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Guest Editor:
A.P. KERSHAW

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PROCEEDINGS

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ROYAL SOCIETY OF VICTORIA

PEER REVIEWED PAPERS

ENVIRONMENTAL HISTORY OF THE NEWER VOLCANICS PROVINCE OF VICTORIA

INTRODUCTION

It is now 40 years since the publication of the Proceedings of the Royal Society of Victoria issue on "The Basalt Plains of Western Victoria'. This provided a comprehensive and systematic overview of present and past environments as known at the time. It is still a major reference for many aspects of the present landscape as well as having historical value. However, apart form some uncertain dating on the western plains flows and distinctive volcanic features, and on archaeological and fossil faunal material, there was little available information on the evolution of the landscape. This issue is focused on presentation of new data and reviews of research undertaken on the volcanic, climatic, vegetational and human history of the region since the 1960s. It demonstrates the importance as well as the future potential for understanding patterns of change in natural and human-modified landscapes not only within the region but also on Australian as well as global scales within the late Cenozoic period. In fact, there are few other parts of the world that have revealed such a fascinating and substantial history.

There is no-one who has dedicated more of his life to the geology of the Newer Volcanics of Victoria than Bernie Joyce. No self-respecting academic goes to the basaltic plains of Victoria without a copy of the classic paper of Ollier and Joyce (1964) from the Proceedings volume and, if at all possible, without Bernie Joyce himself. He has been the inspiration behind much of the research undertaken and many have relied on his substantial and willingly imparted knowledge to facilitate their research. The editors, one of whom who has benefited from his insights and friendship over at least the last 30 years, together with all contributors, are honoured to dedicate this volume to him. Some indication of his contribution to the region is contained within a summary of his research contribution (Appendix 1).

The idea for this volume arose out of an Australasian Quaternary Association Conference held in Port Fairy in January 2001 where Bernie Joyce led yet another field excursion around the Western Plains and also gave the keynote address. Appropriately, his update on the volcanology of the volcanic plains is the first of ten papers contained in this issue. He outlines the development of geological knowledge of the Newer Volcanic Province, arranged by subprovince. Lava flow chronosequences help define the periodicity of volcanic activity, and the interesting proposition of the paper is that future volcanic activity is possible and even likely. The nature and locations of any future eruptions are presented as scenarios, along with the implications of this startling possibilty for people and emergency management.

The next three papers provide case studies on the nature of volcanic activity, recent age determinations and resulting volcanic products and landforms. The volcanic structure of Lady Julia Percy Island, examined by Jane Edwards, Ross Cayley and Bernie Joyce, is distinctive in revealing the oldest dates (Late Miocene) for activity within the Newer Volcanics Province and for providing the best example of rare subaqueous formations in Australia. Despite its apparent age, features are well preserved and described in relation to two identified phases of activity, in some detail. This study contrasts with that of nearby Mt Rouse (Fabijan Sutalo and Bernie Joyce) which is one of the more recent volcanic features, dating to about 350,000 years before present. The volcano itself is a complex scoria and lava structure that has given rise to a lava shield and to the longest lava flows in Victoria. These flows display the 'stoney rise' topography that characterizes younger flow surfaces widespread over the Western Plains. The distributions and chronosequences of the flows are defined, and reasons are put forward for long lava flow emplacement at Mt Rouse. A further contrast is provided by Lin Sutherland, Ian Graham and Horst Zwingmann who emphasise, from the age and petrographic and geochemical characteristics of basalts in eastern Victoria, that the Uplands Province is related to those of western Victoria and form a part of the Newer Volcanics of this State. Both the origin of the lavas and their present distribution and topographic expression are investigated. Despite the geographical separation, these basalts were extruded during the peak activity (2-4 million years ago) in the Newer Volcanics Province of western Victoria.

The contribution of John Sherwood, Ben Oyston and Peter Kershaw brings together three different approaches to dating of the age of the Tower Hill volcano that has proved problematic for many years. Thermoluminesence dating of an exposure of Tower Hill ash, radiocarbon dating of remains of plants buried by the Tower Hill ash and radiocarbon dating of the basal lake sediments in a scoria cone crater within Tower Hill produced consistent dates around

30,000 to 35,000 years. This eruption is one of several that occurred during the latest phase of volcanic activity within Victoria.

The numerous sediment-filled maars provide ideal sites for palaeoecological study, and these have been exploited from the time of the initial PhD project of Habib Yezdani in the late 1960s. Four papers are devoted to pollen-based new and review studies mainly from these maar sediments. The oldest record is from the most recent sediments of what is considered to be an old crater lake, now the Daylesford racing car track, in the Western Uplands (Kale Sniderman, Paul O'Sullivan, Julian Hollis, and Peter Kershaw). Fission track dates, together with the pollen stratigraphy, indicate that it is most probably Late Pliocene in age. High resolution pollen analysis reveals marked variation in vegetation probably reflecting orbital scale climatic cyclicity. During the wettest phase, diverse rainforest, characteristic of much of the Tertiary period in southeastern Australia, was well represented while the driest phase was dominated by vegetation more typical of present day wetter sclerophyll forests. The record provides an important but temporally restricted insight into the nature of the transition from a rainforest to sclerophyll vegetation dominated landscape and unfortunately stands alone in recording this period time in any detail within southeastern Australia.

More substantial information is available for significant chunks of the Quaternary period from the papers of Peter Kershaw, Donna D'Costa, John Tibby, Barbara Wagstaff and Henk Heijnis, and Kate Harle, Peter Kershaw and Eric Clayton. The former covers about the last million years, from the end of the Early Pleistocene to the Holocene, represented in volcanic crater lake deposits within and just outside the township of Terang. Although discontinuous and minimally dated, the combined record is the only one covering this long period of time from the land surface of Australia. Perhaps surprisingly, the latest part of the Early Pleistocene appears to have been drier than today. The vegetation was dominated by grassland with some cover of trees, of which *Callitris* was a major component. After this time the global pattern of glacial-interglacial cyclicity is very apparent with greater coverage of trees, largely *Eucalyptus*, during warmer and wetter interglacials, with some re-emergence of rainforest pollen, probably derived from expansions in the Otway Ranges. Greater detail on the last two glacial-interglacial cycles is provided in the latter paper, from Lake Wangoom, close to Warrnambool. Numerical techniques are used to refine the nature of vegetation communities represented in the landscape from the pollen data. It is determined that each interglacial period has a distinctive pollen and vegetation signature and that, in line with other records within the Australian region, there is a long term trend towards more open canopied vegetation. Although climate is probably the major factor, landscape burning by Indigenous people or even volcanic activity, may have also contributed to this trend.

A broader regional view of vegetation since the Last Glacial Maximum is provided by Peter Kershaw, John Tibby, Daniel Penny, Habib Yezdani, Rhys Walkley and Ellyn Cook. The eleven pollen diagrams represented include major features of published records, and unpublished records including the original ones of Yezdani. They illustrate the development of the present landscape from a time of cooler and drier climate when grassland steppe covered the western plains, through a period when Casuarinaceae was prominent to the present dominance of *Eucalyptus* woodland. Regional variation can be attributed to different landscape characteristics and, to some extent, places where trees survived the hostile conditions of the last glacial period.

In the second last paper, Heather Builth provides a fascinating picture of the way that Indigenous people utilized and modified the unique features of the 'stoney rise' landscape of the Mt Eccles lava flow and associated swamp and river systems to develop a sophisticated system of eel aquaculture. Evidence is derived from detailed investigation and geographical information system mapping of eel trap systems, culturally modified trees and house sites.

Together, these papers illustrate the scientific importance of the Newer Volcanics landscapes and the contributions they are making to the understanding of volcanic activity generally, to regional and global climates, to vegetation dynamics and to details of past human settlement and activity. Research is continuing in a number of areas to fully exploit this unique scientific resource. Studies have begun on identification of ash layers within sediment deposits to provide a clearer picture of the pattern and timing of volcanic activity that has bearing on when the next eruptions might be expected. In line with a global trend, projects have been initiated on high resolution palaeoecology of lake sediments to document climatic variability on decadal to millennial scales which will relate more closely to instrumental records of climate and allow analysis and modelling of patterns and causes of droughts and other extreme events. Past human impact is being examined to try and date the times of intensification of Indigenous settlement and development of the eel trap systems and to determine the causes and timing of resulting from European settlement. Such data, it is hoped, will contribute to future sustainable management of the plains and help protect the volcanic structures and precious archives preserved in the volcanic lake sediments.

Both these features are presently under threat. The 'stoney rises', that have largely been spared the ravages of human exploitation due to difficulties of access and cultivation, are now being targeted for agricultural expansion with the recent development of rock crushing equipment. Consequently, much of the evidence for sophisticated Aboriginal settlement and aquaculture may be soon lost and with it the opportunities for full understanding and reconstruction of these systems. Many of the lakes are experiencing increased salinitiy levels and occurrences of outbreaks of toxic algae and it is predicted that, with a continuation of falls in water levels experienced over the last few decades, some may disappear. Recent moves to intensify human occupation of slopes surrounding volcanic crater lakes could exacerbate these problems. In relation to decreasing water levels, it is still not determined to what extent this trend, that has resulted in Lake Keilambete, for example, now reaching its lowest levels for the last 10,000 years (Roger Jones pers. comm.), is the result of natural climatic variability or human impact. However, continuation of this trend is predicted from climatic models with enhanced greenhouse warming.

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APPENDIX 1. THE RESEARCH CONTRIBUTIONS OF BERNIE JOYCE (1962-2003)

The following list includes the major publications of Bernie Joyce that provide an indication of his breadth of interest and expertise in Cenozoic geology and landscapes and that are considered to be of interest to a variety of people, especially those in Victoria. The list excludes a substantial additional output in the form of conference abstracts, newsletter items, reviews and many field guides. It is clear that Bernie has maintained his research, including the supervision of many student projects, on the Newer Volcanics of Victoria, especially of the Western Plains, thoughout the last 40 years. Also apparent from the publication list is the output from his association with CRC LEME where he worked on the development of regolith studies and research in Victoria, with liaison between the CRC, universities and the Geological Survey of Victoria

Although he retired from his position as Senior Lectuer in the School of Earth Sciences, University of Melbourne, where he had taught for 35 years, he became an Honorary Principal Fellow in the School and appears to have increased his research activity. In Western Victoria, he is currently working on using regolith landform mapping of the volcanic plains, including the use of radiometric imagery, to develop a chronosequence of eruption activity which will allow the a better assessment of volcanic risk and hazard in southeastern Australia. Under a grant from Emergency Management Australia in 1999, he also set up a website on Disaster information in Victoria, and in June 2002, as Chair of the Communities Working Group Meeting of the Global Disaster Information Network (GDIN), he prepared a report on Disaster Information for Communities: Needs and Means. Most recently he co-authored the Geomorphology chapter in the monumental edition of the *Geology of Victoria* volume published in 2003.

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A.P. Kershaw
Centre for Palynology and Palaeoecology,
School of Geography and Environmental Science,
Monash University,
Vic 3800

THE YOUNG VOLCANIC REGIONS OF SOUTHEASTERN AUSTRALIA: EARLY STUDIES, PHYSICAL VOLCANOLOGY, AND ERUPTION RISK

BERNARD JOYCE

School of Earth Sciences, The University of Melbourne 3010, Victoria, Australia

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The young volcanic regions of southeastern Australia are known as the Newer Volcanic Province, which can be divided into four main subprovinces. The Western Plains subprovince and the Mt Gambier subprovince in southeastern South Australia occupy broad plains, while the Western Uplands subprovince is the elevated east-west spine of Western Victoria, with the Great Divide running along its crest. Small areas of youthful volcanism are also found in the Eastern Uplands subprovince.

Beginning about 6-7 Ma ago, but mainly since 5 Ma, a new volcanic province formed on both the Uplands and the Plains, and nearly 400 small, monogenetic, scoria cones, maars and lava shields have been built up by Strombolian/Hawaiian eruptions. Fluid basalt flows have spread laterally around vents, often for many tens of kilometres down river valleys. Where the lava flows have blocked drainage, lakes and swamps have formed. Phreatic eruptions have deposited ash and left deep craters, often now with lakes. The study of the province began in 1836, and now, over a century and a half later, while the cause of activity still remains unexplained, future activity is believed to be likely.

Key words: volcanology, history, catalogue, dating, ages, eruption risk.

THE NEWER Volcanic Province (NVP) of southeastern Australia consists of an area of 15 000 km^2 of thin lava flows and limited ash deposits, with nearly 200 scoria cones (commonest in the western part of the Western Uplands) and about 200 lava volcanoes (mostly on the northern part of the Western Plains, and the eastern part of the Western Uplands) (Ollier & Joyce 1964, Joyce 1975; see Fig. 1). There are also about forty maars, which are concentrated on the southern edge of the plains, along with young scoria cones, over the axis of the underlying Tertiary basin (Ollier & Joyce, 1964). The youngest dated eruption is that of Mt Gambier in nearby southeastern South Australia, at 4000-4300 B.P. (Blackburn et al. 1982). The highest volcano is Mt Elephant, near the centre of the plains. It rises a striking 240 m above the plains to an elevation above sea level of 393 m, with a crater 90 m deep, and is similar in size to Mt Kooroocheang, the highest volcano in the Western Uplands. First identified as a volcanic area nearly 170 year ago, the NVP is now one of the best studied of the world's many young basaltic monogenetic lava fields.

RECOGNITION AND EARLY STUDY OF THE NEWER VOLCANIC PROVINCE

Quaternary volcanism has left well-preserved cones, craters and crater lakes, scoria with iridescence, and stony rise lava flows with ropy and glassy surface textures - in fact such an obvious youthful appearance overall that in 1836 the explorer Major Mitchell, who was the first person to recognise the area as volcanic, suggested that eruption had been "within the memory of man". Mitchell (1838) provided the first written description of the Western Plains "We now travelled over a country quite open, slightly undulating and well-covered with grass…vast plains, fringed with forests and embellished with lakes …the open plains extended as far as the eye could reach…" Mitchell had no difficulty in identifying volcanic cones, craters and lava flows (see further discussion in Branagan 1989).

Tyers (1840) described the Plains region following his government surveying expedition, and soon the volcanic nature of the NVP became well known locally.

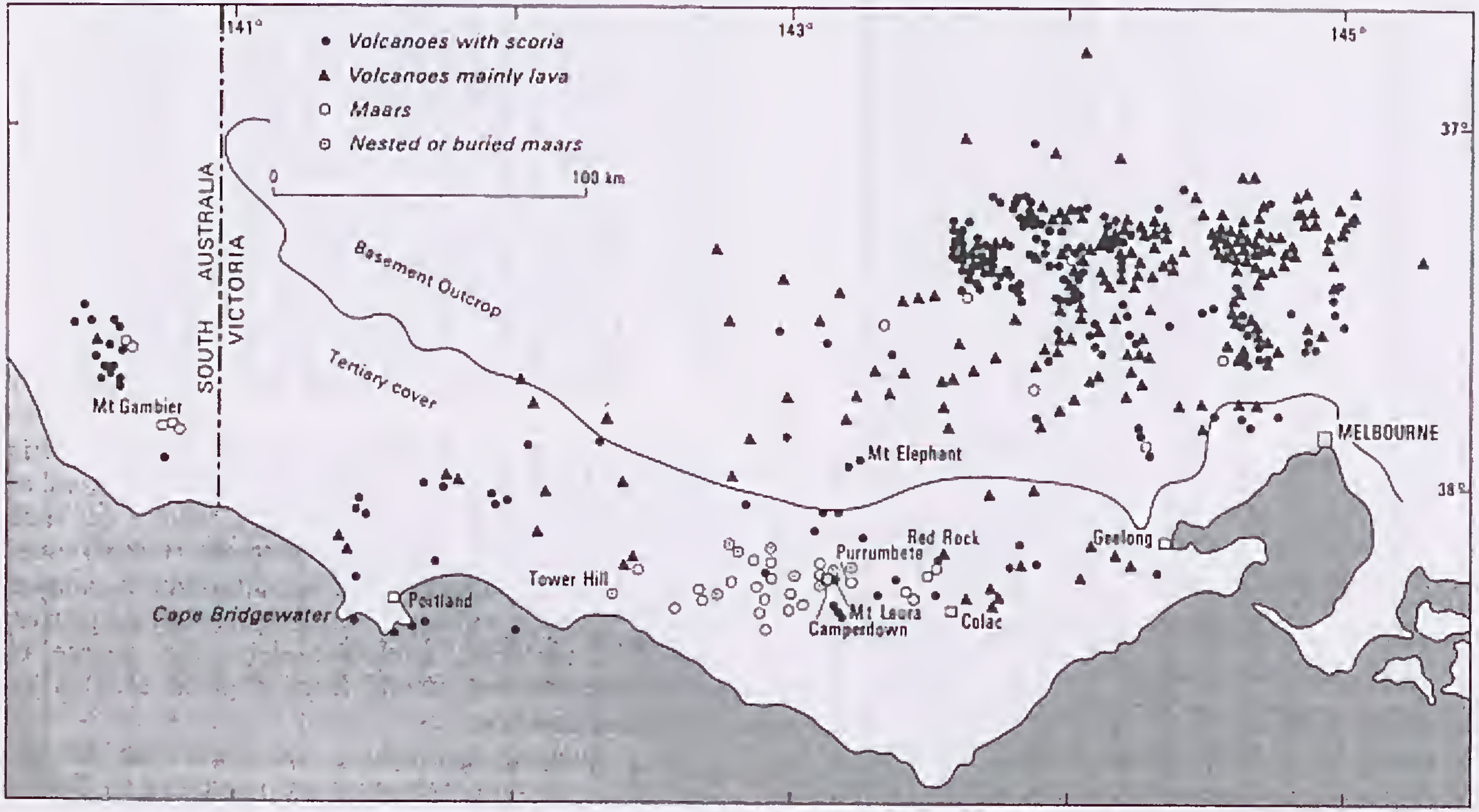

Fig. 1. Volcanoes of the main parts of the Newer Volcanic Province by type, based on Joyce 1975 (from Johnson 1989).

Westgarth (1846) wrote the first scientific article on the region, and this was published in the Tasmanian Journal of Natural Science. Wathen (1853) was the first to mention the volcanic regions in an international scientific journal, the Quarterly Journal of the Geological Society of London, while Brough-Smyth's 1858 publication in the same journal was the first significant report in an important overseas scientific journal, and included a sketch map showing "the Positions of Extinct Volcanos" (not all accurate) as well as several geological cross-sections and a plan of Tower Hill. In 1859 Selwyn published a general account of the volcanic area, based on his early mapping in central Victoria.

Descriptions of the region in books included Westgarth (1848) and Wathen (1855). Of importance at this period was the work of Bonwick, an inspector of schools, who recorded his observations of Western Victoria and recognised, described and interpreted many of its geological features in his 1858 book. In 1866 in the Proceedings of the recently founded Royal Society of Victoria Bonwick compared the volcanic rocks and features of Victoria with those of the area around Rome. In 1869 Brough-Smyth produced his monumental compilation on "The Gold Fields and Mineral Districts of Victoria" in which many features of the volcanic province are described and discussed.

Working across the border in South Australia was the Reverend Julian Tenison Woods whose important book (Woods 1862) described the volcanic features of Mt Gambier and Mt Schank in detail. Woods' lectures at Portland (1865) also included discussion of volcanic features.

Perhaps most significant at this time was the summary by Selwyn and Ulrick (1866), who described the Tertiary basalts of Victoria and noted the "wide-spreading sheets" of the Newer Volcanics and the "conical or mammaloid hills", many of which have "very perfect central crater-basins".

They distinguished two types of crater basins - those with deep freshwater lakes or shallow swampy lagoons, such as Mount Gambier and Tower Hill, and those which were dry, well-grassed and thickly timbered, such as Mount Noorat and Mount Elephant. They concluded that "most of them were subaerial volcanic vents, forming low islands in the tertiary seas, under the waters of which the lava streams flowed and were consolidated". They suggested that Purrumbete, Gnotuk, Terang and Keilambete "may perhaps also have been the sites of old craters" but concluded that "many of them are accidental depressions due to other causes" and compared them with the lakes of the northwest of Victoria.

Selwyn and Ulrich (1866) also included a table which listed 79 "volcanic cones and crater hills", and most of these were shown on a colour folding map at 32 miles to 1 inch (reduced from an 1863 sketch map at eight miles to one inch).

They recorded that "Extensive basaltic caves are not uncommon in the western district" and described Skipton Cave, giving the dimensions of the chambers, and noting the presence of bats and thick deposits of their excrement. Analyses of basalts, both Older Volcanic and Newer Volcanic, were also given.

Several publications of Hart (for example1901) and by Hall (1907) led into the work of the twentieth century. These writers were largely concerned with the lavas and tuffs of the volcanic areas.

Early twentieth-century studies

J. W. Gregory, first Professor of Geology at the University of Melbourne, discussed the region in his 1903 textbook (revised in1912). The next major study was by Grayson & Mahony (1910) who with university students mapped the Colac-Corangamite region in a report published by the Geological Survey of Victoria. They were also to make the erroneous claim, repeated many times since (see discussion in Joyce 1984) that "It is the third largest plain of its kind in the world".

Skeats (1909) reviewed infromation on the volcanic rocks of Victoria. Fenner (1921) described the craters and lakes of Mount Gambier in South Australia. Skeats & James (1937) described the volcanic areas of western Victoria in an article for the Royal Society of Victoria, developing the ideas of Mitchell and early geologists; they particularly described and discussed the stony rise flows, and the lava caves found in them, comparing what they saw with features from other volcanic areas around the world.

Hills prepared a map of the Physiographic Divisions of Victoria as part of the Physiography of Victoria section of Skeats (1935), and markied on the map just over 100 centres of eruption in central and western Victoria. Later Hills (1938) was successfully able to estimate the age of the volcanics using a physiographic approach. Edwards (1938) described the petrology and geochemistry of the NVP in detail. Crawford (1940), and Edwards and Crawford (1940) described the volcanic rocks of the Gisborne district.

More recent studies

E. D. Gill (1950, 1953), from the Museum of Victoria, was one of many workers who began a new phase of study in the NVP. During this period Condon (1951) described and mapped the lower Werribee River region, Coulson (1954) the Daylesford region, Yates (1954) the Ballarat district, and Hanks (1955) the plains north of Melbourne. The Geological Survey of Victoria published detailed mapping in the far western part of the NVP by Boutakoff (1963), also described by Coulson (1941).

C. D. Ollier, with Joyce and others, made a series of studies of lava caves, flows and volcanoes in the 1960s (Ollier & Joyce 1964, Ollier & Brown 1965), and attempted to identify all points of eruption in the NVP. In 1963 Gill organised a symposium on "The Basalt Plains of Western Victoria" which was published in 1964 as volume 77 of the Proceedings of the Royal Society of Victoria, and included amongst a number of papers Gill (1964) and Ollier and Joyce (1964).

A complete catalogue of Newer Volcanic eruption points in Victoria, incorporating earlier work, was prepared in 1967 by O. P. Singleton and E. B. Joyce for an international series, but never published (Singleton and Joyce 1970). A related catalogue covered the South Australian eruption points (Walker 1967).

Since the 1970s continuing work by students at the universities of Melbourne, Monash and La Trobe has added new details, especially of the Plains volcanoes. The Singleton and Joyce (1970) catalogue remains unpublished, but has been discussed by Singleton and Joyce (1969), Ollier (1967, 1969) and Joyce (1975 and later), and many details have been incorporated into the volcanic heritage review of Rosengren (1994).

With the invention of radiocarbon dating in 1950, Gill began dating samples related to past volcanic activity from the mid-1950s, and obtained the earliest dates for the Tower Hill eruption (Gill 1967). Potassium-argon dating work by McDougall and other workers commenced in the late 1960s (McDougall et al. 1966, Aziz-ur-Rahman and McDougall 1972, Wellman and McDougall 1974). Cosmogenic and OSL dating is now helping to date the younger volcanic activity of the area (Stone et al. 1997). A recent review of dating studies is given in Graham et al. (2003).

Some controversy exists, such as the dating of Mt Gambier (see Sherwood et al. 2004) and in general a number of the younger scoria, lava flow and maar volcanoes have been found to be older than suggested by past estimates and dating. In general a period of higher activity over the last 30,000 to 50,000 is indicated for the central and western part of the Western Plains subprovince.

In other scientific studies, Irving and Green (1976) described the geochemistry and petrogenesis of the "Newer basalts" of Victoria and South Australia, followed up by later workers (see review in Graham et al. 2003). Heat flow in the Plains was assessed as higher than average by Cull (1982) but further studies (Cull 1991) have failed to support this. Hilmanysah (1985) worked on the eruption hazard of the NVP, later reviewed by Blong (1989).

Why volcanism in the NVP commenced where and when it did, and continued for so long, is still not fully understood (Duncan and McDougall 1989, Lister and Etheridge 1989). Recent reviews of the NVP include Joyce (1988), Nicholls and Joyce (1989), Cas (1989), Graham et al. (2003), and Price et al. (2003). Birch (1994) provides a useful illustrated summary.

THE NEWER VOLCANIC PROVINCE

The Western Plains subprovince

The Western Plains consist of a major volcanic plain, often called the Western District Volcanic Plains, and a generally flat coastal plain (see Joyce et al. 2003). The latter is a depositional surface left by the final retreat of a series of Tertiary–Quaternary transgressions, and later partly modified by fluvial and aeolian erosion anddeposition. This depositional surface also underlies much of lava and ash deposits of the Volcanic Plains. At depth are the Tertiary marine sediments of the Otway Basin.

The Western Plains are generally less than 200 m above sea level and are a major part of the Newer Volcanic Province of southeastern Australia. They extend from the border with South Australia in the west, as far as Melbourne in the east, and northwards to the junction of the Plains with the Western Uplands.

The youngest lava flows form 'stony rises' with a characteristic relief of up to 20 m. They have sharp boundaries, commonly stepping down onto the surrounding plain by up to 15 m, and are readily recog-

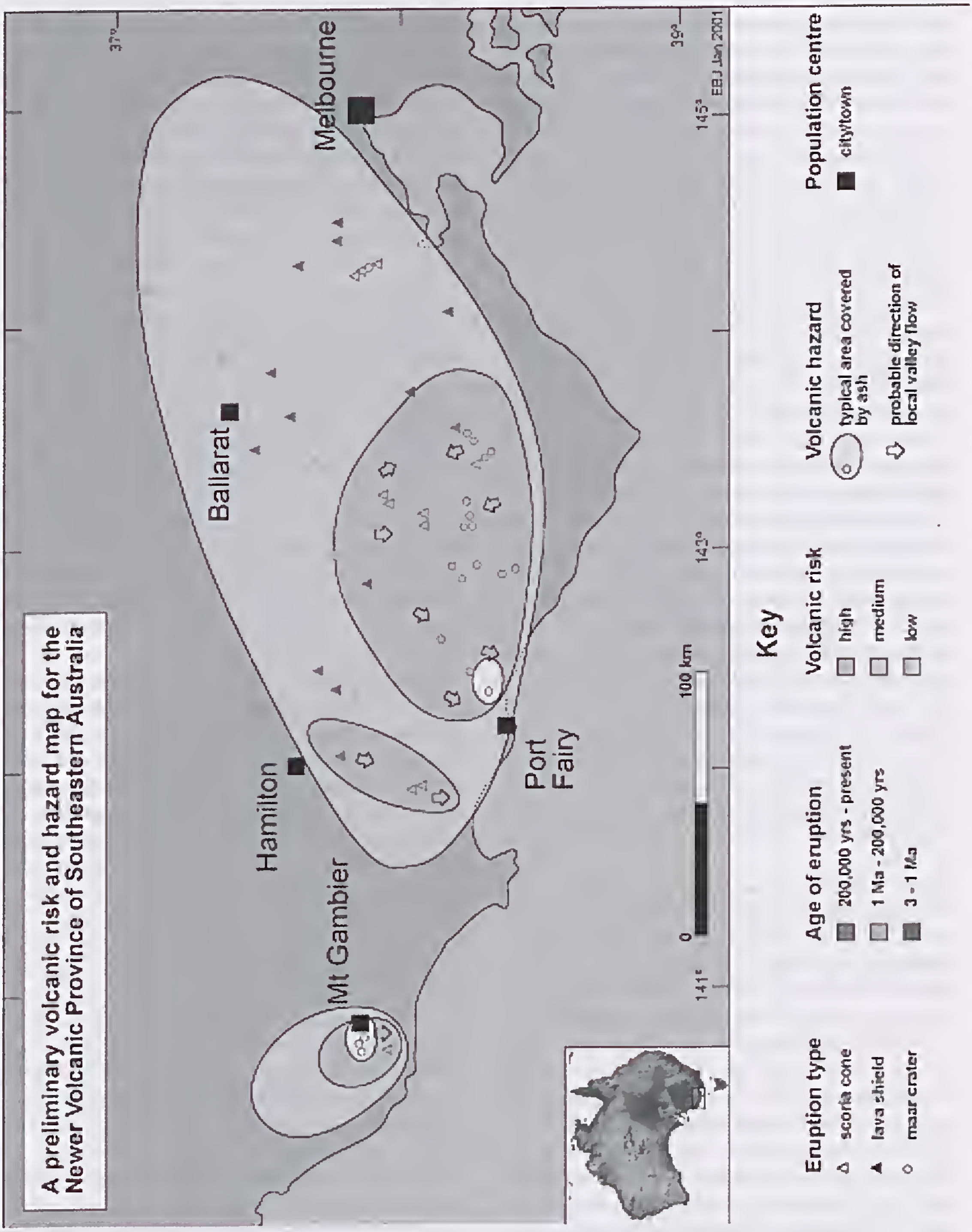

Fig. 2. Mapping of eruption types and ages with an indication of volcanic risk and hazard for the Newer Volcanic Province (Joyce 2001a).

nisable by their characteristic irregular stony surfaces, thin soils and woodland cover. These young lava flows have a shallow, brown to black clay soil through which boulders protrude on the slopes and in depressions. Basalt outcrops occur on the rises. The stony rise flows form extensive areas around individual volcanoes (e.g. Mt Eccles, Mt Napier, Mt Rouse), spreading radially as a series of lobes which overlap to build up a sheet of lava. The outbreak of tongues of liquid lava from inside the lobes and the collapse of the original surface over the evacuated area formed the irregular hummocks, ridges and sinuous or basin-like depressions of the stony rises.

Around Mount Porndon there are extensive plateau areas, with irregular collapsed areas further from the vent and distinct lobes at the outermost edge of the lava field, where the flows run out on to the floor of Lake Corangamite. K–Ar and radiocarbon dates indicate ages of less than 1 Ma for stony rise flows, and many eruptions are less than a few hundred thousand years old (Joyce 1999).

Most flows on the plains are thin, often from 2 to 10 m, and in detail consist of individual units as little as 0.5–1 m thick. Valley flows are often mappable for long distances, for example the Harman Valley flow from Mount Napier extended 20 km (Ollier & Joyce, 1973) and a valley flow from Mount Eccles travelled 50 km. Valley flows can be up to 100 m or more thick, and often composed of several distinct flows. The somewhat older subdued stony rise flows from Mount Rouse, dated at about 300,000 years, followed pre-existing valleys for 60 km to the coast (Sutalo & Joyce 2004). In each case the lava remained fluid by flowing within lava tubes in the interior of the flows.

