra Lakes. Abundant lake side food sources would have included marsupials, reptiles, emu eggs, mussels and fish of the same species that presently occur in the Murray and Darling Rivers.

LAKE CULLIVEL

A local comparison with Lake Urana is provided by another lunette-bordered lake about 20 km to the east. Lake Cullivel is of particular interest because its catchment is isolated from both Colombo Creek which is fed by the Murrumbidgee River during major floods and Billabong Creek (Fig. 9.2). As a consequence its record is indicative of local hydrological conditions with no runoff input from the southeastern highlands. Lake Cullivel's eastern shoreline reveals a sedimentary sequence similar to that at Lake Urana Section 8. Bordering the lake floor is a 0.3 m thick wedge of beach sand backed by a single transverse dune rising 8 m above the lake floor. A 2 m surficial unit of fine sand overlies a well-developed calcareous soil grading down to subplastic sandy clays (Fig. 9.10). TL samples 1.2 m below the dune crest and 0.5 m below the carbonate horizon of the buried soil yielded ages of 16.8 ± 1.8 ka (W902) and 34.6 ± 3.1 ka (W903), respectively. The two units at Lake Cullivel appear to correlate with the Bimbadeen and Coonong units at Lake Urana and suggest that local catchment hydrology exerted a strong control over lake behaviour and episodes of lunette formation at both sites. Like Lake Urana, Lake Cullivel appears to have been full at about the time of the LGM.

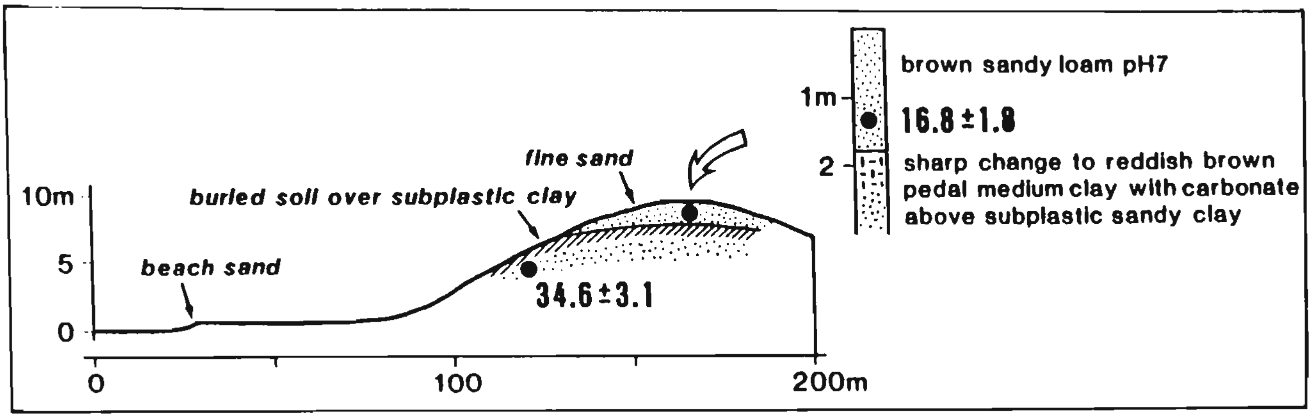


Fig. 9.10. Stratigraphic section of the Lake Cullivel lunette. TL dates given in ka.

DISCUSSION

Although the stratigraphy of Lake Urana's lunette system is not complex and the pattern of TL dates is internally consistent, the sequence of Late Quaternary climatic change inferred from the sedimentary facies departs significantly from the previously accepted model for southern Australia as outlined by Bowler (1986a) and Colhoun (1991).

Bowler's (1986a) scheme of hydrologic and climatic change is largely based upon the evidence of inland lakes and dune fields and is therefore of particular interest here. According to Bowler cool and moist conditions prevailed across southern Australia from before 50 ka until about 30 ka; inland lakes were full of fresh water, river discharges were high and the desert and Mallee dune fields were stabilised by vegetation. By 35 ka the first signs of a shift to more arid conditions had appeared. At Lakes Eyre and Frome in Central Australia and Lake Mungo in western NSW, lake levels oscillated and clay, gypsum and other salts were deflated from exposed lake floors to build marginal transverse dunes (Bowler, 1986a). At Lake Mungo aeolian deposits of this period include traces of desert dust and suggest that

dunefields to the west had commenced. Up to 25 ka the pattern of lake oscillation was complex with short periods of full stage alternating with fluctuating but generally lower levels. The approach of the glacial maximum at a radiocarbon age of 18 ka* was accompanied by a marked intensification of aridity. The maximum advance of glaciers in Tasmania and at Kosciusko appears to have coincided with the peak of aridity and environmental stress (Colhoun,1991). Although lower temperatures reduced evaporation rates these were more than compensated for by decreased precipitation. The result was a severely desiccated landscape swept by strong westerly winds. Lakes dried, stream discharges were reduced, water tables fell and a phase of massive dune building and reactivation occurred as vegetation cover became depleted (Bowler and McGee, 1978). Lunettes were now constructed predominantly from lake floor materials rather than shoreline beaches (Bowler, 1983). After about 15ka the general character of the present landscape was established with climatic conditions broadly similar to those of today. Rivers adopted their present channel patterns and trees reappeared in the riparian vegetation (Bowler,1986a).

For the most part this model of climatic change has been dated by radiocarbon which can be unreliable, particularly because of possible contamination with younger ^{14}C beyond about 30 ka*. Although TL and uranium series methods greatly extend the datable age range it is now clear that radiocarbon and calendar years do not correspond exactly to one another. Holocene radiocarbon dates can be corrected on the basis of the dendrochronological evidence (Stuiver, 1978) and Barbetti and Flude (1979) concluded from palaeomagnetic evidence that radiocarbon ages at 40 ka* might be too young by as much as 5500 years. Recently Bard et al. (1990) provided a conversion series to 30 ka based on radiocarbon and U-Th dating of corals in Barbados. They showed that calendar and U-Th ages agreed in the dendrochronological range and that before 9 ka radiocarbon years are systematically too young with a maximum difference of 3500 years at ~20ka. Hence the radiocarbon age of 18.5 to 16 ka for the glacial maximum corresponds to 22 to 19.5 ka in calendar, U-Th or TL years (see Chapter 4 for discussion).

At Lake Urana two Late Quaternary units are present in the lunette system: the earlier sand and clay facies of the Coonong Formation and the later sand dominated Birnbadeen Formation. TL dates on the Coonong Formation show that its sandy core was deposited from about 55 ka to about 35 ka when a generally full lake environment prevailed. This phase correlates directly with Bowler's (1986a) Mungo lacustral phase radiocarbon dated as older than 35ka*. At Lake Urana a shift to

oscillating lake levels and clay dune formation at about 35 ka also conforms to similar changes at Lake Mungo and other locations at a radiocarbon age of 35 to 30 ka*.

After 30 ka the pattern of lake behaviour and lunette formation at Lake Urana departs dramatically from the accepted model. The Bimbadeen Formation, which is very strongly dominated by quartz sand, indicates at least intermittently high lake levels from 30 ka until at least 12 ka. TL dates on this unit were carried out on nearly ideal homogeneous fine sands and reveal excellent stratigraphic consistency. As a result they are regarded with confidence.

At Lake Urana it is possible that local catchment pecularities may have contributed to high water levels between about 30 and 12 ka independently of regional climates. Although the lake receives most of its water from Urangeline Creek, discharge can also be received from the Murrumbidgee River via Yanco and Columbo Creeks and Billabong Creek when floodwaters spill over low catchment divides (Fig. 9.2). The possibility of flow augmentation from the Murrumbidgee System in particular, cannot be ignored. Indeed the delta in Lake Urana at the terminus of Coonong Creek (Fig. 9.2) is larger than might be expected from its catchment area alone.

