A REVIEW OF THE CENOZOIC PALYNOSTRATIGRAPHY OF THE RIVER VALLEYS IN CENTRAL AND WESTERN NEW SOUTH WALES

HELENE A. MARTIN

School of Biological, Environmental and Earth Sciences, University of New South Wales, Sydney Australia 2052 (h.martin@unsw.edu.au)

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The palynology of sediments from the Murray, Murrumbidgee, Lachlan, Macquarie and Namoi River Valleys of the Western Slopes of New South Wales reveals remarkably similar patterns in the alluvium of all of the valleys. Mid Miocene and older palynofloras found on the flood plains are rarely (if ever) seen in the valleys where almost all of the palynofloras are placed in the late Miocene-Pliocene *M. galeatus* Zone. A few palynofloras of the Pleistocene *T. pleistocenicus* Zone are found at the top of the sequence. The alluvial fills of the palaeovalleys are similar also: in a basal late Miocene-Pliocene unit: the sands and gravels are almost entirely quartz whereas the upper unit of Pleistocene age has a variety of resistant rock types and only a minor quartz component. The alluvium of these river valleys is an important groundwater resource.

In the mid Miocene, a time of high sea level, the rivers of the Western Slopes discharged into the flooded Murray Basin. Following major falls in sea level in the late Miocene, there was a basin-wide time of erosion/non-deposition and entrenchment of the river valleys. Denudation associated with this regression removed older sediments in the valleys and probably carved out the valley-in-valley structures. Tectonic events were probably small and only maintained the elevation of the Highlands.

The palynofloras indicate a substantial change in the vegetation and climate over this time: from rainforest and a wet climate in the mid Miocene to eucalypt sclerophyll forest and a drier, more seasonal climate in the late Miocene-Pliocene to woodlands/grasslands and a much drier climate in the Pleistocene. Deposition of the basal quartz rich alluvial unit occurred under a high rainfall, high-energy regime whereas the upper unit was deposited under a drier climate and low energy regime.

Eustasy was a major forcing factor in the Neogene, but by Pleistocene time, the Murray Basin had become isolated from the sea and the much drier climate had become the major forcing factor.

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INTRODUCTION

In the late 1950's the then Water Conservation and Irrigation Commission (now the NSW Office of Water) began a drilling program to investigate the groundwater potential in the Lachlan River Valley. Prior to this time, most bores and wells were sunk for stock water and domestic use and did not exceed 30 m in depth. Test drilling soon revealed good quality water in much higher yields at greater depths, suitable for irrigation and town water supply (Williamson, 1986). The program was extended to the other river valleys of the Western Slopes (Fig. 1) and the valley fills are an important groundwater resource.

This program required evidence from palynology for stratigraphic correlations, as only the Cenozoic sand and gravels rather than the older basement reliably yielded good quality water. Once the palynology of the Lachlan River Valley was established (Martin, 1987), similar patterns were found in the palynology of the other valleys down the Western Slopes of the Eastern Highlands (Martin, 1991), suggesting a similar geological history for all the valleys. This study explores the geological and environmental evolution of the valleys.

Today, the rivers of the Western Slopes drain into the Murray Darling River System which discharges to the sea at the mouth of the Murray in South Australia. During most of the Cenozoic, however, they drained

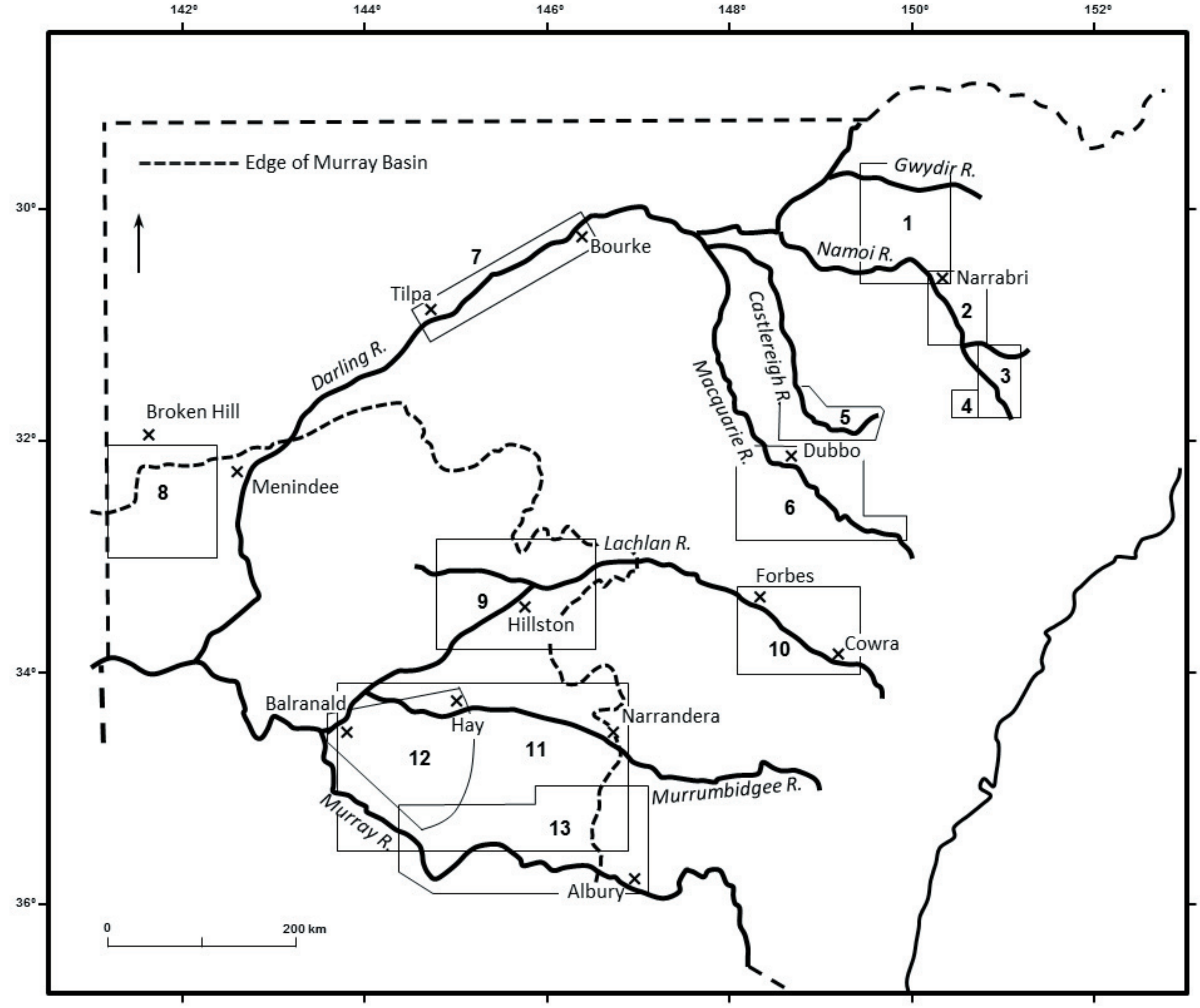

Figure 1. The stratigraphic palynology of the sediments has been studied in the areas as follows: 1. Namoi and Gwydir River Valleys (Martin, 1980). 2. Namoi River Valley, Baan Baa to Boggabri (Martin, 1994). 3. Mooki River Valley, (Martin, 1979). 4. Spring Ridge District (1981a). 5. Castlereagh River Valley (Martin, 1981b). 6. Macquarie River Valley (Martin, 1999). 7. Darling River (Martin, 1997). 8. Lake Menindee region (1988). 9. Murray Basin, Lachlan area (Martin, 1984b). 10. Lachlan River Valley (Martin, 1987). 11. Murray Basin, Murrumbidgee area (Martin, 1984a). 12. Murray Basin, the Hay- Balranald-Wakool Districts (Martin, 1977). 13. Murray River (Martin, 1995).

into the Murray Basin that opened to the Southern Ocean (the "Murravian Gulf") (Fig. 2). The extent of marine influence can be correlated with the global supercycles of relative rise and fall of sea level (Brown and Stephenson, 1991; Macphail et al., 1993).

The uplift of the Eastern Highlands and hence formation of the Western Slopes has been a subject of much debate. Most current hypotheses accept that there has been little landscape evolution in many regions since the early Cenozoic (e.g., Young and McDougall, 1985; Veevers, 1991; Van der Beek et al., 1999). Initial uplift has been attributed to isostatic rebound due to erosional unloading or associated with Cretaceous rifting of the eastern margin of the continent (e.g., Webb et al., 1991). There have been few claims of substantial uplift in the Cenozoic (e.g. Holdgate et al., 2008) and this view has been contested (e.g. Vandenberg, 2010). Most studies conclude that further uplift during the Cenozoic has done little more than maintain Highland elevation (e.g. Taylor et al., 1983; Young and McDougall, 1985). Studies of the Lachlan River Valley (Bishop and Brown, 1992) and

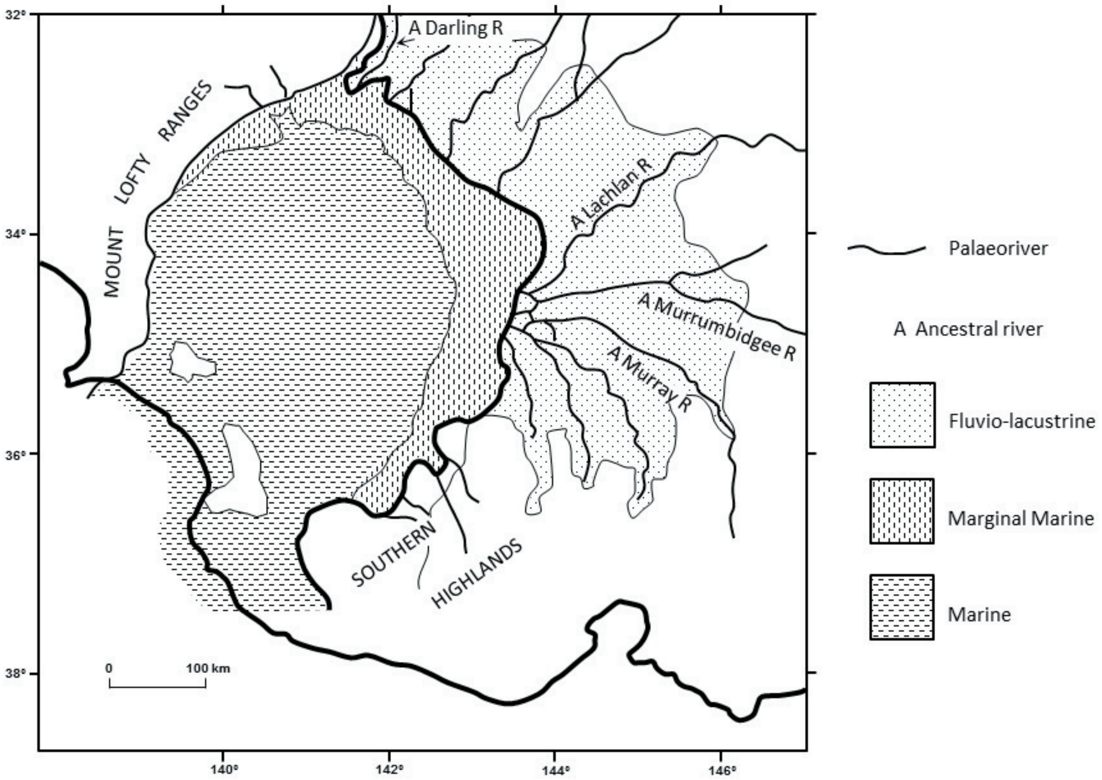

Figure 2. Early to mid Miocene paleogeography showing the marine incursion at its maximum extent in the mid Miocene and the ancestral rivers from the Western Slopes flowing into the Murray Basin. After Stephenson and Brown (1989).