Lava tubes or tunnels, known locally as lava caves, are a major feature of the NVP (Webb, Joyce & Stevens 1993) and the caves of the Byaduk area in the flows from Mt Napier, and the caves of the nearby Mt Eccles complex, are features of international importance (Ollier & Brown 1965, Joyce & Webb 1993).

Maar craters formed by phreatic eruptions are concentrated along the Colac-Camperdown-Warrnambool line, following the axis of the underlying Tertiary Otway Basin and reflecting the presence of groundwater in limestone aquifers at depth. A possible east-west structural control, related to the uplift of the Otway Range to the south, is shown by east-west fault scarps. The offshore volcano of Lady Julia Percy Island (Edwards et al. 2004) and the volcanoes forming the major headlands southwest of Portland, lie near the same boundary.

Volcanic ash (tephra) is not extensive in the NVP. Ash deposits, locally known as tuff or “sandstone” or sometimes “wombat”, are common in the Colac–Camperdown-Warrnambool region, coming from the maar volcanoes such as Bullenmerri and Gnotuk. Ash may extend downwind (east) from maar vents for up to 8 or 10 km, as at Tower Hill, some 33,000 years old, near Warrnambool (Sherwood 2004). Evidence from modern volcanoes elsewhere suggests thin but extensive ash deposits may also have been associated with scoria cone eruption (Blong 1989); these have presumably now weathered to soil mantles.

Crater lakes are well developed in the maars of the Colac–Camperdown area, and are commonly brackish to saline, for example Lake Keilambete, and Bullenmerri and Gnotuk (Ollier & Joyce 1973), although a few are freshwater, for example Lake Purrumbete. Studies of palaeolake level and salinity (Jones et al. 2001) ostracods (De Deckker 1982) and especially of pollen (D’Costa et al. 1989; Harle et al. 2002), have provided dating and elucidation of crater-lake histories. Tower Hill has shallow lakes which dry out at times but later reform. Several other crater lakes have become permanently dry in the 20th century, for example Lake Wangoom and Lake Terang. Lake Surprise at Mt Eccles is an unusual elongate crater lake.

The effects of basalt flows on drainage systems include the displacement of streams laterally, the ponding of streams against flow edges (e.g. Buckley’s Swamp northeast of Mt Napier), and the formation of lakes, swamps and disordered drainage on the flows themselves. In some cases, for example around Geelong, and along the course of the Curdies River south of Mount Porndon, lateral stream valleys have themselves been filled with further lava, forming further lateral streams. On much of the Plains, the low relief and continuing volcanic activity has allowed only shallow and poorly integrated drainage systems to develop, except for the major incised valleys of the Moorabool–Barwon system near Geelong, in part due to tectonic uplift, and the Hopkins – Mt Emu Creek river systems near Warrnambool and the coast; the latter, with their terraces and floodplains, are the only major drainage lines to cross the centre of the Plains and reach the coast.

Mt Clay (189 m high) is a large tuff volcano which sits on an uplifted block of Tertiary sediments northwest of Portland (Boutakoff 1963). The Staughtons Hill volcanic complex, south of Terang, consists of a maar, several broad scoria mounds and a small, spatter-rimmed crater, sitting on a block of Tertiary sediments elevated some 60 m and now marked by solutional sinkholes (Joyce 1975). The uplift probably occurred at about the same time as the volcanic eruption.

Little seismic activity is on record for the Western Plains over the past 100 years (Gibson et al. 1981) since the major Warrnambool earthquakes of 1903 and the offshore Kingston/Beachport (South Australia) earthquake of 1897.

Mt Gambier subprovince

Separated by some 50 km from the nearest volcanoes of the Western Plains are the young volcanoes of Mt Gambier and Mt Schank (Sheard 1978, 1983). Other earlier eruption points lie on a fault-bounded block to the northwest (Fig. 1). These volcanoes overlie the Tertiary Gambier Basin, with similar subsurface geology and depositional and tectonic history to that of the Otway Basin which underlies the Western Plains of Victoria.

Domal uplift and faulting is associated in South Australia with the Mt Gambier volcanic complex, and also found in areas to the north and northwest (Joyce 1992).

The Western Uplands subprovince

The Western Uplands is an elevated region of Palaeozoic sedimentary rock and granite which extends westwards from a line running due north from Melbourne. The eruption of over 250 scoria and lava volcanoes produced valley flows and small lava plains on a previously uplifted and dissected upland (see Joyce et al. 2003). The flows filled valleys at least as deep as the present valleys, and the thickness of the lava, often more than 100 m, allowed slow cooling and the development of columnar jointing, exemplified for example at Barfold Gorge, and the Devil's Kitchen near Linton. In places continued eruption completely buried the original dissected topography to give small lava plains, for example in the Ballarat–Creswick area (Taylor et al. 2000). The largest volcano in the Uplands is Mt Kooroocheang, (also known as Mt Smeaton), north of Creswick, which rises 200 m above the plain to an elevation above sea level of 676 m. Mt Warrenheip and Mt Buninyong are large young cones near Ballarat.

The valley-filling lavas preserved underlying alluvium as "deep leads". The Campaspe lava flow is over 85 km long, making it possibly the longest flow in Victoria (Coceani 1999). Some deep leads contained gold, and were extensively mined in the 19th century. The mining records have allowed reconstruction of the pre-eruption drainage patterns, which are in general very similar to the present stream systems (Taylor & Gentle 2002).

Post-eruption incision at the edges of valley flows has formed deep gorges flanked by plateaus, and in places twin lateral streams have developed, such as Goodmans Creek and Pyrites Creek to the north of Bacchus Marsh, which lie on each side of the 3.48 Ma Mt Bullengarook flow, which now forms a plateau. The Guildford Plateau, southwest of Castlemaine, is another remnant of a flow with incised lateral streams. Waterfalls often develop on the edge of lava plateaus, for example Trentham Falls, Lal Lal Falls, and Turpins and Mitchells falls (near Barfold).

Near Bacchus Marsh, at the eastern margin of the Western Uplands, intermittent movement on the Rowsley Fault has produced a scarp from 90 to 270 m high and caused strong rejuvenation of the Lerderderg and Werribee rivers and Parwan Creek. This incision produced spectacular gorges in the resistant Palaeozoic sediments and granites upstream, and wide valleys in soft Tertiary sediments underlying Newer Volcanic lava flows along Parwan Creek and the lower course of the Werribee River. Lava flows dated at 4 Ma are folded monoclinally across the fault (Joyce 1975), and younger flows are warped on the nearby Lovely Banks Monocline, north of Geelong, suggesting that movement began in the late Pliocene, and probably continued into the Quaternary.

Earthquakes are associated with the Rowsley Fault, for example the ML 4.7 Balliang earthquake of 2nd December 1977. Another concentration of earthquake activity in the Western Uplands extends from Bendigo southwest towards Ballarat. Overall however, the Western Uplands area is seismically much quieter than the eastern parts of Victoria.

The Eastern Uplands subprovince

Several small areas in the Uplands of Eastern Victoria had been recognised as part of the NVP. The Morass Creek Volcanics of Hills (1938) were later dated and renamed the Uplands Province by Wellman (1974). To the north of Benambra erosional remnants of several flows extend north-south along valleys for at least 20 km and this area has now been redescribed and further dated by Sutherland, Graham & Zwingmann (2004).

ERUPTION RISK

If activity in the NVP had been regularly spaced over time, simple arithmetic (400 volcanoes in 5 Ma) would suggest there would have been an eruption every 12,500 years. The most recent eruption which has been dated is Mt Gambier, at 4000-4300 B.P. (Blackburn et al. 1982), so on that basis we are well within the possible period for future activity.

Individual lava flows have been dated by K/Ar, radiocarbon, and other isotopic techniques. A more detailed chronosequence of lava flows, cones and craters can be built up from observed changes in landforms, drainage, soil and regolith, using field mapping, air photos and satellite imagery, and new airborne geophysical imagery (Joyce 1999). Such work is helping assign ages to otherwise undated flows, and we can see cycles of activity through time, notably a period of more concentrated activity in the late Quaternary in far Western Victoria (Joyce 2001a). Perhaps a dozen volcanoes may have erupted within the last 20,000 to 30,000 years - this would be an eruption every 2,000 years or so. However if eruptions were in clusters, as seems likely, there may have been somewhat longer periods between each cluster.

Future eruption

Australian volcanologists agree that further eruption is possible (Blong 1989), and may well be overdue. A future eruption would not be the renewal of activity at an existing volcano, but the initiation of a new volcano. The pattern of age distribution in the NVP can be used to suggest where a future eruption is most likely (Fig. 2).

Little warning of an eruption would be expected. Minor seismic activity with small earthquakes might precede the eruption by some weeks, and there could also be minor uplift or subsidence of the ground surface, and perhaps changes in ground temperature, and the exhalation of volcanic gases and steam.

The types of eruption to be expected are:

- maar crater formation with ash falls for several kilometres downwind i.e. to the east;
- cinder/scoria cone formation by fire-fountaining; and
- lava shield building and associated long valley flows.

These three types may occur separately, or in combination. For example an initial maar eruption may be followed by cone building within the maar crater (Tower Hill), or a series of lava flows and the building of a lava shield may be followed by final scoria cone formation (Mt Napier).

Activity might last for weeks or months, or for some years. If eruptions are clustered, further volcanoes, perhaps of a different type, may form near the initial eruption site, thus affecting a wider area for a longer period. Fumarolic activity and minor gas and ash eruption may continue for many years after the end of the main eruption.

Maar activity would provide particular problems from ashfall if upwind of a town or one of the major cities of the area, such as Melbourne or Ballarat. Lava flows would follow the general slope and move down pre-existing valleys (Fig. 2). Hazard impacts would include property and infrastructure damage by lava and ash fall; the effects of ash fall on people, farm animals and crops; water pollution and stream changes; grass and forest fires; and earthquakes and ground deformation. Emergency management would be concerned with evacuation planning, diversion or control of flows, removal of ash and scoria, control of fires and floods, and the repair and rebuilding of infrastructure, especially roads and bridges (see discussion in Blong 1984). A risk and hazard map (such as Joyce 2003) can suggest where a future eruption might occur (Fig. 2). To allow planning for preparedness and mitigation, eruption scenarios should be developed and publicised. Public education will be necessary, both within the local community, and for planners within local government and emergency organisations (Joyce 2001b).

Future studies

Intraplate volcanism is widespread around the world, but a major problem is explaining why such activity occurs. The detailed information now available for the NVP makes it an ideal region to attempt to solve this problem (see discussion in Price et al. 2003, Cas 1989, Johnson 1989).

The geological heritage values of the NVP are well documented (Joyce & King 1980, Joyce & Webb 1993) and can provide an important way of promoting hazard and risk concepts to the local inhabitants (Joyce 2001b). Recent threats to this heritage, which is of national and international significance, include quarrying (Mt Leura), housing development (Lake Gnotuk, Mt Aitken) and landform destruction (Byaduk lava flow from Mt Napier). However new reserves have been developed at Mt Elephant and Mt Rouse volcanoes, and there have been recent improvements to interpretation at other sites (Mt Leura, Byaduk flow), and the development of the Volcanic Trail, a recent National Trust landscape study of the Stony Rises, and the establishment of the Volcano Discovery Centre at Penshurst, near Mt Rouse volcano, are all promising developments. In the future the integration of volcanic research, local history study, and heritage interpretation could be the key to developing a greater awareness of volcanic risk and hazard in the Newer Volcanic Province southeastern Australia.

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GEOLOGY AND GEOMORPHOLOGY OF THE LADY JULIA PERCY ISLAND VOLCANO, A LATE MIOCENE SUBMARINE AND SUBAERIAL VOLCANO OFF THE COAST OF VICTORIA, AUSTRALIA.

J. Edwards[1], R.A. Cayley[2]* & E. B. Joyce[3]

[1]39 Hansen Street, West Footscray, Victoria 3012
[2]Geological Survey of Victoria, PO Box 4440 Melbourne, Victoria 3001
[3]School of Earth Sciences, The University of Melbourne, Victoria 3010
*Author for correspondence; email: Ross.Cayley@dpi.vic.gov.au

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Lady Julia Percy Island is an intraplate, offshore volcano near Port Fairy in southwestern Victoria. The island is about seven million years old. Early volcanic activity formed a subaqueous edifice of pillow lava and associated hyaloclastite, above which lies a pahoehoe flow. Subsequent subaerial eruptions produced pyroclastic flows, plains-type lava flows and scoria deposits. Lava flow features which are the best preserved examples of their type in Victoria include pillows with multiple crusts and hollow tubes, hyaloclastite, pahoehoe flows with ropy and spongy lava textures and gas-formed canals. Extensive erosion has exposed much of the internal structure of the volcano, including a volcanic vent at Pinnacle Point. The steep and near-continuous coastal cliffs preserve numerous different ancient sea level markers as wave-cut platforms, sea caves, a stranded boulder beach, and the transition from subaqueous to subaerial lava textures. Ancient wave-cut platforms also occur beneath present sea level. Bulk rock major and minor element variation indicate that all the lavas of the island belong to the same source, are not highly fractionated, and ascended rapidly through the crust to the surface. They have alkaline compositions that closely resemble that of typical ocean island basalt.

Key words: Lady Julia Percy Island, Newer Volcanics, radiometric dating, Miocene, submarine volcanism, pillow lava, hyaloclastite, geochemistry, volcanic textures, palaeo-sealevels, neotectonics

LADY Julia Percy Island lies approximately 22km southwest of Port Fairy, 4km off the coast of southwestern Victoria, Australia (Fig. 1). The ocean setting of this volcano provides excellent rock exposures as coastal cliffs, which expose the internal structure of the volcano and one of its vents. Continued rapid erosion maintains clean cliff faces, which reveal primary volcanic features rarely well exposed in the rock record. In particular, the island provides some of the best insights available in Australia into the processes leading to the formation of pillow lavas and hyaloclastite, pyroclastic flows and pahoehoe lavas. The detailed description of the characteristics of the myriad of well preserved diagnostic primary volcanic features at Lady Julia Percy Island presented here—particularly the pillow lavas and associated hyaloclastite deposits—will aid in the recognition and interpretation of similar features in the local Recent and ancient rock records.

This paper describes the geology of the island, presents new K/Ar radiometric age data, reconstructs a possible eruption history, and also documents geomorphological features related to past sea levels. A brief social history of the island is also presented.

HISTORY

Aboriginal history

The Gunditjmara people of southwestern Victoria referred to Lady Julia Percy Island as Deen Maar (Dawson 1881) or Dhinmar (Matthew 1904), and considered it to have spiritual significance. Their dead were wrapped in grass and buried with their heads directed towards the island so that their spirits could be lifted to the clouds (Dawson 1881) or spirited to the island to await reincarnation (Matthew 1904). The discovery of sharp chert blades and possible grinding tools (Gill & West 1971) suggests that aboriginal people visited the island, presumably either by braving the rough sea and dangerous landing in locally made canoes, or by walking from the main-

Fig. 1. Locality map.

land during periods of lower sea level. Local indigenous ethnohistory is documented by Debney & Cekalovic (2001).

European discovery

In 1800 Lieutenant James Grant, commander of the surveying vessel H.M. Lady Nelson, became the first European explorer to sail through the strait between New Holland and Van Dieman's Land. On December 6th he noted a "...large, inaccessible island off the S.E. coast of New Holland...". This he named Lady Julian's Island, in honour of Lady Julian Peircy. However, the name recorded on his chart is Lady Julia Percy's Is, the name adopted in 1802 by Matthew Flinders who produced a more accurate chart of Terra Australis. Also in 1802, Nicholas Baudin, commander of the French ship 'Le Geographe', (re)discovered "a small island off Cape Reamur" (Grant's Lady Julian's Island) which he named Isle Fourcroy (Learmonth 1934). In 1836 Major Mitchell sighted a large island from the Portland Bay district, and concluded it was "one of the Lady Julia Percy's Isles" (Learmonth 1934). Modern maps refer to the island as Lady Julia Percy Island (Department of Crown Lands and Survey 1982). In 1840 a trigonometrical station was established on the island as the western point in a survey of the Victorian coast between Melbourne and the Glenelg River, followed by a second station in 1863 (McCoy Society 1936).

The island's resources have been exploited in various ways. As early as 1798 the Chinese were slaughtering seals off several Victorian islands, including Lady Julia Percy Island, and by the mid-1800s the seal colonies had all but disappeared (Learmonth 1934). Prior to 1876 a small cave deposit of guano at Seal Bay (then referred to as Scalers Cove) was mined, and in 1868 rabbits and guinea fowl were introduced as a food source for shipwrecked sailors. An emergency station for castaways was also established. Between 1879 and 1908 various applicants were granted grazing licences for pigs, cattle and horses on the island (McCoy Society 1936). Now protected as a fauna and flora reserve, the island is listed on the Register of National Estates, and the seal colony has re-established to become one of Victoria's largest.

Previous work

Pioneer work on Lady Julia Percy Island was carried out during the McCoy Society expedition of 1935–1936. The island was surveyed, and the geology and petrology of the island rocks briefly described (McCoy Society 1936). Two Australites were found on the island. Several ecological expeditions visited the island between 1948–1963 (Pescott 1965). The Geological Society of Australia lists the island as a geological monument of national significance (King 1988), although no detailed geological work was undertaken until 1994 (Edwards 1994).

REGIONAL SETTING

Lady Julia Percy Island lies within the Tyrendarra Embayment of the Otway Basin—a type example of a passive, continental margin basin (Falvey 1974), formed by rifting between Australia and Antarctica (Weissel & Hayes 1972). Extensive Cainozoic volcanism in this region forms the Western District Volcanic Plain of southwestern Victoria (Hills 1940), and represents intraplate activity immediately adjacent to the extensional continental margin.

Literature documenting the characteristics of east Australian volcanism has been well summarised and discussed by Johnson (1989) and Price (et al. 2003). In Victoria, Cainozoic volcanics are subdivided on the basis of both geographic distribution and age. Lady Julia Percy Island lies within the Western Dis-

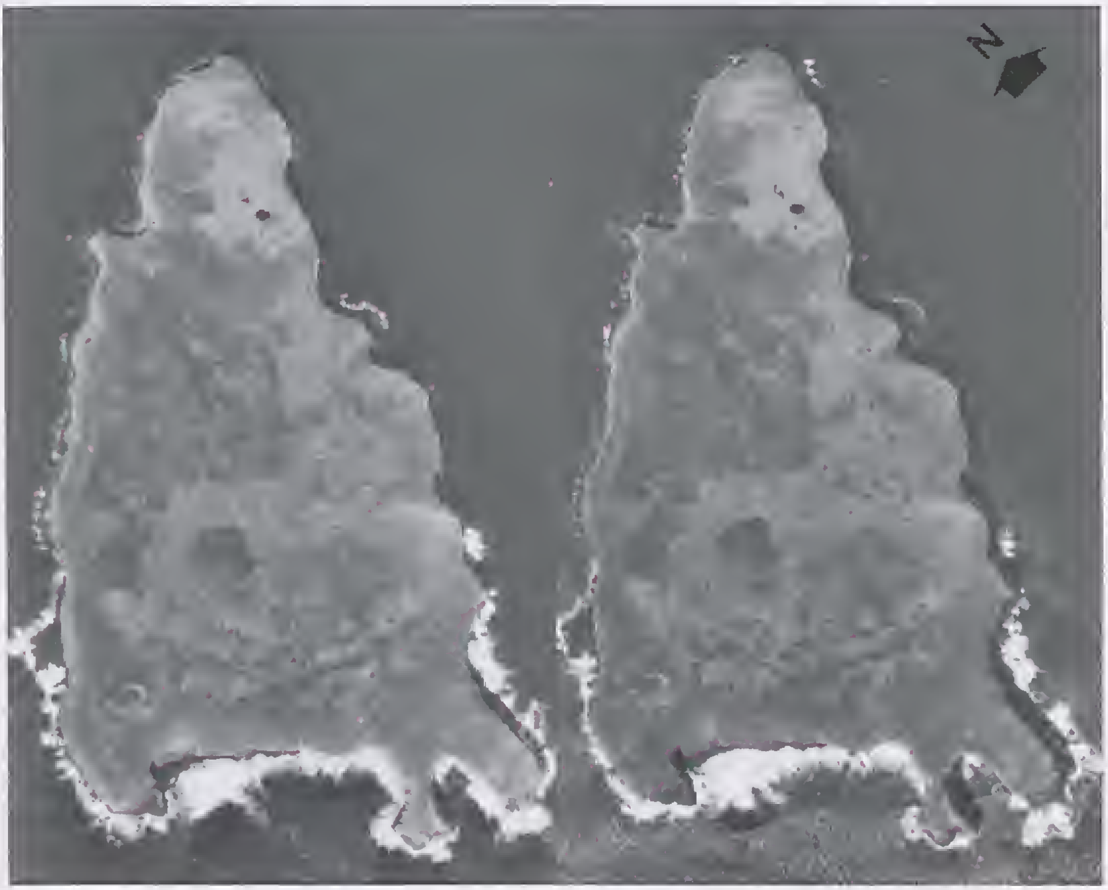


Fig. 2. Stereographic air-photos, Lady Julia Percy Island. The remnants of a vent are exposed in the cliffs of the goose-necked promontory of Pinnacle Point (bottom-right), the highest point on the island at 46m. This point is separated from Thunder Point (bottom-right) by Horseshoe Bay, a deeply-incised cove. The prominent palaeo-wave-cut McCoy Platform (bottom-left) lies just west of Seal Bay. Dinghy Cove, the usual access to the flat plateau on the island, is the sheltered bay at top-left.

trict Province (Price et al. 2003) and is amongst the southernmost Newer Volcanic eruption points in western Victoria. The Victorian Newer Volcanic series, together with the western lava fields of northern Queensland, are the youngest and most extensive lavas in Australia (Nicholls & Joyce 1989). In Victoria they are mostly plains basalt lavas which are predominantly subalkaline to mildly alkaline, and include olivine basalt and minor amounts of tholeiite, basanite, hawaiite and olivine nephelinite (Irving & Green 1976).

The most significant subaqueous volcanic deposits of the province include pillow lava which formed in a lake at Exford South (Condon 1951), and exposures of pillow lava and hyaloclastite at Lady Julia Percy Island. The Newer Volcanic province as a whole has been active since the Late Miocene (Aziz-Ur-Rahman & McDougall 1972), and several eruptions have occurred since Aboriginal occupation. The most recent dated event is 4900 years ago (thermoluminescence age obtained for baked sand beneath lava at Mount Schank; Smith & Prescott 1987).

PHYSIOGRAPHY

Lady Julia Percy Island represents the eroded remains of an offshore, volcanic edifice that rests upon Miocene Port Campbell Limestone. Airborne magnetic data (Geological Survey of Victoria 1999) show that this volcanic sequence is not, and has never been, joined to the mainland by a lava flow.

The island's surface is essentially a flat plateau covering approximately 129ha (Norman et al. 1980). It rises gently towards the southwest, from an elevation of about 30m at Dinghy Cove, to 46m on the remnant of a small volcanic cone at Pinnacle Point. The top of the plateau reflects the upper surface of essentially flat-lying lava flows. A slight (<1m high) rise just north of, and parallel to, the 35m contour represents the flow edge of the youngest lava flow (Fig. 2). Bathymetric data (Fig. 3) suggests that the island once covered an area at least twice as large as present, but has been significantly shortened from the south and southwest by wave erosion.

There is no permanent fresh water on the island. Rainwater collects in several small, shallow ephemeral swamps and pours over the cliffs into the sea, or percolates through joints in the upper lava flows to emerge as springs in the cliff faces. The most prominent spring, The Drip, trickles across the entrances of Fern and Seal caves at the back of Seal Bay.

Regolith

The plateau soils of Lady Julia Percy Island have been described by Edmonds (McCoy Society 1936). The acidic (pH 4.8–6.7) loam soil is generally less than 500 mm deep and contains volcanic rock fragments and limonitic pisolites. It is mostly derived from the *in situ* alteration of the upper lava flows. Basalt gravels occur towards the centre of the plateau. Two low-lying aeolian dunes along the southern edge of the plateau are composed of mafic mineral crystals derived exclusively from the lavas.

GEOLOGY

The Lady Julia Percy Island lavas are fine grained rocks with a groundmass of plagioclase, augite, olivine and accessory magnetite, with microphenocrysts of olivine and plagioclase. Edwards (1994) provides a detailed discussion of the petrography and geochemistry of these lavas, and selected total rock analyses are given in Appendix 1. Major element geochemistry shows that they are weakly fractionated alkali basalts that closely resemble typical OIB compositions. Such lavas are relatively rare in southwestern Victoria, as most alkaline Newer Volcanic rocks are basanitic scoria and pyroclastic deposits (Johnson 1989). Minor and trace element data indicate that the Lady Julia Percy Island lavas have not undergone significant amounts of crustal contamination, and have probably ascended rapidly through the crust to the surface. A lack of variation in the geochemistry between the lavas indicates that they probably shared a similar magma source. These lavas do contain anomalously high lead concentrations, but this is typical of many basaltic lavas and granitic rocks of western Victoria, and reflects a lead-enriched mantle source beneath the province (Hergt et al. 1991; White pers comm. 1994).

Lady Julia Percy Island preserves evidence of two distinct phases of volcanic activity (Figs 4 & 5):

- initial quiet effusion of basaltic lava which formed a subaqueous volcanic edifice, composed predominantly of pillow lava and hyaloclastite, capped by a thin subaerial pahoehoe flow, and
- later subaerially erupted pyroclastic flows, plains-type lava flows, scoria and vitric ash deposits.

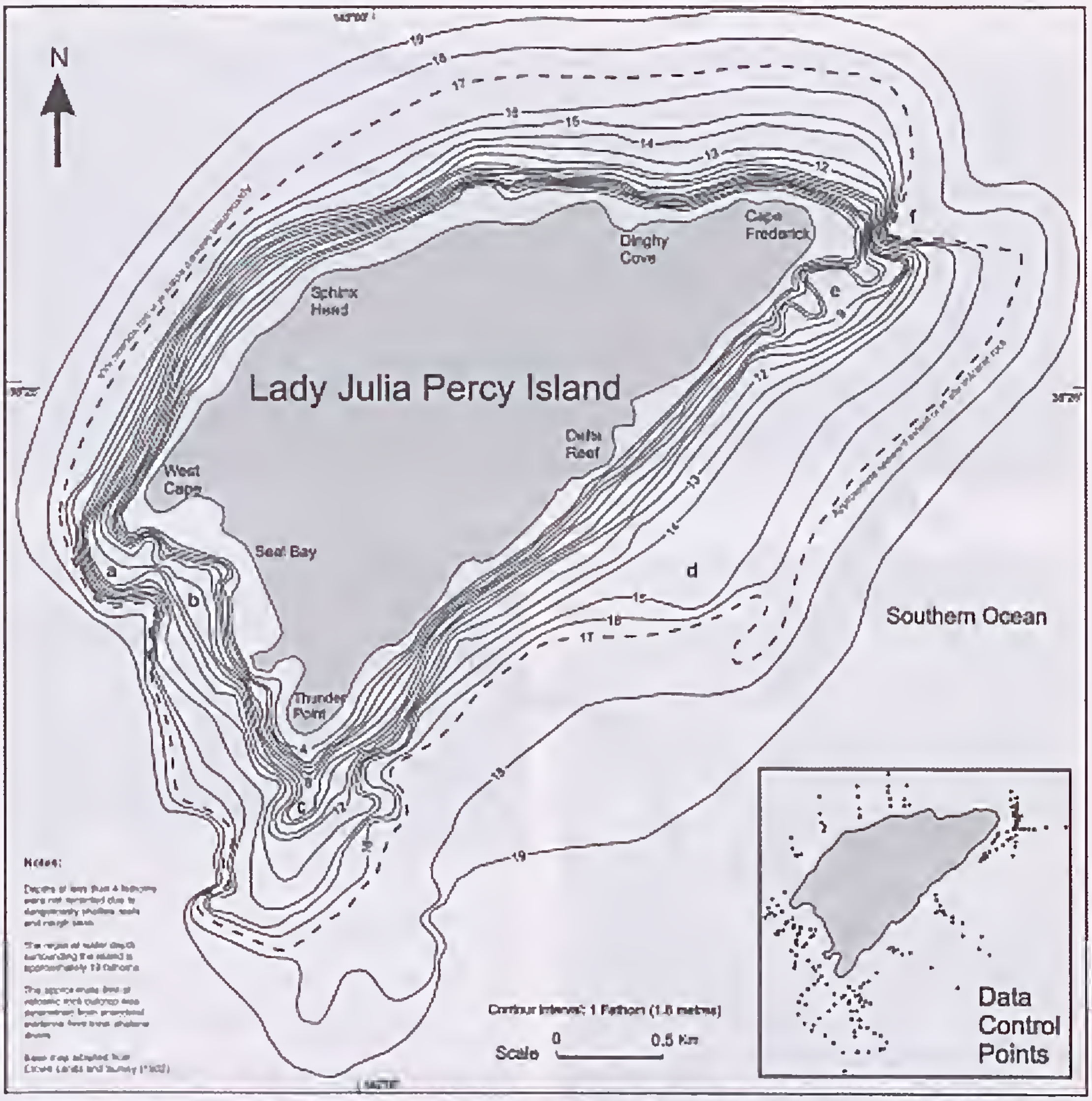


Fig 3 This bathymetric map highlights the formation of the present Lady Julia Percy Island due to differential modification of the original volcanic delta. The northern edge of the seamount rises consistently and moderately steeply from the sea floor. In contrast the southern edge has been more greatly modified by prevailing southwesterly weather systems. Geomorphic features near West Cape (a), Seal Bay (b), Thunder Point (c) and Delta Reef (d) are interpreted to be submerged wave-cut platforms. The submerged bench and steep slope east of Cape Frederick (e and f) are more sheltered and may therefore be primary volcanic features.

These two volcanic episodes were sourced from different vents, and radiometric dating presented below shows that they occurred approximately 1.6 million years apart.

First phase of volcanism

Initial volcanism produced a subaqueous volcanic delta composed predominantly of basaltic pillow lava with associated hyaloclastite and an overlying subaerial pahoehoe flow. Only a small portion of the original seamount remains as Lady Julia Percy Island, but the exposed volcanic features are among the best preserved in Australia.

Pillow lavas. Today the pillow lavas extend from the sea floor to 5m above sea level in the southwest, to a maximum of 15m above sea level at Dinghy Cove.