However, Lake Cullivel is not fed by adjacent catchments and it possesses a very similar stratigraphic record to that at Lake Urana. Here high lake levels at around 17 ka clearly reflect hydrologic conditions in the local catchment. Of course the presence of high water levels at Lake Cullivel (and Lake Urana) does not imply heavier precipitation than at present. On the contrary, hydrologic calculations (Galloway, 1965; Coventry, 1976) based on a conservative glacial maximum temperature reduction of 6° C (Chappell and Grindrod, 1983; Colhoun, 1991) an evaporation rate of 1000 mm (cf present rate of 1800 mm) and Schumm's (1968) runoff curves suggest that Lake Cullivel could have been maintained by a mean annual precipitation of as little as 330 mm or about 70% of the present precipitation (Table 9.6). Although the runoff estimates are based upon North American data (Langbein et al., 1949) they appear to be reliable. For example, measured mean annual runoff rates for Billabong Creek (Fig. 9.2) and the Murrumbidgee River upstream of Narrandera are 0.017 m and 0.088 m respectively (Water Resources Commission, 1972). These values correspond closely with estimates of 0.016 m and 0.090 m respectively based on local climatic statistics (Atlas of Australian Resources, 1986) and Schumm's (1968) graph.

Table 9.6. Present and glacial maximum hydrologic budgets for Lake Cullivel.

	Present	Glacial Maximum
Lake area (km^2)	13[a]	13
Catchment area (km^2)	900	900
Annual lake evaporation (m)[b]	1.80	1.00
Annual precipitation (m)[b]	0.47	0.31
Annual runoff (m)[c]	0.01	0.01
Annual Lake losses ($m^3 \times 10^6$)[d]	23.4	13
Annual Lake gains ($m^3 \times 10^6$)[d]	15.1	13

Notes: a Lake Cullivel is normally dry under the present climatic regime.

b Evaporation and precipitation data from Atlas of Australian Resources (1986).

c Runoff based on Schumm (1968).

d Lake losses and gains based on a simple hydrologic equation in which losses are by evaporation from the lake surface and gains are by precipitation on the lake and catchment runoff.

Regardless of the precipitation regime at ~17 ka, the evidence at Lake Cullivel supports the presence of a permanent lake. In this sense the hydrologic regime was characterised by more effective precipitation than at present and must have also contributed to high water levels at Lake Urana independently of catchment configuration. Although Bowler (1986b) argues that aridity and high ground water tables might occur simultaneously during periods of transition from humid to arid conditions, Lakes Urana and Cullivel appear to have experienced generally high water levels from about the time of the LGM until at least 12 ka. There is no evidence in the Bimbadeen Formation of the intense glacial maximum desiccation documented from other lunettes in southern Australia (Bowler, 1976).

CHAPTER 10

CONCLUSION

The relict landscapes of the Riverine Plain of southeastern Australia have been investigated by means of several techniques including air photograph and satellite image interpretation, field survey, GIS based digital mapping, stratigraphic analysis and TL dating. The present research program has successfully used TL to establish the antiquity of surface fluvial and aeolian features on the Plain. It has developed a new interpretive model of palaeochannel evolution and contributed to knowledge of Late Quaternary environments in southeastern Australia.

TL DATING OF PALAEOCHANNELS, LUNETTES AND MARGINAL DUNES

TL dating has, for the first time, demonstrated that the major surface palaeochannels and aeolian features of the Plain developed during the last full glacial cycle between about 105 and 10 ka when global and regional climatic and hydrologic environments were generally very different from those of the present interglacial episode (Porter, 1989).

Four major sequential palaeochannel episodes have been mapped and TL dated on the Murrumbidgee sector of the Plain commencing with the Coleambally phase between 105 and 80 ka and progressing through the Kerarbury (55 to 35 ka), Gum Creek (35 to 25 ka) and Yanco (20 to 13 ka) phases until the establishment of the present fluvial regime at the beginning of Oxygen Isotope Stage 1. Figure 10.1 summarises the major phases of fluvial, lacustrine and aeolian activity on the Plain.

At Lake Urana in the eastern Riverine Plain a dual lunette dating from approximately 50 ka was found to consist of two major formations (Page et al., 1994a). The older Coonong Formation, which dates from 50 to 35 ka, is comprised of a sandy deep water phase core mantled by a clay-rich unit deposited when the lake contracted and lake floor muds were exposed. The younger Bimbadeen Formation, which dates from about 30 to 12 ka, is very strongly dominated by quartz sand and indicates deep fresh water lake

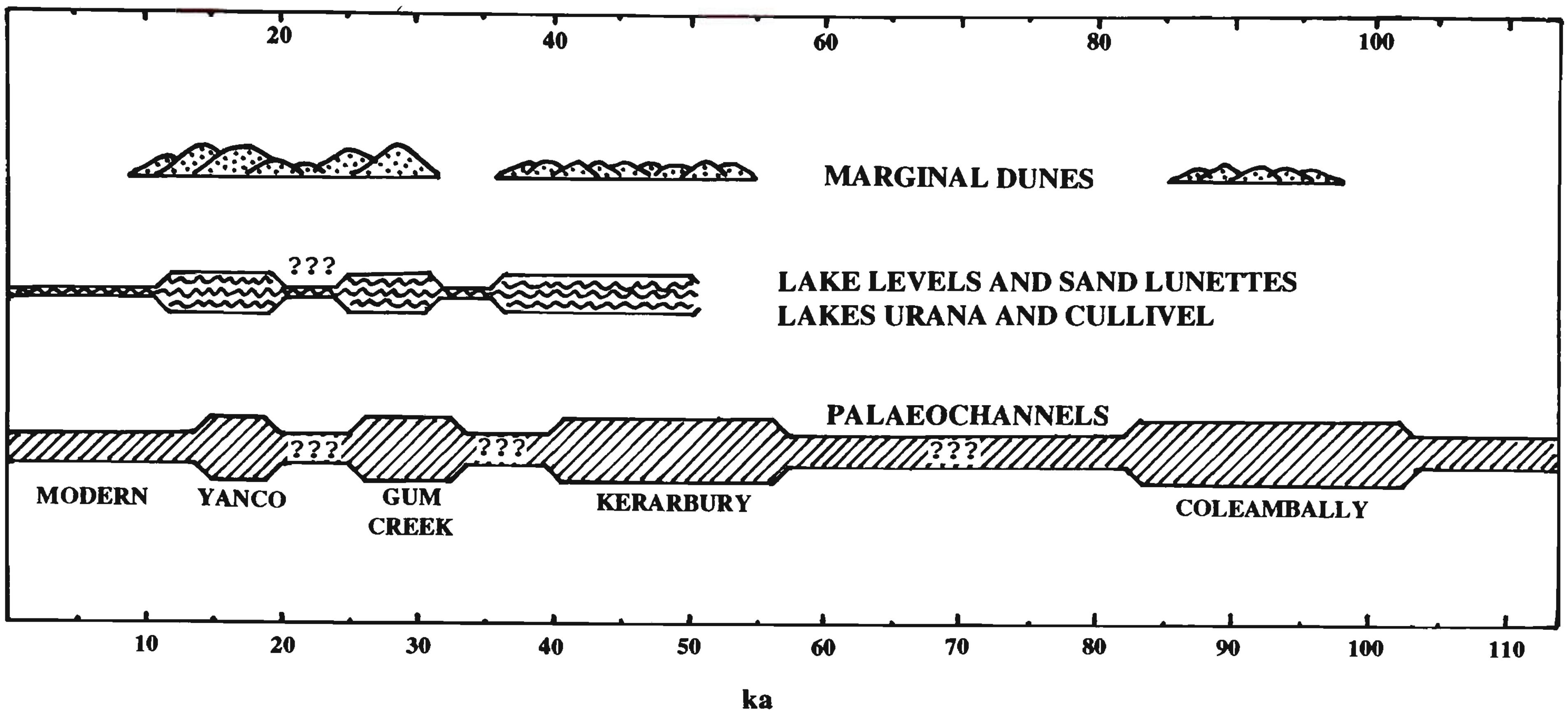


Fig. 10.1. Schematic representation of phases of fluvial, lacustrine and aeolian activity on the Riverine Plain. Band width is proportional to the intensity of activity. Ages (ka) based upon TL dates in Figure 6.14.

environments. The two stratigraphic units at Lake Urana were also found in the nearby Lake Cullivel lunette.

Marginal dunes dated on the Riverine Plain provide evidence of initial formation during periods of palaeochannel activity and subsequent partial reworking between 20 and 12 ka during the well-documented (Wasson, 1989) episode of widespread continental dune mobilisation in Australia in Oxygen Isotope Stage 2.