Macquarie River Valley (Tomkins and Hesse, 2004) infer uplift has occurred in the Neogene.

Interpretations of the paleovegetation and climate indicate that both have changed considerably over the course of the Cenozoic. The vegetation was predominantly rainforest that required a wet climate during the Palaeogene. In the Neogene, the vegetation was predominantly sclerophyll forests that indicate a drier climate. The mid to late Miocene was a time of dramatic change (Martin, 1987, 2006; Macphail, 1997). All the evidence suggests that that there was a precipitation gradient during the Cenozoic, parallel to that of today, i.e. it was dryer to the west and wetter to the southeast.

Eustasy, tectonics and climate have all had some influence on the histories of the valleys. This study attempts to evaluate the relative importance of each factor through the Neogene.

METHODS

The NSW Office of Water (and its predecessors) supplied sediment samples from bores. Most of the samples were cuttings but some samples from cores are included. Core samples were preferable but in most cases, they were not available. The possibility of contamination is greater with cuttings, both from carry down with the circulating drilling mud and from cavings, but with proper drilling and sampling procedures, reliable samples may be obtained. For investigative drilling, the mud is circulated until it is clean of the coarse fraction and this greatly reduces contamination. Additives to the mud are not used (R.M. Williams, pers. comm.). If there is contamination it can be detected, either in the sediments themselves or in the preparations. A number of bores penetrate both the Cenozoic and the older basement and sampling across the boundary gives some indication of contamination. Usually, there is very little or no contamination unless sampling has occurred very close to the contact. The large number of barren samples interspersed with the polleniferous samples would not be possible if contamination was a problem (Martin, 1995).

The samples were first soaked in water then treated with hydrochloric acid to remove all carbonates if present. They were then treated with hydrofluoric acid to remove silicates. These two acids together removed all mineral matter. If sand and/or gravel was present, it was removed by decanting early in

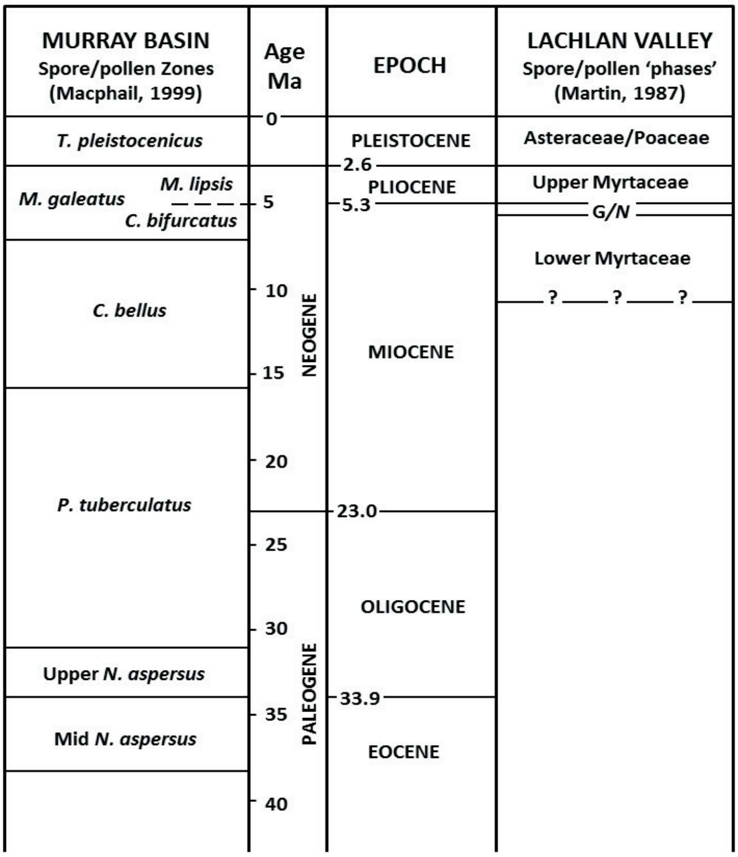

Figure 3. Summary of the palynological zones and the ages they indicate. G/N, Gymnosperm and/or Nothofagus phase. The time scale follows Ogg (2004) with the exception of the late Pliocene Pleistocene boundary that follows Ogg and Pillans (2008). Nomenclature follows Macphail (1999). See text.

the treatment. Processing times and concentrations varied with the nature of the sample. All treatments were done with cold solutions.

The organic residues were oxidised with cold Schultz solution (nitric acid saturated with potassium perchlorate), usually with a 10% concentration for 10 minutes, but this stage was carefully controlled according to the nature of the sample. The treatment aimed to remove degraded organic matter that obscured the pollen, but if too severe, it would also destroy pollen. Treatment with an alkali (10% sodium carbonate solution) removed the dark coloration, making the samples suitable for examination under the microscope. Again, times and concentrations varied, depending on the nature of the sample. The oxidative and/or alkali treatment may have been omitted with samples that were naturally highly oxidised. Strew samples of the residues were then mounted on a microscope slide in glycerine jelly (Martin, 1999).

Spore and pollen types were identified according to descriptions in Martin (1973a), Stover and Partridge (1973), Macphail and Truswell (1989; 1993) and Macphail (1999) and were counted along transects across the slide to establish the relative abundance of the common types. Testing showed that a count of 120-140 grains was a sufficient sample to represent the quantitative aspects of the palynofloras. The slides were then extensively scanned for any uncommon types missed in the count. The results were used to assign the assemblage to a palynological subdivision that could be used for stratigraphy of the alluvial fill of the valley.

The early work used palynological subdivisions ('phases' in Martin, 1973b; 1987) based on quantitative evidence in the Lachlan River Valley for there was no published zonation of the Neogene in southeastern Australia that could be used. Inferred ages for the 'phases' were attempted from the geology in relation to basalts in the region. Basalt was intersected in bores 1.5 km upstream from Eugowra on Mandagery Creek, a tributary of the Lachlan River. The mineralogy and chemical composition was sufficiently similar to basalt at Toogong, some 21 km further upstream, suggesting a common source for both basalts (Williamson, 1986). The Toogong basalts have been dated at 12.2 million years (Wellman and MacDougall, 1974), or middle Miocene. More than 70 m of sediment above the basalt contained the typical sequence of 'phases' found in the Lachlan Valley and hence are upper Miocene and younger. Up to 9 m of sediment below the basalt failed to yield pollen (Williamson, 1986; Martin, 1987).

The subdivisions of Martin (1973; 1987) and their inferred ages are listed below and in Fig. 3. (Note: these inferred ages required testing but that was not possible at that time. However, they served the practical purpose of allowing some stratigraphic control in these unconsolidated sediments that was necessary for groundwater exploitation).

1. The lower Myrtaceae phase of upper Miocene

age. Pollen of Myrtaceae is abundant and Casuarinaceae may sometimes be common. Fern spores may occasionally be abundant. *Nothofagus* is not present or rare and the gymnosperm content is usually low with *Podocarpus* the most common type. Fern spores may be abundant in some assemblages. A few rainforest angiosperms, e.g. *Quintiniapollis psilatispora* (*Quintinia*) and *Pseudowinterapollis* (Winteraceae) may be present also. This phase represents mainly sclerophyll vegetation.

2. The *Nothofagus* phase of ?upper Miocene-lower Pliocene age. The *Nothofagus* content (*Fuscospora* and *Lophozonia* pollen types*)* is relatively abundant. Rainforest angiosperms are more common and there is a greater diversity of gymnosperms.
3. The gymnosperm phase of ?upper Miocene-lower Pliocene age may form a discrete entity above the *Nothofagus* phase or may replace it stratigraphically. The gymnosperms are more diverse and include *Dacrydium*, *Dacrycarpus* and Araucariaceae. The *Nothofagus* and Gymnosperm phases represent more of the rainforest element and may be useful for local correlation.
4. The upper Myrtaceae phase of upper Pliocene age is very similar to the lower Myrtaceae phase, with the exception of the gradual disappearance of rainforest pollen types, and an increase in the Asteraceae (daisies) and Poaceae (grasses) pollen towards the top of the sequence. If the *Nothofagus* and Gymnosperm phases are not present in the sequence, then the lower and upper Myrtaceae phases cannot be separated. It also represents sclerophyll vegetation.
5. The Asteraceae/Poaceae phase of Pleistocene age. Asteraceae and Poaceae pollen become abundant. Rainforest angiosperms and gymnosperms are rare. This phase represents woodlands and grasslands.

The palynofloras found in these phases are listed in Tables 1 and 2.

A palynological zonation based on diagnostic species for the Neogene was described for the Murray Basin and published by Macphail and Truswell (1993) and Macphail (1999). A similar palynological zonation described for the Neogene of the Gippsland Basin was published by Partridge (2006). These zonations (Macphail, 1999; Partridge, 2006) are based on diagnostic species and are considered more reliable for correlation over large areas whereas the system of Martin (1973b, 1987) may reflect local ecological environments that can vary considerably over large areas. The zonation for the Gippsland Basin (Partridge, 2006) has been independently dated using marine foraminiferal zonation and that for the Murray Basin has been correlated with the Gippsland Basin (Macphail, 1999). Zone equivalents of the Murray Basin that are applicable to the river valleys and their flood plains are as follows:

1. The Middle *Nothofagidites asperus* Zone Equivalent of upper Eocene age indicated by the first appearance of *Triorites magnificus* and *Anacolosidites sectus*. *Proteacidites rectomarginus* and a diversity of *Proteacidites* spp. are typical of the zone. *Nothofagus* (*Nothofagidites* spp.), especially the *Brassospora* type dominates the palynofloras. The last appearance of *T. magnificus* marks the top of the zone.
2. The *Proteacidites tuberculatus* Zone Equivalent of lower Oligocene to lower Miocene age. *Acaciapollenites miocenicus*, *Corsinipollenites* cf. *C. epilobioides*, *Diporites aspis* and *Foveoletes crater* indicate the zone. *Nothofagidites*, the *Brassospora* type dominates the assemblages but Casuarinaceae (*Haloragidites harrisii*), Myrtaceae (*Myrtacidites)* spp. or *Phyllocladidites mawsonii* may occasionally be abundant.
3. The *Canthiumidites* (als *Triporopollenites*) *bellus)* Zone Equivalent of upper lower Miocene to middle Miocene age. The first appearance of *T. bellus* and *Symplocoipollenites austellus* mark the base of the zone. *Haloragacidites haloragoides* and *Rugulatisporites cowresis* are also indicator species. *Nothofagus* spp, Podocarpaceae and Araucariaceae are the dominant pollen types.
4. The *Monotocidites galeatus* Zone Equivalent of upper Miocene to lower Pliocene age (Macphail, 1999). The first appearance of *M. galeatus* denotes the base of the zone. *Myrtaceidites* spp. (Myrtaceae) and Casuarinaceae are the dominant pollen types. There are two sub-divisions: the *Foraminisporis* (als *Cingulatisporites*) *bifurcatus* of upper Miocene age and the *Myrtaceidites lipsis* of early Pliocene age, each denoted by the first appearance of their nominate species. Partridge (2006) has elevated these two sub-zones to zones, in place of the *M. galeatus* Zone.
5. The *Tubulifloridites pleistocenicus* Zone Equivalent of upper Pliocene-Pleistocene age (Macphail, 1999; Partridge, 2006). *T. pleistocenicus* is consistently present and species of Asteracae (*Tubulifloridites* spp.) and Poaceae (*Graminidites media*) become abundant.

The sequence of lower Mytaceae, *Nothofagus*,

Table 1. Palynofloras in Bores 14747 and 14505 of the Lachlan Formation (*M. galeatus* Zone Equivalent), from Martin (1969). Spore/pollen species are described in Martin (1973a) and are expressed as percentages of total count. For location of bores, see Fig 5. For further distribution and botanical affinities of the spore/pollen species, see Martin (1987). Taxonomy follows Macphail (1999) where appropriate. Subtotals of important botanical groups are given in bold for comparison with the Cowra Formation. Phases are as follows: 1, Upper Myrtaceae phase. 2, Gymnosperm phase. 3, *Nothfagus* phase. 4, Lower Myrtaceae phase.