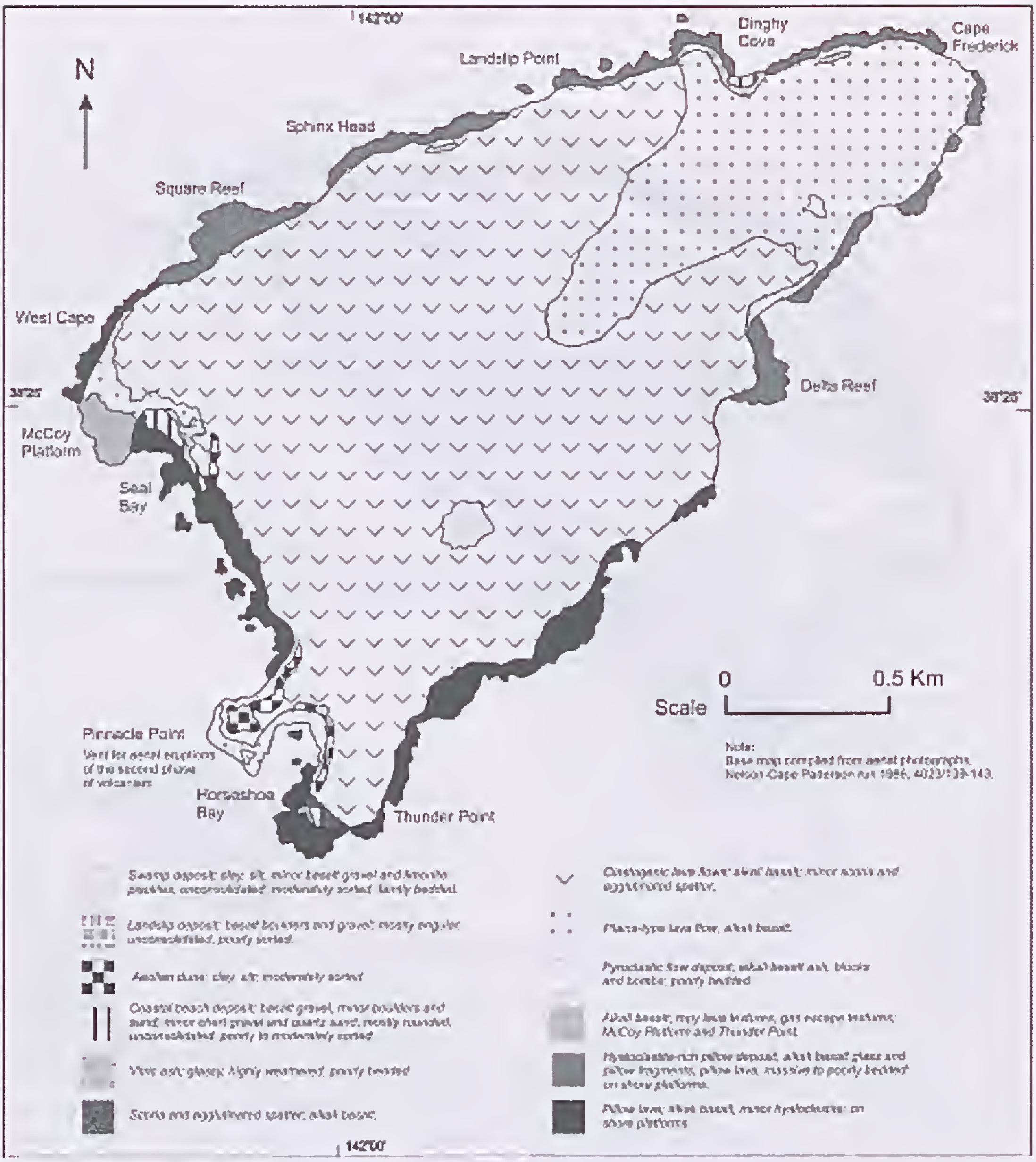


Fig. 4. Geology of Lady Julia Percy Island.

South of Square Reef and Delta Reef the volcanic succession is comprised of an almost solid mass of interlocking pillows, while to the north, pillows are intimately associated with hyaloclastite (Fig. 6). Minor thinly bedded volcanic gravel also occurs between pillows at Seal Bay and McCoy Platform. At Pinnacle Point the deposit is intruded by the vent of younger subaerial eruptions.

The dip direction and amplitude of pillows is highly inconsistent. Subvertical pillows are exposed at Seal Bay and horizontal pillow masses form the surface of small shore platforms between Square Reef and Landslip Point. The majority of pillows however, dip to the north and northwest at 15°–30° (Fig. 5). This preserves the approximate angle and direction of the original flow front which grew from a

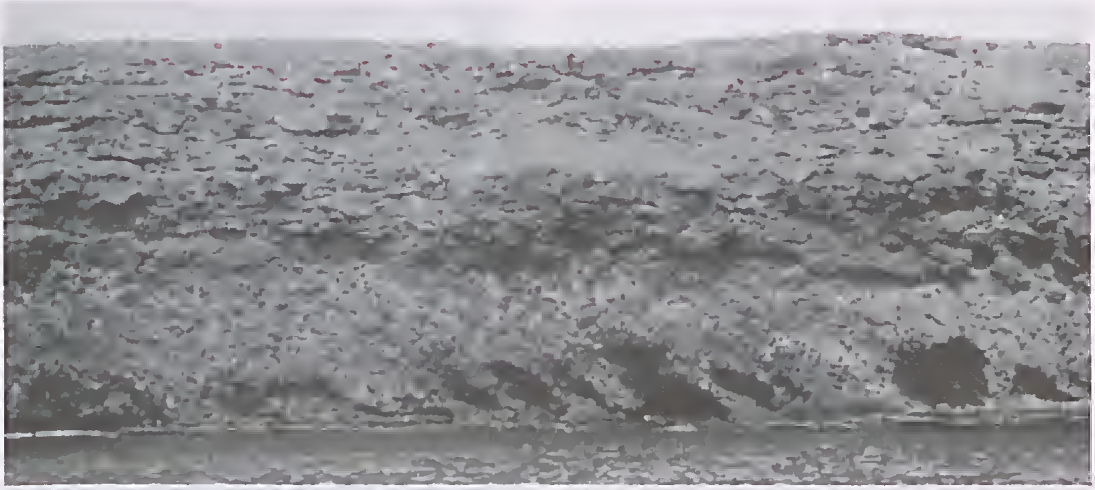


Fig. 5. NW view of the southern coastline between Delta Reef and Cape Frederick. North-dipping submarine pillow lavas and associated hyaloclastite deposits are capped by flat-lying subaerially-erupted plains-type lava flows.

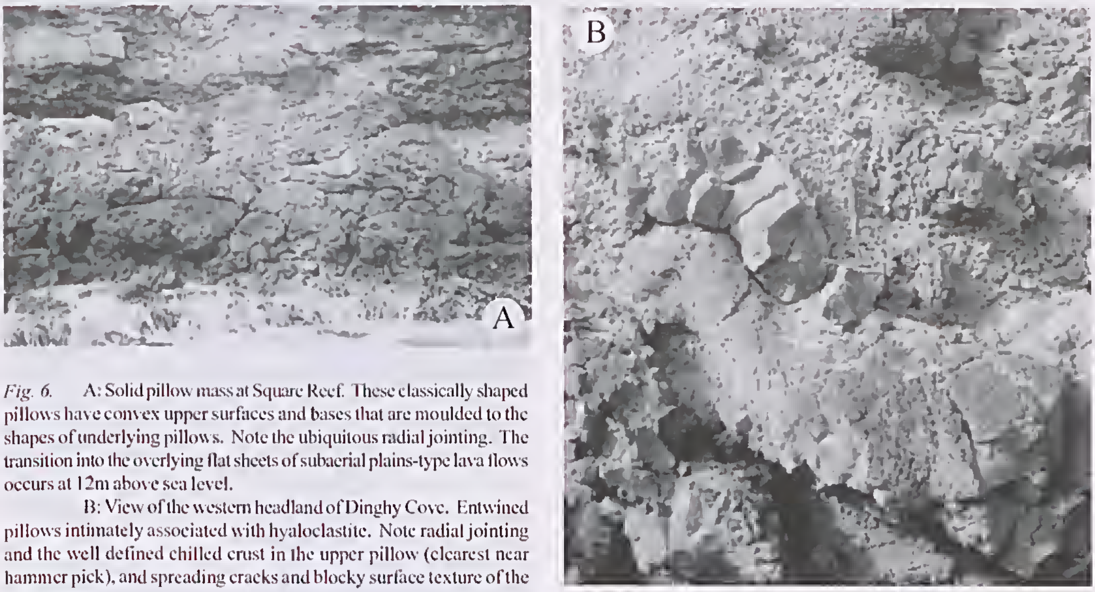


Fig. 6. A: Solid pillow mass at Square Reef. These classically shaped pillows have convex upper surfaces and bases that are moulded to the shapes of underlying pillows. Note the ubiquitous radial jointing. The transition into the overlying flat sheets of subaerial plains-type lava flows occurs at 12m above sea level.

B: View of the western headland of Dinghy Cove. Entwined pillows intimately associated with hyaloclastite. Note radial jointing and the well defined chilled crust in the upper pillow (clearest near hammer pick), and spreading cracks and blocky surface texture of the lower pillow.

submerged vent south of the island (see *Pahoehoe flow* for discussion on geopetal surfaces and tilting of island).

Pillow morphology is extremely varied. The true length of pillows is obscured by other pillows or hyaloclastite, but several at Cape Frederick can be traced for at least 40m. In plan, pillows are mostly sinuous and interlocking with neighbouring pillows (Fig. 6). They range from 200mm to approximately 1.5m in diameter, and in cross-section range from spherical to flattened ellipses. Most spherical pillows are completely surrounded by hyaloclastite which provided lateral support as they cooled (Snyder & Fraser 1963). Where individual pillows lie directly upon others they have convex upper surfaces, but their bases are moulded to the rounded surface of underlying pillows (Fig. 6), indicating that when emplaced they were sufficiently fluid to deform (Henderson 1953).

Most pillows are heavily jointed and cracked. Radial cooling joints are virtually ubiquitous. Narrow cracks (≤10mm) perpendicular to the long axis of a pillow formed as the pillows propagated forward. Other cracks in the chilled crust accommodated changes in the direction or dip of the slope over which the pillow flowed, forming in the same manner as crevasses in a moving glacier. Longitudinal and transverse spreading cracks are also common (Fig. 7). These are 20–50mm wide and up to 500mm long and probably formed by the stretching of pillow crusts as lava was continually forced into the pillow tube (Snyder & Fraser 1963; Yamagashi 1985). Many pillow surfaces also display a ropy lava texture, or the bread-crust texture of Krakatau-type volcanic bombs produced by the rapid cooling and subsequent shrinking of the pillow surface (Fuller 1932).

Many pillows are hollow and contain within them features that allude to the complex and varied nature of pillow formation. Inner pillow surfaces may be smooth and glassy, indicating quenching due to water invasion immediately following the evacuation of lava (Fuller 1931; Moore et al. 1973). Small inward-protruding ridges (≤20mm wide, ≤200mm long) parallel to spreading cracks in the outer surface of a pillow also have quenched textures, probably due to rapid chilling by water entering new cracks during pillow growth. Lava flow features within hollow pillows include stalactites, lava tongues and lava benches. Short (<20mm) irregularly shaped stalactites with sharp protrusions and small, drip-like bulbous ends formed after the main flow of lava through a pillow had ceased. Congealed lobate lava tongues (Fig. 8) represent the final flow of lava through a pillow tube after its lava source was exhausted or blocked, or revival of lava flow within an earlier formed pillow tube (Moore et al. 1973). Stacked pancake-like lava benches formed when several pulses of lava flowed through a pillow. These are good geopetal structures as their flat lower surfaces indicate the horizontal plane at the time of pillow formation (Waters 1960). All these features have unquenched surfaces suggesting that water did not invade these pillow tubes immediately after they were emptied of lava.

Small (≤5mm) spherical and sub-spherical vesicles are scattered throughout the pillow lava and may account for up to 5% of the volume of the rock. These are most common towards the upper, outer edge of each pillow, indicating that when pillows reached their resting place they were sufficiently fluid to allow gas bubbles to rise (Moore et al. 1973).

Individual pillows display graduated changes in petrographic, compositional and microscopic textural characteristics. These changes record a cooling gradient resulting from rapid quenching as the lava erupted into water (Kawachi & Pringle 1988).

Fig. 7. Longitudinal and transfer spreading cracks in a pillow lobe surrounded by hyaloclastite, western headland of Dinghy Cove.

Fig. 8. Congealed lava tongue overlying a lava bench in the hollow tube of a drained pillow lobe, western headland, Dinghy Cove. Note the tiny lava stalactites extending from the irregular surface of the roof above the lava tongue, and the hyaloclastite that completely encloses this particular pillow.

Changes in crystallinity, grain size, and the number of minerals present can be used to define three major concentric bands in each pillow:

- the outer glassy margin forms a shiny black crust (≤5mm thick) composed of basaltic glass with fine perlitic fractures characteristic of rapidly quenched lava (Carlisle 1963; Moore et al. 1973). A few euhedral plagioclase and olivine crystals are present, and probably represent crystals formed within the magma chamber prior to eruption–they lack reaction coronas or extensive corrosion. The degree of crystallinity increases gradually from about 20% at the outer pillow edge, inwards to 40% bordering the spherulitic zone (Fig. 9);
- the spherulitic zone (≤20mm thick) is transi-

tional between the pillow margin and the core of the pillow. It begins with the appearance of opaque acicular, or needle-shaped crystallites which gradually increase in number until the entire glass groundmass has been replaced. Many are concentrated around the edges of pre-existing crystals, particularly feldspar. They also commonly form small (≤0.02mm) spherulites and dendritic inclusions within feldspar grains and glass. Towards the centre of the spherulitic zone, feldspar begins to appear in the groundmass as tiny (≤0.25mm), curved and whispy crystals. Similar to the outer layer, plagioclase and olivine microphenocrysts are present. Small (2–3mm diameter) soft mineral cubes are probably palagonite (Fig. 9); and

- the pillow centre is a dark grey, fine-grained alkali basalt. It begins with the appearance of pyroxene, which accompanies olivine, plagioclase, augite and magnetite to form an aphanitic groundmass which supports occasional microphenocrysts (≈1mm) of olivine and plagioclase. Although the inner core is essentially crystalline, the groundmass locally contains up to 5% glass.

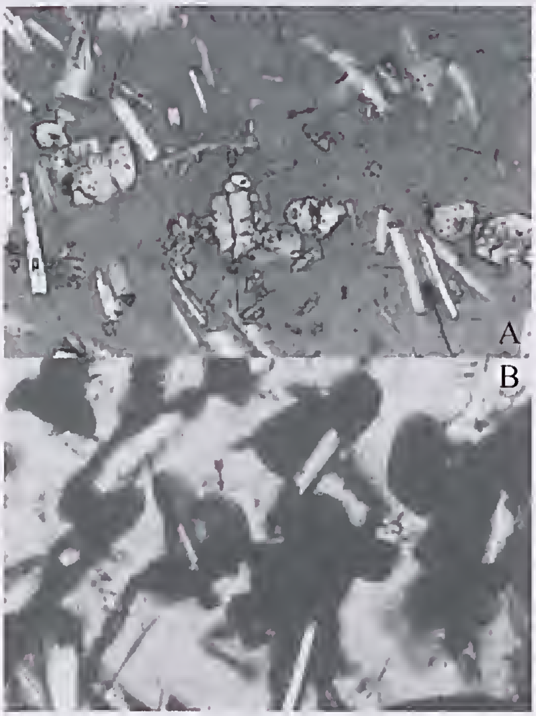


Fig. 9. A: Outer glassy margin of a pillow (Dinghy Cove). The basaltic glass (g) is altered to palagonite and contains well formed crystals of plagioclase (p) and olivine (o). Arrow indicates perlitic fractures. PPL; Field of view 20mm.

B: The spherulitic zone begins with the appearance of opaque crystallites, seen here to form dark spherulitic clusters (arrow) in the basaltic glass. Pale elongate crystals are plagioclase. PPL; Field of view 6.5mm.

Many pillows exposed in the cliffs of Lady Julia Percy Island display two sets of these concentric bands formed as a result of repeated quenching as water entered the inner tube of the pillow through cracks or joints after successive lava pulses (Moore et al. 1973; Snyder & Fraser 1963).

Hyaloclastite. Hyaloclastite is a submarine volcaniclastic sediment formed by the non-explosive quench fragmentation of chilled glassy outer pillow rims in cool water (McPhie et al. 1993). At Lady Julia Percy Island hyaloclastite occurs to the north of Square Reef and Cairn 2, but is best exposed in the cliffs around the headlands of Dinghy Cove where it forms a substantial proportion (≤30%) of the total volume of the subaqueous volcanic pile.

Hyaloclastite is composed of fragments of the glassy outer chilled margins of pillows with minor small (≤5mm), angular crystalline basalt fragments similar to pillow centres. Palagonite coats most fragments and forms the matrix of the deposit. Hyaloclastite is intimately associated with the pillows. The morphology of hyaloclastite fragments and the structure of the deposit as a whole are related to the distance from the source pillows from which fragments have been displaced.

Within 100mm of the edges of pillow lobes hyaloclastite is a massive, poorly sorted and grain supported (≤80%) deposit. Fragments range from coarse ash and lapilli to minor larger fragments (10–20mm diameter). Smaller fragments are highly angular, and characteristically display smooth, concave faces due to parting along conchoidal fractures. Larger fragments have highly irregular shapes and are often preserved in situ, close to–or partly attached to–the chilled margin of the pillow from which they were derived. Many display a jig-saw type fit with adjacent fragments. This suggests that as the hyaloclastite formed, it was covered quickly by subsequently formed pillows and protected from displacement or erosion. Displacement of fragments from their source pillow was probably mostly caused by the continued formation of hyaloclastite below, or the expansion of the pillow from which the fragments were formed. With greater distance from the pillow margins hyaloclastite becomes increasingly matrix supported (≤50%), and fragments become smaller and more rounded. The morphology of the distal fragments may have resulted from reworking and redeposition processes, or reflect the presence of perlitic fractures in

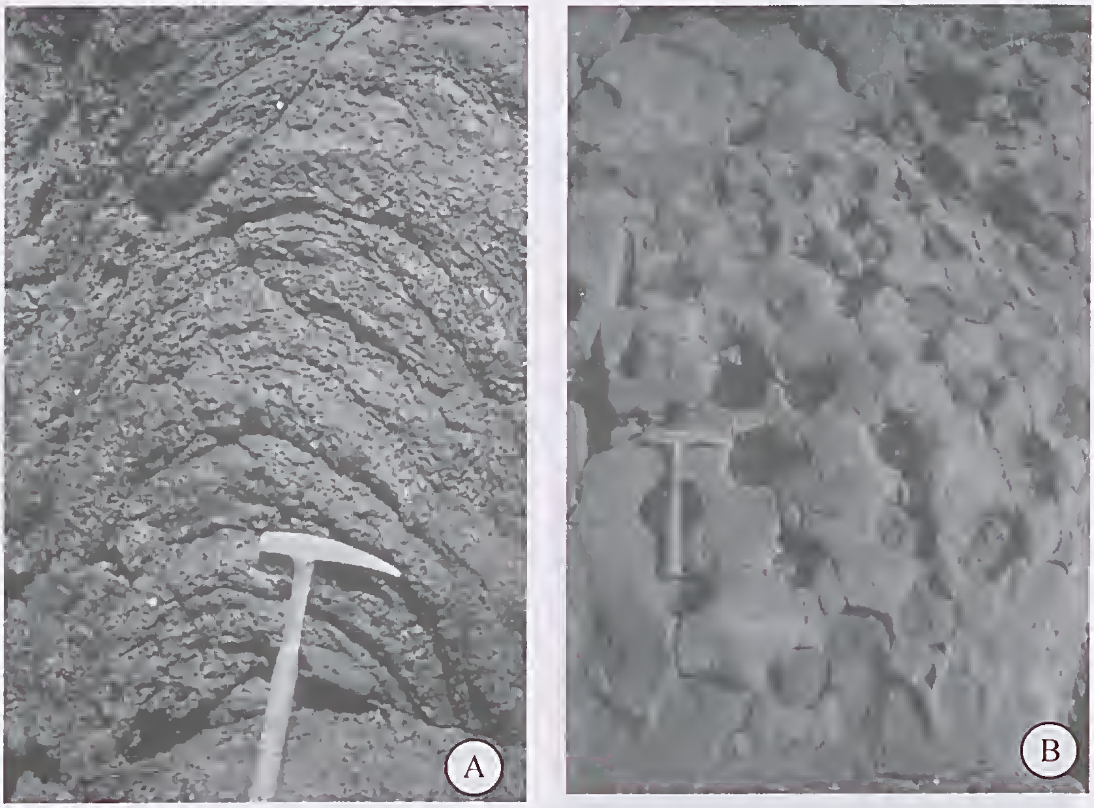


Fig. 10. Some features of the Pahoehoe lava flow, McCoy Platform. A: Ropy lava textures common to Hawaiian-type pahoehoe lavas and; B: Vertical pipe vesicles.

the basaltic glass from which they are derived.

In several places around the island hyaloclastite is bedded. High in cliffs west of Dinghy Cove inaccessible hyaloclastite beds dip at the same angle and direction as nearby pillows, but are truncated to the east by massive hyaloclastite. This bedding may represent redeposition by slumping shortly after formation (Smith & Batiza 1989). Elsewhere, hyaloclastite forms a bedded lapilli deposit. This deposit is thickest at Seal Bay (≤2m) where it is intimately associated with pillow lavas, enclosing several pillows and filling cracks in their surfaces. In places it has been compressed by overlying lava and squeezed upward into gaps between overlying pillows. Beds are up to 50mm thick, are well sorted and fine upwards, and indicate significant reworking and deposition, possibly by wave action in shallow water (Honnorez & Kirst 1975; Smith & Batiza 1989).

Pahoehoe flow. The subaqueous deposit grades into, and is capped by a single alkali basalt pahoehoe flow. This contact marks the transition from subaqueous to shallow water and subaerial volcanism, and therefore marks the approximate sea level at the time of eruption. The textural and morphological changes from pillows to pahoehoe resulted from a change in the environment into which the lava from the first eruptive phase flowed—from below sea level to close to, or above the sea surface—as the volcanic edifice grew. As such, there is no soil or obvious erosional features at this boundary. The upper flow lies directly upon friable and uncemented (therefore easily eroded) hyaloclastite that shows no evidence for redeposition and reworking, indicating that it was covered and protected shortly after it was formed.

The contact is quite irregular, often difficult to distinguish, and dips gently (0.3°) southeast, from about 15m (Dinghy Cove) to 3m (Thunder Point) above sea level. The flow ranges from 0.5m thick at Dinghy Cove where it overlies pillow lava and hyaloclastite, to 3m thick at Thunder Point where it fills a depression in the surface of the subaqueous deposit. The base of the flow is slightly glassy and marked by a thin parting (≈20mm thick) indicating rapid cooling. Geopetal surfaces–secondary carbonate deposits within gas voids in the flow–show that the island has tilted at least 4° to the southeast since their formation, suggesting the initial surface of this flow probably sloped to the north. This indicates that the flow probably originated from the same submerged vent that sourced the pillow magmas.

The flow is best exposed as the surface of McCoy Platform. Here its base conforms to the upward-convex shape of the underlying pillows. Volcanic features typical of Hawaiian-type lava flows not commonly seen in Victorian mainland lavas are spectacularly well preserved here (Fig 10). Ropy surface textures are common, and consist of numerous parallel corrugations which run across flow tongues, and are deformed convexly towards the direction of flow. In the centre of McCoy Platform numerous vertical pipe vesicles, up to 100mm in diameter, probably formed prior to solidification in a stationary lava pond which filled a hollow in the surface of the underlying pillow deposit.

The internal structure of the flow is well exposed at Thunder Point where it is comprises numerous ~300mm thick subhorizontal flows, each separated by a thin horizontal parting. Each flow is characterised by a well developed distributary tube system (Fig.11):

- the upper 10–20mm is a dense lava with minor spherical vesicles (1%), grading downward into a 50–100mm thick, highly vesiculated (50–60%) lava;
- the centre of each layer features small lava tubes with irregularly shaped, upward arched roofs and flat floors. The tubes are about 100–150mm high, up to 500mm wide, and some are wholly or partially infilled by secondary carbonate material. Tubes run parallel to each other along the centre of each flow, and are separated by thin walls of vesicular lava; and
- the floor of the lava tubes is 50–100mm thick and highly vesicular, grading downwards to a thin (10–20mm) dense lava base.

Each thin layer represents a pulse of highly gaseous lava. The highly irregular shape and rough, vesiculated walls of the openings in the pahoehoe flows indicate that they are gas blisters formed by coalescence of adjacent vesicles in the centre of each flow unit, which causes the flow to part. Concentric layers with differing vesicle size and abundance are caused by shearing as the lava flows after it has begun to cool and solidify (McPhie et al. 1993).

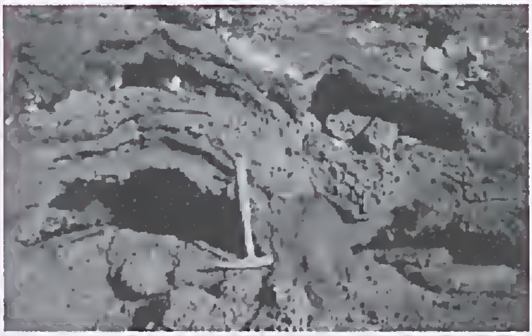


Fig. 11. Internal structure of pahoehoe flow, Thunder Point. Note the distributary tube system within each thin flow. The tube in the lower right corner has a false lava base and secondary carbonate has begun to fill the tube to the top left.

Lava globules. The pahoehoe flow is a fine grained crystalline lava composed mainly of plagioclase, olivine and pyroxene, and a minor amount of interstitial glass similar to, although slightly coarser than, the inner pillow lavas. However, a unique feature of this flow is numerous small (≈5mm) subrounded to rounded, irregular and ellipsoidal dark grey lava globules and globule aggregates (≤15mm), many of which contain a sub-spherical void or vesicle. These are scattered randomly throughout the less vesicular portions of the flow where they locally form up to 50%, although mostly less than 25%, of the lava. These globules represent a late stage melt that is slightly more fractionated than the general host rock (see analyses by Edwards 1994), and preserve a volcanic texture that has not been recorded elsewhere in the Victorian Newer Volcanic lava fields.

The globular textures are probably the result of a more volatile-rich residual magma formed during the low-pressure (near surface) crystallisation of the alkali basalt. They indicate that the magma experienced decompression during its ascent towards the surface, forming melt-separates and vesicles. The spherical globules at McCoy Platform are crystalline masses of radiating elongate (1–2mm) crystals of andesine, sanidine, augite, ilmenite, and minor olivine. The globule margins are sharp and clearly defined by a rim of small (0.1–0.2mm) plagioclase and augite crystals, which indicate that the host lava had essentially crystallised and stopped flowing prior to the introduction of the residual material which subsequently filled gas vesicles. Unlike the host rock the globules contain little olivine, an early formed mineral in these lavas, but a significant amount of late-crystallising ilmenite. The lack of typical hydrous, late crystallising minerals such as amphibole

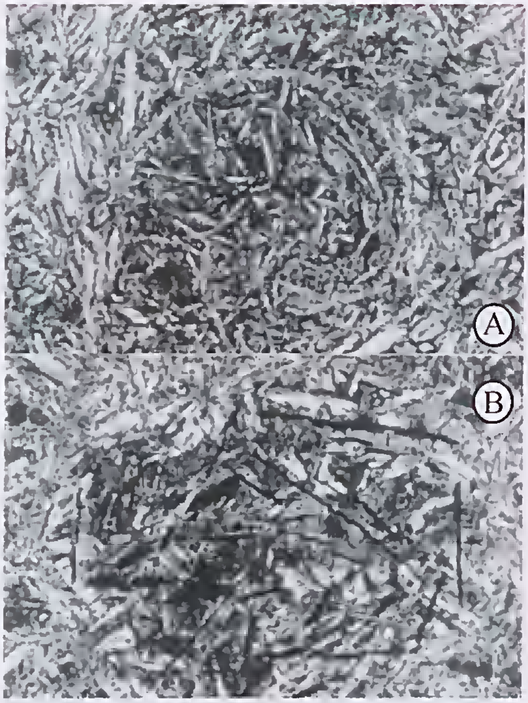
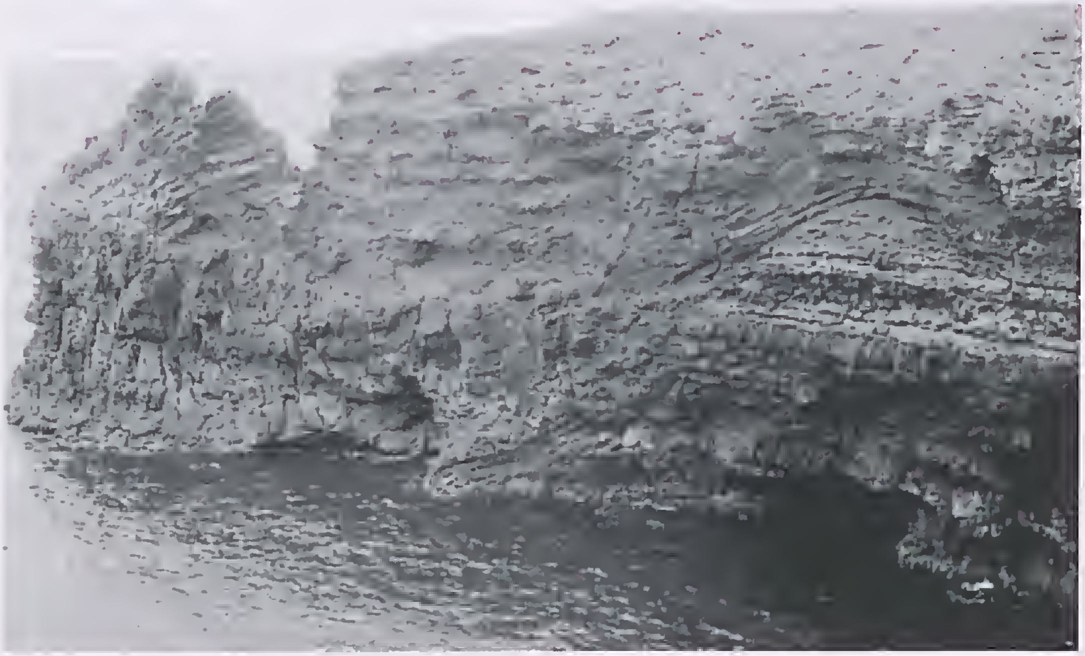


Fig. 12. Globules in the pahoehoe lava. A: Almost spherical globule with a well defined rim of plagioclase and augite crystals. Note the higher concentration of late-crystallising ilmenite within the globule. (Dinghy Cove) PPL; Field of view 40mm. B: Emulsion-like globule with elongated pyroxene (a) and ilmenite (i). Note the coarser grain size of the globule compared to that of the host lava. (McCoy Platform) Cross polars; Field of view 20mm.

suggests that the globule melt was not H_2O-rich, but never-the-less, the larger grain size of most globules relative to the host rock suggests that there was a significantly higher volatile concentration within the crystallising globule magma compared with the parent magma. Rapid crystallisation of such volatile-rich magma can explain the relatively coarse mineral grains and quench-like textures. In contrast, at Dinghy Cove globules form emulsion-like textures with interlocking crystal edges with the finer grained host rock. Internal foliation (crystals parallel to the globule boundaries) and curved plagioclase crystals indicate flow during crystallisation (Fig. 12). These textures demonstrate that the globules are primary volcanic features. They were formed from residual material that was present prior to the complete solidification of the host magma.