Despite initial concern about the ability of TL to date fluvial sands reliably because of possible poor zeroing or bleaching of the residual TL signal during sediment transport (Spooner et al., 1988), several lines of evidence permit confidence in the dating results. Perhaps the most impressive support comes from the remarkable stratigraphic consistency of the dates with no overlap between sequential palaeochannel systems, except in error bars of the temporally contiguous Kerarbury and Gum Creek Systems (Fig. 6.14). Important also is the strong agreement between radiocarbon and TL ages for the youngest palaeochannels with radiocarbon dates on the Murray, Goulburn and Darling in the 19 to 11 ka* range, and TL dates on the Murrumbidgee Yanco sediments from 19 to 13 ka.

Clearly, if the youngest Riverine Plain palaeochannels date from before the establishment of the modern river regime at about 10 ka*, it is difficult to argue for a large residual TL component in the Yanco System dates. The veracity of TL dates in the present study is also supported by corroborative channel and marginal dune dates and by statistically indistinguishable age estimates calculated in the easily bleached 325°C TL plateau region (Spooner et al., 1988) and also in the more robust 375°C plateau region favoured by David Price of the University of Wollongong. If partial bleaching of the sediment prior to deposition was a problem, the correlation of ages determined from these two temperature peaks would be low.

With TL dates, errors of ± 10% at one standard deviation are characteristic (Aitken, 1990). For this reason it is difficult to reliably distinguish between dates within the one palaeochannel system where the total time span might be only 55 to 35 ka. For example, it is invalid to attribute stratigraphic significance to a

difference between dates of say 41 ± 4 and 50 ± 5 ka, however tempting it might be for interpretative reasons. Similarly, this difference cannot be taken as evidence of dating inconsistency if the samples were collected from a single stratum. Of course published radiocarbon errors refer only to statistical laboratory counting uncertainty and do not attempt to address the total experimental, environmental and statistical uncertainty as is the case with TL. Thus it is not surprising that stated radiocarbon dating errors are commonly significantly less than those associated with TL.

REVISED PALAEOCHANNEL MODEL

A second major finding of the present study has been strong support for Bowler's (1978) doubts about the validity of Pels' (1971) widely accepted model of palaeochannel evolution from early bedload dominated prior streams to later suspended load ancestral rivers. WRD stratigraphic records and supplementary borings have shown that coarse sand aggraded prior stream channels are typically bordered by extensive sequences of upward-fining alluvium consisting of basal pebbly coarse sands overlain by loams and clays. These sediments are diagnostic of lateral migration by mixed-load streams and suggest that the Coleambally, Kerarbury and Gum Creek Riverine Plain Systems experienced alternate episodes of channel activity with frequent transitions from stable laterally migrating mixed-load mode to vertically aggrading bedload mode. The complete sequence of channel evolution appears to consist of a series of steps.

1. The development of laterally active sinuous mixed-load channels.

2. A shift to bedload dominated aggrading channels as the result of a change in the ratio of sediment to water delivered from the confined valley headwater region.

3. Vertical accretion, reduced sinuosity, increased width to depth ratio and the development of levees adjacent to the shoaling channel.

4. Channel avulsion and, eventually, the establishment of a new mixed-load system elsewhere on the Plain with the burial of the old channel under a

blanket of fines, sometimes including a mantle of calcareous aeolian dust derived from the Mallee region to the west.

The switches in channel mode were probably caused by threshold exceeding floods or sequences of floods which mobilised large volumes of bedload in the confined upstream valley. Modelling of flood hydrographs and sediment transport suggests that, for any one flood, a significant proportion of the coarse grained sediment entering the eastern Riverine Plain would not reach the Mallee exit region. The excess sediment would have entered channel storage on the Plain and contributed to bed aggradation, channel shoaling, levee formation, marginal dunes and finally, the formation of distributaries by avulsion.

Although the mixed-load and bedload channel modes can be roughly equated with Pels' (1971) ancestral and prior stream types the simple model of an early phase of prior streams followed by a later phase of ancestral streams is not supported. Indeed, the sequence within each palaeochannel phase, apart from the Yanco, is the reverse of that envisaged by Pels (1971). Each mixed-load phase terminated with channel aggradation and the transition to typical prior stream characters.

The final laterally migrating Yanco palaeochannels carried considerable amounts of coarse sand and were associated with large marginal sand dunes. However, these channels do not appear to have suffered a terminal prior stream style phase of aggradation and reduced sinuosity, possibly because of the impact of significant climatic change accompanying the onset of the Holocene (Oxygen Isotope Stage 1). Termination of the Yanco System was marked by a transition between 13 and 10 ka to the highly sinuous, slowly migrating suspended load channels presently operating on the Riverine Plain. Thus, it should be noted that to view the ancestral Kotupna, Coonambidgal II, Acres Billabong and Yanco streams as simply larger versions of the modern suspended load rivers on the Riverine Plain is also a gross simplification. The mixed-load phases of channel activity were generally associated with greater volumes of bedload transport, both in absolute terms and relative to suspended load, more rapid lateral migration and a larger component of coarse grained floodplain sedimentation than the modern rivers (Bowler, 1978). The state of river activity between the distinctive Coleambally, Kerarbury, Gum Creek and Yanco fluvial phases is

uncertain. Undoubtedly, rivers traversed the Plain in between times, but their relative inactivity has left a record not yet recognised or described (Fig. 10.1).

PALAEOENVIRONMENTS

It is convenient to summarise patterns of environmental change during the last full glacial cycle in relation to the well-established deep sea oxygen isotope record which was subdivided into 5 major stages by Shackleton and Opdyke (1973) with boundaries as set out in Table 10.1. These boundaries, which were used in the present study, correspond closely with the Vostok Ice Core stages of Jouzel et al. (1987) and were adopted by Nanson et al. (1992a) in their study of Australian wetting and drying over the past 300 ka. Recent revisions of the stage boundaries by Imbrie et al. (1984) and Martinson et al. (1987) have resulted in relatively minor adjustments except at Stage 3/2 where the boundary has been brought forward from 32 to 24 ka (Table 1). This amendment is of considerable importance for the present findings on the Riverine Plain and is discussed below.

Table 10.1. Oxygen isotope stage boundaries. (After Shackleton and Opdyke, 1973; Imbrie et al., 1984 and Martinson et al., 1987).

OXYGEN ISOTOPE STAGES	1	2	3	4	5
Shackleton and Opdyke (1973) Age (ka)	0 - 13	13 - 32	32 - 64	64 - 75	75 - 128
Imbrie et al. (1984) Age (ka)	0 - 12	12 - 24	24 - 59	59 - 71	71 - 128
Martinson et al. (1987) Age (ka)	0 - 12	12 - 24	24 - 59	59 - 74	74 - 130

Oxygen Isotope Stages 5 and 3

Secure TL dating of phases of enhanced palaeochannel activity and deep water lake conditions on the Riverine Plain has permitted regional and even global correlation with other indicators of climate change including sea-level change (Chappell and Shackleton, 1986), the deep sea oxygen isotope record (Porter,

1989), temperature and dust flux variation in the Antarctic Vostok core (Jouzel et al., 1987; Petit et al., 1990) and the Australian continental record (Nanson et al., 1992a; Kershaw and Nanson, 1993). In general, phases of enhanced fluvial and lacustral activity appear to occur during episodes characterised by what Porter (1989) describes as average or typical glacial age conditions, ie., intermediate between the short-lived extremes of the glacial and interglacial maxima.

On the Riverine Plain the Coleambally palaeochannel phase correlates with a similar episode in the Murray-Goulburn region to the south (Fig. 6.14) and also with a major phase of enhanced fluvial activity in northern and central Australia and coastal New South Wales during Oxygen Isotope Stage 5 (Nanson et al., 1992a). It is difficult to know when this stage started with intensity for much of the dating favours the declining stages of activity within individual channels. However, the general picture indicates a period of activity between about 105 and 80 ka.