	Bore				14747				14505
Spore /pollen species	Depth (m)	48.6	66.2	67.8	79.4	80.5	83.8	86-88	58-61
	Phase	1	2	2	3	4	4	4	2
SPORES	Nearest Living Relative								
Cingulatisporites bifurcatus	Anthocerotae	0.5		0.5		0.5		10.5	
C. ornatus	Hepatiacea							0.5	
Cyathea porospora	Cf. *Cyathea aeneifolia*		0.5						
C. (=*Cyathidites*) *palaeospora*	Cf *Cyathea australis*		9.0	5.5	21.5	1.5	0.5	1.0	
C. granulosporis = *Cyathidites subtilis*	*Cyathea* sp.		1.0		5.5				
Deltoidospora granulomargo	-		2.5		4.0	3.5	1.0		
D. inconspicua	?Adiantaceae		2.5	2.5		3.0	0.5	4.5	
Gleicheniidites circinidites	Cf *Gleichenia microphylla*	0.5	1.5	0.5	2.5		1.0		1.0
Hypolepis spinspora	Cf. *Hypolepis* spp			1.0			1.0		
Klukisporites lachlanensis	-				2.0				
K. granulomargo	-							0.5	
Laevigatosporites ovatus	-	1.5	5.5	6.5	2.5	2.0	0.5	2.0	
Lycopodium sp.	Cf. *Lycopodium* spp.	0.5	0.5						
Osmundaceae spp	Cf. Osmundaceae spp	0.5		1.5	1.0			0.5	
Polypodiidites sp	Cf. Polypodiaceae				1.0				1.5
Reticuloidosporites minisporis	-			1.0		1.0	1.0		0.5
Verrocatosporites sp.	Cf. Polypodiaceae			0.5			0.5		
Total spores		**3.5**	**23.0**	**19.5**	**40.0**	**11.5**	**6.0**	**19.5**	**3.0**
GYMNOSPERMS									
Araucariacites australiensis	Araucariaceae		2.5	2.5	2.0				9.0
Cupressaceae	Cupressaceae								2.0

Dacrydium (=*Lygistipollenites*) *florinii*	*Dacrydium* spp.		1.0	2.5	1.5				5.0
Microcachryidites antarcticus	*Microcachrys*		1.0	0.5	1.5				1.0
Podocarpus (*Dacrycarpites*) *australiensis*	*Dacrycarpus*		6.0	7.5		0.5			12.5
P. (*Podocarpidites*) *elliptica*	*Podocarpus* sens lat.	2.0	9.5	10.0	3.0	1.5		5.0	14,5
Total gymnosperms		**2.0**	**20.0**	**23.0**	**8.0**	**2.0**	**0**	**5.0**	**44.0**
ANGIOSPERMS-Dicotyledons									
Acaciapollenites myriosporites	*Acacia* spp.	3.0		0.5		2.0	0.5	2.5	
Banksieaecidites minimus	Banksieae	1.0		0.5					
Casuarina (=*Casuarinidites*) *cainozoica*	Casuarinaceae	9.0	14.5	4.5	4.0	25.0	49.5	8.0	21.0
C. (=*Haloragacidites*) *harrisii*	Casuarinaceae	4.0	0.5	6.5	1.0	7.0	0.5	4.0	3.0
Total Casuarinaceae spp.	**Casuarinaceae**	**13.0**	**15.0**	**11.0**	**5.0**	**32.0**	**50.0**	**12.0**	**24.0**
Dodonaea sphaerica	*Dodonaea* spp		1.0	0.5	0.5	1.0	1.5	0.5	1.5
Drimys (=*Pseudowinterapollis*) *tetradites*	Winteraceae		2.5	2.0	1.0		0.5		1.0
Ericipites cf *E. scabratus*	Ericaceae	0.5	1.0					0.5	
Haloragis (=*Haloragacidites*)	*Gonocarpus/Haloragis*	11.5		2.0	1.0	2.5	1.5	1.0	3.0
Micrantheum spinyspora	*Micrantheum* spp.	0.5		1.0			1.0		
Myrtaceidites eucalyptoides	*Corymbia* spp.	5.5	1.5	2.0	1.5	5.5	1.5	2.5	1.5
M. eugeniiodes	Eugeniiae	1.0		1.0	0.5	0.5		0.5	2.0
M. mesonesus	*Eucalyptus/Meterosideros*	13.0	2.5	2.5	0.5	3.0	5.5	4.0	2.5
M. parvus	Myrtaceae	3.5	6.0	2.0	4.5	4.5	1.0	1.5	2.5
M. rhodamnoides	*Austromyrtus/Rhodamnia*		0.5	1.5	0.5				
M. xanthomyrtoides	Cf. *Xanthomyrtus* spp.		0.5		0.5	0.5			
Myrtaceidites spp. indet.	Myrtaceae	21.0	9.5	6.0	2.0	24.0	19.0	29.5	5.0
Total Myrtaceidites spp.	**Myrtaceae**	**44.0**	**20.5**	**15.0**	**10.0**	**38.0**	**27.0**	**38.0**	**13.5**
Nothofagus (=*Nothofagidites*) *aspera*	*N. cunninghamii/N. moorii*		1.0		1.0				
N. brachyspinulosa	*N. gunnii/N. fusca*				18.5				
N. emarcida	*N*. subgen. Brassospora			0.5				0.5	
Nothofagus spp.	*Nothofagus*				0.5		1.0		
Total *Nothofagidites* spp.	***Nothofagus***		**1.0**	**0.5**	**20.0**		**1.0**	**0.5**	
Polyporina bipatterna		1.0							
P. (=*Chenopodipollis*) *chenopodiaceoides*	Chenopodiaceae	0.5	0.5	2.0			0.5	1.0	

Polyporina sp.				0.5					
Proteacidites adenanthoides	Cf. *Adenanthos*	0.5							
P. callosus	Proteaceae	1.0							
P. subpalidus	Proteaceae				0.5				
P. subscabratus	Proteaceae			1.0	1.0	1.0			
P. symphyonemoides	Cf. *Symphyonema*			0.5		0.5			
P. truncatus	Proteaceae		0.5						
Proteacidites sp. indet.	Proteaceae	0.5	1.5	1.5	0.5			0.5	
Quintiniapollis psilatispora	*Quintinia* spp				0.5				
Stephanocolpites oblatus	-	1.0	1.5	1.5			0.5	0.5	
Tricolpites mataurensus	-	1.0	1.5	0.5	0.5	1.0	0.5		
Tricolporopollenties cooksonii	-	2.5	1.5	1.0	1.5	1.5	1.5	2.0	2.0
Tubulifloridites antipodica	Asteraceae					0.5			
T. simplis	Asteraceae	1.5	0.5	0.5		1.5	1.5	6.5	
Total *Tubulifloridites* spp.	**Asteraceae**	**1.5**	**0.5**	**0.5**		**2.0**	**1.5**	**6.5**	
Unidentified dicotyledons		8.5	1.5	5.5	8.0	0.5	2.5	1.0	1.0
ANGIOSPERMS MONOCOTYLEDONS									
Graminidites media	**Poaceae**	**1.0**	**3.0**	**5.5**		**3.0**	**3.5**	**7.5**	**1.0**
Liliacidites spp.	-	2.0	1.5	2.0	1.5	1.0	0.5	1.5	2.0
Monosulcites spinosus	-				1.0	0.5			
Restionaceidites (=*Milfordia*) *hypolaeneoides*	Restionaceae		1.0	0.5					3.5

Table 2. Palynofloras found in the Asteraceae/Poaceae phase (=*T. pleistocenicus* Zone Equivalent) of the Cowra Formation, from Martin (1969). Spore/pollen species are described in Martin (1973a) and are expressed as percentages of total count. Taxonomy follows Macphail (1999) where appropriate. For further distribution and botanical affinities of the spore/pollen species and location of bores, see Martin (1987). Subtotals of important groups in the palynofloras are given in bold for comparison with the Lachlan Formation.

Spore/pollen species	Bore Depth (m)	14578 17.3-17.8	12438 14.3-15.5	12438 19.2-20.1
SPORES	Nearest Living Relative			
Lycopodium sp.	*Lycopodium* sp.	1.5	3.0	
Deltoidospora inconspicua	?Adiantaceae	1.0		
Cingulatisporites bifurcatus	Hepataicae	4.0	10.0	
Reticularisporites (=Rugula-tisporites) cowrensis	-	1.0	3.5	
Total spores		**7.5**	**16.5**	
GYMNOSPERMS				
Podocarpus (=*Podocarpidites*) *elliptica*	*Podocarpus* sens lat.			0.5
Total gymnosperms				**0.5**
ANGIOSPERMS:				
DICOTYLEDONS				
Acaciapollenites myriosporites	*Acacia*		1.5	
Casuarina* (=*Casuarinidites*) *cainozoicus	**Casuarinaceae**	**0.5**	**1.0**	**0.5**
Dodonaea sphaerica	*Dodonaea* spp.	0.5		
Haloragacidites haloragoides	*Gonocarpus/Haloragis*		1.0	
Micrantheum spinyspora	*Micrantheum* spp.			2.0
Myrtaceidites eucalyptoides	*Corymbia* spp.	1.0	8.5	1.0
M. mesonesus	*Eucalyptus/Meterosideros*	5.5		
M. parvus	Myrtaceae	1.0	2.5	
M. protrudiporens	Myrtaceae	3.0	2.0	
Myrtaceidites spp. indet.	Myrtaceae	13.5	21.5	10.0
Total Myrtaceae		**24.0**	**24.5**	**11.0**
Onagraceae sp indet	Onagraceae		1.0	
Polyporina bipatterna	-	0.5		
P. (=*Chenopodipollis*) *chenopodiaceoides*	Chenopodiaceae	0.5	1.5	2.5
P. granulata	-	0.5		1.0
P. reticulatus	-	0.5		0.5
Polyporina spp.	-	4.5	0.5	2.5
Proteaceae cf. *Grevillea*	*Grevillea*		0.5	
Asteraceae cf Cichoreae sp. = *Fenestrites*	Asteraceae: Cichoreae		1.0	
Tubulifloridites antipodica	Asteraceae	1.0	2.0	
T. pleistocenicus	Asteraceae	13.5	5.5	45.5
T. simplis	Asteracee	23.0	15.5	18.5
Total *Tubulifloridites* spp.	**Asteraceae**	**37.5**	**24.0**	**64.0**
ANGIOSPERMS: MONOCOTYLEDONS				
Graminidites media	**Poaceae**	**23.0**	**83.5**	**14.0**
Liliacidites sp.	-		1.5	
Restionaceidites (=*Milfordia*) *hypolaeneoides*	Restionaceae			1.5
Sparganiacepollis sp.	Sparganiaceae	0.5		

Gymnosperm and upper Myrtaceae phases of the river valleys is thus equivalent to the *M. galeatus* Zone of the Murray Basin (see Fig. 3). The diagnostic species *M. galeatus*, *C. bifurcatus* and *Dodonaea sphaerica* are common to both sequences and the general quantitative aspects of abundant Myrtaceae and/or Casuarinaceae are similar in both. However, there are some notable differences: e.g., the diagnostic species *Myrtaceidites lipsis* of the both the Murray and Gippsland Basins has not been found in any of these river valleys, and an equivalent of the *Nothofagus* phase in the river valleys has not been reported from the Murray Basin. These differences reflect the environmental/ecological differences between the marginal marine environments of the Murray and Gippsland Basins and the totally non-marine and upland environments of the river valleys.

The Asteraceae-Poaceae assemblage of the river valleys is equivalent to the *T. pleistocenicus* Zone of the Murray Basin. Both have the nominate species and abundant Asteraceae (daisies) and Poaceae (grasses).