The second phase of volcanism

Subaerial volcanic activity followed the earlier predominantly subaqueous eruptions. This second phase of volcanism erupted from a different vent, now exposed at Pinnacle Point and within Horseshoe Bay on the southwestern edge of the island (Fig. 13). There is no significant erosion and no soil is developed on the surface of the pahoehoe flow. In many



environments this might indicate that little time elapsed between the two volcanic phases. However, given the extremely exposed nature of island to the erosive forces of the Southern Ocean environment, it is probable that any weathered material was rapidly blown or washed away, maintaining a fresh upper surface on the pahoehoe flow. The subaerial sequence is about 15m thick and began explosively, forming a small pyroclastic flow deposit. This was followed by quiet effusion of flat-lying plains-type lava flows, and terminated with lava fountaining which produced vitric ash. Although these volcanic features are relatively small, cliff exposures provide a unique opportunity to examine a section through the centre of a volcanic vent, and in places, provide insights into how pyroclastic flows and plains-type lava flows develop.

Fig. 14. Pyroclastic flow exposed in cliffs at Thunder Point (see also Fig. 13). The pick lies against the middle section of flow unit. Notice the upward increasing percentage of large basalt blocks. There is a sharp transition to the top section that is thinly bedded and much finer grained.

Pyroclastic flows. The small volcaniclastic deposit is centred around Pinnacle Point, and is exposed in the cliffs along the southwest of the island, approximately 20m above sea level. It extends less than 400m from the vent. It has a maximum thickness of 8–10m at Pinnacle Point but thins rapidly to 2–3m at Thunder Point, and to only a few centimetres thick beyond there. Close to Pinnacle Point this pyroclastic deposit is truncated by overlying subaerial lava flows.

Although the gross morphology of this deposit is similar to that of the maar rims common to the western volcanic district, it does not exhibit the usual characteristics of a phreatomagmatic tuff-producing eruption. Fine grained material makes up a relatively small proportion of the deposit, and there is very little air-fall planar bedding or base surge cross-bedding. A high proportion of large basalt blocks, reverse grading, and the lack of sag structures (Cas & Wright 1988) indicates formation as a pyroclastic flow deposit. The volcaniclastic debris flowed along the surface as a result of the rapid collapse of a small, dense eruption column which reached only a short distance above the vent (Cas & Wright 1988) — essentially a sputtering, or boiling event.

This deposit is only accessible in the eastern headland cliffs of Horseshoe Bay, where it is composed of two pyroclastic flows (Fig. 14). Each flow consists of three units distinguished by differing textural and structural characteristics:

- the basal layer (100–200mm thick) is composed of planar beds which conform to the flat-lying lava below and are laterally continuous to the edge of the deposit. In Horseshoe Bay they dip steeply (45–55°) to the base of Pinnacle Point. Beds are up to 50mm thick, fine upwards, and are composed of mainly small (1–2mm) clasts. Successive beds are generally composed of coarser fragments which ultimately grade into the coarser middle section of the flow. The basal layer represents the initial surge of fine-grained material along the surface from the vent in front of the main body of the flow.
- the middle layer forms the bulk of each pyroclastic flow and dips shallowly (5°) away from the vent. At Thunder Point it is about 1.0m thick but thins rapidly from here and cannot be traced beyond the headlands of Horseshoe Bay. It is massive and highly unsorted, with grainsize ranging from fine ash (≤1mm) to large basalt blocks (≤800mm). It contains about 70% clasts which vary from angular blocks, to rounded bombs, and highly irregular grains. Clasts are texturally variable, ranging from highly vesicular and almost scoriaceous lava with ropy textures, to massive dense lava. Minor accessory lithics (≤1%) are carbonate sediments, probably Port Campbell Limestone or Gellibrand Marl country rock ejected during the eruption. These have been heated and recrystallised during the eruption, and have not retained original textures. Clasts are lightly bonded by a matrix composed of secondary clay minerals and minor altered basaltic glass. These materials thinly rim the clasts, making a large proportion of the de-

Fig. 13. Volcanic vent at Pinnacle Point, viewed across Horseshoe Bay from Thunder Point. This vent intrudes pillow lavas from earlier submarine volcanic eruptions (bottom-right). The first eruption produced pyroclastic flows (light material middle-right), subsequently truncated by plains-type lava flows seen draped over them at angles of up to 30°. What remains of the throat of the vent is now filled with massive columnar-jointed basalt (bottom-left). The thinly bedded lava and scoriaceous layers (upper-left) at the top of the pinnacle fused to form the clastogenic flows that cap the southern portion of the island.

posit matrix supported. The most striking feature of the section is the reverse grading of the larger clasts. In general, larger fragments increase in average size towards the top of the section, while the finer grained population remains constant throughout the deposit. There is a sharp transition to the upper layer;

- the upper layer is fine grained (1–2mm) and generally less than 100mm thick. It fines upwards, and may be massive or display planar and minor cross bedding. This fine grained surge and air-fall material indicates that a cloud of fine ash accompanied the flow.

Subaerial lava flows. Pyroclastic activity was followed by relatively quiet subaerial effusion of five low-volume, thin (3–4m) plains-type alkali basalt flows which form the bulk of the upper portion of the island. Around Horseshoe Bay the flows truncate and thin over the top of the underlying pyroclastic deposit, but thicken from there and form the flat-lying surface of the island.

Excellent exposures near the vent at Pinnacle Point show that these flows have developed as numerous interbedded thin lava and scoriaceous bands, presumably short pulses in a single eruptive event, which fused to form a single flow. The remnant of an agglutinated spatter rampart forms a 2m high deposit at Thunder Point.

Each flow displays a characteristic sequence of textures. The lower half of each flow is characterised by dense lava with minor spherical vesicles ($\leq 1\%$). This grades upwards into highly vesicular lava (50–60%), which in turn is overlain by scoriaceous rubble and lava spatter. Several flows display an irregular–possibly erosional–lower contact with the upper rubble layer of the flow below.

These lavas commonly display crude vertical jointing. Joints are generally most pronounced in the upper parts of each flow where cooling occurred more quickly. True columnar jointing is found only at the base of Pinnacle Point in part of the neck of the volcanic vent. Columns here are vertical.

Scoria and lava spatter. Final subaerial activity was an episode of lava fountaining from the same vent. At Thunder Point, the deposit is essentially a 2m high pile of fused scoriaceous fragments which may once have formed a cone or rampart around the vent. At Pinnacle Point, this deposit is an interbedded succession of thin lava flows and spatter layers (≤ 300mm), representing a series of clastogenic flows produced by the amalgamation of hot spatter fragments close to the vent. These flows did not move far and are interlayered with deposits of spatter which cooled too quickly to form a flow. Such layering probably reflects the pulsating nature typical of such eruptions. The top and bottom of each lava flow is welded strongly to fragments above and below. Further from Pinnacle Point the layers are fused into a single lava flow. The edge of this deposit forms a geomorphologically prominent ridge across the island close to Horseshoe Bay.

Vitric ash. Vitric ash deposits are preserved in small patches distal to the scoria material scattered along the top of the northern cliffs between Cape Frederick and Sphinx Head. These conformably overly the uppermost lava flows, but are largely concealed by soil. Where exposed the ash is highly weathered and friable, never greater than 400mm thick, and forms sub-horizontal beds 60–80mm thick. It is composed mainly of highly altered basaltic glass with tiny scattered crystals that may be plagioclase, and augite or olivine. Minor highly vesicular basaltic lithics and scattered cuspate shards of uncrystallised volcanic glass are also present. The latter are possibly fragmented walls of vesicles and indicate an explosive magmatic eruptive genesis (Heiken, 1974), derived either from the final eruption on the island or from the air-fall component of a phreatomagmatic eruption on the nearby mainland.

GEOCHRONOLOGY

The pillow lavas were considered unsuitable for dating due to the likelihood of excessive radiogenic argon trapped in the rapidly quenched volcanic glass, and the upper subaerial lava flows were too altered. However, two samples, one from each of the identified volcanic phases, were suitable for total rock potassium/argon (K/Ar) dating by Amdel Limited, South Australia (Appendix 2):

- Pahoehoe lava immediately above the pillows at Dinghy Cove yielded an age of 7.80 ± 0.08 Ma. This age represents the youngest preserved product from the first volcanic phase from a vent which lies submerged somewhere to the south of the island.
- A dense basalt block from the pyroclastic flow at Thunder Point revealed an age of 6.22 ± 0.06 Ma. This age represents rocks produced close to the end of the second volcanic phase from the vent exposed at Pinnacle Point on the southwest coast of the island.

Ancient Sea LevelMarkers	Locality	Height (+/- sea level)
shore platform	McCoy Platform	+18m
pillow/pahoehoe contact	cliffs around the island	to 15m
erosional indentation	cliffs around the island	+10m
shore platforms	Thunder Point and Pinnacle Point	+3m
boulder beach	near Delta Reef	+3m
sea caves	Fern and Seal caves at Seal Bay	+1.5m
sea caves	Horseshoe Bay, and Thunder Point to Delta Reef	0m and +3m
submerged platform	West Cape	-5m
submerged platform	Cape Frederick	-14.5m
submerged platform	Seal Bay	-16 to -18m
submerged platform	Delta Reef	-25 to -27m

Table 1 Summary of the geological and geomorphological ancient sea level markers preserved at Lady Julia Percy Island.

The volcanic rocks of Lady Julia Percy Island are thus Late Miocene in age, and were produced during two discrete phases of volcanic activity approximately 1.6 Ma apart. These ages are significantly older than commonly quoted maximum ages for Newer Volcanics in the Western District Province of Victoria.

Significance of the geochronology

The Western District Province is generally regarded as a relatively young phenomenon, with quoted ages ranging from a few thousand years, mainly for young scoria cones, to a maximum of around 3–4.6 Ma for the more extensive plains lava flows (McDougall et al., 1966; King, 1985; Joyce, 1988; Price et al., 2003).

The 6–7 Ma age for Lady Julia Percy Island is not unique to the Newer Volcanic series, although most ages comparable to this have previously been obtained from west-central Victoria. Such rocks were grouped separately, due to their apparently earlier age and their different rock associations (eg. volcanics of the Central Highlands Sub-province and the trachyte-basalt association of the Macedon–Trentham Province; Price et al. 2003). Wallace (1990) has proposed that, based on a study of 61 K/Ar dates, the Newer Volcanics of the Western District region can be subdivided into several distinct groups based on eruption age. His oldest group (Group 1) includes ages ranging from 5.83–7.1 Ma. Even earlier volcanic activity may have occurred at 8–8.5 Ma, as evidenced by a zircon fission-track age peak around 8.4 Ma recorded from locally-sourced Stony Creek Basin sediments at Daylesford (K. Sniderman & P. O'Sullivan pers comm. in Willman et al. 2002).

The results obtained from Lady Julia Percy Island add to a growing collection of recent data that show the maximum age of the Newer Volcanics series within the central and southern portions of the Western District Province is significantly older than previously suggested. For example, olivine basalt from the Newer Volcanic lava plains just east of Ararat has a K/Ar age of 6.07± 0.11 Ma (Cayley et al. 1995). The Ararat example lies well within the Western District Province. It overlies approximately 70m of even older basalt flows, indicating that the lava plains were already well established in the Western District Province by the Late Miocene (Cayley & McDonald 1995). The Ararat data and the new geochronology for Lady Julia Percy Island indicates that eruption centres and basalt flows with ages well in excess of 5 Ma (Late Miocene) are widely distributed in Western District Province.

This conclusion seems at odds with the current widely accepted impression of a considerably younger age for the Western District Province compared with other parts of the Newer Volcanics series (eg. Price et al. 2003). This impression has grown from the many published radiometric dates that are in the range of several thousands to 3–4 million years (eg. McDougall et al. 1966; Wellman 1974; Day 1989). These are mostly from the intact volcanic edifices and related flows that rise above—and rest upon—

much more extensive lava flows. Sampling has necessarily been largely restricted to the fresher, younger surface features of plain (eg. Gill 1978; Stone et al. 1997), introducing a young-age bias to ages published for the Newer Volcanics of the Western District Province. Dates obtained for older lava flows are less common and are less widely distributed geographically (eg. King, 1985). Even where older flows are exposed, they are typically deeply weathered and unsuitable for conventional dating techniques.

Lady Julia Percy Island offers a rare opportunity to observe and sample some of the oldest and best preserved Newer Volcanic rocks in the Western District Province. Its island geography has enabled it to remain isolated and protected from burial by younger lava flows. Moreover, fresh rock is continuously exposed as a result of rapid coastal erosion. Therefore, although the 6–7 Ma ages obtained for the sequence on the island are older than those commonly published for this region, they are entirely consistent with other recent geochronology from the Western District Province, and with the known and expected age range of the Newer Volcanics series in Victoria as a whole.

ANCIENT SEA LEVEL MARKERS

In the Tyrendarra Embayment, Cainozoic eustatic oscillations are recorded by the depositional sequence of marine and fluvial sediments. The 6.22–7.80 Ma age of the Lady Julia Percy Island lavas place their eruption at some time during the regression of the sea from the area, prior to the transition from limestone deposition to that of the fluvial sediments (Hanson Plain Sand) which overlie the Port Campbell limestone onshore, and underlie much of the Newer Volcanic Plain of Victoria (Tickell et al. 1992).

Several ancient sea levels are recorded in the cliffs of Lady Julia Percy Island. The only non-erosive marker is that of the subaqueous/subaerial lava flow contact. As the formation of pillows depends upon many factors, including lava extrusion rate and water confining pressure (Yamagashi 1985), this boundary only approximates relative sea level at the time that pillow formation ceased. Today it lies 15m above sea level, indicating that at about 7Ma the sea surface was probably some metres higher than present. Just how much higher is problematic, as there is no preserved record of the effect of vertical movements due to processes such as post-eruptive subsidence or tectonic uplift. Evidence for a previous sea level at +15m is not widely recognised along nearby mainland coasts, although some erosional features at +12 to +15m have been noted in the headlands of Portland Promontory (Boutakoff 1963). However, unlike erosional sea level markers, and irrespective of the absolute sea level, this marker probably represents nothing more than a transient sea level during the eruption of a lava flow, rather than one maintained for a significant period of time.

In addition there are several geomorphic ancient sea level markers preserved at different levels both above and below present-day sea level at Lady Julia Percy Island, and include sea caves and wave-cut platforms (Table 1). These are the result of erosive modification of the volcanic pile subsequent to its eruption. One such feature—a prominent indentation in the cliffs approximately 10m above sea level—is inferred from offshore photographs of the island. It is most obvious within the pillow deposit close to Dinghy Cove. As this feature does not correspond to a geological boundary, and cuts across the top of the pillow deposit into the subaerial flows, it is interpreted as the beginning of a wave-cut shoreline developed during a higher-than-present sea level.

Wave-cut platforms occur along the southern shores, reflecting present-day erosion at sea level where the strong prevailing winds form the most powerful waves. Other wave cut platforms and sea-caves are elevated at various heights above the present sea level. These are also mostly found in the cliffs of the southern headlands. The McCoy Platform at West Cape is the largest of these, and lies approximately 18m above the present sea level. Its surface displays the characteristic well developed pebble-worn potholes and rock pools, and honeycomb weathering textures typical of present-day Victorian wave-cut platforms. Bathymetric data also identifies several submerged platforms along the southern flank of the island. In contrast, a submerged bench adjacent to Cape Frederick has not been exposed to south-westerly waves and may therefore be a primary volcanic feature, possibly the edge of a lava flow.

At the southern edge of Delta Reef, an inaccessible boulder beach is preserved in the entrance of a sea cave approximately 3m above the present sea level. It is a 3–5m thick deposit composed of rounded basalt pebbles and boulders up to approximately 1m diameter, and similar in appearance to the present day beach deposits at Dinghy Cove and Seal Bay. The deposit is exposed as a vertical cliff section, and is therefore probably cemented by secondary minerals.

Coastal geomorphological features of the nearby mainland coast preserve ancient sea levels that are both higher and lower than present, and include numerous stranded beaches and shore platforms, and drowned river valleys along the coast between Port Fairy and Warrnambool. These are summarised in Edwards (1994). The most widespread evidence for an ancient sea level in this region is at +3m and includes sea terraces, cliffs and caves around Portland Promontory, and a shore platform cut into Miocene limestone at Two Mile Bay. The stranded boulder beach, and several stranded platforms and sea caves are preserved at this level on the island. However, together these represent an incomplete record of a complex succession of relative sea level rises and falls that have overlapped and been superimposed upon each other, in areas possibly with differing tectonic histories. In the absence of datable material and a detailed understanding of local tectonics, the Lady Julia Percy Island ancient sea level markers cannot be directly compared to any of the Holocene levels preserved on the nearby mainland, which limits their use at present.

CONCLUSION

Lady Julia Percy Island is one of the earliest known eruption centres of the Western District Province of the Newer Volcanic lava plains of Victoria. It offers a unique opportunity to observe a wide range of spectacular and well preserved volcanic structures, textures and relationships not found together elsewhere in Victoria.

Initial subaqueous deposits of well developed pillow lavas and associated hyaloclastites are the best deposits of their kind in Australia, and have preserved a fantastic array of the classic morphologies and textures seen forming in subaqueous lavas today. Of particular interest is the well exposed gradual transition from subaqueous to subaerial textures marking the sea level at the time of eruption. At this transition, pillow morphologies merge into pahoehoe lava—the well preserved internal structures of which provide important clues to the ways such flows propagate. This lava also displays an unusual texture of small lava globules. The globules are interpreted to have formed from late-stage residual magma filling vesicles just prior to complete solidification of the host magma.

Subsequent subaerial deposits of the second phase of volcanic activity were sourced from Pinnacle Point. Here, cliff faces provide a rare opportunity to examine the internal anatomy of a volcanic vent. Of special interest are the internal structures of reversely graded pyroclastic flows, subaerial lavas and several clastogenic flows, all of which demonstrate aspects of how these volcanic features developed.

The spectacular exposures of volcanic features are maintained by the unrelenting erosion of coastal cliffs. Lady Julia Percy's island geography has also protected it from burial by younger lavas, which on the nearby mainland have thickly covered the majority of the earliest New Volcanic features. The 6.2–7.9 Ma ages for Lady Julia Percy Island, in conjunction with recent radiometric ages for other Newer Volcanic eruptions in the onshore part of the Western District Province, support the contention that the present subdivision of the Western District lava plains into several provinces on the basis of age (and/or compositional differences; Price et al., 2003) may reflect an incomplete geochronological dataset across the region rather than significant differences in the age of volcanic activity.

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APPENDIX 1

Selected total rock X-ray fluorescence analyses of Lady Julia Percy Island lavas.

	1	2	3	4	5	6	7	
SiO_2	47.50	47.91	48.34	50.38	48.05	48.46	48.89	**SiO_2**
TiO_2	2.06	2.06	2.12	1.84	2.15	2.05	2.28	**TiO_2**
Al_2O_3	13.43	13.84	13.76	14.43	13.68	13.60	13.79	**Al_2O_3**
Fe_2O_3	13.26	11.58	12.69	12.20	13.15	12.16	12.34	**Fe_2O_3**
MnO	0.17	0.15	0.17	0.13	0.16	0.17	0.16	**MnO**
MgO	8.65	8.54	8.20	6.85	8.66	8.66	7.43	**MgO**
CaO	8.22	9.04	8.49	8.49	8.31	8.31	8.32	**CaO**
Na_2O	3.48	3.61	3.62	3.62	3.85	3.34	3.77	**Na_2O**
K_2O	1.49	1.31	1.56	1.14	1.61	1.47	1.64	**K_2O**
P_2O_5	0.51	0.51	0.53	0.40	0.55	0.49	0.57	**P_2O_5**
SO_3	936	551	182	185	207	333	290	**SO_3**
Cl	836	1824	900	383	574	402	1178	**Cl**
Cr	243	223	217	257	239	223	180	**Cr**
Ba	404	384	393	285	414	331	396	**Ba**
Sc	14	20	20	25	20	21	20	**Sc**
Ce	72	55	53	66	74	44	84	**Ce**
Nd	22	51	37	60	29	49	28	**Nd**
V	173	176	171	174	165	168	174	**V**
Co	45	48	49	57	43	51	47	**Co**
Cu	97	54	97	100	84	71	62	**Cu**
Zn	124	119	133	131	129	117	135	**Zn**
Ni	178	185	183	198	219	275	175	**Ni**
Ga	20	21	21	16	22	19	21	**Ga**
Zr	176	186	181	159	190	182	191	**Zr**
Y	21	22	23	28	23	20	27	**Y**
Sr	592	623	595	498	655	582	600	**Sr**
Rb	32	28	32	24	32	29	34	**Rb**
Nb	38	39	41	28	42	37	44	**Nb**
Th	5	6	2	9	5	3	4	**Th**
Pb	8	6	4	13	6	8	4	**Pb**
As	0	6	3	-6	0	-2	0	**As**
Mo	5	1	2	-1	4	0	3	**Mo**
U	0	1	3	1	0	0	0	**U**
Loss	0.01	1.37	0.30	0.26	-0.35	1.15	0.27	**Loss**
Total	**99.17**	**100.38**	**100.10**	**100.02**	**100.15**	**100.15**	**99.81**	**Total**

Samples:

1. Outer chilled margin of a pillow, Dinghy Cove (AMG 585788–5747300).
2. Centre of a pillow, Dinghy Cove (AMG 585788–5747300.
3. Pahoehoe lava flow, Dinghy Cove (AMG 587890–5747830).
4. Pahoehoe lava flow, McCoy Platform (AMG 58665–5747150).
5. Lava block from pyroclastic flow, Thunder Point (AMG 587000–5746390).
6. Subaerial lava flow, Dinghy Cove (AMG 587900–5747800).
7. Subaerial lava flow, Pinnacle Point (AMG 58685–5746550).

APPENDIX 2

Potassium–Argon analyses.

Sample	**%K∅**	**^{40}Ar*(×10−^{11}moles/g)**	**^{40}Ar*/ ^{40}Ar$_{Total}$**	**Age$^{\#}$**
Pahochoe flow, final product of the first phase of volcanism, 15,5m above sea level, sea cliffs, Dinghy Cove. (AMGω 587890–5747830)	1.3557 1.3577	1.8395	0.812	7.80 ± 0.08
Lava block from pyroclastic flow, second phase of volcanism, 21m above sea level, sea cliffs, Thunder Point (AMG 587000–5746390)	1.328 1.330	1.4368	0.609	6.22 ± 0.06

∅ Mean K value is used in the age calculation.
* Radiogenic ^{40}Ar.
\# Age in Ma—error limits for analytical uncertainty at one standard deviation.
ω Co-ordinate system AGD 66.

Constants:
^{40}Ar = 0.01167 atom %
$\lambda\beta = 4.962 \times 10^{-10} y^{-1}$
$\lambda\epsilon = 0.581 \times 10^{-10} y^{-1}$

Analyses conducted by Amdel Limited, Mineral Services Laboratory, South Australia, report numbers G8948/91 and G830100G/94.

LONG BASALTIC LAVA FLOWS OF THE MT ROUSE VOLCANO IN THE NEWER VOLCANIC PROVINCE OF SOUTHEASTERN AUSTRALIA

FABIJAN SUTALO & BERNARD JOYCE

School of Earth Sciences, The University of Melbourne 3010, Victoria, Australia

Sutalo, F. & Joyce, B., 2004:11:14. Long basaltic lava flows of the Mt Rouse volcano in the Newer Volcanic Province of Southeastern Australia. *Proceedings of the Royal Society of Victoria* 116(1):37-49. ISSN 0035-9211.

Mt Rouse is a complex scoria and lava volcano situated 250 km west of Melbourne, in the Western Plains subprovince of the Newer Volcanic Province of Southeastern Australia. The basaltic lava flows of Mt Rouse have travelled southwards a distance of 60 km and extend to the present-day coast at Port Fairy. The flows branch and rejoin, and pass through narrow pre-existing valleys less than 100 m wide, providing one of the best examples of long lava flows in Western Victoria. The 'stony rise' topography of the flows indicates that lava sheet inflation and associated lava tube systems were the mechanisms for long lava flow development.

Detailed field work, including Regolith Terrain Unit mapping of the region, indicates a single source for all the flows, allowing a reassessment of the age of the flows. K/Ar dates of about 0.32 Ma from lava 15 km south of the volcano, and about 0.3 Ma from near Port Fairy, give the age of the activity, which is exceptional in having an estimated volume some three times the average of other large eruptions in the Province.

Key words: volcano, basaltic, lava, long flow, age of eruption

THE NEWER Volcanic Province (NVP) covers an area of 15 000 km^2, and has nearly 400 points of eruption of Pliocene to Recent age. It includes the Western Plains subprovince, known locally as the Western District, with extensive lava fields and some 100 or so eruption points (Ollier & Joyce 1964), as well as areas of more concentrated activity in the Western Uplands subprovince, the eastern Uplands subprovince, and smaller areas in the Mt Gambier subprovince across the border in Southeastern South Australia.

The Western Plains subprovince is characterised by gently undulating plains, with many small pyroclastic cones that rarely reach more than 200 m above the general level. Many of the younger centres are typically surrounded by aprons of lava with stony rise topography. The earlier basalt flows have well-developed or evolved soil and are weathered and eroded to an undulating landscape. The younger flows have the characteristic blocky, rugged stony rise topography associated with well-preserved volcanoes such as Mt Napier, Mt Eccles and Mt Rouse. Younger flows are often found filling valleys which had been incised into earlier flow landscapes. Given the long history of eruption, and the high degree of activity in geologically recent times, further activity seems possible, and even likely, so the volcanic province as a whole may be referred to as 'dormant', rather than extinct.

THE MT ROUSE VOLCANO

Mt Rouse is one of many volcanoes in the Western Plains subprovince of the NVP of Victoria. It is situated 240 km west of Melbourne and just 1 km southeast of the town of Penshurst (Fig. 1). Mt Rouse is a composite scoria and lava cone rising approximately 120 m above the level of the surrounding lava fields, and reaching an elevation of 367 m above sea level.

The main scoria cone, with a slope of about 20°, has the form of a horseshoe, encircling the main crater, which is elongated in an east-west direction and breached to the west (Fig. 2). A small ridge of spatter, about five m high and 35 m long, runs along the spur of the scoria cone near the summit of Mount Rouse (Whitehead 1991).

To the south of the main peak is a smaller scoria and ash cone with an almost perfectly-circular 360 m diameter crater rimmed with lava, and inside the crater very steep walls drop 40 m to a semi-permanent lake. The steep sides of this crater indicate that it was partly produced by collapse and the lake lies below the level of the surrounding stony rises. A small

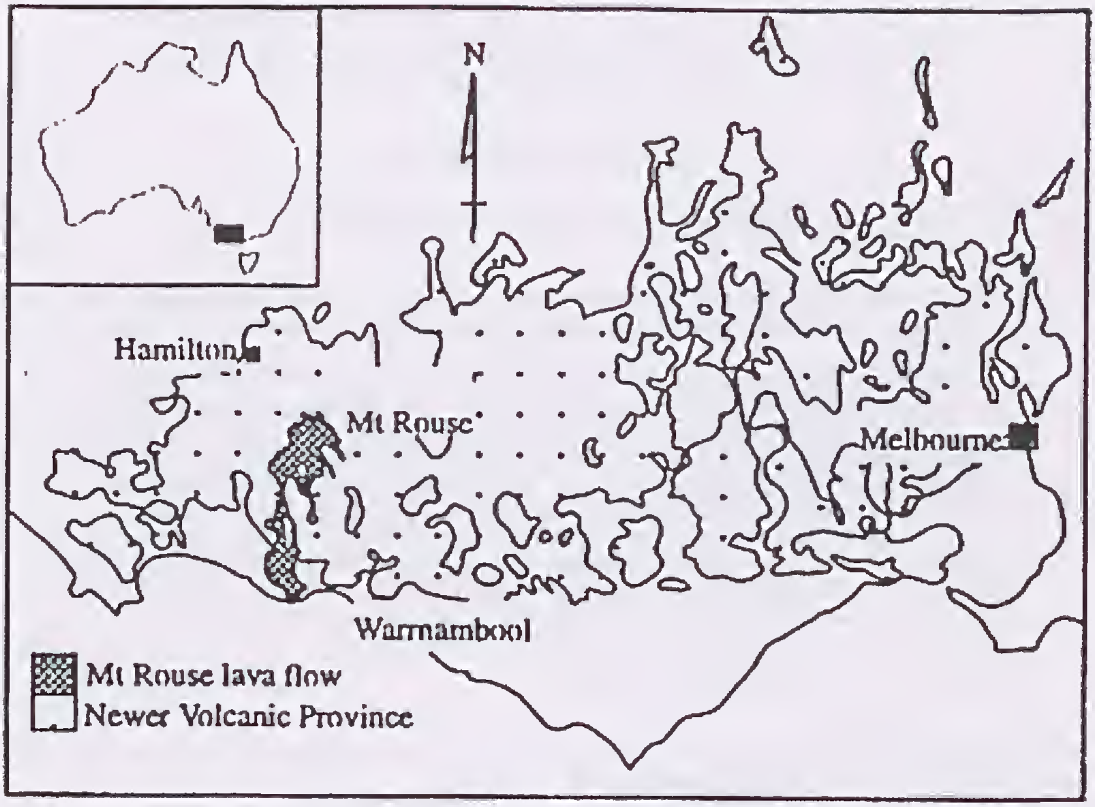

Fig. 1. The Newer Volcanic Province in Western Victoria showing the extent of the Mt Rouse flows (Sutalo 1996).

lava channel to the east on the stony rises lava shield can be traced back to this crater, indicating that it was the source of extensive flows (Sutalo 1996). The vent probably began as a maar eruption, later becoming a lava lake and flow source, before a final collapse or withdrawal of lava produced the deep crater we see today (Fig. 2).

The flows of the Mt Rouse volcano are strikingly different to other flows of the NVP of southeastern Australia because they cover three times the average area, with approximately three times the volume of lava erupted (Joyce & Sutalo 1996). Previously it was believed that the Mt Hamilton flows, originally mapped as a single area of stony rise flows on the Ballarat 1:250 000 map sheet (King 1985), were of twice the average area. However, detailed mapping of this area by MacInnes (1985) has demonstrated the existence of a second major eruption point, Mt Fyans, which produced the southern half of the area of flows originally attributed to Mt Hamilton. Each of these vents, as a result, has an area and volume of eruption from each vent similar to the average for the NVP. Mt Rouse now remains as the single largest lava source in the NVP.

Gibbons & Gill (1964), drawing on earlier work by Gibbons & Downes (1964), described the topography and soils of the Mt Rouse flows as part of a single land-system, the *Girringurrup Land-System*, later renamed the Rouse RTU by Ollier & Joyce (1986), who suggested an age range of two to one Ma for such flows in the NVP. After further mapping of the Skipton & Willaura 1:100 000 map sheet areas, Joyce (1999) suggested a younger age range of 0.2 to 1 Ma for the Rouse RTU.