The Kerarbury phase between about 55 and 35 ka occurs within the Stage 3 Sub-pluvial (Nanson et al., 1992a) and correlates with the Mungo lacustral phase recorded at many of Australia's southern inland lakes including Lake Urana (Bowler, 1986a; Page et al., 1994a). The continental Australian pollen record suggests that this period was characterised by widespread woodland and forest vegetation and generally cool, moist conditions (Kershaw and Nanson, 1993). Bankfull discharges on the Riverine Plain during this period, which are estimated to have been between 3 and 6 times those of the present, reflect reduced evaporation rates and a significantly enlarged winter snowpack in the southeastern highlands. The latter probably imposed a strong seasonal flow regime with flood peaks concentrated during the spring thaw. Increased production of coarse bedload sediment in the catchment was probably the result of more intense physical weathering in upland areas associated with a lower periglacial limit (Galloway, 1965) and accelerated mass movement and erosion aided by a lowered treeline (Davies, 1967).

Oxygen Isotope Stage 2

Perhaps the most puzzling finding on the Riverine Plain is the evidence of enhanced fluvial activity and high levels at Lakes Urana and Cullivel during Oxygen Isotope Stage 2 when, according to the presently accepted climate model for Australia, conditions were generally arid. Landscape aridity deduced from the evidence of clay lunette construction, continental dune mobilisation, atmospheric dust flux and the pollen record is thought to have peaked at the LGM around 22 ka or 18.5 ka* (Bard et al., 1990; Petit et al., 1990; Colhoun, 1991; Nanson and Kershaw, 1993).

On the Riverine Plain Oxygen Isotope Stage 2 as defined by Shackleton and Opdyke (1973) contained most of the Gum Creek palaeochannel phase between 35 and 25 ka and all of the Yanco palaeochannel phase between 20 and 13 ka (Fig. 10.2). TL dates at Lakes Urana and Cullivel indicate high levels between 20 and 12 ka and also between 30 and 25 ka with a preceding drying phase indicated by clay pellet deposition in the Coonong Formation at around 35 ka. What is not clear from the TL dates on the Riverine Plain is the situation between 25 and 20 ka. The absence of dates in this period (Fig. 10.2) may be either a statistical fluke or an indication of a brief period of aridity centred on the LGM between moister periods leading into and trailing the time of maximum refrigeration.

An examination of other published research revealed that the evidence for aridity during the majority of Stage 2 is by no means unanimous. Any detailed consideration of dating evidence in this period should be mindful of the discrepancy of about 3500 years between radiocarbon and calendar years at about 20 ka (Bard et al., 1990). This is particularly important in a consideration of Bowler's (1986a) radiocarbon dating of the brief, but intense, period of lake desiccation and clay lunette formation at 18.5 to 16.5 ka* (22 to 20 ka) because this episode does appear to coincide with the TL dating hiatus on the Riverine Plain.

A number of studies suggest that enhanced fluvial activity and higher lake levels occurred both before and after the LGM. Lake George, near Canberra, is

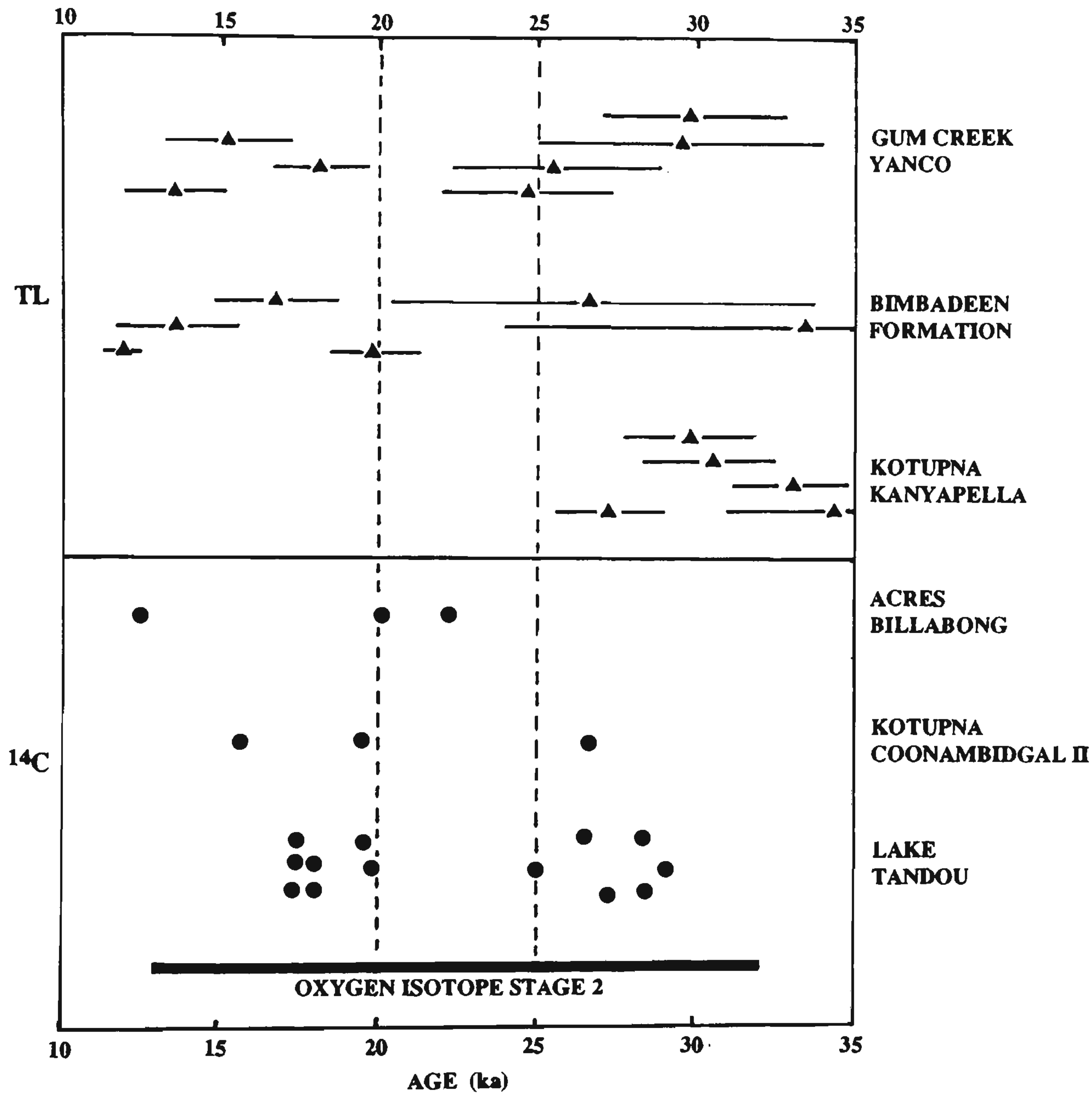


Fig. 10.2. Massed plot of TL and ^{14}C Murray Basin dates in Oxygen Isotope Stage 2. All ^{14}C ages (ka*) converted to ka using Bard et al. (1990). TL errors to one standard deviation. ^{14}C errors (all less than 400 years) not plotted.

presently part of a closed catchment. It is intermittently dry with maximum recorded historical water levels about 5 m above lake bottom. Coventry (1976) found shoreline evidence for lake levels 37 m above lake bottom between 30 and 24.5 ka when the lake sometimes overflowed to the west through Geary's Gap. After a period of apparently low levels the lake recovered to a depth of between 9 and 13 m at about 17.5 ka (15 ka*).

At Lake Tandou in western New South Wales Hope et al. (1983) radiocarbon dated a quartz sand lunette formation (the Bootingee) at 27 to 15 ka*. This unit clearly indicates the presence of deep fresh water conditions through much of Oxygen Isotope Stage 2. However, in detail there are seven dates between 16.4 and 14.9 ka* (20 and 18 ka) and seven dates between 26.9 and 22.1 ka* (30 and 25.5 ka) but none in the intervening period. Although no clay pellet phase is present in the Bootingee Unit the possibility of a pause in sand deposition as the result of lower lake levels or complete drying between 25 and 20 ka cannot be dismissed.