For this study, the Murray Basin zone equivalents of upper lower Miocene to middle Miocene *C. bellus* Zone, upper Miocene to lower Pliocene *M. galeatus* Zone and the upper Pliocene to Pleistocene *T. pleistocenicus* Zone are used. The upper Miocene-lower Pliocene *Nothofagus* and/or gymnosperm phase of the river valleys is retained as it has proved to be a distinct local stratigraphic horizon. When the recent changes to the Geologic Time Scale are taken into account, viz. the recognition of the base of the Quaternary at 2.6 Ma (Ogg and Pillans, 2008), effectively incorporating the uppermost stage of the Pliocene into the Pleistocene, the age of the *M. galeatus* Zone becomes upper Miocene to Pliocene and that of the *T. pleistocenicus* Zone becomes Pleistocene (Fig. 3).

The palynology is presented in long profiles of the valleys, with the bores adjusted for height above sea level.

THE PALYNOSTRATIGRAPHY OF THE RIVER VALLEYS

The Lachlan, Macquarie and Namoi River Valleys have been the focus of investigations for they have major groundwater potential and are considered first. The Murray, Murrumbidgee, Castlereagh and Darling River Valleys have not been investigated as intensively but there is sufficient evidence to show the overall patterns of alluvial deposition.

Lachlan River Valley

The Lachlan River catchment occupies an area of about 90,000 km^2. The river begins in the Great Dividing Range and the headwaters arise at elevations of up to 1,400 m at Mt. Canobolas. Most of the high relief country is east of Cowra with only 2% classed as rugged or mountainous. Alluvial flats of significance commence about 13 km upstream of Cowra and 75% of the catchment is classed as flat. Downstream of Cowra, the alluvial flats become extensive and most of the undulating landscape of the middle catchment has been cleared (Williamson, 1986; Green et al., 2011a)

The extensive flood plain environment of the western part of the catchment is generally less than 200 m in elevation and features many wetlands and effluent streams. Under normal conditions, the Lachlan River is a terminal system with little water flowing past the Great Cumbung Swamp at the end of the river. Only in large flood events does water flow into the Murrumbidgee River (Green et al., 2011a).

Test drilling reveals a buried ‘valley-in-valley’ structure downstream from Cowra to Jemalong Gap. Remnants of an older valley floor are shown as a shelf that maintains a depth of 27-30 m below present drainage level but the depth of the valley carved in the old valley increases markedly with distance downstream. Williamson (1986) attribute this valley-in-valley structure to successive tectonic movements but suggests an alternative possible mechanism in the effects of change in global sea levels (Williamson, 1986).

The alluvium in the Lachlan Valley is divided into two distinct units: the basal Lachlan Formation and the overlying Cowra Formation. The Lachlan Formation consists of a series of interbedded sediments ranging from gravels to clays. The sands and gravels consist almost entirely of different kinds of quartz and sometimes pebbles of chert but they do not contain resistant rock types found in the catchment. The clays may be divided into variegated clays and carbonaceous clays: the latter are the best for palynology. The sands and gravels of the Lachlan Formation yield good quality water of low salinity suitable for irrigation and town water supply (Williamson, 1986).

The Cowra Formation disconformably overlies the Lachlan Formation, i.e. there is an hiatus in deposition between the two, and the strata range from gravels to clays, all of which are predominantly brown. The sands and gravels consist of the resistant rock types found in the catchment and in this respect, they differ significantly from the Lachlan Formation. Carbonaceous clays are rare in the Cowra Formation. The Cowra Formation yields water only suitable for stock and domestic purposes (Williamson, 1986).

There is another unit found in elevated positions and often occurring as hill cappings: the Glen Logan Gravels. This unit consists of quartz gravel in a red-brown silty matrix. It is thought that they are remnants of a formerly more widespread unit that is stratigraphically below the Lachlan Formation and is probably the source of the quartz sands and gravel in the latter (Williamson, 1986).

Longitudinal sections show the palynology of the valley and alluvial plain and onto the Murray Basin (Figs 4, 5). All of the palynofloras in the valley fit the upper Miocene to Pliocene *M. galeatus* Zone, with the exception of the upper lower Miocene to mid Miocene *T. bellus* Zone at the base of the Jemalong Gap bore. This bore is exceptional, being located in the gap between the Jemalong and Corridgery Ridges, the only feasible gap where the ancient Lachlan River could go, and has an exceptionally long sequence of carbonaceous clays (Williamson, 1986). The base of Bore 30484 has an assemblage lacking diagnostic species and is mainly *Nothofagus*, the *Brassospora* type that is more

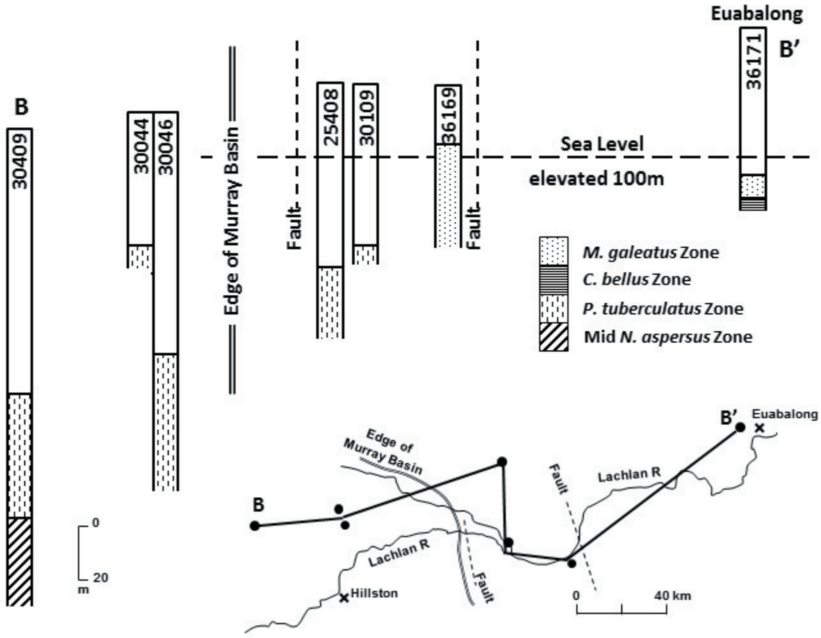

Figure 4. Palynology of the Lachlan River, the alluvial plain section (from Martin, 1987). For the ages the zones indicate, see Fig. 3.

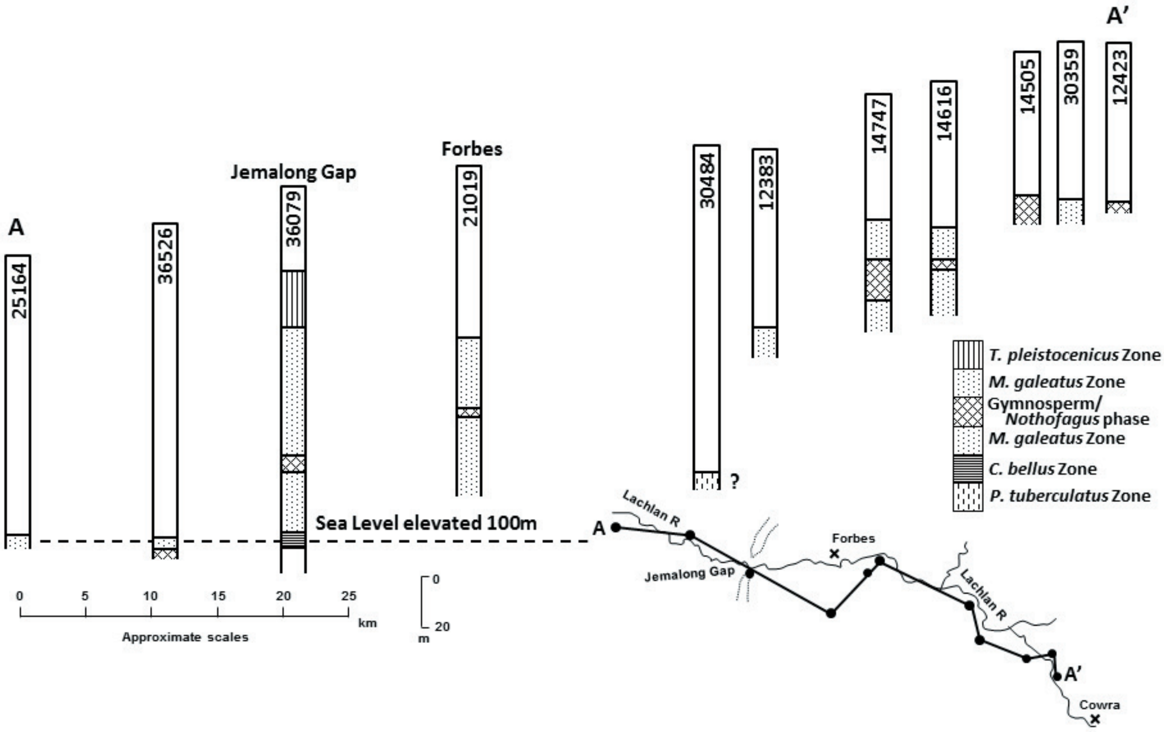

Figure 5. Palynology of the Lachlan River Valley, the upstream section (from Martin, 1987). For the ages the zones indicate, see Fig. 3.

typical of the lower Oligocene to lower Miocene *P. tuberculatus* Zone, but it could equally be an aberrant *T. bellus* Zone. This bore is situated in the deepest part of the alluvium on a former course of the river. The sequence was first worked out for Bore 14747 (Fig. 5) where the Gymnosperm and *Nothofagus* phases are distinct. Further downstream, these two phases appear together. These two phases define a useful local stratigraphic level.

The Pleistocene *T. pleistocenicus* Zone is not found in the valley, except for the Jemalong Gap bore where the uppermost polleniferous unit appears to be intermediate between the *M. galeatus* Zone and the *T. pleistocenicus* Zone. It occurs, however, in the tributaries of the Lachlan River (Martin, 1987).
The *T. bellus* and *M. galeatus* Zones are found further downstream of Jemalong Gap (Fig. 5). The sediments of the Murray Basin are much deeper and the Middle *N. asperus* Zone (upper Eocene) and *P. tuberculatus* Zone (lower Oligocene to lower Miocene) are found here.

Macquarie River

The Macquarie River originates in the Great Dividing Range south of Bathurst and flows in a northwesterly direction to join the Darling River system near Brewarinna. The Macquarie-Bogan Catchment covers an area of more than 74,000 km^2. (The Bogan River runs parallel to the Macquarie R. to the southwest and the catchment between them is ill defined. The Bogan River is an intermittent stream.) Elevations across the catchment range from 1,300 m in the mountains south of Bathurst to about 120 m near Brewarrina in the northwest. Below Dubbo, the valley is predominantly alluvial plain with an elevation of less than 300 m (Middlemis et al., 1987; Green et al., 2011b).

The valley consists of Palaeozoic Lachlan Fold Belt rocks and Mesozoic sedimentary units deposited in the Sydney-Gunnedah Basin. Basalts in the Dubbo region range in age from 12.3 to 14.2 million years (Ma). Sparse remnants of at least two widespread Cenozoic depositional episodes are common in the upper Macquarie area. These sediments are mainly coarse grained and are found on the older, elevated terraces (Smithson, 2010). A buried ‘valley-in-valley’ form is seen between Wellington and Dubbo (Tomkins and Hesse, 2004), similar to that in the Lachlan Valley.