Gibbons & Gill (1964) said the Mt Rouse flows were characterised by "smoothly-rounded stony rises with infilled swales" and "The difference in height between rise and contiguous hollow varies up to 40 ft, while the distance between rises varies from 50 ft to a few hundred yards". Although the flows are now largely treeless, the original vegetation is believed to have been "a sparse savannah woodland of manna gum and blackwood…or lightwood…on the rises, with a wet tussock grassland of snow-grass…in the swales" (Gibbons & Gill 1964).

The pattern of soils was described by Gibbons &

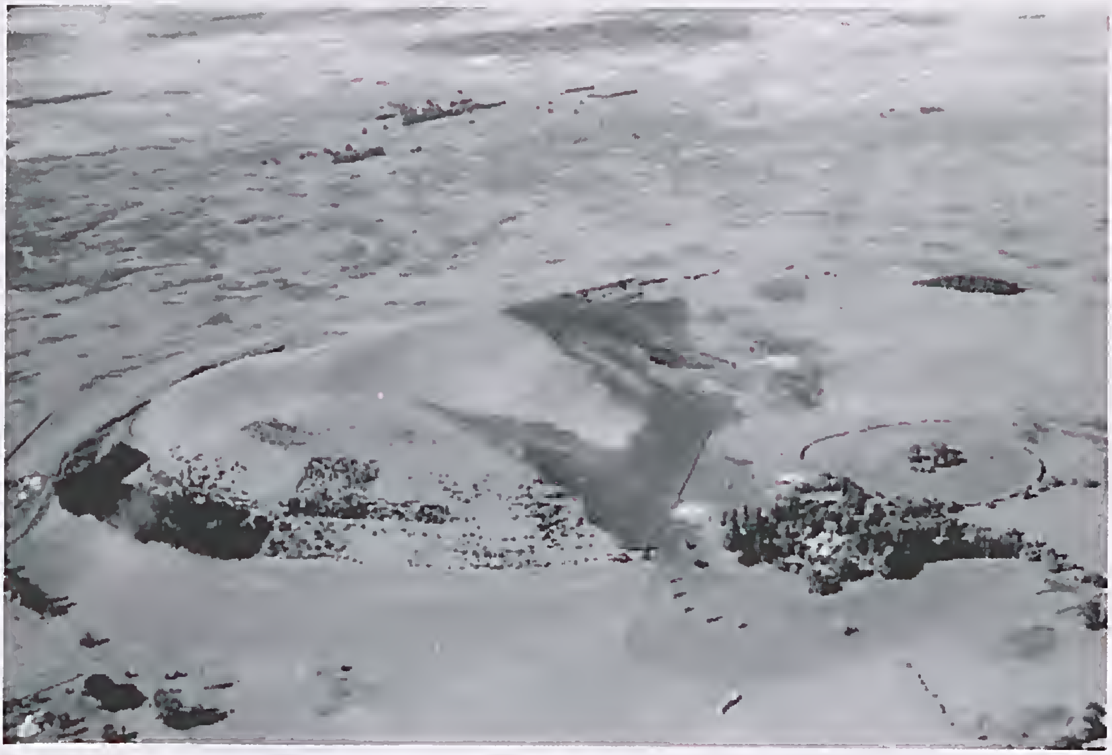

Fig. 2 Aerial oblique view of Mt Rouse, looking southeast across the main cone, with the smaller crater and lake to the right, and stony rises of the Lava Shield beyond (photo L. K. Elmore ?1960s).

Gill (1964) as a simple catena. "On the rises are thin reddish chocolate soils…with abundant rounded basalt boulders half-buried in the soil and with onion weathering. These soils become darker further down the sides of the rises until, in the swales, they are black, heavy and cracking, sometimes with free carbonate and usually gilgaied…"

The Mt Rouse lava flows have been mainly studied at a regional map scale, apart from the descriptions in Elias (1973), Whitehead (1991), and Ollier (1985). Two distinct ages have been suggested for the Mt Rouse eruption and flows (McDougall & Gill 1975, Ollier 1985, Gray pers. comm. 1996), suggesting the possibility that one or more hitherto unrecognised eruption points exist in this large area of flows. In this study the flows have been mapped in detail for the first time, with additional use of new regolith landform mapping techniques. Published and unpublished dates have been summarised and evaluated, and finally conclusions reached about the physical volcanic history of Mt Rouse.

METHODS

To determine the physical volcanic history of Mt Rouse, detailed mapping for the first time of the long and voluminous Mt Rouse flows has been carried out at a scale of 1:25 000, using recently available State Government topographic maps (Sutalo 1996). Aerial photography at a scale of 1:80 000 has also been used, as well as airborne radiometric and magnetic imagery from the Geological Survey of Victoria. Extensive field work was used to check the mapping, with an altimeter used to measure relative elevations.

This work allowed the detailed description of geomorphological features and the determination of likely mechanisms of formation of flow features. Flow margins are readily apparent in the field, and can be confirmed on magnetic imagery.

A wide range of soils and weathering profiles can be found on lava flows of different ages in Victoria, and these, in conjunction with differences in the geomorphic features of the flows, can be used to map flows into groups according to age. Radiometric im-

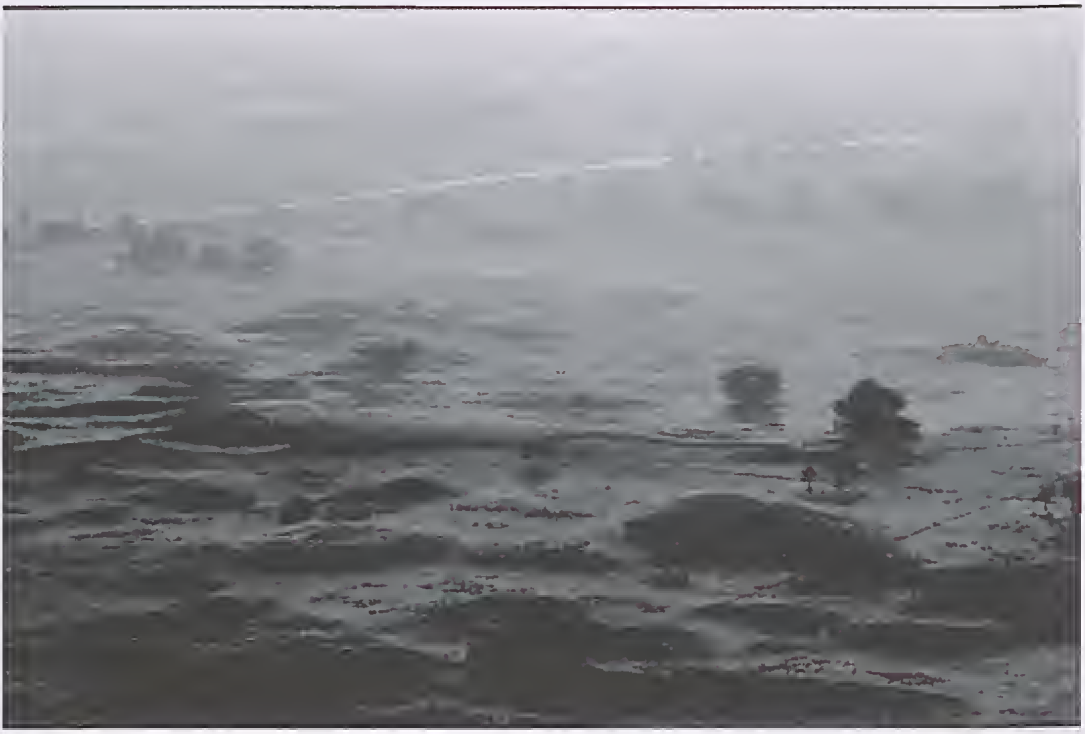

Fig. 3. Stony rises of the Lava Shield, looking northeast from Mt Rouse into the morning sun (photo E. B. Joyce 1966).

agery in the standard colour presentation shows the Rouse flows in a red-brown colour, which contrasts clearly with the blues and greens of adjacent older flows, and is also readily distinguished from the bright red of the youngest flows in the NVP, such as Mt Eccles and Mt Napier, to the west. Ollier & Joyce (1986) used a mapping unit called a Regolith Terrain Unit (RTU) which combined descriptions of soils, weathering and geomorphology to distinguish and map discrete terrain units. In other studies, general application of this technique has extended the information available from absolute dating on the Western Plains, and allowed deductions of the way volcanicity has varied through time and across the province, as well as indicating frequency of eruptions, variations in the type of volcano, and the volume of the material produced (Joyce 1999).

These new regolith landform mapping techniques have been applied to several major flows in the NVP, using aerial photographs and radiometric and magnetic imagery e.g. MacInnes (1985) at Mt Hamilton. It is applied here to the Mt Rouse flows for the first time. In addition, flow morphology has been examined, and recent ideas on flow emplacement have been considered (Joyce & Sutalo 1996). A regional search for lava channels and lava tubes or caves which would have acted as feeders was also part of the field mapping.

Lastly, the mineralogy of the flows has been examined using thin sections and X-ray fluorescence spectrometry - XRF (Sutalo 1996) to look for any evidence of variations between flows.

All available published and unpublished dates have been summarised and evaluated.

MT ROUSE AND ITS FLOWS

Well-preserved flows from Mt Rouse form an extensive lava shield around the volcano (Fig. 3). A number of long flows extend beyond the shield, and the Rouse-Port Fairy Flow is one of the longest lava flows in Victoria, extending 60 km to reach the coast (Fig. 4). The lava field area is greater than 450 km^2, three times the average area of other lava fields in Western Victoria. The flows can be divided into two broad areas, connected by narrow lava-filled valleys or channels. One broad area lies immediately south of

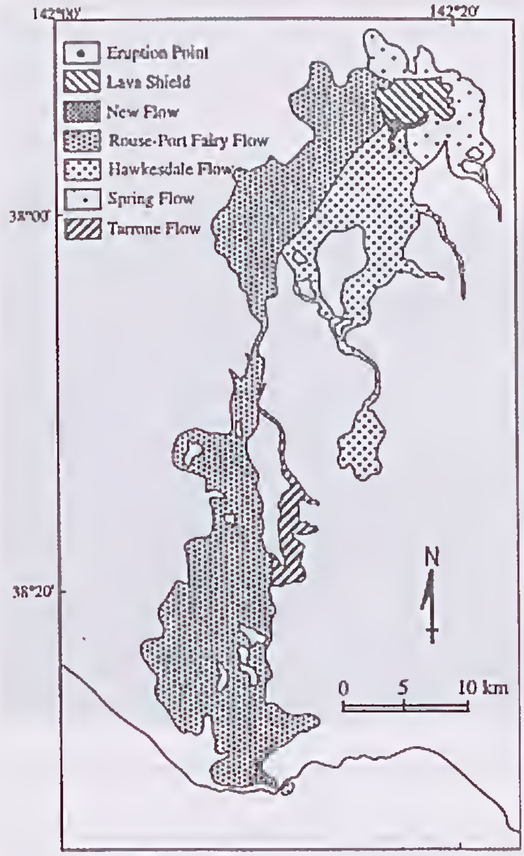

Fig. 4. Distribution of main lava flows from Mt Rouse (Sutalo 1996).

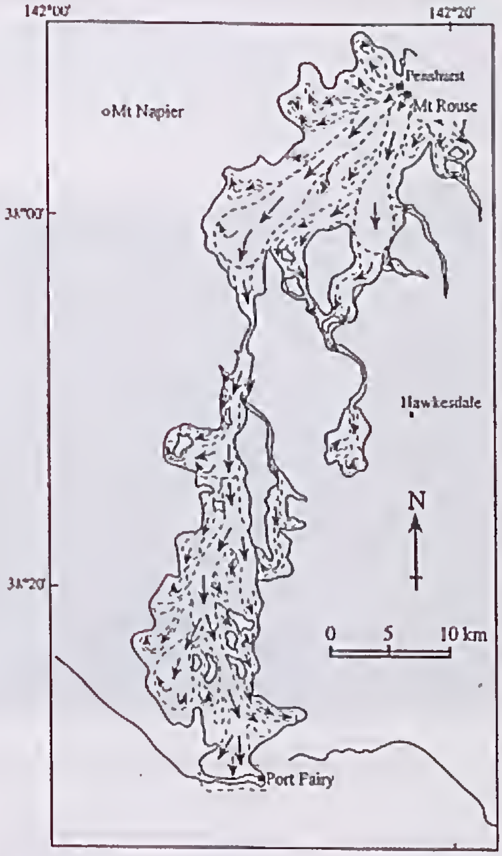

Fig. 5. Interpreted preferred pathways taken by individual lava flows within the Mount Rouse lava field, prior to formation of the Lava Shield and New Flow (Sutalo 1996).

the volcanic cone, and the other lies further south and reaches the coast at Port Fairy (Fig. 5). The characteristic feature of the flows is the irregular, hummocky rises and depressions known in Victoria as 'stony rises' (Skeats & James 1937). Mount Rouse provides one of the best examples of stony rise topography in the NVP.

Natural stream drainage channels on the Mt Rouse flows are rare. Low-lying areas and depressions within the flows form small, ephemeral swamplands, while the tops of stony ridges and flows are well drained. The modern drainage has not yet incised deeply into the Mt Rouse lava field.

Soils and regolith

Sutalo (1996) retained the Mt Rouse flows as a single large Regolith Terrain Unit (RTU), following Ollier & Joyce (1986), but mapped and sub-divided the area of flows into eight smaller RTUs, based on variations in topography, soils, regolith and drainage development. These units reflect the catena concepts in the earlier mapping of Gibbons & Gill (1964).

The distinct RTUs of Mt Rouse flows do not necessarily represent flows of different ages but rather variations in the way individual parts of a single flow sequence were emplaced (Joyce & Sutalo 1996). The aim of the detailed regolith terrain mapping was to help determine the relative sequence of the flows, and in particular decide whether the Mt Rouse flows originated from a single vent producing very large and long flows, or whether the flows were erupted from several vents within the area. The results of the regolith mapping by Sutalo (1996) have been incorporated into Figures 4 & 5.

In the last few kilometres of the flows, near the coast, the regolith cover appears to thicken, and this

Fig. 6. Bare stony surface of a typical flow ridge in the Mt Rouse lava field – hammer for scale (photo E. B. Joyce, as in Sutalo 1996, his Fig. 4.2 p.37)

may be due in part to an addition of sand from the coastal dunes around Port Fairy (Joyce & Sutalo 1996).

Regional topography

The Mt Rouse flows have travelled over gently sloping topography. The slope angle from the base of the scoria cone to the coast is approximately 2.5°. The landscape in general now slopes to the south-west, but the Mt Rouse lava flows cut across this contour trend and flowed more directly south, following pre-existing drainage valleys with this direction. Details of the palaeodrainage of the region are described in Ollier (1985).

The northern and southern parts of the Mt Rouse lava field are broad and flat in nature with lava flows spreading laterally over an extensive plain with only a gentle slope. The central parts of the Mount Rouse lava flows are quite different. Here the southward-slope increases substantially, with about a 120 m drop over a distance of 20 km (Sutalo 1996). Most of the narrow lava-filled valley flows are found in this area. The lava flowing from Mt Rouse travelled more quickly down these pre-existing valleys and in the process formed lava tubes which insulated the lava, allowing it to travel further by cooling more slowly.

The crests of some Mt Rouse flows are up to 15 m higher than those of adjacent but earlier Newer Volcanic flows which form the surrounding plains (Fig. 6). This distinct relief difference is the result of lava flow inflation, which has raised the original flow surface above the level of the valley floor and then further above the level of the original plain. Lava flow inflation is the lifting of the solid crust as broad sheets by the continual injection of molten lava into the interior of the flow (Keszthelyi et al. 1996).

DISTRIBUTION AND CHRONOSEQUENCE OF THE MT ROUSE LAVA FLOWS

Distribution of lava flows

The lava flows of Mt Rouse cover a large area to the east, west and south of the eruption point (Fig. 4).

To the north of Mt Rouse, flows cover only a small area, with the northern edge of the lava flows marked by a small lateral stream, Penshurst Creek, which flows northwest. To the south-east of Mt Rouse two short and narrow flows have travelled down earlier valleys of Spring Creek and Whitehead Creek for several kilometres and subsequently small lateral streams have developed along the flow edges. Further to the west and south of Mt Rouse, stony rise relief decreases, and parallel lateral flow ridges are found towards the centre and along the margins of the flows. It appears the lava has banked up against existing higher topography to the west, and the Eumeralla River is a lateral stream which now marks the western edge of these flows. (For further details of palaeo- and modern drainage, see discussion in Ollier 1985).

The main northern mass of lava flowed southwards and passed through two narrow palaeovalleys. The lines of these valleys are still more or less followed by the modern Moyne River and Back Creek. The Hawkesdale Flow took the eastern Moyne River route. This lava flow branches and rejoins around higher areas of lava which are older than those from Mt Rouse. These areas of higher, earlier lavas surrounded by flows are here called inter-flow 'islands' (also known on Hawaii as *kipuka;* Ollier (1985) used the USA term steptoes). The narrowest sections of these valley flows from Mt Rouse are approximately 100 m wide, and referred to here as 'gates'.

The largest lava flow originating from Mt Rouse is the Rouse-Port Fairy Flow. This travelled through the narrow Back Creek palaeovalley and the flow is less than 1 km wide over a distance of more than 5 km, and at its narrowest the 'gate' is only 400 m wide. This flow widens to the south as it becomes less confined, with the main section of flow averaging 10-15 km in width.

The Tarrone Flow (Fig. 4) is a very distinct flow in a now lava-filled valley. It is most probable that the Rouse-Port Fairy Flow had a break-out or spillover of some kind, producing the Tarrone Flow. It left the main Rouse-Port Fairy Flow, passed through a narrow, 100 m wide 'gate' about 30 km south of Mt Rouse, and continued south along the valley until it ended resting up against the higher elevation margin of its parent Rouse-Port Fairy Flow, some 12 km down slope from where it originated. The diversion of the Tarrone Flow has produced a major inter-flow 'island' 10 km long and 2 to 3 km wide (Fig. 4).

In the last few kilometres of the Rouse-Port Fairy Flow, near the coast, the addition of windblown coastal sand and silt flattens the relief between the stony rises and the depressions, and a separate RTU can be mapped (Sutalo 1996). At the coast itself, the end of the flow is marked by a relatively straight east-west shoreline about 5 km long, and a series of lava tongues extends under the dune-beach system to form shore line 'breakers' (platforms) and reefs. Aeromagnetic surveys over the region indicate that the Rouse-Port Fairy lava flow ends approximately a few hundred metres off the present coast. In contrast, similar airborne imagery over the Mt Eccles Tyrendarra flows to the west of Port Fairy shows magnetic signatures extending about 5 km out to sea, and the dating of Mt Eccles indicates that the sea-level at the time of that eruption was lower than at present. However the coincidence of the present coast and the southern end of the Mt Rouse flows is probably the result of the flows forming a resistant edge to modern coastal erosion, and need not indicate where the sealevel was at the time of the Rouse eruption.

Chronosequence of the Mt Rouse lava flows

The main lava flows recognised in the Mt Rouse lava field are shown in Figure 4. The flows can be placed in a chronological framework using differences between the flows, including distinctive geomorphological features, flow relationships, and sometimes slight differences in mineralogy of the flows. However, it was found that soils do not help with distinguishing individual flows.

The Rouse-Port Fairy Flow

The main Rouse-Port Fairy Flow is the oldest and longest lava flow from Mount Rouse, and extends for a distance of 60 km. The stony rise relief is comparatively low, and generally not more than 5-7 m. Typically honeycomb-textured basalt boulders are embedded in the soil of the stony rises.

The southern part of the Rouse-Port Fairy Flow is interpreted as a single large flow which has divided into two lava flows further down slope, producing as a break-out the Tarrone Flow. Further south the Tarrone Flow splits again, forming three lava tongues and passing around four small inter-flow 'islands'.

Several large distinctive flow tongues of the Rouse-Port Fairy Flow also extend northwestwards from just west of the volcano, for a distance of over 5 km (see Fig. 5). Parts of both of these flows have parallel longitudinal ridges. It is believed that these ridges are remnants of flows which contained lava tubes, and the depressions between the ridges represent areas of collapse. Smaller ridges of the same kind are common throughout the Mount Rouse lava field.

The Spring Flow

The Spring Flow is another early flow which spread to the north and southeast from Mt Rouse, following the course of an earlier Spring Creek for about 6 km and with a total length of 12 km.

The Hawkesdale Flow

The Hawkesdale Flow is the second major flow from Mt Rouse and at 27 km the second longest flow unit. It makes up about half of the eastern side of the lava field. To the south it flows through several narrow 'gates', before stopping about eight km south-west of the township of Hawkesdale (Fig. 5). (It does not reach as far as the Tarrone Flow, as Ollier's (1985) Fig. 2 would seem to indicate). In the west two narrow valley flows leave the main flow, passing around a large 'island' (Ollier's Moorilah Steptoe) and rejoining the main flow further south. Compared to the Rouse-Port Fairy flow, the relief of the Hawkesdale flow is more rugged, with differences in height between stony rises and depressions sometimes greater than 10 m.

The boundary to the northwest with the Rouse-Port Fairy Flow has been inferred, based on differences in relief seen on aerial photographs, and the distribution of stony ridges. Major differences between the two flows are also seen in their narrow valley sectors. The topography of the valley flows of the Rouse-Port Fairy Flow is of wide, flat-topped ridges, usually occurring near the middle of the flows. The narrow lava-filled valleys of the Hawkesdale Flow are comprised of multiple lateral stony ridges with 'collapsed' depressions in between, merging into a single lateral ridge or a series of numerous hump-like ridges (7-12 m high) further to the south.

The Lava Shield

Immediately surrounding the volcano is a low-angle lava shield, which extends for a radius of about 3 km. This lava shield is the youngest of the main flow units. It has a very uneven, rugged stony rise surface of ridges, depressions and hollows (Fig. 2). Relatively fresh, sub-angular to angular boulders and blocks (50-100 cm average diameter) are scattered over the surface. The soil is thin, and mainly confined to cracks between boulders. The relief of the rises is similar to that of the Hawkesdale Flow, but the distance between rises is much less, with rises less than 50 m apart.

It seems likely that the lava shield represents the successive build-up of small lava flows originating from relatively minor eruptions. It is believed that these flows erupted late in the history of Mt Rouse, and the lava shield rests on earlier flows.

A single lava cave was discovered during the mapping of the Rouse flows, with a collapse entrance, rock fall and possible extensions of the cave now below the watertable. About 15 m of flow units are exposed in the walls of the collapse. It has been called Huttons Cave, and lies on the western edge of the Lava Shield about 2 km south of Penshurst (Penshurst South 1:25 000 topographic map 7322-2-S, grid coordinates 612900mE, 580500mN). A plan and cross-section of the cave is given in Sutalo (1996) Appendix 1.

The New Flow

The fifth lava flow group is the New Flow, which consists of a number of small but distinct flows on the south-western edge of the Lava Shield. The flows are approximately 5 km long, and overlie the Hawkesdale Flow, so stratigraphically appear to be recent flows, with a relief of 10-15 m above the other stony rise flows to their east, west and south. Whitehead (1991) traced these flows back through the stony rises of the lava shield to the southern crater of Mt Rouse, making them the youngest of the Mt Rouse flows. Whitehead (1991) stated that the flows emerged from tubes within the lava shield, rather than flowing over the surface of the lava shield, but evidence of lava tubes was not seen in this area (apart from Huttons Cave, further to the north, on the western edge of the Lava Shield.)

EMPLACEMENT OF LONG LAVA FLOWS

Special conditions must have existed for the lava from Mt Rouse to have flowed as far as Port Fairy, 60 km to the south. Only the Campaspe valley flows, at 65 km, exceed the length of the Mt Rouse flows (Coceani 1999). Much work has been done on long lava flows worldwide, to gain a better understanding of processes involved in their formation.

In general, the volume and length of lava flows decreases as the silica content increases (Williams & McBirney 1979). Thus basaltic flows such as those of Mt Rouse are usually more voluminous and longer than high silica rhyolite flows. Walker (1973) analysed the factors affecting the length of lava flows. He considered effusion rates to be the most important controlling factors on lava formation and showed that the distance travelled by a lava flow is proportional to the effusion rate, probably due to the effects of cooling. Lava erupted at higher rates would travel further before cooling lowered its viscosity and inhibited movement. Walker believed that viscosity merely controls the thickness of a lava extrusion, and only indirectly affects the length. Also the effect of the angle of slope of the underlying land surface, though not negligible, is small in relation to other factors.

However, in reality the control of lava lengths is very complex. For instance, effusion rate itself is dependent on a large number of factors: vent shape and dimensions, viscosity, yield strength and magma pressure gradient within the volcano.

Malin (1980) found there to be little support for a direct relationship between flow length and effusion rate in the 87 Hawaiian lava flows he examined. "A statistically more significant relationship exists between flow length and total volume of material extruded" (Malin 1980: 307). However Malin showed that no single factor is most important. Cross-sectional area (probably dependent on the slope, viscosity, and cooling rate), effusion rate, and the total volume all play important parts in the governing of emplacement of lava flows. " One reason for the observed relationship in Hawaii may be that tube-fed flows, with approximately constant cross-sectional area, advanced farther than other types of flows for similar effusion rates and volumes (Malin 1980: 308). It is quite possible that the Hawaiian lava flows would have continued to move many tens of kilometres farther had they not reached the sea".

Atkinson (1990) studied the world's longest lava tube systems, the Undara lava tubes in Northern Queensland - one flow extends over 160 km. It is believed that the flows formed in a very short period of time (a period of three weeks is suggested) and this great length is attributed to a very high effusion rate and favourable topography. Ollier (1985) suggested that the effusion rate might be less important than the continuity of flow in time. Lava tubes will block if an eruption ceases just long enough for the lava to solidify. If the lava is erupted without interruption, it is more likely that a single very long flow is produced, with a lava tube system operating continuously for a long period.

In order to produce a long lava flow the lava must be able to travel a great distance before it cools and freezes. The best way to avoid cooling of lava during transport is by insulating emplacement, as seen in the form of inflation crust rises and lava tube systems. Swanson (1973) indicated that lavas within tubes flowed virtually isothermally, cooling at a rate of only 10^0 C/km. Malin (1980) states, "if flow length were limited by cooling to solidus temperatures, such eruptions could have possibly produced flows as long as 200 km" (p.308), quite sufficient to explain the 60 km Mt Rouse flow.

Hon et al. (1994) studied the emplacement and inflation of pahoehoe sheet flows of active lava flows on Kilauea Volcano, Hawaii. From observations and measurement they established that given sustained lava supply, sheet flows follow a progression from thin sheets to thick inflated flows that are emplaced as a sequence of 'flow lobes'. A flow lobe is the package of lava that is contained within its own crust. Successive sheet-flow lobes remain hydrostatically interconnected and inflate to the same thickness (Keszthelyi 1995).

Hon et al. (1994) concluded that during long-lived eruptions, preferred pathways develop within older portions of the sheet flow that are no longer actively inflating; these pathways evolve into lava tube systems which efficiently deliver lava at velocities of several kilometres per hour to a flow front that may be tens of kilometres away. Keszthelyi et al. (1996) concluded that "long lava flows on the Earth are dominantly (perhaps exclusively) emplaced as inflation pahoehoe flows".

Lava crust inflation mechanisms can be used to explain the development of the Mt Rouse lava flows. Over time lavā inflation sheets may develop one or more lava tube systems following preferred pathways, especially in confined valley flows. Observations of aerial photographs and field-based geomorphology studies have enabled reconstruction of the preferred pathways taken by individual lava flows within the Mount Rouse lava field (Fig. 5).

The best evidence found to indicate the presence of lava tubes in the Mount Rouse lava field is Huttons Cave, discovered and mapped during this study. This 14 m deep collapsed lava tube is found 2 km west of the scoria cone, on the edge of the lava shield (Sutalo 1996, Appendix 1: 64). There is no evidence at the surface of any ridge extending over the cave - rather the cave underlies later lava flows. Water-filled cavities in the bottom of the east and west walls of the cave are interpreted as the drainage pathway of a lava tube leading away from the volcano. Huttons Cave is very similar in appearance to the Byaduk lava caves of Mt Napier, which are collapsed lava tubes (Ollier & Brown 1965).

The Mt Rouse flow was a lava crust inflation and tube-fed flow, as is indicated by its length and its surface morphology, with stony rises and low depressions which are possibly inflationary and compressional features, and many large, paired and lateral stony ridges (indicative of collapsed lava tubes or lava sheets). The flows were probably emplaced in a short time, perhaps only weeks. The fluid nature of the lava flows is indicated by the apparent ease with which the lava has several times divided into flows which continued further down slope, travelling through narrow 'gates', and passing around such obstacles as 'islands' composed of remnants of higher and older lava flows.

MINERALOGY

The Mt Rouse basalts are alkali basalts and are petrographically remarkably similar along the 60 km length of the flows. An excellent example is provided by the Tarrone Flow, which is a branch flow fed from the main Rouse-Port Fairy flow (Fig. 4) and shows little variation from the parent flows to its north, being indistinguishable from them both in hand specimen and thin section. Thus it is appropriate to describe a single, general basalt type. (Note however that the lava flow sub-divisions shown in Fig. 4 are based on geomorphological features and do not imply or require significant petrographic differences.)

Hand specimens of basalt collected from the surfaces of the flows are vesicular (10-15% range) with some vesicles up to 1.5 cm in length. Fresher samples are granular, dark-grey to grey-blue in colour, and very fine-grained with vesicular texture. Small phenocrysts of plagioclase and light green olivine can be seen in hand sample, with small phenocrysts of blue-black clinopyroxene visible in the groundmass in some cases. In most samples the green colour of fresh olivine has been altered to a brown-yellow, and feldspars have altered to a white clay, making them conspicuous in hand specimen. Calcite, zeolite minerals and limonite (a combination of Fe-oxides – goethite and hematite - and clays) often form in the vesicles.

In thin section, the Mt Rouse basalts have a fine-grained interlocking matrix, with crystals seldom greater than 1 mm. The most abundant mineral is plagioclase, which is approximately 50% of the rock. It occurs as lathes, which have a maximum size of 1.3 mm long with an average of 0.5 mm, and also interstitially. These lathes preserve well-defined multiple twinning unlike anhedrally-shaped strongly-zoned crystals that display ill-defined twins with strong undulose extinction.

Clinopyroxenes as mostly fine grains make up about 20% of total rock composition and are disseminated throughout the groundmass as fine subhedral crystals. Phenocrysts are found in the southern flows near the coast, and also in the northern areas, especially in the lava shield, but make up only a few percent of the total amount. Olivine is about 15% of the rock composition with grains averaging approximately 0.5 mm in length. Most of the samples collected show very little evidence of alteration except for partial alteration of olivine to a translucent, reddish-brown iddingsite, mainly concentrated on the outer edges of and along fractures in the olivine grains. The primary opaque minerals in the Mt Rouse basalts are magnetite, commonly occurring as small square-planar minerals, and lesser ilmenite.

The incompatible trace elements for Mt Rouse show close similarities to those of alkali ocean island basalts (OIB), i.e. enriched in the more incompatible elements, and depleted in elements chemically similar to the heavy rare earths (i.e. Y). The Mt Rouse alkali basalts are typical intraplate magmatic rocks. The close similarities between samples from different parts of the Mt Rouse flow are consistent with these rocks representing a single magmatic unit, and fed from a single magma chamber at depth.