In the Willandra chain there is considerable evidence of higher lake levels in the periods before and after the LGM. Bowler (1986a) notes that following a period of low levels at about 36 ka*, water levels rose again at 32 ka* and remained relatively high until about 25 ka*. The final drying episode (Zanci phase) was preceded by a pulse of fresh water at about 19 ka*. Following the arid phase of clay lunette construction water returned briefly to the upper lakes (Mulurulu and Garnpung) at 15 ka* but did not reach the lower parts of the system.

The proposition of a short arid glacial maximum sandwiched between more pluvial periods is supported by Wasson and Donnelly (1991) who note that lakes in inland South Australia and Victoria show a major lacustral prior to 24 ka, a dry period between 24 and 20 ka and then a rise of water levels peaking at 14 ka. Their findings are supported by studies in central and southern Africa where Perrot and Street-Perrott (1982) describe high lake levels, higher stream discharges and widespread forest vegetation between about 28 and 25 ka but lower lake levels and generally more arid conditions at about 23 ka. Soon after the LGM lakes in southern Africa appear to have recovered with generally high levels occurring between 20 and 13 ka (Brook et al., 1992).

In combination with the above findings, radiocarbon dates on Kotupna and Acres Billabong palaeochannel deposits at 19 to 11 ka* and TL dating of environments in the eastern Riverine Plain Lakes Urana and Cullivel, the evidence of enhanced Murrumbidgee palaeochannel activity between 35 and 25 ka and 20 and 13 ka is difficult to refute (Fig. 10.2). Oxygen Isotope Stage 2, and particularly the short period enclosing the LGM, remains something of a problem. Clearly, the palaeochannel data do admit to the possibility of a short arid interregnum of perhaps four or five thousand years between 25 and 20 ka, between the more humid Gum Creek and Yanco System phases on either side. This pattern, which is similar to that described by Wasson and Donnelly (1991), is clearly contrary to the widely accepted pattern of severe aridity in southern Australia throughout all of, or even the majority of, Oxygen Isotope Stage 2 as defined by Shackleton and Opdyke (1973) and other workers (Nanson et al., 1992a). Because an important climatic boundary appears to lie at around 25 to 24 ka the recent revision of the Oxygen Isotope Stage 3/2 boundary to 24 ka (Imbrie et al., 1984; Martinson et al., 1987) appears to be of considerable merit in the interpretation of terrestrial environments in Australia and southern Africa. Whether an additional boundary at about 20 ka is warranted remains to be determined but it is likely that conditions between the LGM and the beginning of Isotope Stage 1 at times resembled those of the period before 24 ka. Clearly, there is much evidence from lakes and river systems in southeastern Australia to support a renewed pluvial phase soon after the LGM.

Oxygen Isotope Stage 1 (the Holocene)

There is now overwhelming evidence for a transition to modern (Holocene) fluvial and lacustrine environments between 15 and 10 ka (Bowler, 1986a). This period was also one of dune stabilisation following a long episode of mobilisation during Oxygen Isotope Stage 2 (Wasson, 1989). In the highlands around Mount Kosciusko the last vestiges of glaciers disappeared and a vegetation cover returned to previously denuded stoney slopes (Martin, 1986). The widespread concomitant increase in the elevation of the treeline and the shrinkage of the area subject to periglacial activity undoubtedly reduced the amount of coarse-grained debris delivered to upper river catchments and contributed to the establishment of the modern suspended load stream regime. As the supply of coarse sandy bedload diminished marginal dune formation dwindled.

FURTHER RESEARCH

The present research program has provided a chronologically calibrated new stratigraphic model for the major palaeochannel systems of the central and southern Riverine Plain of southeastern Australia. It has also shown that certain lake systems in this region contain sandy lunette formations which were deposited synchronously with phases of enhanced fluvial activity. However, several major areas require further research.

The peak of the LGM at about 22 ka is widely regarded as being associated with extreme aridity in southern inland Australia. The clear evidence in the present research and certain other studies of higher lake levels and enhanced stream flows both before 25 ka and after 20 ka requires further investigation. Given the inevitable ± 10 per cent errors of TL dates it is clear that corroboration by other more precise dating techniques is desirable. Systematic differences between radiocarbon and calendar ages, which reach a maximum at about the time of the LGM, must also be taken into account. A stratigraphically controlled comparative TL and radiocarbon dating program at the much-studied Lake Mungo 'Walls of China' lunette might be expected to provide valuable insights into conditions during Oxygen Isotope Stage 2.

The proposed palaeochannel model of the present study invokes repeated shifts from mixed load high sinuosity rivers on the Plain to bedload dominated low sinuosity aggrading rivers. However, the great majority of TL dates were carried out on channel infills and not the earlier lateral accretion deposits. Detailed TL dating of bore hole cross sections would provide an indication of the age of initiation and also the duration of each palaeochannel phase. WRD sections across the Waddi Reach of the Kerarbury System are particularly suited to this work.

Although the surface deposits of the Riverine Plain have now been shown to span at least the last full glacial cycle the ability of TL to date to 300 ka and beyond provides the potential for dating palaeochannel phases of the penultimate and earlier glacial cycles. Extensive palaeochannel deposits revealed in a WRD borehole section along Main Road 321 south of Darlington Point provide an excellent starting point for such a study but deeper pebbly sand

deposits of the Shepparton Formation are widely documented in bore holes elsewhere on the Plain (Brown and Stephenson, 1991).

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APPENDIX 1

SAMPLING STATIONS ON RIVERINE PLAIN

MURRUMBIDGEE SECTOR

MAP REFERENCE	SITE NAME	TL REF	TL AGE (ka)	COMMENTS
393200-6131100	Emery Dune Coleambally System Yamma Arm	W905	11.8±0.7	Low marginal sand dune southwest of Emery Pit. Sample collected in reddish fine sands 1.3m below surface.
388900-6131800	Kulki Pit Coleambally System Yamma Arm	W745	86.8±7.5	Iron oxide stained cross-bedded pebbly coarse sand channel infill 6.5m below surface and 2m above mottled grey-brown clay base. Surface soil red-brown earth with pisolitic carbonate.
402400-6138200	Gala Vale Pit Coleambally System Yamma Arm	W758	83.5±7.1	Cross-bedded pebbly coarse sand 6m below surface. Stratigraphically equivalent to W745. Surface soil red-brown earth with pisolitic carbonate.
394200-6131700	Emery Pit Coleambally System Yamma Arm			Large pit on WRD Stannard Section.
390400-6116900	Bundure Pit Coleambally System Bundure Arm	W904	100.4±9.0	Cross-bedded pebbly coarse sand 3.5m below surface. Surface soil red-brown earth with sheet and pisolitic carbonate U/Th age 10.5±1.6.
403100-6109500	Thurrowa Road Pit Yanco System	W1557	15.2±2.0	Coarse grey sands 4.7m below surface and 1.5m above above mottled clay base. Surface soil brown medium clay with friable carbonate - no pisoliths.
274900-6110100	Rhyola Section Yanco System	W1559	18.2±1.5	Well-preserved channel section. Sample from 2.1m below aggraded bed in wet coarse sands 1.8m above grey clay base. Surface sediments grey clays of channel infill.
275600-6108500	Rhyola Dune Yanco System	W1365	19.4±1.6	Marginal dune in partly mobile field. Sample 4m below surface in fine sands. Upper dune contained midden unit with charcoal, shells, stone flakes.
302600-6100700	Wanganella Pit Yanco System	W1558	13.6±1.6	Coarse sands 3.5m below surface and 2.2m above clay base. Surface soil grey heavy clay with no carbonate. Subject to modern flooding.
281000-6139800	Romani Rd Pit Kerarbury System Romani Rd Arm	W1362	47.8±6.1	Cross-bedded coarse sands 5m below surface and 1.7m above mottled heavy clay base. Surface soil red-brown earth with pisolitic carbonate.