The sands and gravels of the basal Cenozoic alluvium in the valley are predominantly quartz with some chert and are interbedded with clays and organic clay. The boundary with the overlying Quaternary alluvium is usually distinct. The sands and gravels of the Quaternary alluvium consist of variable lithologies with a quartz content of only about 5% (Smithson, 2010). The clays and silts are mainly orange, red and brown in colour. The Cenozoic alluvial fill of the valley is thus very similar to that of the Lachlan River Valley, and Middlemis et al. (1987) adopt the names Lachlan and Cowra Formations (respectively) for them, the names used by Williamson (1986) for the equivalent sediments in the Lachlan River Valley. The Quaternary alluvium is deposited on an erosion surface (Tompkins and Hesse, 2004).

A longitudinal section of the valley (Fig. 6) shows the palynology. Only the upper Miocene to Pliocene *M. galeatus* Zone is found upstream of Narromine, in the valley, with some occurrences to the south and west of Narromine. Minor amounts of *Nothofagus* are found in some bores, suggestive of the *Nothofagus* phase. The upper lower Miocene to mid Miocene *C. bellus* Zone is found south and west of Narromine, in the alluvial plain and marks the course of former channels. One occurrence of the lower Oligocene to lower Miocene *P. tuberculatus* Zone is found west of Narromine. Mesozoic basement assemblages have been recorded from a number of the bores (Martin, 1999). The tributary Bell River (Fig. 7) has both the upper Miocene to Pliocene *M. galeatus* Zone and Pleistcene *T. pleistocenicus* Zone.

Namoi River Valley

The Namoi River catchment covers an area of about 42,000 km^2, from the Great Dividing Range near Tamworth to the Barwon River near Walgett. Elevations range from over 1,500 m in the south and east to about 130 m on the alluvial floodplain in the lower catchment west of Narrabri. Major tributaries of the Namoi River include Coxs Creek, the Mooki River and others further upstream of Boggabri. On the floodplain west of Narrabri, where the river has a low gradient, there is an increase in frequency of lagoons and the development of several anabranches and effluent streams (Green et al., 2011c).

The majority of the upper Namoi alluvium overlies the sedimentary and volcanic rocks of the Permian-Triassic Gunnedah Basin, the Jurassic Oxley Basin sandstones and to the west, the Jurassic Pilliga Sandstones of the Great Artesian Basin. The alluvium of the Namoi River, the Coxs Creek and Mooki River is divided into two layers: the shallower Narrabri Formation and the deeper Gunnedah Formation. The Narrabri Formation yields water only suitable for stock. Good quality water suitable for drinking can be found in aquifers across large areas of the Gunnedah Formation and the highest yields are found in the coarse sediments of the main

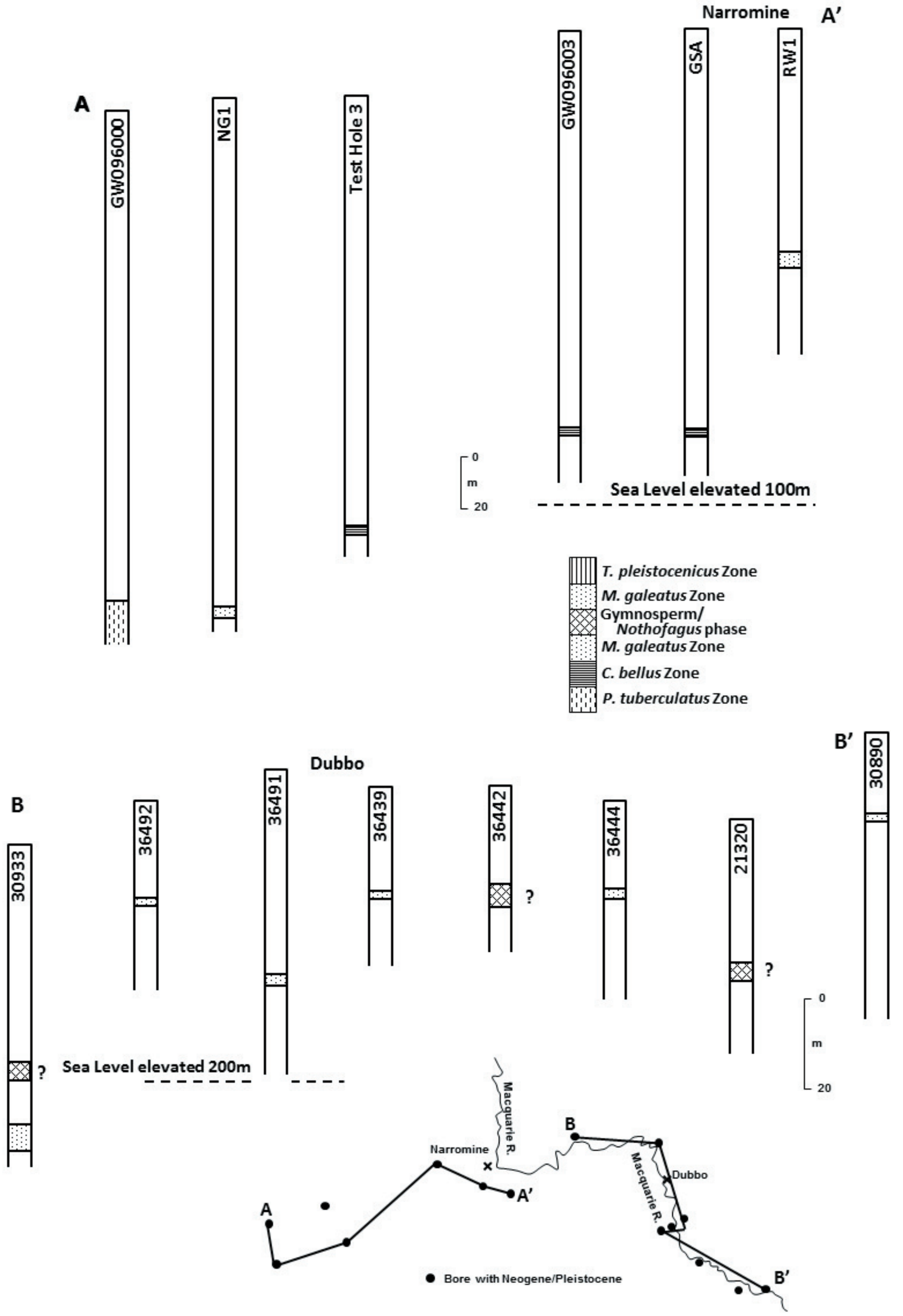

Figure 6. Palynology of the Macquarie River Valley (from Martin, 1999). Section A-A’, the alluvial plain. Section, B-B’, the river valley. For the ages the zones indicate, see Fig. 3.

palaeochannel that in most cases does not follow the present drainage system (Barrett, 2012). On the alluvial plain west of Narrabri, there is the older Cubbaroo Formation underlying the Gunnedah Formation. It was deposited in a pre-Cenozoic channel following the northern limits of the alluvium (Williams et al., 1989). This division of the alluvium into three units in the lower Namoi is probably an

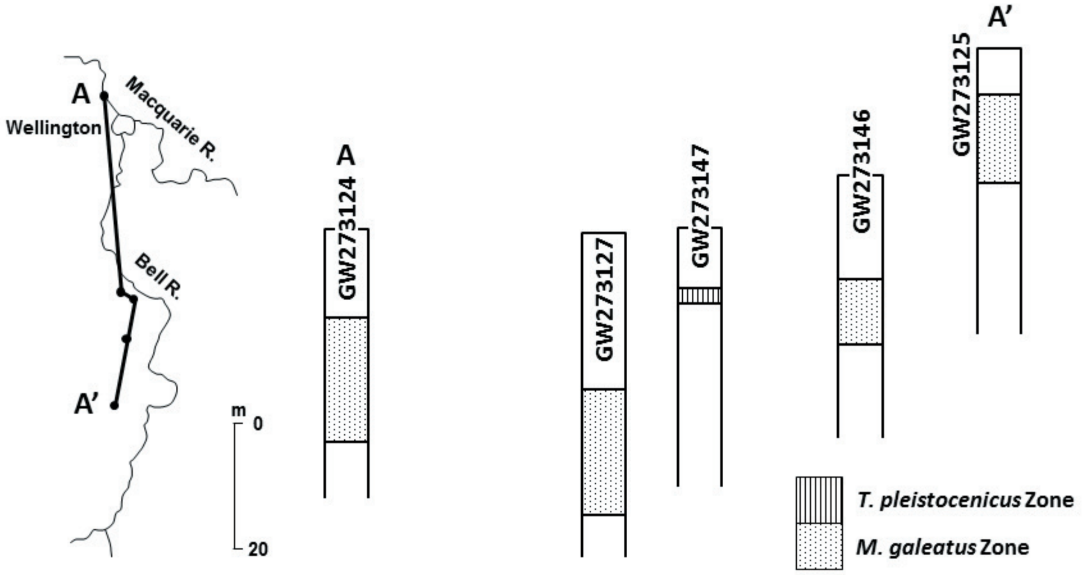

Figure 7. Palynology of the Bell River, a tributary of the Macquarie River (Martin, unpubl.).

over-simplification (B. Kelly, pers. comm.) for the alluvium has many aquifer zones that hold water with widely varying salinities (Williams et al., 1989).

The palynology of the alluvial plain is presented in the Appendix Fig. 8. Only the upper lower Miocene to mid Miocene *C. bellus* Zone is found west of Narrabri and it indicates a palaeochannel of the former course of the river (Young et al., 2002). The palynology shows that the Cenozoic sediments overly an early Cretaceous basement. The palynofloras found near Narraabri (Fig. 8) fit the upper Miocene to Pliocene *M. galeatus* Zone but with an appreciable Asteracea/Poaceae content.

The palynology of the Namoi River upstream of Narrabri and of Coxs Creek (Fig 9) shows the upper Miocene to Pliocene *M. galeatus* Zone with abundant Myrtaceae and Casuarinaceae. The informal *Nothofagus* phase, with relatively little *Nothafagus*, more abundant fern spores and gymnosperms is identified in two bores in the same comparable stratigaphic position as that of the Lachlan River Valley, i.e. well down in the M. *galeatus* Zone. Araucariaceae may be relatively abundant in the *Nothofagus* phase, but also at a much shallower depth, near the top of the *M. galeatus* Zone. The Pleistocene *T. pleistocenicus* Zone may be found at shallow depths. Some bores yielded basement Permian assemblages (Martin, 1994).

The Namoi River upstream of Gunnedah and the Mooki River (Fig. 10) both yield the upper Miocene to Pliocene *M. galeatus* Zone and the Pleistocene *T. pleistocenicus* Zone, the latter at shallow depths. The basement assemblages are Permian also (Martin, 1979). Narrow geological constrictions along the length of the valley have had a significant affect on how the alluvial sediments were deposited (Barrett, 2012).

Murray River Valley

The Murray River begins it course in the high peaks of the Southern Alps of New South Wales and Victoria. Altitudes range from about 2,200 m in the east, to about 150 m at the Hume Dam near Albury. The Upper Murray Catchment occupies about 15,330 km^2 and about one third of that is in New South Wales (NSW Department of Primary Industries Office of Water, 2013a). The Murray Riverina Catchment, downstream of the Hume Dam covers 14,950 km^2 in southern New South Wales. It begins in the gentle hills of the south western slopes where elevations range from 300-600 m. Downstream of Corowa, the river moves onto the flat plains of the Riverina where elevations are less than 200 m (NSW Department of Primary Industries Office of Water, 2013b).

The alluvial fill of the valley covers a basement of Lachlan Fold Belt metamorphics and granites. Downstream of Corowa, the Tertiary alluvium covers the Lower Permian Oaklands-Coorabin coal measures and further west, the river continues over the Murray Basin (Martin, 1995).