DATING OF THE MT ROUSE LAVA FLOWS

The degree of weathering and soil formation can be used to estimate the relative age of the Mt Rouse lava flow, and of the surrounding earlier lava flows from other volcanoes. The earliest flows on the Western Plains, dated by K/Ar at 4.5 Ma, show deep kaolinitic profiles with mottling and occasional ironstone development, and suggest the effects of late Tertiary hot and wet climate. Flows of intermediate age (1-3 Ma) have one to two metres of brown clay soil and form a level, relatively stone-free plain, with well-developed gilgai. Flows of less than 1 Ma, many of which are late-Quaternary in age and some less than 20,000 B.P., have well-preserved flow surfaces and little or no soil cover, and are associated with lakes and swamps due to disrupted drainage (Joyce 1999). These young flows show the stony rise topography characteristic of Mt Rouse, Mt Napier and Mt Eccles, and other areas of long and voluminous flow on the Western Plains.

Overall the geomorphological and regolith evidence suggests a young age for the Mt Rouse flows, and this is supported by K/Ar ages for four samples from the Mt Rouse-Port Fairy flows, to the south near Port Fairy, where McDougall & Gill (1975) obtained ages of 0.312±0.005 Ma, 0.301±0.008 Ma, 0.404±0.017 Ma, and 0.438±0.007 Ma. Using more recent decay constants, Ollier (1985) re-calculated these figures to 0.320 Ma, 0.309 Ma, 0.415 Ma, and 0.450 Ma respectively.

New dates for lava flows immediately south of Mt Rouse have been obtained by Gray (pers. comm. 1996), with ages of 0.35 Ma and 0.32 Ma for basalt samples from the upper section of the Hawkesdale Flow, some 20 km south of Mt Rouse. These ages are consistent with the ages (above) reported for flows near Port Fairy by McDougall & Gill (1975).

Ollier (1985) found that the pyroclastics of the scoria cone at Mt Rouse were unsuitable for isotopic dating, but he obtained a date for a single, fresh-looking lava flow interbedded with the eastern scoria margin of the deep southern crater. The sample, which would seem from field relationships to be part of the Lava Shield flows and so part of the final stages of the Mt Rouse activity, gave an age of 1.82±0.004 Ma. Generally the K/Ar method of dating has been found unsuitable for the lavas of the Mt Rouse flows because they are vesicular and often partly weathered. Ollier (1985) was careful to point out that his single sample was fresh and unaltered in appearance and hence suitable for K/Ar dating.

Discussion of dates

Throughout the NVP the formation of pyroclastic scoria cones is associated with the last stages of volcanism (Joyce & Sutalo 1996). The interbedding of the lava flow with scoria implies that the date obtained by Ollier (1985) is late in the volcanic history of Mt Rouse. McDougall & Gill (1975) maintain that it is unlikely that the ages they obtained near Port Fairy are too old, but do not discuss the possibility of them being too young. The 1.5 Ma difference between the dates for the coastal flows and upper Hawkesdale flows, and the flow interbedded with scoria at Mt Rouse dated by Ollier, suggests that: (i) there are two flows and thus two distinct periods of high volcanic activity; (ii) the flows dated south of Mt Rouse and near Port Fairy are not from Mt Rouse but from a second or third source; or (iii) the discrepancy in dates must be attributed to an error in the dating of the sample obtained by Ollier.

The Mount Rouse basalts are very distinctive compared to the nearby flows of the basalt plains, and the flow boundaries have now been closely mapped. No volcanic vents have been found in the vicinity of Port Fairy that could be an alternative source for the flows dated by McDougall & Gill. The RTU mapping and flow mapping in the field described in this paper indicate that the lava flows dated by McDougall and Gill near Port Fairy and by Gray nearer Mt Rouse are all from Mount Rouse. Geomorphic and regolith relationships over the entire flow suggest that two distinctive periods of eruption for Mt Rouse are unlikely. It is concluded that the age obtained by Ollier is not correct. On the other hand the consistency of the dates obtained by McDougall & Gill (1975) near Port Fairy, and nearer to Mt Rouse by Gray (pers. comm. 1996), suggests they are more reliable, and all the Mt Rouse activity took place some 0.3 Ma ago.

Eruption sequence

1. Large volumes of very fluid lava were extruded from the Mt Rouse volcano to form the major Rouse-Port Fairy Flow. Lava inflation sheets formed the broad lava fields to the west and south-west of the eruption point, and lava of the Spring Flow flowed down the short Spring Creek valley to the east and south.
2. Overflow from lava sheets of the Rouse-Port Fairy Flow sent flows down narrow pre-existing stream valleys, lava tubes developed, and fed the flows, and lava reached the coast at Port Fairy, 60 km south of the eruption point.

3. The Tarrone Flow branched from the central section of the Rouse-Port Fairy Flow and followed a narrow stream valley, passing around a large inter-flow 'island,' and stopping 12 km further down slope up against the margin of its higher elevation parent flow.
4. Further extrusion of lava from Mt Rouse produced the major Hawkesdale Flow, which branched down a number of pre-existing stream valleys, forming many inter-flow 'islands'. The flow stopped short of rejoining the main Rouse-Port Fairy flow, due to ridges of older stony rise topography (not from the Mt Rouse volcano).
5. The main scoria cone was built by fire-fountaining, and ash fell on the plains to the north and northwest.
6. A new eruption centre was formed to the south of the main cone, perhaps initially by maar eruption, and a scoria-rimmed lava lake overflowed along a lava channel to the east of the crater, producing the Lava Shield unit, built up of successive small lava flows, and burying any previous flows.
7. Further flows, mapped here as the New Flow, spread southwards beyond the southern margin of the lava shield, fed from tubes within the lava shield.
8. Ash and scoria erupted from the new crater, burying the lava channel (6) on the crater rim, and finally subsurface withdrawal of lava from the lava lake produced a deep pit crater.
9. The pit crater developed a shallow lake.

CONCLUSIONS

Mt Rouse erupted about 350,000 years ago. The basaltic lava flows of Mt Rouse are the longest in Western Victoria, covering a distance of 60 km from north to south. The stony rise topography of the lava flows shows that lava sheet inflation and associated lava tube systems provided the mechanisms for long lava flow development. Emplacement of the flows probably occurred relatively quickly, possibly over a period of a few weeks to a few months.

Detailed mapping has shown that more than one eruption point is unlikely. There is no alternative source for the near-coastal basalts near Port Fairy, and all the mapped flows apparently originated from Mount Rouse. (The basanite dome of Whitehead (1991) six km southwest of Mt Rouse, does not appear to be directly related to the Mt Rouse eruption, showing no obvious flow contribution to the Mt Rouse flows, and may be a separate volcano of older age). The distinct homogeneity in petrography and geochemistry for all the Mt Rouse basalts, and the geomorphology and regolith of the flows, strongly support the conclusion that Mt Rouse was the eruptive centre for all the flows.

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LATE CENOZOIC BASALTS, UPLANDS PROVINCE, N.E. VICTORIA: IN RELATION TO THE NEWER VOLCANICS BASALTS OF WESTERN VICTORIA

Frederick L. Sutherland[1], Ian T. Graham[1] & Horst Zwingmann[2]

[1]Geodiversity Research Centre, The Australian Museum, 6 College St, Sydney, NSW 2010
[2]CSIRO Petroleum, PO Box 1130, Bentley, WA 6102

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The Uplands Province of NE Victoria consists of two petrographically and geochemically similar basalt types of two distinct ages (2.3 and 3.6 Ma) that erupted as flows during peak Pliocene volcanic activity in the Newer Volcanics Province of western Victoria (2-4 Ma). The lavas are enriched transitional olivine basalts whose trace element chemistry has characteristics of both the Plains and Cones series basalts of the Newer Volcanics Province. Detailed isotopic studies (Sr, Nd, Pb) on the older basalt suggests that mixed asthenospheric melt-crustal interactions occurred during basalt genesis. The basalts have been moderately dissected since their initial eruption at 3.6 Ma, with an average downcutting rate of 5 mm/yr.

Key words: Uplands Province, Newer Volcanics Province, olivine basalts, isotopes, petrogenesis, Pliocene, erosion rate.

THE UPLANDS Province of north-eastern Victoria, (previously the Morass Creek volcanics of Hills, 1938) was first correlated with the Newer Volcanics Series by Howitt (1879). These volcanics were mapped as such on the Geological Survey of Victoria maps up until 1902. After this, all the volcanic occurrences east of Melbourne were assigned to the Older Volcanics Series (Hills 1938), although Easton (1937) still related them to the Newer Volcanics Series. On the Tallangatta Geological Survey of Victoria map (Bolger and King 1976), they were named as the Morass Creek Basalt Unit and given a Late Pliocene age, completely separate from the Older Volcanic Series.

The origin of enriched geochemical signatures observed in many continental intraplate basalts such as the Late Cenozoic basalts of Victoria is an ongoing debate that follows two main schools of thought:

1) these signatures come from a subcontinental lithospheric mantle source (e.g. Allegre et al. 1982; McDonough et al. 1985; Turner and Hawkesworth 1995; Stewart and Rogers 1996; Price et al. 1997).

2) these signatures reflect crustal contamination of asthenospheric mantle or plume-derived melts en route to the surface (e.g. Hawkesworth and Vollmer 1979; Carlson et al. 1981; Chesley and Ruiz 1998).

Here, we present new geochemical and isotopic data for the Uplands Province basalts and compare them with the Newer Volcanics Province of western-central Victoria. We comment on the enriched geochemical signatures within these Late Cenozoic basaltic provinces, in relation to the two cited models, and their relationships to mid ocean ridge basalts (MORB) and oceanic island basalts (OIB) sources. Two MORB-types are represented in the underlying eastern Australian asthenosphere, Indian-type MORB (I-MORB) and Pacific-type MORB (P-MORB).

GEOLOGICAL SETTING

The Uplands Province (Wellman 1974) lies in the eastern highlands 9 km north of Benambra. Several basaltic flows extend for at least 20 km along the valley floors of Deep Creek, Morass Creek and Mitta Mitta River (Fig. 1). Hills (1938) described the physiographic settings, recognised several superimposed flows along cliff sections and believed a hill rising above Frasers Tableland marked an eruptive centre. According to Easton (1937), the basalts flowed along the valleys of the tributary streams and the valley of Gibbo River where they dammed the river and initiated a lake. Wellman (1974) equated these basaltic rocks with the Newer Volcanics Province of Western Victoria on the basis of their young age, physiographic settings, vesicular nature of the flows, and the common occurrence of 'iddingsitised' olivine. He estimated the original volume of basalts to be

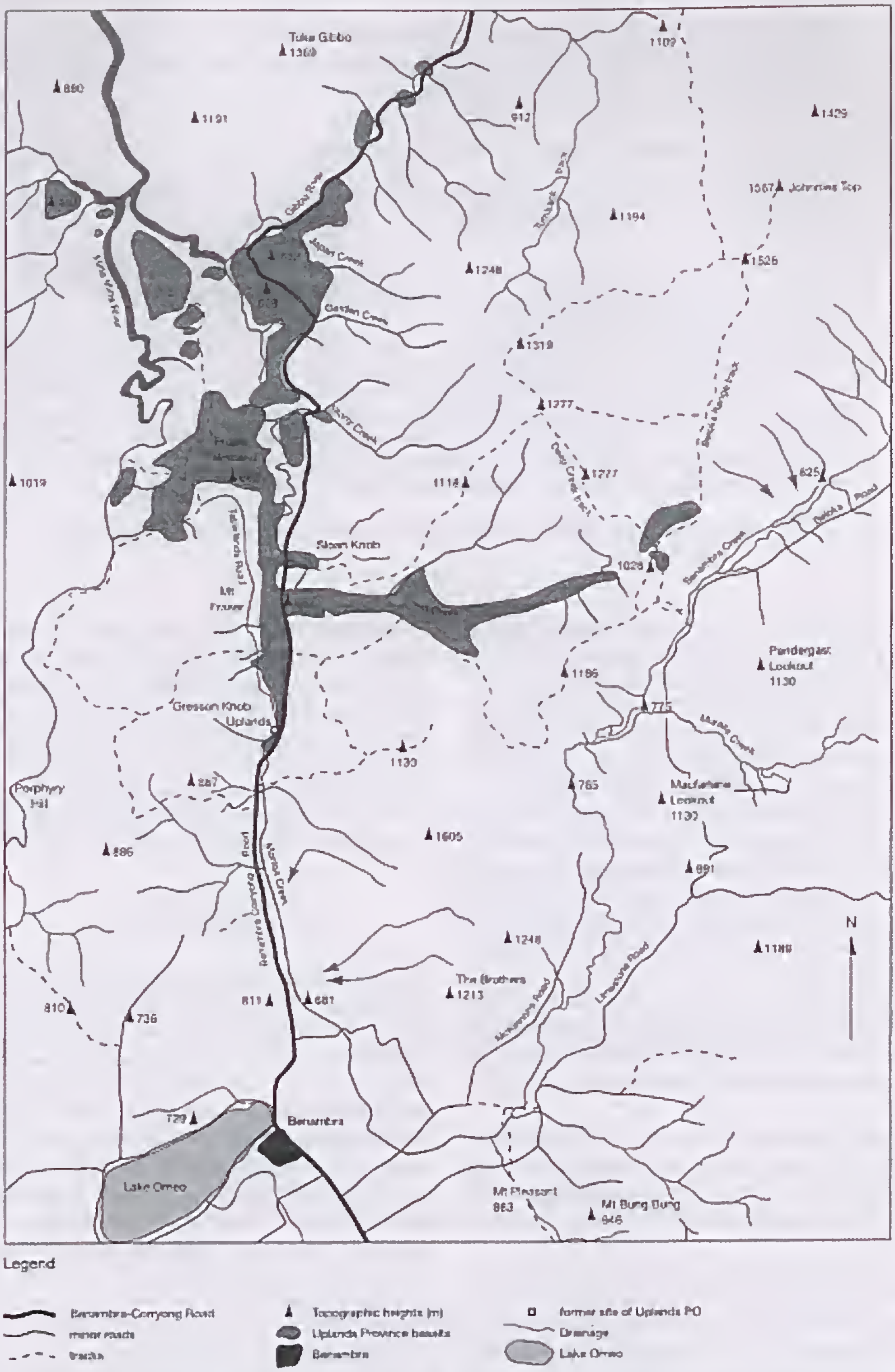


Fig. 1. Location and extent of the Uplands Volcanic Province (Geology adapted from Bolger and King, 1976). Map area extends from 147° 37' E to 147° 52' E (west to east) and 36° 42' S to 37° 00' S (north to south).

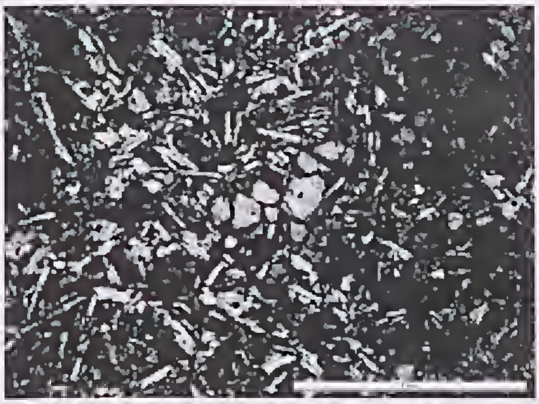


Fig. 2. Photomicrograph of basalt from Stony Creek (field of view 4 mm across; crossed polars).

some 2 km^3, based on their present thickness and extent.

Most of the flows infill relative topographic lows in the area. In some cases, the basalts directly overlie the foliated Ordovician metasedimentary sequence (e.g. the hill above Deep Creek crossing at 620m asl; 36° 49.8'S 147° 42.6'E). Elsewhere, they overlie weathered Lower Triassic alkali granitic rocks of the Mount Leinster Complex (e.g. Stony Creek at 620m asl; 36° 48.0'S 147° 42.8'E). Overall, individual flows are generally only a few metres thick, but where Morass Creek has deeply incised through the area, flows of up to at least 50m thickness are seen (e.g. near 36° 49.8'S 147° 42.6'E), suggesting infilling of a steep palaeovalley.

Two distinct flows are discernible between 920 and 960m asl along the forestry track off Beloka Road, about 3 km north-west of Pendergast Lookout (near 36° 49.9'S 147° 47.5'E). Here, a fine-grained relatively massive micro-vesicular olivine basalt flow with a weathered vesicular top and base is sharply overlain by a highly scoriaceous fine-grained olivine basalt with a highly vesicular base. The overlying basalt occupies a channel cut into the lower basalt and the adjacent metasediments suggesting a period of lateral drainage incision between the two phases of eruption. The basalts reach their highest elevation here, suggesting an eruptive source from the east, from where flows descended into Deep Creek valley to below 680m asl. Further sources may lie in the centre of the field near Fraser Tableland, as vertical dyke-like basalt bodies (2m wide and 3m high) intrude the main basalt tongue at Stony Creek (36° 48.0'S 147° 42.8'E) and may represent feeders for higher flows. The basalts reach their lowest topographic levels to the north-west, where they descend to 500m asl near the junction of the Gibbo and Mitta Mitta Rivers.

PETROGRAPHY

All of the basalts studied are petrographically very similar, though two textural types are apparent; a fine-grained relatively massive micro-vesicular olivine basalt and a fine-grained highly scoriaceous olivine basalt. Under the microscope, they exhibit micro-porphyritic to glomeroporphyritic intergranular textures, generally defined by moderately common phenocrysts and phenocrystic aggregates of olivine and rarer titanian augite, set in a groundmass of non-aligned plagioclase laths, along with intergranular olivine and titanian augite (Fig. 2). Accessory phases include abundant apatite (generally prismatic 'needle-like' grains), platy ilmenite and equant magnetite. Minor phases in some flows include late segregations of feldspar and devitrified glassy patches.

Basalt phases

Olivine phenocrysts (0.25 to 3mm, av. 0.5mm) are generally ovoid subprismatic grains with sharp boundaries against the groundmass phases. They range from weakly fractured unaltered to highly fractured, marginally altered grains. Many contain tiny subhedral equant opaque spinel inclusions. Skeletal, highly embayed xenocrystic grains are rare. The phenocrystic aggregates range up to 2mm across and contain grains with embayed boundaries.

The phenocrystic and groundmass titanian augite grains are all weakly pleochroic (paler to darker pink-brown or colourless to pale pink), anhedral to subhedral, equant to prismatic grains (<<0.1 to 2mm). Most occur in interlocking intergranular aggregates. Some show compositional zoning (with dark pink-brown rims and colourless cores) and many have cuspate-lobate boundaries with groundmass phases, particularly plagioclase. Some grains have narrow replacement rims of chlorite/goethite. Within moderately fractured grains, there is also fracture replacement by fine-grained chlorite/goethite.

Plagioclase (<0.1 to 1.3mm, av. 0.5mm) forms subhedral laths with embayed boundaries with other groundmass phases. Well-developed multiple twin lamellae are common and some crystals show moderate to well-developed core to rim zoning from more calcic to sodic compositions. Alkali feldspar occurs as a late interstitial phase, commonly as cuspate-lobate forms. Most are untwinned, although some grains have well-developed simple and polysynthetic twin lamellae, indicative of anorthoclase. Chalcedonic quartz/chlorite pseudomorphs after former glass form cuspate-lobate patches in some basalts.

Vesicles/Amygdales

Vesicles and amygdales range in size from <<0.1 to 35mm, and are mostly spherical to ellipsoidal, though cuspate-lobate forms appear within some basalts. They range from empty (vesicles) to a range of infillings (amygdales) including:

1. Zoned narrow walls of chlorite/goethite with central infillings of carbonates.
2. Complete infillings of carbonates.
3. Complete infillings of prismatic zeolites.

Alteration within the basalts varies from very minor (goethite along fractures) to pervasive (partial replacement of ferromagnesian phases and interstitial mixtures of chlorite and goethite). Secondary assemblages vary and include:

1. Fracture and rim-related replacement of olivine by fine-grained mixtures of chlorite/goethite (iddingsite).
2. Goethite replacement of opaques and ferromagnesian minerals.
3. Chlorite rims around titanian augite.
4. Interstitial patches of chlorite.
5. Carbonate/chlorite replacement of olivine.
6. Fine-grained mixtures of clays and quartz replacing alkali feldspar.
7. Interstitial patches of zeolites.

ANALYTICAL METHODS

Potassium-argon analysis

The K-Ar isotopic age determination was made on basalt chips (< 10mm across), crushed with a shatter box (Siebtechnik ring grinder with chrome steel barrel) into a <500 μm fraction. Potassium concentration was determined by atomic absorption (Varian AA 20) using Cs at a concentration of 1000 ppm for ionisation suppression. A 100 - 200 mg of sample aliquot was dissolved with HF and HNO_3 (Heinrichs and Herrmann, 1990), and then diluted to 0.3 to 1.5 ppm K for the atomic absorption analysis. Ar isotopic determination followed a similar procedure to Bonhomme et al. (1975). The sample was pre-heated under vacuum at 80° C to reduce atmospheric Ar adsorbed onto the mineral surfaces. Argon was extracted from the separated mineral fractions by fusing the sample within a vacuum line serviced by an on-line ^{38}Ar spike pipette. The isotopic composition of the spiked Ar was measured using a high sensitivity on-line VG3600 mass spectrometer. The ^{38}Ar spike was calibrated against the international standard biotite GA1550 (McDougall and Roksandic 1974). After fusion of the sample in a low blank Heine resistance furnace, the released gases were purified with a Cu_2O getter for the first step and two TiO_2 getters for the second step. Blanks for the extraction line and mass spectrometer were systematically determined and the mass discrimination factor was determined periodically by airshots. International standards were measured for calibration purposes. The uncertainty for the argon analysis is below 1 %. The K-Ar age was calculated using ^{40}K concentration and decay constants recommended by Steiger

Location	Rocktype	K (%)	^{40}Ar (%)	Age (Ma)
[1]Stony Creek	Massive basalt	1.33	8.62	3.59 ± 0.44 (± 2 σ)
[2]2km N Uplands PO	Scoriaceous basalt	1.57	59.2	2.32 ± 0.06 (± 2 σ)
[2]3km N Uplands PO	Scoriaceous basalt	1.48	59.3	2.33 ± 0.06 (± 2 σ)

([1] this study; [2] recalculated ages of Wellman, 1974)

Table 1. K-Ar wholerock geochronology for the Uplands Province.

and Jager (1977). The age uncertainty takes into account the errors during sample weighing, $^{38}Ar/^{36}Ar$ and $^{40}Ar/^{38}Ar$ measurements and K analysis. The sample analysed yielded a low radiogenic ^{40}Ar concentration of 8.62%, which produced the relatively high uncertainty.

Major and minor elements

The major, minor and selected trace elements were analysed by Maggi Loubser at the XRF and XRD Facility, University of Pretoria, Pretoria, South Africa, using X-ray fluorescence (XRF). Initially, samples were ground to <75 μm in a mild steel milling vessel, roasted at 1000°C to determine Loss On Igni-

Sample	DR 16926	DR 16930	DR 16899
Locality	Stony Creek	Gibbo Park	Uplands PO
Latitude	36° 48.0' S	36° 45.8' S	36° 50.0' S
Longitude	147° 42.8' E	147° 41.8' E	147° 42.3' E
Elevation	640m	520m	640m
Rock type	Massive basalt	Vesicular basalt	Scoriaceous basalt
SiO_2	48.52	50.09	49.72
TiO_2	1.92	1.95	1.96
Al_2O_3	14.48	15.59	14.93
Fe_2O_3	2.31	2.43	2.33
FeO	8.33	8.75	8.40
MnO	0.15	0.16	0.15
MgO	7.76	7.62	7.39
CaO	8.45	8.34	8.18
Na_2O	2.96	3.23	3.55
K_2O	1.62	1.65	1.59
P_2O_5	0.53	0.59	0.54
LOI	1.24	0.90	0.19
Total	98.27	101.30	98.93
CIPW Norm, Anhydrous, with $Fe_2O_3/(FeO+Fe_2O_3) \sim 0.2$.			
Or	9.86	9.71	9.51
Ab	25.80	27.21	30.41
An	22.09	23.07	20.36
Mt	3.46	3.51	3.43
Il	3.76	3.69	3.77
Ap	1.29	1.39	1.29
Di	14.23	11.62	13.94
Hy	8.13	7.74	3.37
Ol	11.37	12.05	13.91
Cm	0.05	0.04	0.04
D.I	35.67	36.92	39.92
An%	46.12	45.88	40.10
Mg No.	62.41	60.81	61.06

Analyst: M.Loubser, Department of Geology, University of Pretoria, South Africa.
Note that analytical totals fall outside normal ranges, due to uncertainties in the ignition loss determinations. The other oxide values fall within accepted ranges for the international rock standards used.

Table 2. XRF major and trace element analyses and CIPW norms.

tion (LOI), and, after adding 1 gram of sample to 6 grams of $Li_2B_4O_7$, fused into a glass bead. XRF analyses were then executed on the fused glass bead using an ARL 9400XP+ spectrometer. For selected trace element analyses, another aliquot of the sample was pressed into a powder briquette.

Trace and rare earth elements (REE)

These were analysed by Dr Andreas Spath at the Geology Department, University of Cape Town, Rondebosch, South Africa, using inductively coupled plasma mass spectrometry (ICP-MS). This involved the dissolution of 50 mg of each sample with a standard acid digestion procedure using ultra-clean HF and HNO_3. Standards were made-up from artificial multi-element standard solutions. The samples were analysed on a Perkin Elmer Sciex Elan 6000 ICP-MS. The instrument operating conditions were typically:

Sample	DR 16926	DR 16930	DR 16899
Rocktype	Massive basalt	Vesicular basalt	Scoriaceous basalt
Sc	16.9	17	17.4
V	169	163	172
Cr	223	196	223
Co	56.7	52.3	64.9
Ni	147	137	147
Cu	53.9	56.8	54.4
Rb	30.5	22.5	24
Sr	697	592	643
Y	17.2	17.7	17.7
Zr	171	177	174
Nb	40.9	42.4	41.9
Cs	1.18	0.34	0.25
Ba	315	275	328
La	24	25.9	24.7
Ce	46.2	49.4	47.4
Pr	5.48	5.89	5.6
Nd	23.1	24.5	23.6
Sm	4.77	5.03	4.95
Eu	1.68	1.75	1.72
Gd	4.89	5.09	4.99
Tb	0.68	0.71	0.69
Dy	3.74	3.88	3.87
Ho	0.68	0.70	0.68
Er	1.69	1.72	1.73
Tm	0.22	0.22	0.22
Yb	1.27	1.33	1.30
Lu	0.18	0.18	0.18
Hf	3.62	3.75	3.69
Ta	3.74	3.85	3.87
Pb	2.67	2.78	2.66
Th	3.00	3.07	3.08
U	0.95	1.02	0.95
Ga*	22	24	22

Analyst: A.Spath, Department of Geology, University of Cape Town, South Africa.
(* determined by XRF; Analyst: M.Loubser, Department of Geology, University of Pretoria, South Africa)

Table 3. ICP-MS trace and rare earth element analyses.

Nebuliser gas flow of 0.81 L/min; Main gas flow of approx. 15 L/min; Auxilliary gas flow of approx. 0.75 L/min; Autolens voltages were ^{9}Be = 8.6V, ^{59}Co = 9.2V, and ^{115}In = 9.8V; the ICP RF forward power was 1100W. The instrument operating conditions were optimised to minimise the formation of doubly-charged ion ($Ba^{2+}/Ba^{+} < 0.03$) and oxides ($CeO/Ce < 0.03$). The instrument sensitivity for ^{103}Rh was approx. 25 000 cps/ppb. Three replicates of each sample were analysed with 20 sweeps per replicate. The dwell times were 35-50 ms per mass peak and the analytical time for each sample was 1:41.58 min. Internal standardisation was achieved using ^{103}Rh, ^{115}In, ^{187}Re and ^{209}Bi. Interference corrections were made for isobaric interferences and for the more severe doubly-charged ion and oxide interferences (particularly on the REE).

Strontium, neodymium and lead isotopes

The techniques for chemical separation and measurement of these isotopes follow procedures described by Zhang et al. (2001). Sr and Nd isotopes were determined by Karen Blacklock from CSIRO Petroleum, North Ryde, Sydney, NSW. The ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd ratios were measured on a VG Sector 354 mass spectrometer with multiple collectors on its fully automatic mode and normalised to ^{86}Sr/^{88}Sr = 0.1194 and ^{146}Nd/^{144}Nd = 0.7219 respectively. Replicate analyses of NBS SRM 987 gave ^{87}Sr/^{86}Sr = 0.710287 ± 0.000012 (external precision at 2σ) and the O'Nions standard gave ^{143}Nd/^{144}Nd = 0.511116 ± 0.000014 (external precision at 2σ).

Lead isotopes were determined by Barbara Gardner and Geoff Denton from CSIRO Exploration and Mining, North Ryde, Sydney, NSW. Lead isotope compositions were analysed on a thermal ionisation mass spectrometer (TIMS VG-ISOMASS 54E) run in fully automated mode after dissolution of samples using acid digestion techniques. The precision on the isotopic ratios based on > 2000 analyses of the international standard SRM 981 and replicate analyses of natural samples is ± 0.05% (2σ) for the ^{208}Pb/^{206}Pb and ^{207}Pb/^{206}Pb ratios and ± 0.1% (2σ) for the ^{206}Pb/^{204}Pb. Data were normalised to international standards NBS SRM 981, by applying a correction factor of +0.08% amu to allow for comparisons between laboratories.

RESULTS

K-Ar dating

Both new (this study) and old (Wellman, 1974) K-Ar dating for the Uplands Province (Table 1) shows that the basalts are Middle to Late Pliocene in age, ranging from 2.32 Ma for scoriaceous basalt at Uplands in the south (Wellman 1974), to 3.59 Ma for massive basalt at Stony Creek near the centre of the province. This age difference of 1.27 Ma suggests at least two episodes of eruption (see above), although further flows between the dated flows may be present.

Major elements

The compositions and norms of three basalts (Table 2) are very uniform with a restricted range, i.e. SiO_2 (48.5-50.1), TiO_2 (1.9-2.0), Al_2O_3 (14.5-15.6), FeO

^{87}Sr/^{86}Sr	(2 σ)	^{143}Nd/^{144}Nd	(2 σ)	εNd
0.704905	0.0013	0.512805	0.0017	3.400

(Analyst: K. Blacklock, CSIRO Petroleum, Sydney, NSW)

^{206}Pb/^{204}Pb	^{207}Pb/^{204} Pb	^{208}Pb/^{204} Pb	Pb (ppm)
18.306	15.544	38.257	1.35

(Analyst: B. Gardner, CSIRO Exploration and Mining, Sydney, NSW)

Table 4. Strontium, neodymium and lead radiogenic isotope data for Stoney Creek basalt (DR 16926).