385600-6174900	Old Homestead Pit Gum Creek System	W996	29.8±2.9	Coarse sands 4.5m below surface and 2.3m above heavy clay base. Surface soil red-brown earth with pisolitic carbonate.
393400-6168900	Akuna Dune Kerarbury System Main Arm	W907 W1364	18.2±1.1 37.1±4.5	Large dune north of Kerarbury palaeochannel. Samples from clean fine sand 2m and 7m below surface.
405100-6157200	McGrath Pit Kerarbury System McGrath Arm	W938	37.8±10.3	Cross-bedded coarse sands 4m below surface and 2m below mottled clay base. Surface soil red-brown earth with pisolitic carbonate. U/Th age 9.8 +1.2,-1.1 ka.
393800-6167200	Kerarbury Pit Kerarbury System Main Arm	W906	45.9±3.8	Trough-bedded pebbly coarse sands 6m below surface and 3m above mottled yellow-grey heavy clay base. Surface soil red-brown earth with pisolitic carbonate.
318500-6183700	Tabratong Section Gum Creek System	W997	24.7±2.8	Cut bank exposure in Murrumbidgee. Trough-bedded coarse sands 2.5m below surface and 3m above mottled heavy clay base. Surface soil truncated but base included carbonate pisoliths.
320600-6184400	Tabratong Pit Gum Creek System	W998	29.4±4.6	Coarse sands 4m below surface and 1.5m above clay base in meander bend. Surface soil red-brown earth with pisolitic carbonate.
300800-6174600	Hay Pit Kerarbury System Hay Arm	W746	46.8±3.0	Trough-bedded coarse sand channel infill 5.8m below surface and 0.6m above mottled heavy clay base.
243100-6121400	Moulamein Pit Kerarbury System Main Arm	W1360 W1363	33.6±2.5 43.2±6.1	Cross-bedded coarse sands of channel infill 3m and 2.8m below surface and approximately 1.6m above thin heavy clay lens, in turn above iron oxide stained sands. Surface soil red-brown earth with pisolitic carbonate.
295600-6134500	Booroorban Pit Kerarbury System Early Romani Arm	W1361 W1445	53.7±6.6 63.7±4.1	Duplicate samples in cross-bedded coarse sands 4m below surface and 3m above mottled clay base. Surface soil red-brown earth with pisolitic carbonate.
410300-6169200	Gogeldrie Scar Gum Creek System	W995	25.5±3.5	Wet coarse sands 4.5m below surface of channel in meander scar. Surface sediments grey heavy clays. Base not determined.
334400-6092900	Conargo Dune Yanco System	W909	14.7±1.2	Fine sand 2.4m below surface of vegetated dune.
527000-6117600	Pioneer Pit -1.1 m	W1371	27.5±2.3	Coarse sand lens in upper fine gravels.
527000-6117600	Pioneer Pit -8.0 m	W1556	≥110±14	Coarse sand lens in lower coarse gravels.
527000-6117600	Pioneer Pit -12.3 m	W1560	≥132±60	Coarse yellow wet sand lens in lower coarse gravels.

262100-6122800	Moulamein East Pit Kerarbury over Coleambally System	W1446	83.0±4.5	Coarse sands 5.5m below surface. Clay base not reached. Surface soil red-brown earth with carbonate.
248300-6137200	Tchelery Pit Kerarbury System Romani Arm			Coarse sands in palaeochannel. Clay base and surface red-brown earth.
252200-6171700	Uara Ck Section Gum Creek System			Present small muddy channel over palaeochannel coarse sands. Clay base.
297500-6130500	Booroorban Dune Kerarbury System Main Arm			Marginal dune east of Kerarbury channel.
328200-6152300	Epsom Downs Dune Kerarbury System Main Arm			Low marginal dune adjacent to Kerarbury Palaeochannel.
338600-6174500	Gum Ck Section 4 Gum Creek System			Surveyed section of Gum Creek.
346900-6166400	Gum Ck Section 3 Gum Creek System			Surveyed section of Gum Creek.
352400-6165100	Gum Ck Section 2 Gum Creek System			Surveyed section of Gum Creek.
361100-6167300	Gum Ck Section 1 Gum Creek System			Surveyed section of Gum Creek.
352500-6167500	Oolambeyan Dune Kerarbury System Main Arm			Marginal dune inside large loop of Kerarbury Palaeochannel near Booroorban.
260500-6122200	Moulamein Fence Section Kerarbury System Main Arm			Surveyed section across leveed Kerarbury Palaeochannel.
230200-6119500	Moulamein Dune 1 (Black Hills) Kerarbury System			Marginal dune east of meander loop in Kerarbury Palaeochannel north of Moulamein.
272300-6108300	Moulamein Dune 2 Yanco System			Marginal dune north of Yanco Palaeochannel west of Rhyola Station.
348200-6114400	Steam Plains Pit Coleambally System Yamma Arm			Coarse sandy channel infill with clay base 5 m below Plain surface. Red brown earth levee soil with pisolitic carbonate.
327100-6115300	Willurah Road Pit Coleambally System Yamma Arm			Coarse sandy in channel infill with clay base 5.8 m below surface. Red brown earth levee soil with pisolitic carbonate.

MURRAY-GOULBURN SECTOR

MAP REFERENCE	SITE NAME	TL REF	TL AGE (ka)	COMMENTS
380900-6126500	Green Gully terrace	W747	93.9±5.2	Cross-bedded coarse sands 5.5m below terrace surface. Surface soil red-brown earth with pisolitic carbonate.
411000-6148200	Cadell Block palaeochannel	W759	94.2±8.2	Cross-bedded coarse sands 4.5m below disturbed surface. Overlying soil not preserved.
398400-6121600	Green Gully - Goulburn Tributary junction terrace	W760	95.3±6.3	Cross-bedded pebbly coarse sands 3.5m below surface of terrace on outside of bend. Surface soil red-brown earth with pisolitic carbonate.
447100-6122900	Strathmerton palaeochannel	W762	90.1±4.3	Cross-bedded coarse sands 6m below surface and 2m above heavy clay base. Surface soil red-brown earth with pisolitic carbonate.
370900-6144400	Green Gully point bar	W748	65.1±3.6	Cross-bedded coarse sand 3m below disturbed surface. Overlying soil not preserved.
430700-6168500	Moonie Road Pit Murray palaeochannel	W1447	56.0±5.2	Cross-bedded coarse sands 3m below ground surface. Surface soil red-brown earth with pisolitic carbonate.
413600-6110400	Barmah Sandhills	W749	27.3±1.7	Silty fine to very fine sands 6m below surface on backslope of lunette inside roadside pit.
413800-6198000	Little Kanyapella lunette	W761	29.8±2.1	Silty very fine sand 2.5m below lunette crest in roadside pit.
413500-6110300	Barmah Sandhills	W752	30.5±2.5	Silty fine sands 5m below lunette crest in road cutting.
430800-6098000	Kotupna dune	W750	33.1±2.6	Clean fine sands 4m below surface in roadside pit 1.5km north of Kotupna Pit.
431000-6096600	McCoy Pit Kotupna channel	W751	34.4±4.0	Medium sand 3.5m below surface and 1m above cross-bedded coarse sands and granules. Surface soil weakly structured clay loam with friable carbonate.
417400-6165600	Deniliquin dune	W910	14.8±0.7	Clean fine sand 1.8m below surface of vegetated dune.
431000-6168700	Moonie Rd dune	W912	18.6±0.9	Clean fine sand 2.2m below surface of dune in small quarry.

APPENDIX 2

SEDIMENT GRAIN SIZE DATA

Table 1 Sediment grain size data - Riverine Plain Palaeochannels.

SAMPLE		φ16	mm	φ50	mm	φ84	mm
Emery Pit	1	-3.50	11.30	-0.69	1.61	1.09	0.47
Bundure Rd	1	-1.00	2.00	0.09	0.94	0.76	0.59
	2	-1.58	2.99	-0.98	1.97	0.76	0.50
Kerarbury Pit	1	-1.39	2.62	0.29	0.82	1.41	0.38
	2	-1.44	2.71	0.14	0.91	1.25	0.42
Steam Plains	1	-1.73	3.32	-0.50	1.41	0.91	0.53
	2	-1.72	3.29	-0.74	1.67	0.41	0.75
Hay Pit	1	-0.59	1.51	0.79	0.58	1.76	0.30
	2	-0.86	1.82	0.88	0.54	1.96	0.26
Booroorban	1	-0.94	1.92	-0.40	1.32	0.31	0.81
	2	-0.70	1.62	0.30	0.81	1.31	0.40
Romani Rd	1	-0.54	1.45	0.43	0.74	1.49	0.36
	2	-1.40	2.64	-0.47	1.39	0.50	0.71
Tchelery Pit	1	-1.04	2.06	-0.09	1.06	1.23	0.43
	2	-1.96	3.89	-0.40	1.32	1.20	0.44
Moulamein	1	-0.53	2.89	-0.60	1.52	0.63	0.65
	2	-1.35	2.55	-0.48	1.39	0.71	0.61
Rhyola Sect	1	-0.20	1.15	0.98	0.51	1.40	0.38
	2	-0.11	1.08	0.86	0.55	1.74	0.30
	3	-1.29	2.45	-0.50	1.41	1.42	0.37
Uara Ck	1	-0.58	1.49	0.20	0.87	1.03	0.49

Table 2 Sediment grain size data - Riverine Plain sand dunes.