The oldest sediments in the valley where the pre-

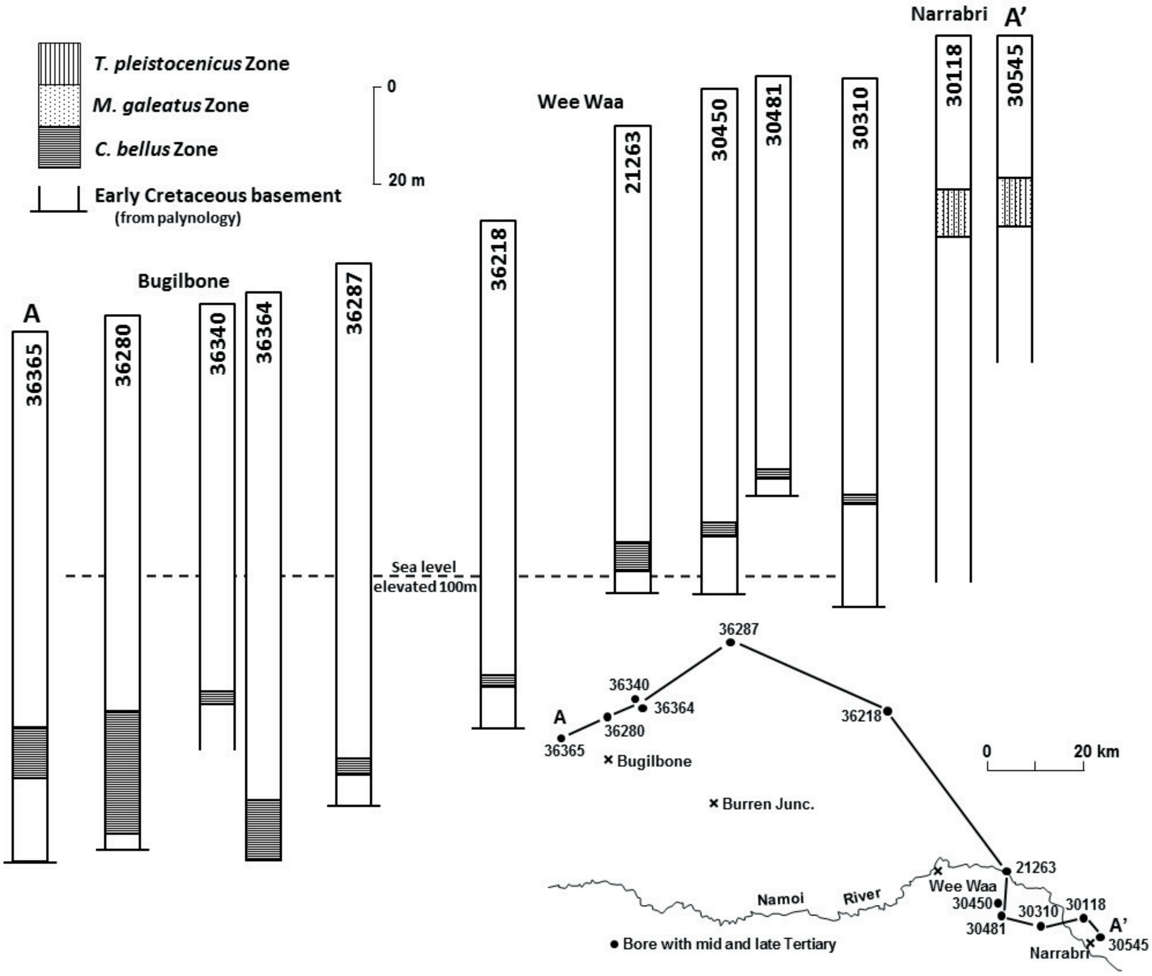

Figure 8. Palynology of the Namoi alluvial plain (from Martin, 1980). For the ages the zones indicate, see Fig. 3.

Cenozoic basement is shallow are equivalent to the late Miocene – Pliocene Lachlan Formation. Downstream to the west of Corowa where these sediments overlie those of the Murray Basin, they are considered equivalent to the Calival Formation. The sands of the Lachlan Formation are quartzose and contain the main aquifers with only the upper part containing rock fragments representative of the present catchment rocks. The Shepparton Formation overlies the Lachlan Formation and is characteristically brown in colour. Quaternary sediments are assigned to the Coonambigal Formation of the Murray Basin (Martin, 1995).

The longitudinal section of the valley (Fig. 11) shows the upper Miocene-Pliocene *M. galeatus* Zone and the Pleistocene *T. pleistocenicus* Zone in the valley upstream of Corowa. The M. *galeatus* Zone is also found on the riverine plain downstream of Corowa. The upper lower Miocene to mid Miocene *C. bellus* Zone and the lower Oligocene to lower Miocene *P. tuberculatus* Zone occur to the west and north of Corowa (not shown on Fig. 8, Martin, 1995).

The upper Miocene-lower Pliocene *Nothofagus* phase may be traced through the sequence in stratigraphically the same relative position as in the Lachlan River Valley alluvium, i.e. well down in the *M. galeatus* Zone.

Murrumbidgee River Valley.

The Murrumbidgee catchment covers 84 km^2 in southern New South Wales. The river rises on the Monaro plains at elevations of 2,200 m and flows westwards to join the Murray River near Balranald, where elevations are less than 50 m. A long narrow flood plain extends upstream of Narrandera to the foothills and yields good quality water suitable for town water supply. Major irrigation areas are found in the western part of the catchment (Green et al., 2011d)

In a small section across the valley at Narrandera,

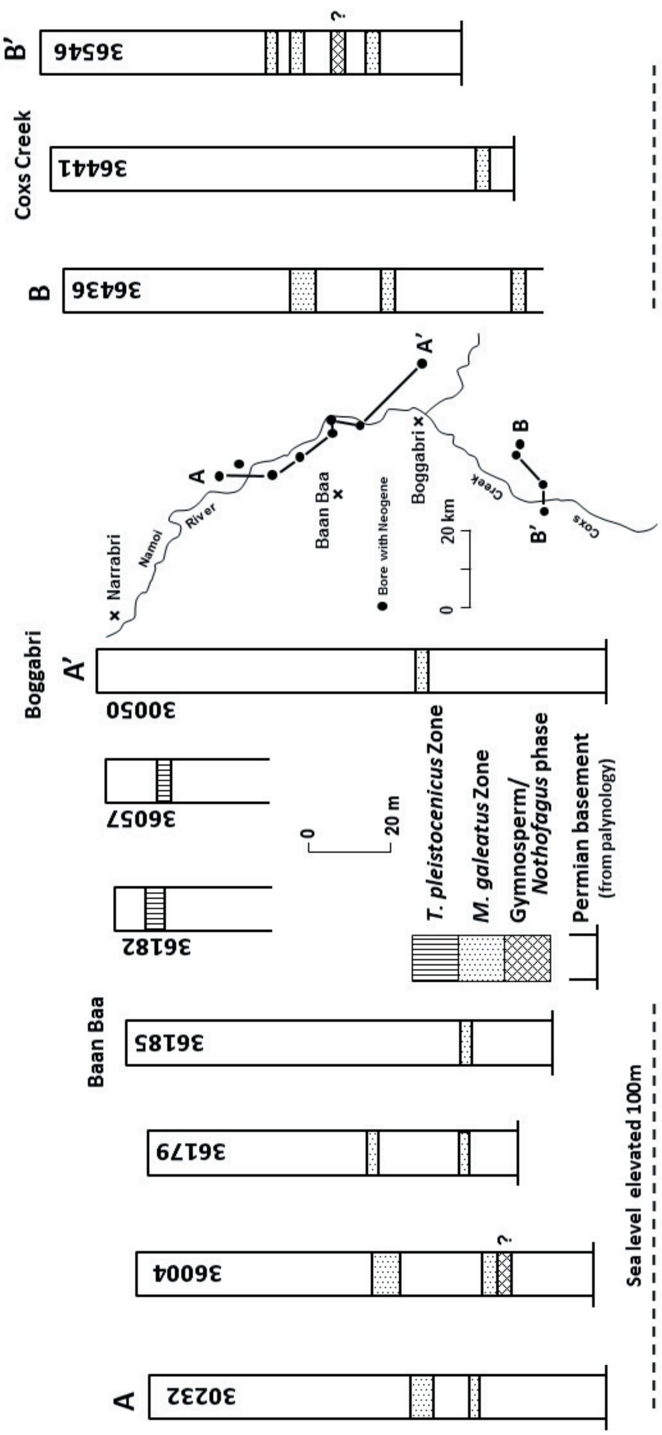

Figure 9. Palynology of the Namoi River Valley, Baan Baa to Boggabri and Coxs Creek (from Martin, 1994). For the ages the zones indicate, see Fig. 3.

the upper part of the sediments is considered the equivalent of the Cowra and Lachlan Formations. The palynology reveals the Pleistocene *T. pleistocenicus* Zone, a *T. pleistocenicus/M. galeatus* intergrade, the upper Miocene-Pliocene *M. galeatus* Zone and the upper lower to middle Miocene *C. bellus* Zone of the Neogene sequence (Martin, 1973b). The deep bores here penetrate sediments of the Renmark Group of the Murray Basin, and yield palynofloras of the lower Oligocene to lower Miocene *P. tuberculatus* Zone and the upper Eocene *N. asperus* Zone that are extensive in the Murray Basin further to the west (Martin, 1984a; 1991). Narrandera is situated on a long, narrow embayment of the Murray Basin that is the earliest recognisable stage of the Murrumbidgee River System (Woolley, 1978).

Upstream at Wagga Wagga, the sediments are considered the equivalent of the Lachlan and Cowra Formations. A small section across the river valley has the upper Miocene-Pliocene *M. galeatus* Zone and the *Nothofagus* phase is particularly well represented with a relatively high content of *Nothofagus,* up to 27% of total count. The fern spore count may be exceptionally high also, 50-80 % of total count but it is very localised as another bore only 100 m away did not yield high counts of spores (Martin, 1973b; 1991).

Castlereagh River Valley

The Castlereagh River begins in the Warrumbungle Ranges near Coonabarabran and flows west to its confluence with the Macquarie River. The catchment has an area of 17,400 km^2 with elevations of 850 m in the east to less than 200 m on the floodplains. Stream flow is highly variable and the sandy bed is often dry (NSW Department of Primary Industries Office of Water, 2013c). The Castlereagh River is somewhat different to the other rivers in that it was not a major tributary (J. Ross, pers. comm.).