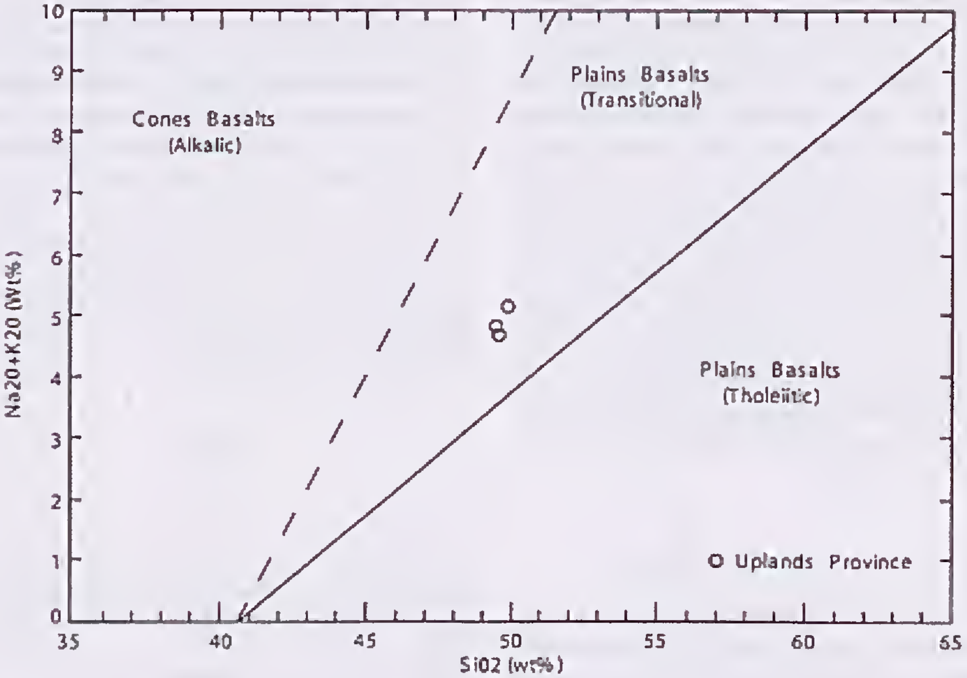


Fig. 3. Total alkalis vs silica diagram (after Vogel and Keays 1997).

(8.3-8.8), MgO (7.4-7.8), CaO (8.2-8.5), Na_2O (3.0-3.6), K_2O (1.6-1.7) and P_2O_5 (0.5-0.6). In normative terms (using a calculated $FeO/(FeO+Fe_2O_3)$ of 0.2), they contain diopside (11.6-14.2), hypersthene (3.4-8.1) and olivine (11.4-13.9), and can be classified as transitional olivine basalts. The Mg values (60.8 - 62.4), differentiation index (35.7 - 39.9) and anorthite% (40.1 - 46.1) suggest they are moderately evolved basalts. On the TAS diagram of Le Maitre (1989), the basalts of the Uplands Province plot as either basalts or trachyandesites. They are essentially hawaiites transitional to olivine tholeiites.

Minor and trace elements

In terms of trace elements (ppm, Table 3), the Uplands Province basalts show little variation in chemistry with moderately high Cu (54-57); moderate V (163-172), Cr (196-223), Ni (137-147), Rb (23-31), Sr (592-697), Y (17-18), Zr (171-177), Nb (41-42), Ba (275-328); and low Hf (3.6-3.8), Ta (3.7-3.9), Pb (2.7-2.8), Th (3.0-3.1) and U (0.9-1.0).

Vogel and Keays (1997) distinguished three main compositional suites amongst the Newer Volcanics Province of Western Victoria using the total alkali vs silica diagram (of Macdonald and Katsura 1964) termed these Cones Basalts (alkalic), Plains Basalts (transitional) and Plains Basalts (tholeiitic). On this diagram (Fig. 3). the Uplands basalts clearly fall into their Plains Basalts (transitional) suite. Furthermore, using the fields for their three basalt suites on trace element plots, the Uplands basalts plot with their transitional basalts on both the Zr vs Nb (Fig. 4) and Sr vs Nb (Fig. 5) diagrams. On the Gd/Yb vs La/Sm diagrams, the Uplands plots lie outside the transitional field due to higher La/Sm ratios, but are much closer to this field than for the other basalt fields. However, on the Nb/Zr vs Nb/Y diagram, they plot just within the field for alkalic basalts, although still close to the transitional field. Thus, in geochemistry, the Uplands basalts resemble the transitional Plains Series basalts of the Newer Volcanics Province, although with minor differences.

On the extended multi-element primitive-mantle normalised diagram (Fig. 6), the basalts exhibit distinct positive anomalies for Nb and Ti, and negative anomalies for Rb, Cs, Pb, Th, Ce, Sc, V, Ni and Cr. This again attests to their transitional nature, suggesting a moderate degree of fractionation.

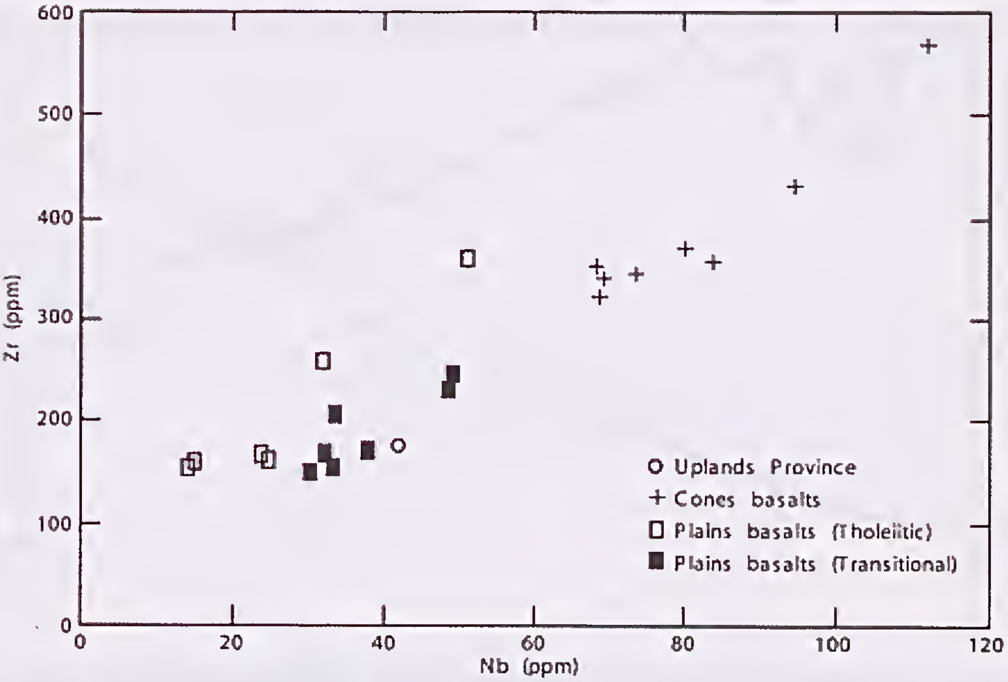


Fig. 4. Zr vs Nb diagram (after Vogel and Keays 1997).

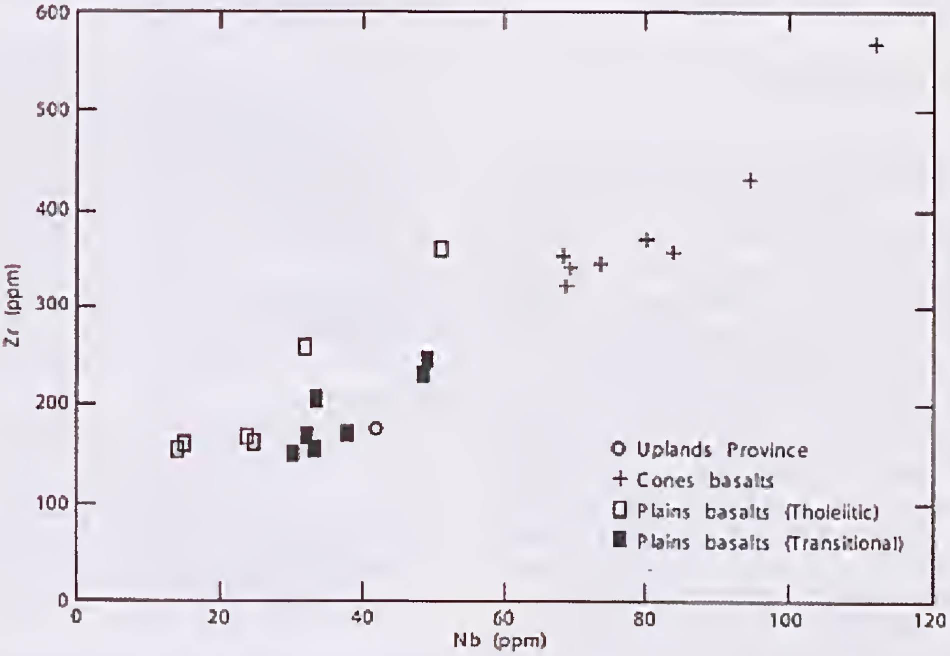


Fig. 5. Sr vs Nb diagram (after Vogel and Keays 1997).

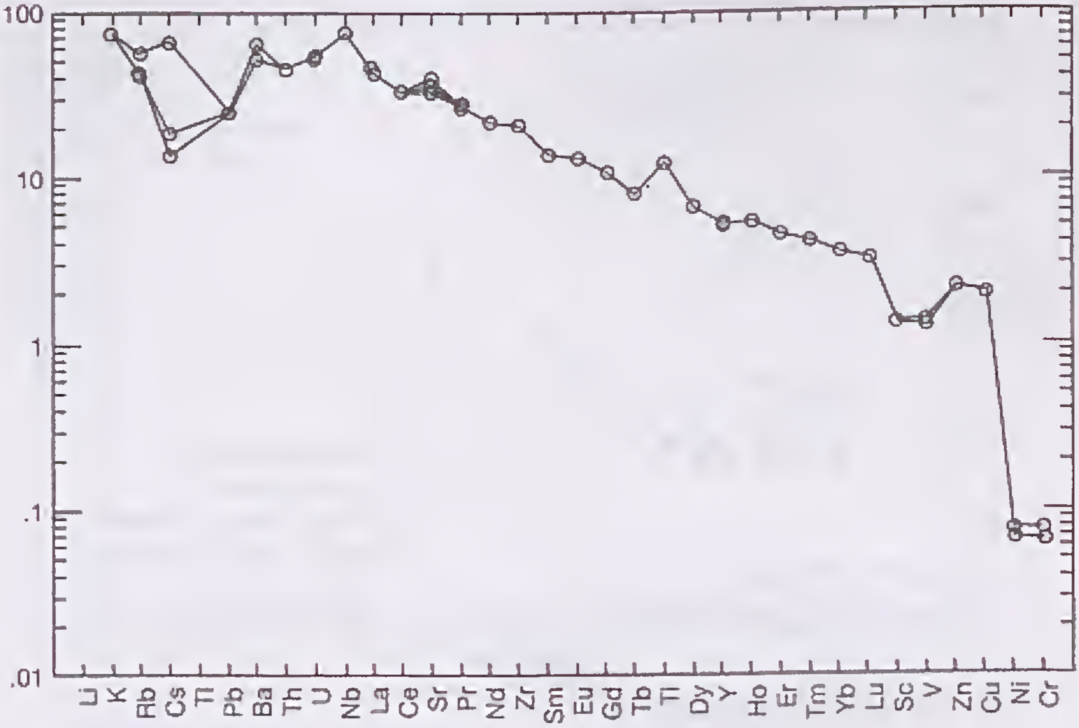


Fig. 6. Primitive mantle-normalised (rock / primitive mantle) multi-element diagram (Note: general degree of parallelism and overlapping between the three samples). Normalising values after Taylor and McLennan (1985).

Rare earth elements (REE)

The Uplands basalts have a uniform REE chemistry (Table 3) with moderate light REE (LREE) abundances (e.g. La 24.0-25.9; Ce 46.2-49.4) and low heavy REE (HREE) abundances (e.g. Ho 0.68-0.70; Yb 1.27-1.33). On the primitive mantle-normalised REE diagram (Fig. 7), the Uplands basalts are more enriched in the LREE compared to the HREE, resulting in a moderately steeply-dipping curve. The overall pattern resembles that for transitional basalts of the Western Plains sub-province of the Newer Volcanics (Price et al. 1997), but with slightly lower HREE concentrations. They suggested that the Plains Series basalts match those found in other intraplate basalt provinces (e.g. Thompson et al. 1983; Huang et al. 1997). Overall, the Uplands Province basalts are significantly lower in HREE compared to typical MORB, suggesting that they were probably generated from a source retaining residual garnet (i.e. possibly the lithospheric mantle).

Sr, Nd and Pb isotopes

The Sr, Nd and Pb isotopic analyses are presented in Table 4. Based on leaching experiments and weathering studies from the Newer Volcanics basalts, Price et al. (1991), concluded that the Sr isotopic characteristics were only slightly modified by late-stage groundwater infiltration (see also McDonough et al. 1985; Price et al. 1997). McBride et al. (2001) using osmium isotopic signatures for these basalts also concluded the basalts were not significantly modified by late-stage alteration. Thus, the isotopic signatures observed in the basalts represent unmodified signatures.

A regional discontinuity was defined in the Newer Volcanics Province, on observed strontium isotopic compositions (whether from the Plains Series or Cones Series) along a N-S line which passes through Mortlake (the 'Mortlake Discontinuity'; Price et al. 1988, 1997; Nicholls et al. 1993). East of this line the basalts generally have a more radiogenic Sr iso-

Fig. 8. εNd vs ^{87}Sr/^{86}Sr diagram. Lithospheric fields Victorian plains and cones basalt plots and Tasmanian basalt plots are adapted from McDonough et al. (1985) and McBride et al. (2001).

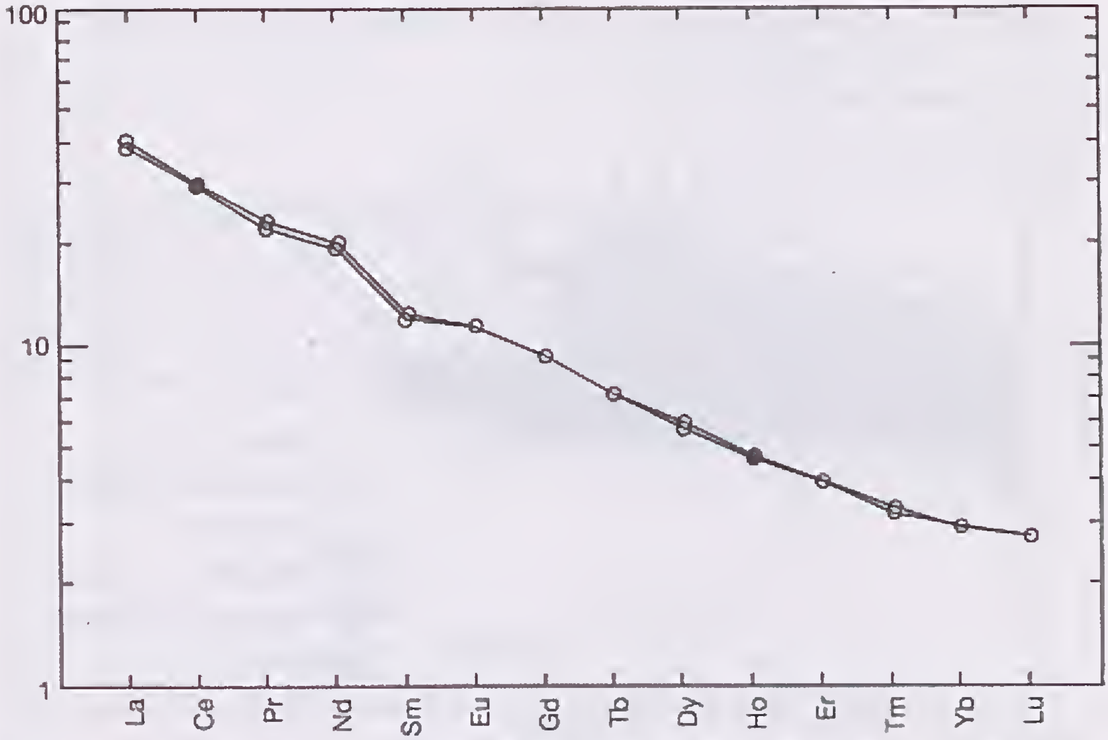
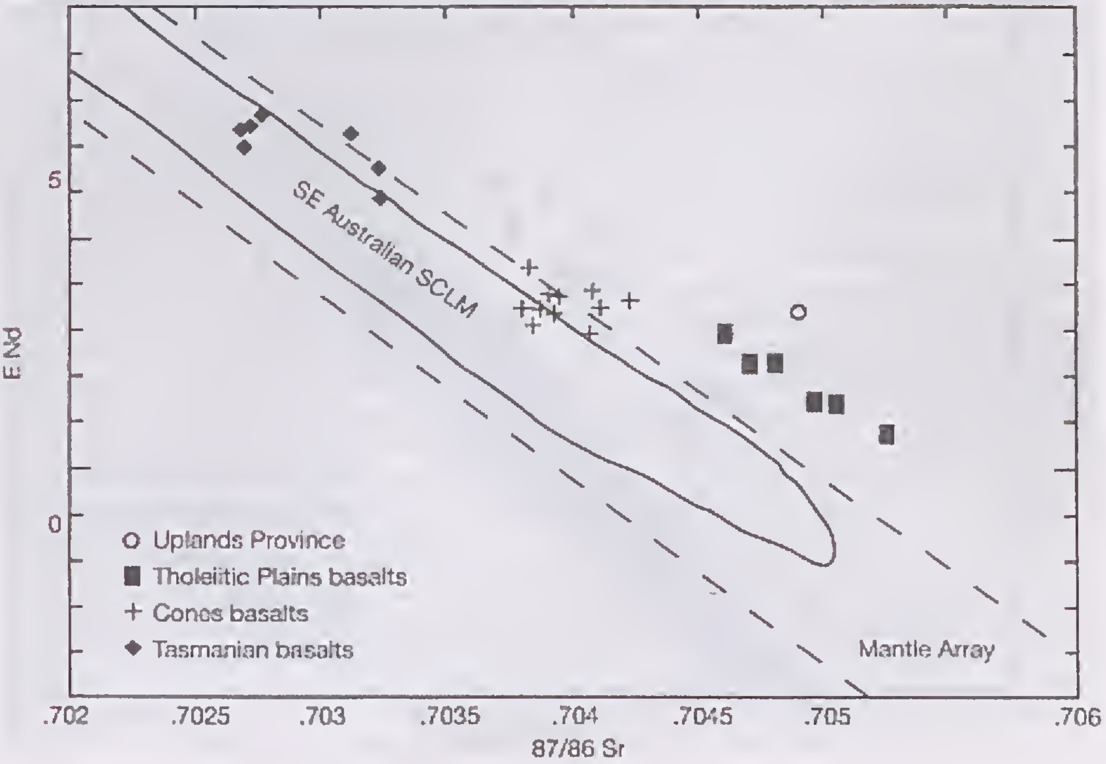
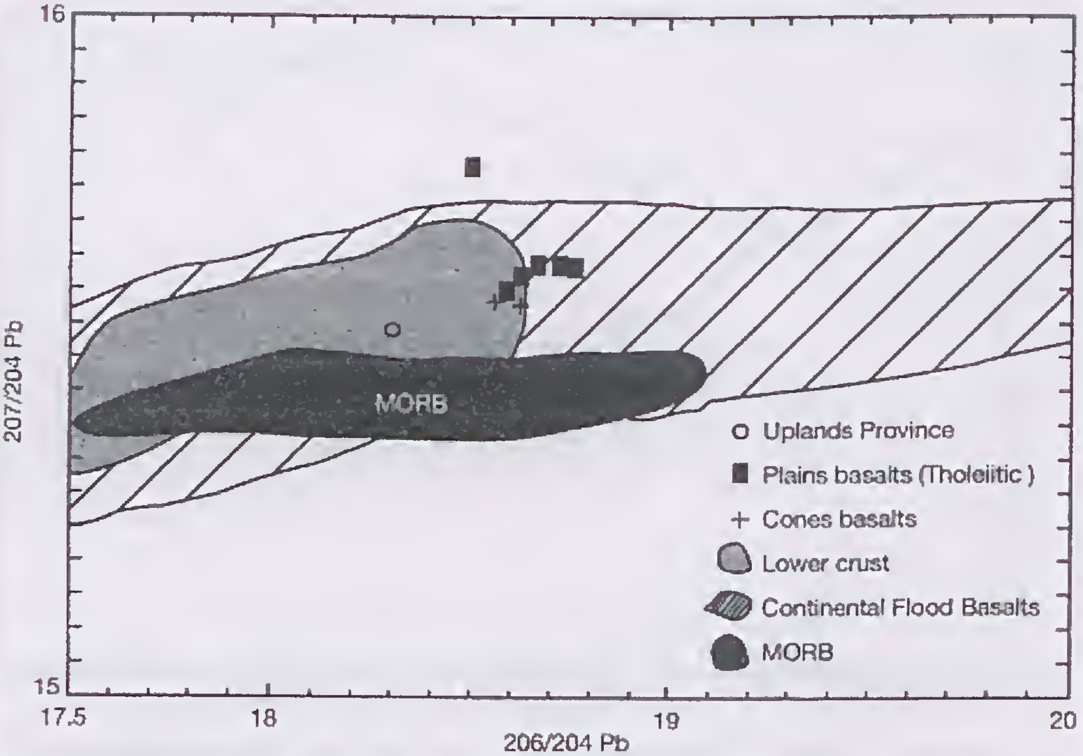
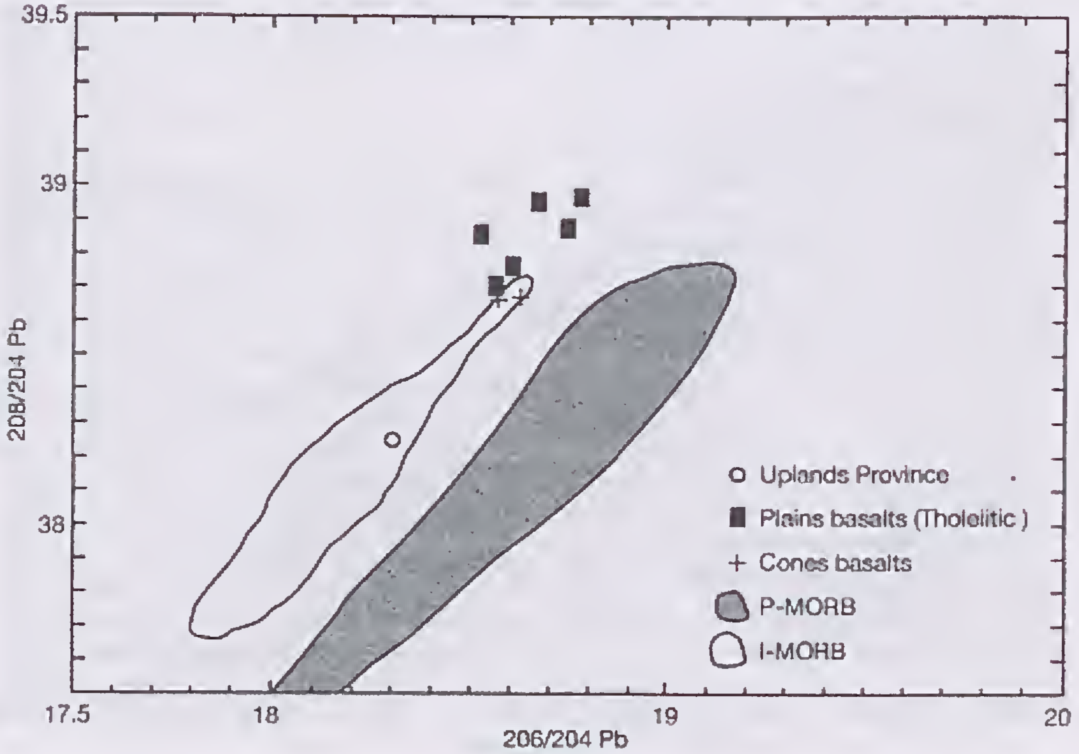


Fig. 7. Primitive mantle-normalised (rock / primitive mantle) rare earth diagram (Note: parallelism and overlapping between the three samples; the element Pm is not included in the array which introduces an artificial anomaly for Sm). Normalising values after Sun (1982).




16
15
207/204 Pb
17.5
18
19
20
206/204 Pb
MORB
Uplands Province
Plains basalts (Tholeiitic)
Cones basalts
Lower crust
Continental Flood Basalts
MORB


39.5
39
38
208/204 Pb
17.5
18
19
20
206/204 Pb
Uplands Province
Plains basalts (Tholeiitic)
Cones basalts
P-MORB
I-MORB

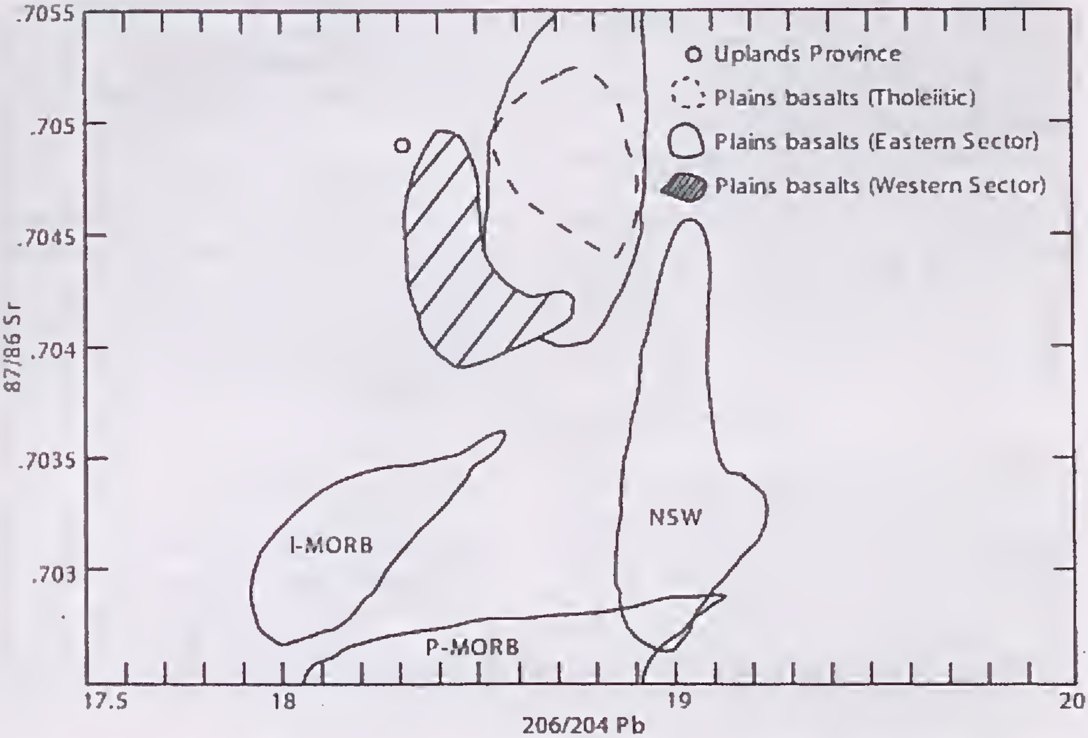


Fig. 10. $^{87}Sr/^{86}Sr$ vs $^{206}Pb/^{204}Pb$ diagram. MORB and NSW basalt fields from Zhang et al. (2001). Plains basalt fields adapted from McDonough et al. (1985) and McBride et al. (2001).

topic signature than those to the west which also includes the Uplands basalt.

On the εNd vs $^{87}Sr/^{86}Sr$ diagram (Fig. 8), the Uplands basalt distinctly plots above the mantle array, and just above the field for the tholeiitic Plains Series basalts of the Newer Volcanics Province.

The $^{206}Pb/^{204}Pb$ value for the Uplands basalt at 18.306, lies just below the values for the Newer Volcanics Province. In terms of Pb isotopic characteristics, all of the Newer Volcanics Province basalts analysed fall well to the right of the geochron (Faure, 1986) suggesting that their sources had experienced a long-term history of elevated U/Pb ratios (McBride et al. 2001). Both the Plains Series olivine tholeiites and Cones Series nepheline hawaiites analysed by McBride et al. (2001) have $^{206}Pb/^{204}Pb$ values ranging from 18.57 to 18.84, within the range for the Newer Volcanics Province (18.4 to 18.9; Price et al. 1997; McBride et al. 2001), and those observed for many ocean-island basalts and continental flood basalt provinces (e.g. Zindler and Hart 1986; Carlson 1991).

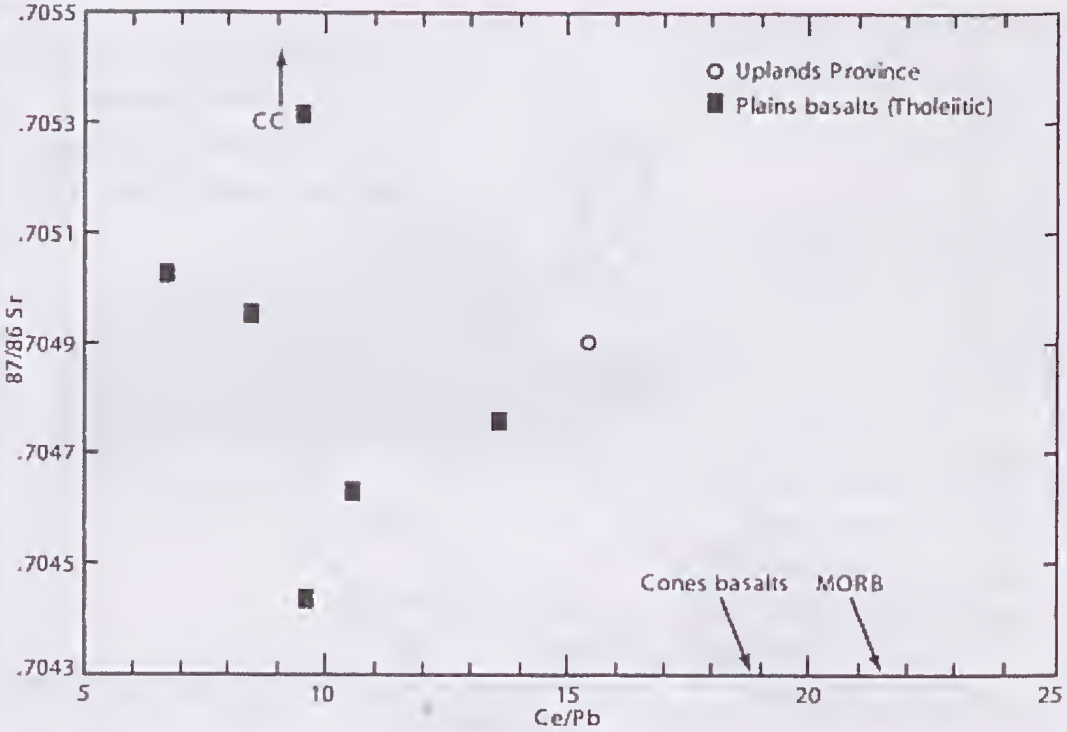
On the $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagram (Fig. 9a), the Uplands basalt plots well away from the Newer Volcanics Province field but well within the Indian Ocean MORB (I-MORB) field and the lower crust. This also applies on the $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagram (Fig. 9b).