SAMPLE (depth m)		ϕ16	mm	ϕ50	mm	ϕ84	mm
Akuna	1	1.40	0.38	2.08	0.24	2.86	0.14
	2	1.58	0.33	2.33	0.20	2.29	0.20
	3	1.88	0.27	2.49	0.18	3.17	0.11
	4	1.59	0.33	2.26	0.21	2.85	0.14
	5	1.91	0.27	2.53	0.17	3.32	0.10
	6	1.33	0.40	1.98	0.25	2.71	0.15
	7	1.39	0.38	1.96	0.26	2.79	0.14
Oolambeyan	1	0.93	0.52	1.64	0.32	2.46	0.18
	2	0.96	0.51	1.76	0.30	2.72	0.15
	3	0.92	0.53	1.60	0.33	2.42	0.15
	4	1.29	0.41	1.91	0.27	2.68	0.16
Epsom Downs	1	1.20	0.44	1.91	0.27	2.75	0.15
	2	1.54	0.34	2.23	0.21	2.94	0.13
	3	1.21	0.44	2.00	0.25	3.22	0.11
Booroorban	1	1.55	0.34	2.35	0.20	3.21	0.11
	2	1.57	0.33	2.36	0.19	3.12	0.12
	3	1.56	0.34	2.31	0.20	3.01	0.12
Moulamein [1]	1	1.02	0.49	2.10	0.23	3.21	0.11
	2	0.98	0.51	1.89	0.27	3.16	0.11
	3.7	3.10	0.12	3.79	0.07	4+	<0.06
Wanganella	1	1.48	0.36	2.07	0.24	2.72	0.15
	2.3	0.86	0.55	1.71	0.31	2.43	0.19
	3.5	0.95	0.51	1.63	0.32	2.29	0.20
	4	1.08	0.47	1.80	0.29	2.45	0.18
Moulamein [2]	1	1.52	0.35	2.18	0.22	2.82	0.14
	2	1.58	0.33	2.23	0.21	2.81	0.14
	3	1.59	0.33	2.27	0.21	2.93	0.13
	4	0.69	0.62	1.76	0.30	2.72	0.15

Table 3. Sediment grain size data - Murrumbidgee point bars near Wagga Wagga.

SAMPLE	ϕ 50	mm
1	-0.03	1.02
2	0.22	0.86
3	-3.46	11.00
4	-3.65	12.60
5	-4.06	16.70
6	-2.35	5.10
7	-0.99	2.00
8	-2.88	7.40
9	-3.10	8.60
10	-0.20	1.1

Note:
1 Largest grains sampled were in range 35 mm to 50 mm
2 Samples 3, 4 and 5 were from regions of apparently armoured bed - note the none of the Pioneer Pit samples possessed as large median sizes

Table 4 Sediment grain size data - Pioneer Pit near Wagga.

SAMPLE	ϕ50	mm
1	-2.10	4.3
2	-1.54	2.9
3	-3.05	8.3
4	-2.28	4.9
5	-2.18	4.5
6	-2.60	6.1
7	-3.30	9.8

Note:

1 Largest grains [sample of 25 clasts from Gauge Datum +1.0 m to -2.0 m]

2 Mean c axis 33.3 mm, maximum c axis 48 mm

APPENDIX 3

MODELLED BED SAND DISCHARGES FOR 100, 15 AND 5 YEAR FLOODS ON EASTERN AND WESTERN SECTION OF THE RIVERINE PLAIN

TABLES SHOWING DAILY DISCHARGES OF WATER AND SAND

Table 1. 100 Year Flood - Eastern Section.

DAY	DISCHARGE M^3/S	SAND DISCHARGE TONNES/M/DAY	SAND DISCHARGE TONNES/M
1	200	30	30
2-3	1000	240	480
4-5	2500	740	1480
6-7	4500	1300	2600
8-9	5800	1700	3400
10-11	5800	1700	3400
12-13	5500	1580	3160
14-15	5100	1470	2940
16-17	4600	1330	2660
18-19	4100	1190	2380
20-21	3700	1080	2160
22-23	3350	980	1960
24-25	3000	900	1800
26-27	2600	770	1540
28-29	2100	610	1220
30-31	1800	510	1020
32-33	1400	370	740
34-35	1180	270	540
26-37	800	180	360
38-39	500	90	180
40	250	30	30

Table 2. 100 Year Flood - Western Section.

DAY	DISCHARGE M^3/S	SAND DISCHARGE TONNES/M/DAY	SAND DISCHARGE TONNES/M
1-2	200	10	20
3-6	500	50	200
7 -10	1250	230	920
11-14	2250	480	1920
15-18	2900	650	2600
19-22	2900	650	2600
23-26	2750	605	2420
27-30	2550	560	2240
31-34	2300	495	1980
35-38	2050	430	1720
39-42	1850	380	1520
43-46	1675	320	1280
47-50	1500	290	1160
51-54	1300	240	960
55-58	1050	180	720
59-62	900	140	560
63-66	700	90	360
67-70	550	60	240
71-74	400	30	120
75-78	250	12	48
79-80	200	10	20

100 YEAR FLOOD - SUMMARY OF SEDIMENT BUDGET FOR THE RIVERINE PLAIN

TOTAL SAND DISCHARGE EASTERN SECTION	33,020 TONNES/M
TOTAL SAND DISCHARGE WESTERN SECTION	23,608 TONNES/M
NET SAND GAIN	1,882,400 TONNES 1,381,071 M^3
MEAN DEPTH CHANGE	+0.035 M

Table 3. 15 Year Flood - Eastern Section.

DAY	DISCHARGE M^3/S	SAND DISCHARGE TONNES/M/DAY	SAND DISCHARGE TONNES/M
1	250	40	40
2-3	500	95	190
4-5	1000	240	480
6-7	2000	580	1060
8-9	2850	810	1620
10-11	2900	820	1640
12-13	2650	750	1500
14-15	2200	630	1260
16-17	1850	530	1060
18-19	1500	420	840
20-21	1200	320	640
22-23	1010	250	500
24-25	750	180	360
26-27	550	110	220
28-29	350	50	100
30	250	40	40

Table 4. 15 Year Flood - Western Section.

DAY	DISCHARGE M^3/S	SAND DISCHARGE TONNES/M/DAY	SAND DISCHARGE TONNES/M
1-2	200	10	20
3-6	250	12	48
7-10	500	50	200
11-14	1000	160	640
15-18	1425	260	1040
19-22	1450	280	1120
23-26	1325	240	960
27-30	1100	190	760
31-34	925	140	560
35-38	750	100	400
39-42	600	70	280
43-46	500	50	200
47-50	375	30	120
51-54	275	20	80
55-58	250	12	48
59-60	200	10	20

15 YEAR FLOOD - SUMMARY OF SEDIMENT BUDGET FOR THE RIVERINE PLAIN

TOTAL SAND DISCHARGE EASTERN SECTION	11,550 TONNES/M
TOTAL SAND DISCHARGE WESTERN SECTION	6,496 TONNES/M
NET SAND GAIN	1,010,800 TONNES 741,599 M^3
MEAN DEPTH CHANGE	+0.019 M

Table 5. 5 Year Flood - Eastern Section.

DAY	DISCHARGE M^3/S	SAND DISCHARGE TONNES/M/DAY	SAND DISCHARGE TONNES/M
1	250	40	40
2-3	480	85	170
4-5	1140	300	600
6-7	1500	420	840
8-9	1350	370	740
10-11	1150	300	600
12-13	1000	250	500
14-15	850	200	400
16-17	670	150	300
18-19	550	110	220
20-21	450	80	160
22-23	320	50	100
24	250	40	40

Table 6. 5 Year Flood - Western Section.