There are few Cainozoic palynofloras in the Binnaway/Gilgandra/Curban part

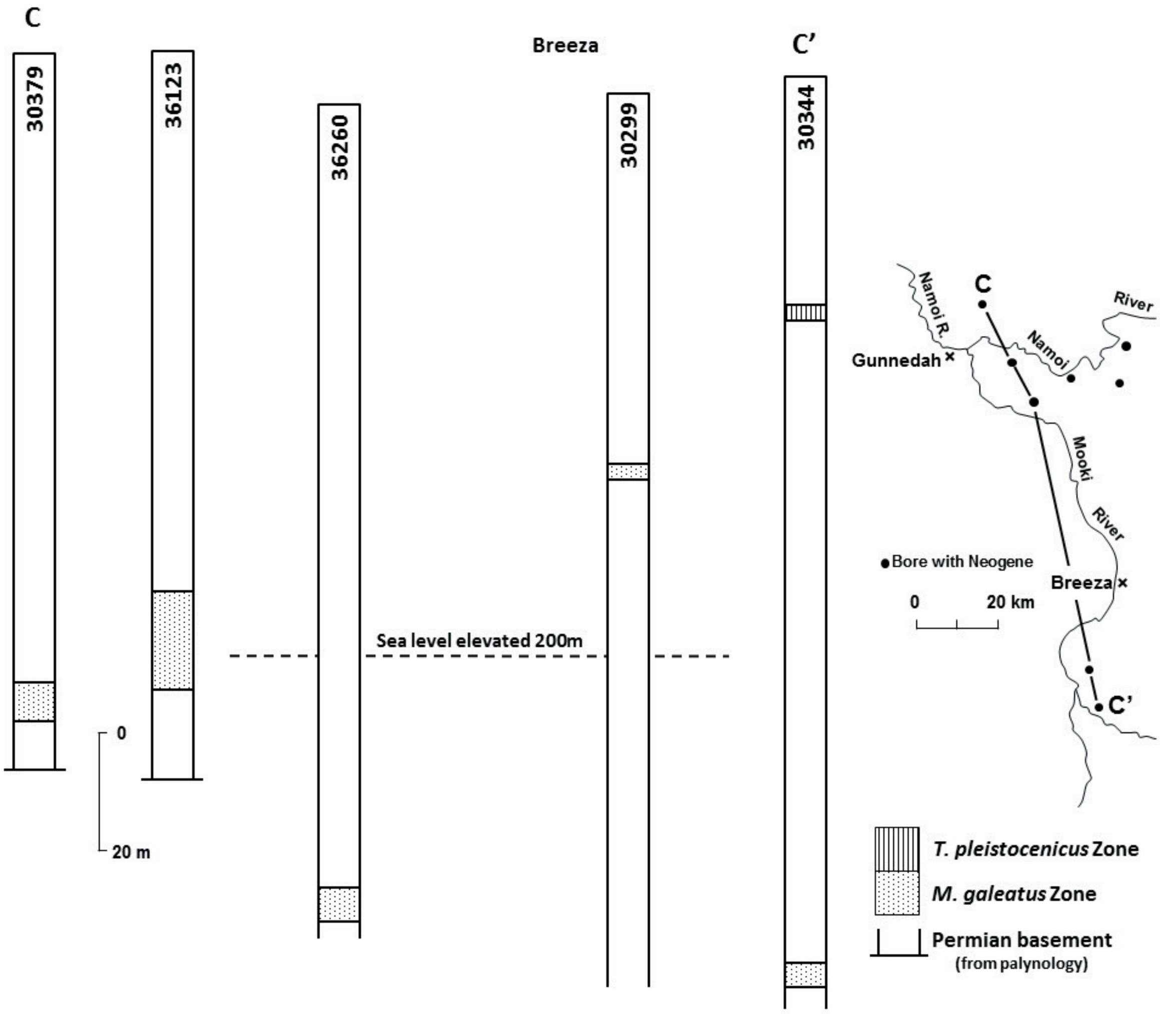

Figure 10. Palynology of the Mooki River Valley, tributary of the Namoi River (from Martin, 1979). For the ages the zones indicate, see Fig. 3.

of the Castlereagh River Valley as basement is rather irregular and palynofloras of Permian/Mesozoic age are encountered at relatively shallow depths (Martin, 1981b). The upper lower to middle Miocene *C. bellus* Zone is found around Gilgandra and downstream, whereas the late Miocene-Pliocene *M. galeatus* Zone occurs around Gilgandra (Martin, 1981b; 1991).

The upper part of the alluvium is consistently brown, yellow, orange or reddish with minor grey streaks or lenses. Consistently grey sediments are encountered at deeper levels, but where palynofloras are recovered, most of them are Mesozoic in age. It is unclear if or how much of the sediments are equivalent to the Lachlan Formation over this irregular basement with so few Neogene palynofloras (Martin, 1981b).

Darling River

Palynology is available from only a few bores along the Darling River, southwest of Bourke (Fig. 1). This part of the Darling does not flow down the Western Slopes but follows an ancient fracture lineament with a series of shallow grabens that act as small basins (Martin, 1997). The Cenozoic sediments form a linear belt along the lineament and are divided into (1) an upper unit of grey silty clay of the modern floodplain and probably the equivalent of the Shepparton Formation in the Murray Basin, and (2) a unit thought to be equivalent to the Renmark Group of the Murray Basin. This latter unit consists of sands and fine gravel, with carbonaceous muds at the base (Martin, 1997).

The upper Eocene *N. asperus* Zone is found at Tilpa, the lower Oligocene-lower Miocene *P. tuberculatus* Zone at Glen Villa and upper lower to middle Miocene *C. bellus* Zone at Jandra, the furthest upstream. The Pleistocene *T. pleistocenicus* Zones

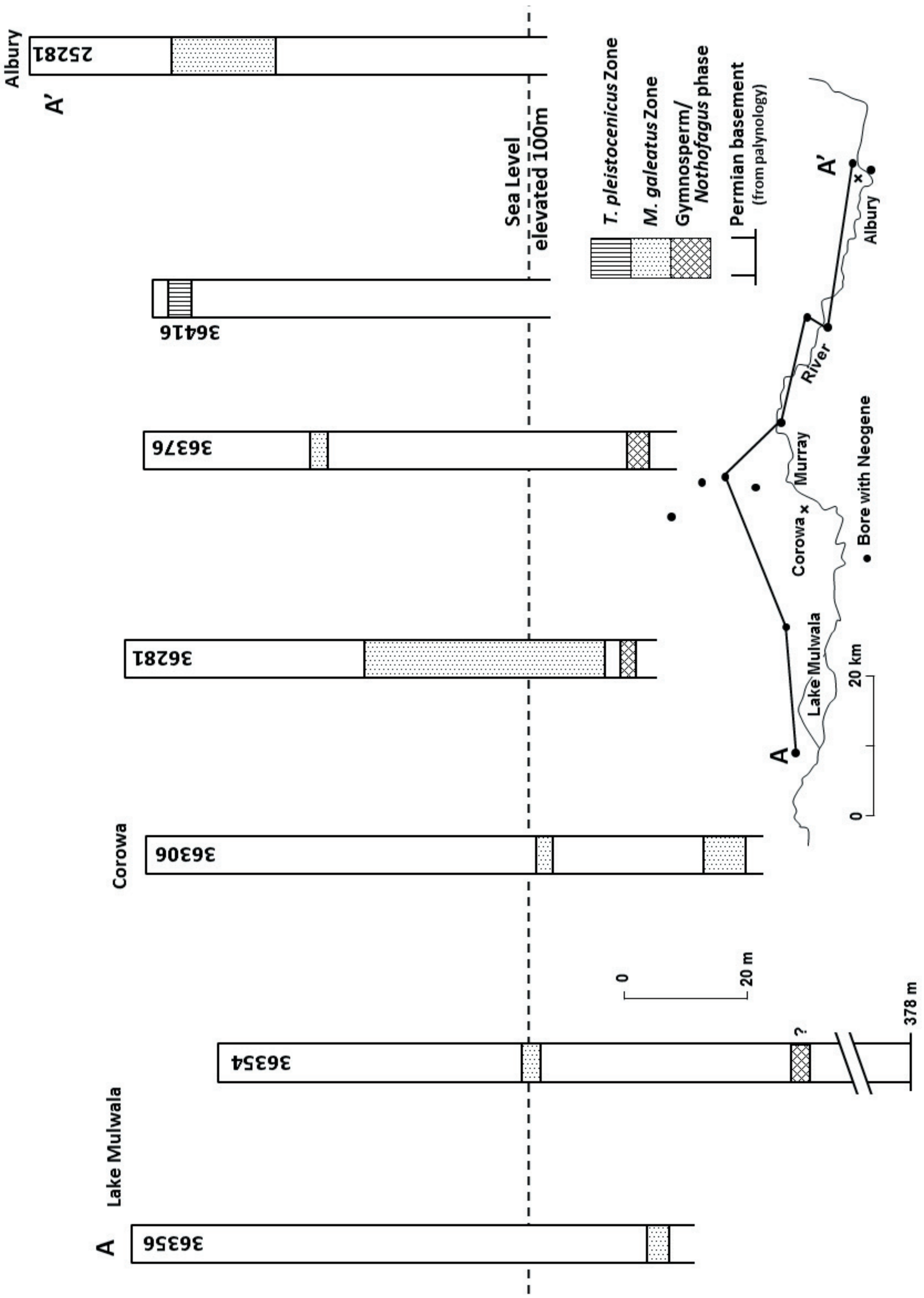

Figure 11. Palynology of the Murray River Valley (from Martin, 1995). For the ages the zones indicate, see Fig. 3

occurs at shallow depths at Louth and Jandra (Martin, 1997).

West of Lake Menindee, a number of bores in an area overlapping the edge of the Murray Basin (Fig. 1) only yielded palynofloras in dark grey clays at depths greater than 70 m. Any grey clays at shallower depths proved barren. It is thought that deep weathering would have destroyed any pollen at shallower depths. The deeper sediments would be equivalent to the non-marine Renmark Group of the Murray Basin, but dinoflagellates are commonly present in the southern part of the area and indicate a marine environment (Martin, 1988). The palynofloras indicate thick sections of lower Oligocene-lower Miocene *P. tuberculatus* Zone. This area would have been near the edge of the upper Oligocene-mid Miocene marine incursion when it was at its maximum extent in the Murray Basin.

Further upstream in the Lower Balonne area near St George, southern Queensland, correlatives of the Lachlan Formation and Pleistocene palynofloras have been identified (Macphail, 2004).

DISCUSSION

The palynological long profiles of the river valleys reveal a striking similarity: accumulation of the alluvial fill started in the upper Miocene in all of the valleys, from the Murray in the south to the Namoi in the north. Isolated occurrences of older sediments in the alluvial fill are rare, although older sediments of more than one age may be found in elevated positions on the sides of the valleys. Older sediments of the upper lower to middle Miocene and the lower Oligocene to lower Miocene are almost entirely restricted to the alluvial plains.

The lithology of the alluvium is also similar in all the valleys. The sands and gravel in a basal unit, corresponding to the upper Miocene-Pliocene *M. galeatus* Zone, consist almost entirely of quartz and yield good quality ground water. The overlying unit, corresponding mainly to the Pleistocene *T. pleistocenicus* Zone, contains a mixture of rock types with quartz a minor component and the ground water is of poorer quality.

The river valleys were in existence long before the Neogene. A long, narrow embayment extending from the Murray Basin into the highland area flanking the Eocene plain to the west is the first recognisable stage of the Murrumbidgee River. This embayment yielded upper Eocene palynofloras at Narrandera. A similar embayment appears to be present east of Hillston, representing the earliest stages of the Lachlan River (Wooley, 1978). The earliest identification of the Murray River is Eocene in age (Macumber, 1978).

Paleogene palynofloras have not been found in the river valleys of the Western Slopes, but both Palaeogene and Neogene palynofloras may be found throughout the Highlands and they are listed in Table 3. These palynofloras owe their existence to a basalt cap that prevented subsequent removal by erosion. Without any such protection, it is likely that any Paleogene sediments in the valleys were removed by an erosive event prior to the deposition of the Neogene sequence. The upper Eocene and upper Oligocene-lower Miocene sediments recovered from the small basin-like structures along the Darling River suggest that older sediments were deposited more widely but palynofloras have only survived subsequent erosion and weathering in these localised structures.

Tomkins and Hesse (2004) studied the Macquarie Valley and found substantial vertical incision in the mid-upper Miocene and interpreted it as evidence of a single, high magnitude uplift event. They suggest that first order tectonics were not synchronous with uplift in the Lachlan Valley and that they were restricted to relatively local spatial scales (Tomkins and Hesse, 2004). If first order tectonics were so different in the mid-upper Miocene of the two adjacent catchments, it is difficult to reconcile how the stratigraphy and palynology of the alluvial fill came to be so similar in both valleys.

A series of erosion terraces that are most pronounced upstream of Cowra and diminish with distance downstream are evidence of a series of relatively minor uplifts (Williamson, 1986). A study of the Lachlan River Valley by Bishop and Brown (1992) concluded that Neogene isostatic rebound in response to denudational unloading has been a significant factor in maintaining highland elevation. Young and McDougall (1985) studied the Eocene basalts of the Shoalhaven valley. Post-basaltic denudation has been slow and there has been little change in the landscape, inferring very little uplift. Taylor et al. (1985) studied the pre-basaltic topography of the northern Monaro and concluded that there has been only minimal change in topography and drainage during the Cenozoic, suggesting no significant uplift. These studies thus infer only relatively minor tectonics that would have done little more than maintain the elevation of the Highlands. Neogene studies of the southern part of the Murray Basin indicate only minor tectonics that eventually closed off the Murray Basin from the sea (Wallace et al., 2005; McLaren et al., 2011).

The stratigraphy of the Murray Basin shows a basin-wide erosion/non-deposition hiatus, the

Table 3. Records of Palaeogene and Neogene Palynology in the Eastern Highlands

Locality	Palynological Zone/Age	Reference
Southern Monaro	*Lygistepollenites balmei* Zone, upper late Palaeocene	Taylor et al. (1990)
Bowral area	*L. balmei* Zone, late Paleocene	McMinn (1989d)
Mt. Royal Range	*L. balmei* Zone, late Paleocene	Martin et al. (1987)
Nerriga	*Malvacipollis Zone*, early Eocene	Owen, (1975)
Bungonia	Lower *N. asperus* Zone, mid Eocene	Truswell and Owen (1988)
Shoalhaven Catchment	Upper *N. asperus* Zone to lower *P. tuberculatus* Zone. Late Eocene-early Oligocene	Nott and Owen (1992)
Invernell area	*P. asperopolis* Zone, mid Eocene and mid *P. tuberculatus* Zone, late Oligocene	McMinn (1989e)
Glenn Innes	*N. asperus* Zone, mid and late Eocene	McMinn (1989a; 1989b; 1989 c)
Spring Ridge, Mooki R.	*P. tuberculatus* Zone, ?Oligocene	Martin (1981a)
Cooma	Oligocene-late mid Miocene	Tulip et al. (1982)
Kiandra	Mid (?Late) *P. tuberculatus* Zone, early Miocene	Owen (1975)
Cadia	C. *bellus* Zone, Mid Miocene	Owen (1975
Mudgee	*C. bellus* Zone, Mid to late Miocene	Martin (1999)
Gulgong area	*C. bellus* Zone, Mid to late Miocene	McMinn (1981)

Mologa Surface (Macumber, 1978), formed when the sea retreated from the basin in the middle early to late Miocene (~ 10 Ma) (Stephenson and Brown, 1989). Macphail et al. (1993) has suggested this unconformity correlates with the 13.8 or (the preferred) 10.5 Ma eustatic sequence boundary of Haq et al. (1987), when there were major falls in global sea levels. Active entrenchment of adjacent highland valleys also occurred at this time (Brown, 1989) when the older sediments in the valleys would have been removed. The lowered base level may have also carved out the valley-in-valley structure reported for the Lachlan and Macquarie Valleys.

A study of Miocene eustasy off the northeastern margin of Australia gives some measure of the late Miocene fall in sea levels. There was a major drop of 53-69 m from 14.7-13.9 Ma (John et al., 2011). There was another major fall in global sea level at 10.5 Ma (Fig. 12), but the sediments were not suitable for an estimation of the extent (John et al., 2011). However, judging from the global sea levels of Haq et al. (1987, Fig. 12), the total fall was probably about 200 m. This latter drop corresponds to the time of the Mologa erosional surface in the Murray Basin and active entrenchment of the highland valleys (Brown, 1989). The fall in sea level drained the Murray Basin and the ancestral Murray River then flowed in a southerly direction to discharge into the sea in western Victoria (McLaren et al., 2011). This major marine regression in the Murray Basin would have affected all of the river valleys synchronously.

There was a short-lived marine transgression/regression in the upper Miocene-Pliocene (~6 Ma, Fig. 12) (Brown, 1989). The rise in sea level resulted in back filling of the previously excavated entrenchments of the highland valleys (Stephenson and Brown, 1989). Subsequently, there were only minor fluctuations in sea level, restricted to the southern part of the basin (Wallace et al., 2005; McLaren et al., 2011). Relatively small amounts of regional uplift defeated the drainage system and the Murray Basin was cut off from the sea. A freshwater megalake, Lake Bungunnia was formed ~2.4 Ma, and at this time, the rivers of the Murray Darling system drained into L. Bungunnia. The ancestral Darling River would have discharged into L. Bungunnia about the Pooncarie-Mildura region, according to the reconstructions of Stephenson and Brown (1989).

With the demise of Lake Bungunnia, the modern course of the Murray River was established ~700 ka

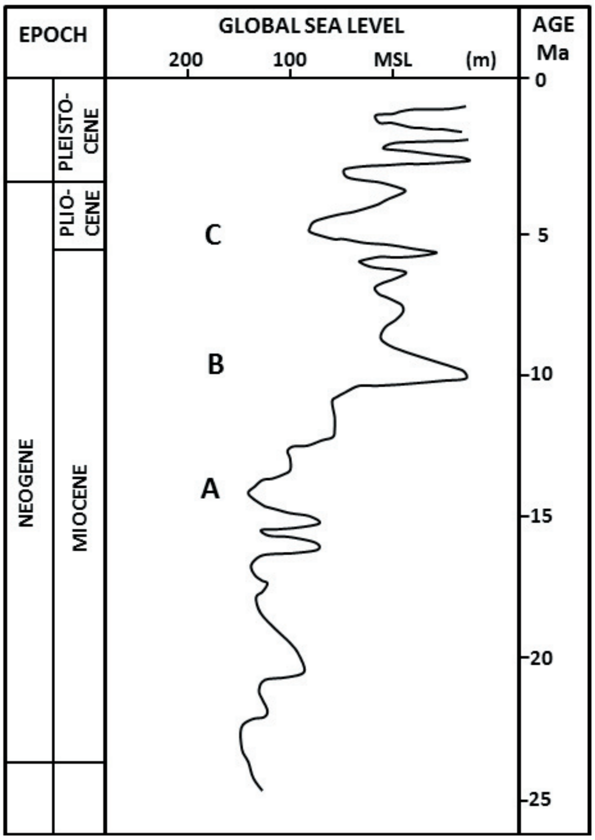

Figure 12. Global sea levels through the Neogene, from Haq et al. (1987). A, the first major drop in sea level ~14.7-13.9 Ma. B, the second major drop in sea level ~ 10.5 Ma (the time of the Mologa erosion/ non-deposition surface in the Murray Basin). C, the short-lived marine transgression/ regression ~ 6 Ma. See text for further explanation.

(McLaren et al, 2011).

Tomkins and Hesse (2004) reject the notion that eustasy could have had an effect on the Macquarie River Valley because of the distance to the coast of over 1,500 km, but Miocene palaeogeography was very different to that of today. The Macquarie River joins the Darling River that would have discharged into the sea about the Menindee region at the height of the mid Miocene marine transgression (Fig. 2), a much shorter course. Tomkins and Hesse (2004, p 285) also describe "deposition ..…. in the upper Miocene-lower Pliocene of the sediment…… demonstrates a rising base level on the alluvial plain…..". This rising base level may have been caused by the short-lived marine transgression/regression about 6 Ma that resulted in the back filling of previously excavated highland valleys (Stephenson and Brown, 1989). This evidence suggests that eustasy from the mid Miocene to Pliocene has had a considerable influence on the histories of the valleys.

The Neogene was a time of changing climate with decreasing precipitation (Macphail, 1997: Martin, 2006). In the mid Miocene *(T. bellus* Zone), rainforest was widespread with precipitation of ≥ 1500 mm pa and relatively high humidity the year round. By upper Miocene-Pliocene time (*M. galeatus* Zone), with mainly sclerophyll forest, precipitation had decreased to ~1500 -1000 mm pa and there was a pronounced dry season and fires occurred on a regular basis. In the short time before the vegetation recovered from the fires, the bare ground would have allowed increased erosion. In the Pleistocene, with woodland/ grassland (*T. pleistocenicus* Zone), rainfall had decreased further, to < 1000 or probably 800 mm pa for the Lachlan River Valley (Martin, 1987).

All the evidence suggests a rainfall gradient parallel to that of today, i.e., it was dryer in the west and wetter to the southeast. This gradient is seen in the palynofloras and particularly in the *Nothofagus* phase. The most *Nothofagus* in the palynofloras is found in the Murray Valley with lesser amounts in the Murrumbidgee and Lachlan Valleys. There is also a gradient seen especially along the Lachlan Valley, with more *Nothofagus* further upstream and this gradient parallels the precipitation gradient (Martin, 1987). It is thought the short-live marine transgression/regression in the upper Miocene-lower Pliocene (Brown, 1989) increased the precipitation and allowed *Nothofagus* to migrate down the river valleys from its refuge areas further up in the Eastern Highlands. This resurgence, however, did not reach the more westerly part of the slopes or the Murray Basin, where, following the rainfall gradient, it would have been drier than in the upper reaches of the valley. (Note: *Nothofagus* is still present in a few highland areas from the most south-easterly part of Victoria to the Queensland border).

In all of the valleys, the change from the quartz rich sands and gravels of the lower alluvial unit to the variable lithologies with little quartz of the upper unit is usually distinct and is described as an erosional surface in the Lachlan and Macquarie Valleys (Williamson, 1986; Tomkins and Hesse, 2004; respectively). As far as the palynological method of dating allows, it occurs about Pliocene-Pleistocene time, but a probable cause is unclear. By this time, the Murray Basin was cut off from the sea, hence isolated from eustatic changes. However, the rivers drained into the megalake Lake Bungunnia, formed about 2.4 Ma, under a climate with a much higher precipitation than today. Lake levels fluctuated with climatic fluctuations (Stephenson, 1986) that probably had some influence on deposition/non-deposition in the river valleys.

Williamson (1986) attributes the quartz in the lower unit to reworking of a formerly widespread older unit(s) whose remnants are found on elevated parts of the valleys. The various lithologies in the upper unit represent the resistant rock types of the catchment. Tomkins and Hesse (2004) ascribe this change in lithologies of the two units as a change in the rock type being eroded. These two explanations are not entirely satisfactory and they rely more on more fortuitous events than anything else. There was a marked climatic change about this time that would have affected the whole of the Western Slopes. The relatively high-energy depositional environment of the lower unit would have decomposed more of the less resistant rock types, leaving the resistant quartz. With the change to decreased precipitation and a lower energy environment in the Pleistocene, there was less erosion and less chemical weathering, which allowed more of the different rock types to survive (Martin, 1987).

CONCLUSIONS

The palynology of all the river valleys of the Western Slopes shows a remarkable similarity. Palynofloras of the upper Miocene-Pliocene *M. galeatus* Zone are the oldest found in the valleys and occur in the basal quartz-rich sedimentary unit. The overlying Pleistocene *T. pleistocenicus* Zone is found in the upper sedimentary unit that has a mixture of rock types and a minor quartz component. Older sediments are found on the alluvial plains and in the Highlands if those in the latter localities have been protected from erosion by a basalt cap, but not in the valleys.

Palaeogeography of western New South Wales during the Neogene was very different to that of today. The mid Miocene was a time of maximum marine transgression in the Murray Basin and the rivers of the Western Slopes drained into the Murray Basin. Major falls in sea levels during the mid-upper Miocene drained the Murray Basin and there was a basin-wide erosion/non-deposition hiatus, with entrenchment in the river valleys that would have removed the older sediments. Subsequently, minor tectonics closed off the mouth of the Murray Basin and the present course of the Murray River is only ~700 ka old.

Tectonics in the Highlands and Western Slopes had a relatively minor and localised impact, probably only maintaining the elevation of the Highlands.

The palynofloras indicate an increasingly drier climate through the Neogene and into the Pleistocene, and change from a high-energy to a low energy erosion/deposition environment that would have influenced the nature of the sediments being deposited.

Eustasy, tectonics and climate have all had some influence on the histories of the river valleys. The major changes in sea level through the Neogene, however, would have impacted on all of the valleys, synchronously, to produce the remarkable similarity of the histories of the valleys. The major change to a much drier climate in the Pleistocene would have impacted on the whole of the Western Slopes, and indeed far beyond the region of this study.

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