DAY	DISCHARGE M^3/S	SAND DISCHARGE TONNES/M/DAY	SAND DISCHARGE TONNES/M
1-2	200	10	20
3-6	250	12	48
7-10	570	65	260
11-14	750	100	400
15-18	675	80	320
19-22	575	65	260
23-26	500	50	200
27-30	425	40	160
31-34	335	28	112
35-38	275	15	60
39-42	250	12	48
43-46	200	10	40
47-48	200	10	20

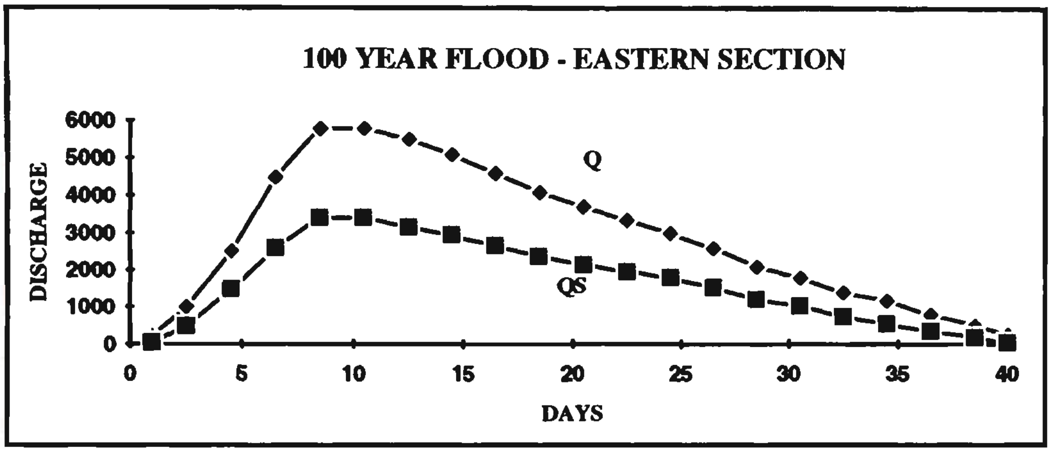
5 YEAR FLOOD - SUMMARY OF SEDIMENT BUDGET FOR THE RIVERINE PLAIN

TOTAL SAND DISCHARGE EASTERN SECTION	4,710 TONNES/M
TOTAL SAND DISCHARGE WESTERN SECTION	1,948 TONNES/M
NET SAND GAIN	552,400 TONNES 405,283 M^3
MEAN DEPTH CHANGE	+0.01 M

FIGURES

HYDROGRAPHS AND SEDIMENT DISCHARGES FOR SPECIFIED MODEL FLOODS TRAVERSING THE RIVERINE PLAIN. WATER DISCHARGE (Q) IN M^3/S AND SAND DISCHARGE (QS) IN TONNES/M OF CHANNEL WIDTH. CHANNELS ASSUMED TO BE RECTANGULAR SECTIONS OF BEDWIDTH 200 M. OTHER ASSUMPTIONS ARE GIVEN IN TEXT CHAPTER 8.

Figure 1. 100 Year Flood.



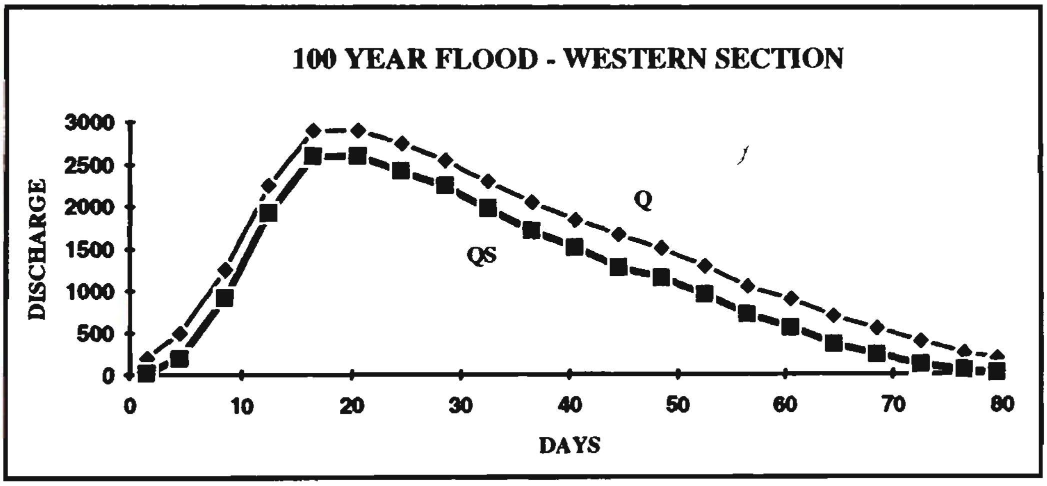
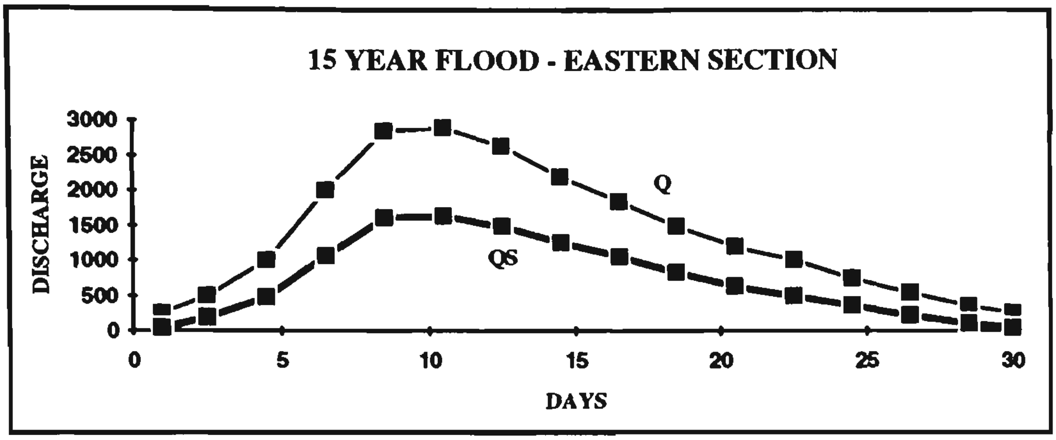


Figure 2. 15 Year Flood.



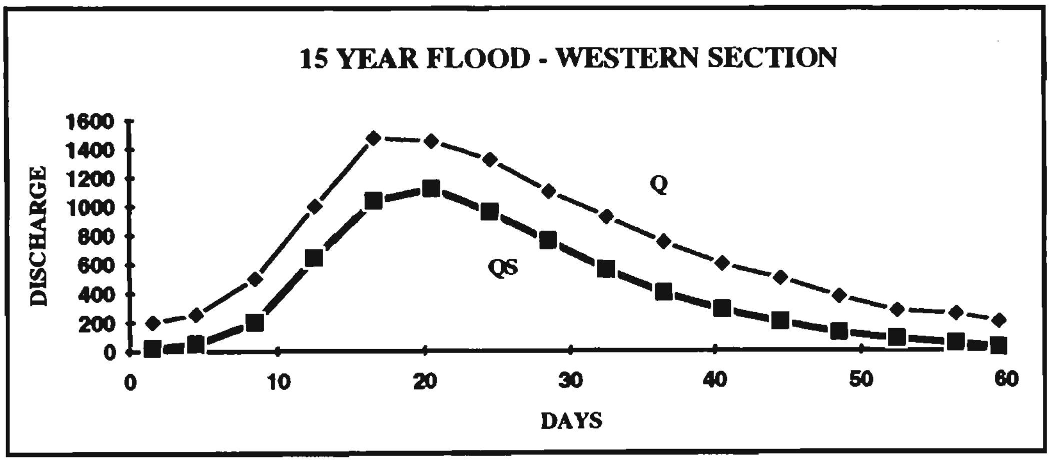


Figure 3. 5 Year Flood.