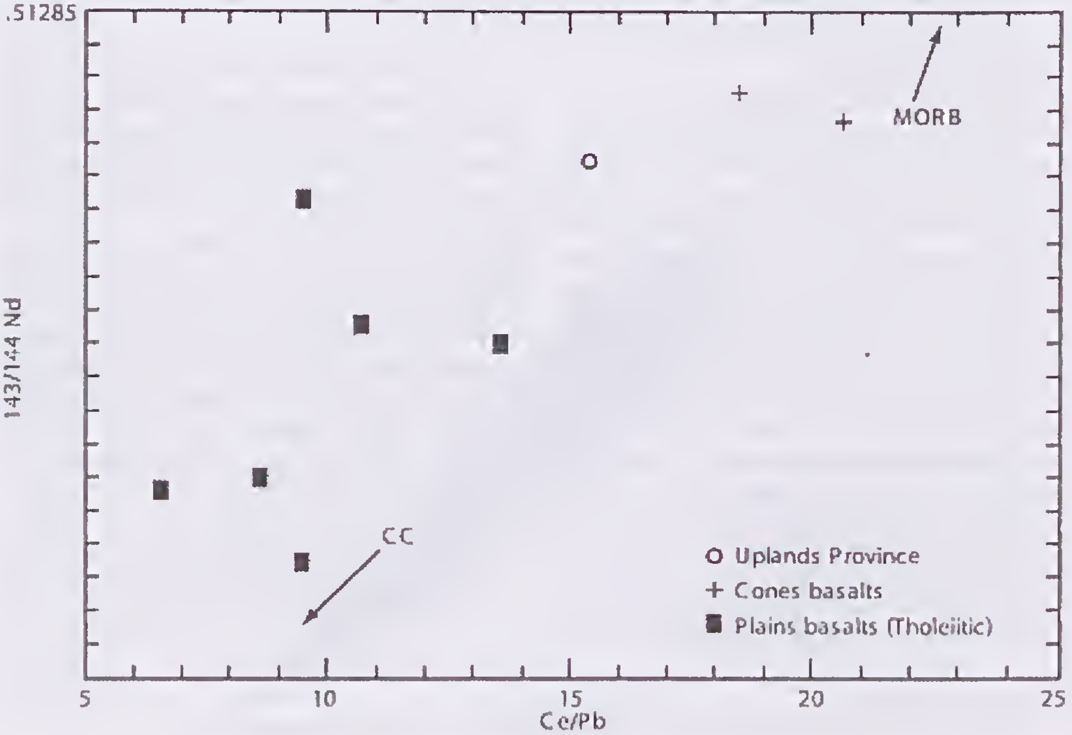
On the $^{87}Sr/^{86}Sr$ vs $^{206}Pb/^{204}Pb$ diagram (Figure 10), the Uplands basalt Province plots away from but close to the tholeiitic Plains Series basalts of the Newer Volcanics Province, being closest to basalts from the western sector. It plots well away from both the New South Wales and Pacific Ocean MORB (P-MORB) fields, but closer to the I-MORB field. On $^{87}Sr/^{86}Sr$ vs $^{208}Pb/^{204}Pb$ values, the Uplands basalt is distinct from the tholeiitic Plains Series basalts of the Newer Volcanics Province.

When εNd is plotted against $^{206}Pb/^{204}Pb$, the Uplands basalt plots again shows a similar disposition to the other fields. In åNd vs $^{208}Pb/^{204}Pb$ values, the

Fig. 9a. $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagram. MORB fields after Zhang et al. (2001). Plains and cones basalt plots adapted from McDonough et al. (1985) and McBride et al. (2001).

Fig. 9b. $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ diagram. Fields and plains and cones basalt plots adapted from McBride et al. (2001).


.7055
.7053
.7051
.7049
.7047
.7045
.7043
87/86 Sr
5
10
15
20
25
Ce/Pb
CC
○ Uplands Province
■ Plains basalts (Tholeiitic)
Cones basalts
MORB


.51285
143/144 Nd
5
10
15
20
25
Ce/Pb
MORB
CC
○ Uplands Province
+ Cones basalts
■ Plains basalts (Tholeiitic)

Uplands basalt has lower ^{208}Pb/^{204}Pb than the Newer Volcanics Province but lies within the same range of εNd values. For εNd against ^{206}Pb/^{204}Pb, the Uplands basalt values are closest to the I-MORB related field for North Queensland basalts.

On the ^{87}Sr/^{86}Sr vs Ce/Pb diagram (Fig. 11A), the Uplands basalt lies near to the field for the tholeiitic Plains Series basalts, while on the ^{143}Nd/^{144}Nd vs Ce/Pb diagram (Fig. 11B), the Uplands basalt plots between the fields for the alkaline Cones Series and tholeiitic Plains Series basalts. On ^{206}Pb/^{204}Pb vs Ce/Pb values, the Uplands basalt is distinct from the alkaline Cones Series and tholeiitic Plains Series basalts due to much lower ^{206}Pb/^{204}Pb ratios.

DISCUSSION

The Uplands Volcanic Province represents an isolated eastern extension of the Late Cenozoic activity that prevailed in central-western Victoria (Price et al. 2003). This is the first detailed study of the Uplands basalts that allows close comparison with the temporally linked Newer Volcanics Province.

Age implications

The two ages determined for the Uplands Province basalts both lie within those for the Newer Volcanics Province (McDougall et al. 1966; Wellman and McDougall 1974), and correspond with the volumetric peak activity for the Plains Series basalts (spanning 2 to 3 Ma). However, the Uplands Province is at least 280km north-east of the nearest outcrops of the Newer Volcanics Province and forms a separate area of activity.

The further dating extends the age range of the Uplands basalts from 2.3 to 3.6 Ma, probably as two distinct episodes, although intermediary activity is possible. Other scattered activity related to the Uplands event may exist elsewhere in eastern Victoria, as alluvial zircon megacrysts in the Tombullup Province, 120 km to the west, include a group with re-set fission track ages of 3.6 ± 1.8 Ma (Australian Museum, Geotrack Report No 53, 1986) and basalt scoria was mapped some 60 km to the south on Barmouth Spur (Willman et al. 1999).

The presence of two basalts separated in age in the same tributary drainage system entering Mitta Mitta River has implications for downcutting rates in this region. Downcutting time to re-excavate the basalt buried valleys is now 60% longer, decreasing previous estimated erosion rates. About 190m thickness of basalt remains in the Morass Creek Section between Stony Creek and Fraser Tableland, suggesting an overall minimum downcutting rate of some 5 mm/yr since 3.6 Ma. The basalt infills would periodically elevate local drainage base levels for more vigorous downcutting to produce the present gorge-like course of Morass Creek.

Geochemical implications

In major and trace elements, the Uplands basalts are transitional types that resemble the Plains Series basalts of the Newer Volcanics Province, but show some differences. Thus, Ba/Nb ratios for Uplands basalts (6.5-7.8) resemble those of the Cones Series alkali basalts (6.1 – 7.3) rather than the Plains Series olivine tholeiites (11.0 – 17.3) which may incorporate crustal contamination and assimilation (McBride et al. 2001). Price et al. (1997) rejected significant influence of upper continental crust in the Newer Volcanics Province basalts, but left open the influence of variable lower crustal contamination. The possibility of such contamination in the Uplands basalts needs consideration to explain their mixed characteristics relative to the Newer Volcanics basalts.

The Uplands basalts show uniform Ce/Pb (17-18) and Nb/U (42-44). An apparent variation in Pb values for the Stony Creek basalt (Tables 3 and 4) may reflect a difference in analytical methods, the ICP-MS results being more consistent with the other basalt values. These reported ratios guide assessment of continental crust influences (see Hofmann et al. 1986), as they are generally uniform in both MORB and OIB basalts, with Ce/Pb (25 ± 5) and Nb/U (47 ± 10), in comparison to continental crust, with Ce/Pb (4) and Nb/U (10). On this basis, the Uplands basalts suggest some crustal residence and contamination has affected their chemistry. Thus, the Uplands basalts trend away from the Newer Volcanics Cones Series alkaline basalts (Ce/Pb 19 - 21; Nb/U 55) partly towards the crust-like compositions of the Plains Series olivine tholeiites (Ce/Pb 7 – 14; Nb/U

Fig. 11A. ^{87}Sr/^{86}Sr vs Ce/Pb diagram. Adapted from McBride *et al.* (2001).

Fig. 11B. ^{143}Nd/^{144}Nd vs Ce/Pb diagram. Adapted from McBride et al. (2001).

22 – 34; McBride et al. 2001).

Isotopic compositions of basalts can also indicate crustal contamination. Thus, while trace element signatures for both Plains Series and Cones Series basalts in the Newer Volcanics are similar to plume-related magmas (McDonough et al. 1985), the Plains Series trend to radiogenic $^{87}Sr/^{86}Sr$ above the mantle array and have high radiogenic Os relative to most OIB values (McBride et al. 2001). The Uplands basalt $^{87}Sr/^{86}Sr$ plots well above the mantle array and also above the field for Plains Series olivine tholeiites. Crustal contamination can be recognised by both high $^{87}Sr/^{86}Sr$ and low εNd values (Ewart et al. 1988; Price et al. 1997) and Uplands basalt with $^{87}Sr/^{86}Sr$ 0.704905 and εNd 3.4 suggests crustal contamination has affected the isotopic systematics en route to the surface. The exact contaminating material is uncertain and may involve Lachlan Orogen components not present at the surface, as suggested by McBride et al. (2001) for the Newer Volcanics Plains Series. Unfortunately, the age of the lower crust in southeastern Australia is still uncertain with estimates ranging from Proterozoic (Cas 1983) to Post-Cambrian (e.g. Gray 1997; Anderson et al. 1998).

On a wider scale, the recent detailed work on the Newer Volcanics Province suggests both Plains and Cones Series basalts are mantle-derived melts (McBride et al. 2001). The Os and Nd isotope characteristics for Plains Series olivine tholeiites suggests variable mixing of two isotopic end-members, continental crust (high χ Os and low ε Nd) and asthenospheric mantle (low χ Os and high ε Nd). Two subgroups were also distinguished in the olivine tholeiites, based on different χ Os, ε Nd and $^{87}Sr/^{86}Sr$ values. However, the Uplands transitional basalts with moderately radiogenic ε Nd and radiogenic $^{87}Sr/^{86}Sr$ differ again from the Plains Series olivine tholeiites adding to the complexity of mantle-crustal melt interactions in the wider Victorian scene.

The Uplands basalts occupy a critical position close to the Indian-Pacific mantle asthenosphere boundary (Sutherland 2003). In terms of Pb isotopes, the Uplands basalt generally plots well within the I-MORB field and distant from the P-MORB field although the $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ values lie within the lower crust field and suggest a mixed asthenospheric melt-crustal interaction. The observed fractionation and contamination effects also obscure precise assignment of the Uplands basalt primary magma source. Even so, Pb isotope values tentatively favour an I-MORB connection similar to the western Newer Volcanics Province, rather than a P-MORB connection that typifies New South Wales basalt fields (see Zhang et al. 1999; Sutherland 2003).

CONCLUSIONS

1. The Uplands Province erupted during peak activity in the Newer Volcanics Province in western Victoria (2-4 Ma).
2. The lavas are evolved olivine basalts with trace element characteristics allied to both the Plains and Cones series basalts of the Newer Volcanics Province.
3. The observed isotope values suggest mixed asthenosphere melt-crustal interactions were involved in basalt genesis.
4. The basalts have been dissected since eruption, at an average downcutting rate of 5 mm/yr since 3.6 Ma.

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THE AGE AND CONTEMPORARY ENVIRONMENTS OF TOWER HILL VOLCANO, SOUTHWEST VICTORIA, AUSTRALIA

J. Sherwood[1], B. Oyston[2] & A. P. Kershaw[3]

[1] School of Ecology and Environment, Deakin University, Warrnambool, Vic. 3280, Australia
[2]URS, 658 Church St., Richmond, Vic. 3121, Australia
[3]Centre for Palynology and Palaeoecology, School of Geography and Environmental Science, Monash University, Vic. 3800, Australia

Sherwood, J., Oyston, B. & Kershaw, A.P., 2004:11:14. The age and contemporary environments of Tower Hill volcano, southwest Victoria, Australia. *Proceedings of the Royal Society of Victoria* 116(1):71–78. ISSN 0035-9211.

Tower Hill ash forms a useful chronological marker for archaeological and geological sites in the Warrnambool-Port Fairy area. The current paper establishes an age of 35 ± 3 ka for the eruption of Tower Hill. Confidence in this age is provided by the agreement of results from three dating techniques on different types of material – accelerator mass spectrometry (AMS) radiocarbon dating of lake core sediments in a crater of the volcano, conventional radiocarbon dating of plant remains in a palaeosol buried by volcanic ash and thermoluminescence dating of quartz grains in a sand covered by the ash. Palynological analysis of lake sediment indicates the presence of a steppe-type vegetation at the time for which no present day analogue exists in Australia

Keywords: radiocarbon, thermoluminescence, palynology, pollen, lake sediments, geochronology

TOWER Hill volcano (38°19'S, 142°22'E) lies towards the southwestern extremity of the extensive volcanic plain of western Victoria and within a few km of the coast (Fig. 1). It is a maar volcano with nested scoria cones (Orth and King 1990). Ash from the volcano covers 150km^2, with deposits being found up to 20km away. The crater itself has a maximum diameter of 3.2km and the northeast crater rim is 110m above the present floor (Orth and King 1990). Prior to the arrival of European people, the surrounding plains were covered in *Eucalyptus*-Casuarinaceae woodland and grassland, with open forest occurring on Newer Volcanic deposits such as those of Tower Hill. The site experiences a warm temperate climate with a mean annual temperature of almost 14°C and a mean annual rainfall of about 750 mm with a winter maximum.

As its name suggests, Tower Hill volcano is a prominent physiographic feature of the predominantly flat southwest Victorian coast (Gill 1978). Its well-preserved geological features were suggestive to earlier investigators of a young eruption age (of the order of 1000 years; Gill 1953). Subsequent research, reviewed by Head et al. (1991), has suggested progressively greater ages for the volcano. It appeared that volcanic activity was older than 20ka, based on radiocarbon dating of material obtained from cores in lake sediments of the volcano. Since lake sediments must have formed some time after the cessation of volcanic activity they indicate a minimum age for the eruption.

Several authors have discussed the value of reliable ages for the eruption of Tower Hill and other western Victorian volcanoes (Coutts 1981; Head et al. 1991; D'Costa et al. 1989). Ash from the volcano forms a useful chronological marker for archaeological and geological sites in the Warrnambool-Port Fairy area. We report here the results of three recent independent determinations of the age of the Tower Hill eruption which are consistent with an eruption of ~35 ± 3ka. The agreement between the dating techniques gives confidence in the assigned age because of the different materials and methodologies involved (Sherwood et al. 1994).

The three methods utilised by us were:

i) Accelerator mass spectrometry radio-carbon dating of material from the basal material of a lake sediment core taken within the Tower Hill crater complex

ii) Thermoluminescence dating of quartz grains from a calcarenite sand underlying Tower Hill Tuff at Thunder Point (approximately 13km SE of the eruption centre)

iii) Conventional radiocarbon dating of woody plant material preserved beneath the original land surface and uncovered during quarry operations in Tower Hill Tuff at Davison's quarry (approximately 1.5km east of the crater).

SITE DESCRIPTION AND METHODS

Radiocarbon dating of Northwest Crater lake sediments

Oldest radiocarbon ages obtained previously from Tower Hill sediments were from the base of a 15.5 m core extracted from the centre of Northwest Crater, contained within the scoria cone complex within the Tower Hill maar (Fig. 1). The conventional radiocarbon ages of 18,330 ± 260 yrs BP (Beta-16156) and 23,260±2540 yrs BP (Beta-16155) were obtained from organic and carbonate fractions of submitted bulk sediments. It was considered that the carbonate fraction age could be too old because of likely incorporation of Tertiary limestone derived from underlying country rock during the volcanic explosions.

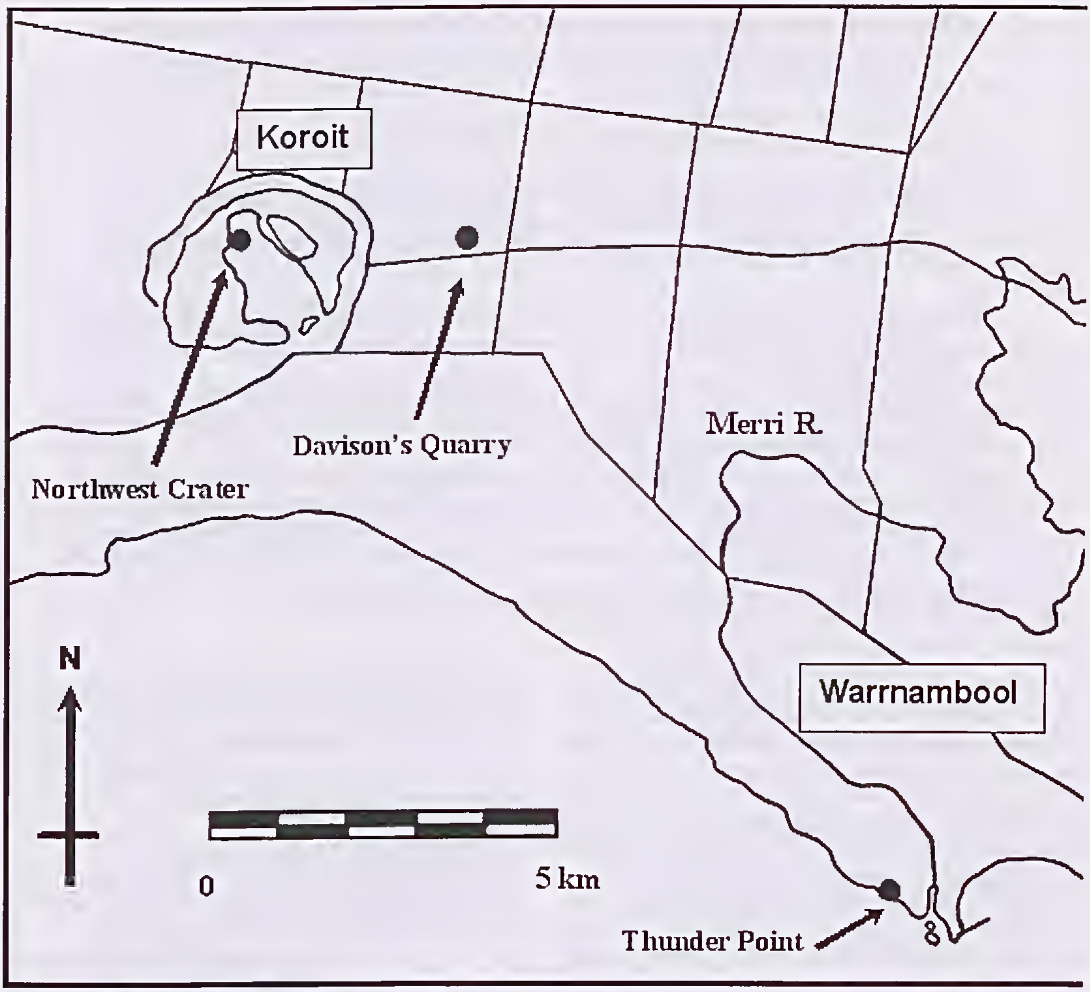

Fig. 1. Locality map for Tower Hill showing Thunder Point and Davison's Quarry.

In recognition of this possibility, extrapolation from younger radiocarbon dates within the sequence was used to estimate the most likely age as *ca* 21,000 yrs BP (D'Costa et al. 1989).

Coring of Northwest Crater was terminated at 15.5m rather than reaching the base of the lake and swamp sediments because of the difficulty of penetrating further using hand-operated equipment. As the site was not accessible to a drilling rig, further sediment collection had to await the design and acquisition of a lightweight mechanical core sampler. Such a sampler, operated by hydraulics, was available for use in 1997. The sampler was attached to a constructed platform in the centre of the crater and cores were extracted, in metre lengths, to a depth of 23.0 m. As the core bottomed in scoria, it was assumed that the total depth of accumulated lake sediment had been sampled.

The lowermost lake sediment was prepared for radiocarbon dating in a similar manner to that for pollen analysis to remove calcium carbonate and other possible contaminants such as mobile organic constituents that might effect a radiocarbon date. The prepared sample was then radiocarbon dated by accelerator mass spectrometry at the University of Waikato, New Zealand. A second sample from the same depth was prepared for pollen analysis to provide some biostratigraphic check on the radiocarbon age and to provide background information on conditions existing at the time of eruption. Preparation of both samples followed standard procedures detailed in Moore and Webb (1978) and included hydrochloric acid and hydrofluoric acid treatments as well as acetolysis.

Thermoluminescence (TL) dating of sand at Thunder Point

TL dating of calcareous sediments in the Warrnambool region has identified major dune building episodes at approximately 500ka, 330ka, 240ka, 200ka, the last Interglacial and the Holocene (Oyston 1996). As part of this research, an interbedded sequence of five aeolianites (coded WTPA) and four palaeosols (coded WTPS) was studied at Thunder Point (Fig. 2). The topmost aeolianite (WTPA5) is a thin sand layer overlain by Tower Hill tuff and lies on top of a distinctive well-developed sandy clay loam (WTPS4), which is unlike any other soils in the sequence.

Samples were collected by augering, taking care to avoid exposing the samples to light. At the same time samples were also taken for moisture and analysis of isotopes of uranium, thorium and potassium – concentrations of these elements being needed to calculate annual dose rates from in-situ radiation. A small contribution is also made by cosmic rays (Smith & Prescott 1987).

TL analysis was conducted on the quartz grains isolated from the calcareous matrix using the total bleach, Australian slide method. Testing of the effectiveness of sunlight bleaching on modern surface samples suggests the total bleach model is appropriate for buried dune samples up to 70ka. The method is more fully described elsewhere (Smith and Prescott, 1987; Sherwood et al. 1994; Oyston, 1996)

The dose rate for TL ages from Thunder Point was determined by alpha counting of material sampled to obtain TL equivalent dose. Given that the TL ages are in general agreement with their stratigraphic position, it is considered that a change. in dose rate due to the influence of adjacent stratigraphic sediment/soil/tuff layers is likely to be insignificant in relation to the errors in the ages.

The soil horizons at Thunder Point were found to have very similar dose rates to the intervening sand layers and so would not change the dose rate calculation significantly. The thin layer of tuff was more than 30 cm from the edge of the sample collection tube. It is considered that this distance would significantly reduce the influence of the tuff on the dose rate in the underlying sand.

It is acknowledged that ideally in-situ dosimetry would be a preferable means of obtaining a dose rate for the Thunder Point sediments, but this technique was not undertaken in this case.

Radiocarbon dating of plant material from Davison's Quarry

Excavation of tuff to a quarry depth of approximately 20m below the present surface revealed the original (pre-eruption) land surface. This consists of a grey soil overlying a yellow-grey mottled clay containing buckshot nodules and large (up to ~0.5m diameter) rounded basalt boulders. The palaeosurface grey soil was quite lithified where sampled and large slabs (up to 1m across) remained intact when lifted. The quarry owner (Mr G. Davison) kindly excavated fresh material and two samples of plant material were collected by breaking up the grey palaeosol.

Sample A was a single piece of dense dark brown timber found in the palaeosol directly beneath the tuff layer, while sample B was composed of brown, cylindrical spongy roots (or rhizomes), of varying diameter up to 1 cm, located commonly about 10cm below the tuff layer in the palaeosol. Sample B was collected approximately 10m east of sample A.

The plant specimens were hand-sorted from fragments of tuff and other debris and dried at 105°C for 6 hours. The dried samples (A – 26.39g; B – 11.08g) were sent to the University of Waikato Radiocarbon Dating Laboratory. There the samples were scraped clean, chopped into fine splinters and milled. After washing with distilled water, they were dried prior to a series of washings that included hot 10% hydrochloric acid, distilled water and hot 5% sodium hydroxide. The sodium hydroxide insoluble fraction was treated again with hot 10% hydrochloric acid, filtered, rinsed with distilled water and dried prior to carbon -14 radiometric analysis.

Calibration of radiocarbon dates

Conventional radiocarbon ages, related directly to the dating of the Tower Hill eruption, have been calibrated to calender years using the Nordic Sea record (Voelker et al. 2000), generally believed to be the most reliable of the available calibration datasets beyond 20,000 yrs BP (Laj et al., 2002). Calibration was undertaken to provide direct comparison with the TL age.

RESULTS

Samples from Northwest Crater, Tower Hill

The radiocarbon age from the base of the Northwest Crater sequence is shown in Table 1 while its relationship to other ages found for this site and a core from the main lake surrounding the scoria complex is shown on Fig. 3. There is good agreement between ages from Northwest Crater and the Main Lake sediments back to the base of cored sediments at Main Lake dated to 11,550 years BP. The continuation of the linear age-depth line through the Northwest Crater age of 18,330 yrs BP was considered unrealistic by D'Costa et al.

Site	Sample	Code	Uncalibrated (yrs BP)	Calibrated (yrs BP)
Northwest Crater	NWC (97) 22.10 m	Wk-6012	29,720 ± 290	34,600 ± 400
Davison's Quarry	A	Wk-7446	32,900 ± 430*	37,400 ± 1,000
	B	Wk-7447	32,990 ± 590*	

Table 1. Calibrated and uncalibrated radiocarbon dates for basal lake sediments from Northwest Crater, Tower Hill and plant remains from Davison's Quarry.

* error is 1 standard deviation and is based on counting uncertainties.

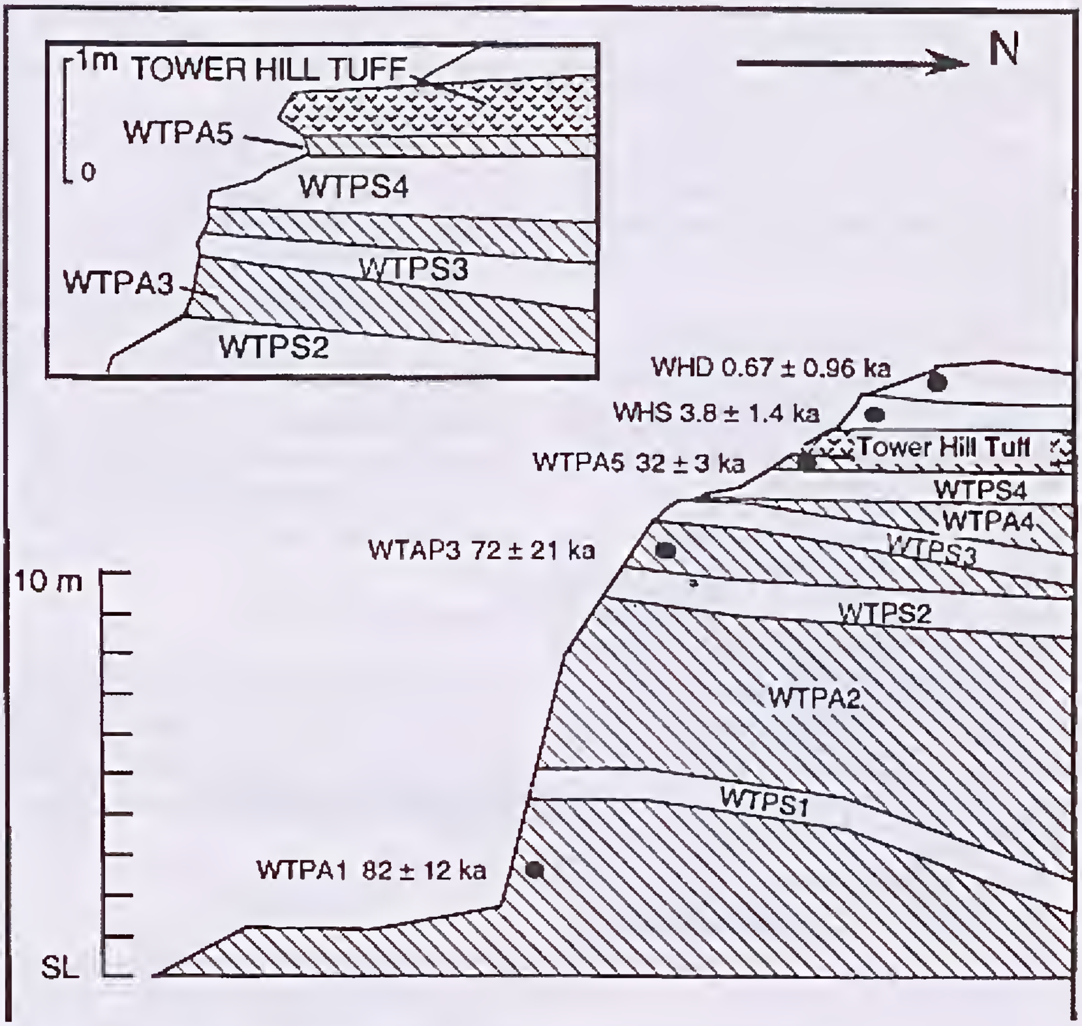

Fig. 2. Cliff section at Thunder Point, Warrnambool, showing the sequence of sedimentary layers dated and their TL ages

(1989) as there were signs of lake drying during the late glacial period (15,000 to 10,000 yrs BP) in line with dry conditions recorded elsewhere in Australia at this time (Kershaw and Nanson 1993). Continuation of this line would also suggest a significantly younger age than 29,720 yrs BP (34,600 calibrated yrs BP) for the base of the sediments. The acceptance of the age of 15,100 yrs BP is consistent with a reduction in the average rate of sediment accumulation during the late glacial period. Of the optional age-depth lines considered by D'Costa et al. (1989) beyond this time, option C was preferred on the grounds that sediment accumulation appeared to be continuous again before the late glacial period and would most likely have been similar to that of the Holocene. The continuation of this line to the base of sediments results in an age very similar to that reported here.

The pollen assemblage associated with the basal age is dominated by terrestrial taxa of which the Poaceae and Asteraceae are by far the most important with 37 and 41% of the dry land pollen sum respectively. The Chenopodiaceae also have notable representation (11%). All woody plants have low values except for *Banksia* (13%) but the present dominant trees of regional vegetation, *Eucalyptus* and Casuarinaceae, each have less than 3% of the pollen sum. Aquatic pollen are relatively sparse and are derived predominantly from the shallow water taxa *Myriophyllum* spp. and *Myriophyllum muelleri*, the latter species suggesting also brackish water conditions. High charcoal levels suggest frequent or intensive burning within the catchment.

These pollen data, like the radiocarbon age, are generally consistent with a last glacial age for the sample (Kershaw et al. 1991). However, the dry land pollen indicate a vegetation cover as extreme, in terms of reduced tree cover, as that during the Last Glacial Maximum (Stage 2) which is considered not to have commenced until about 29 ka, according to the marine oxygen isotope stratigraphy (Martinson et al. 1987). Although the statistical range around the conventional radiocarbon age could almost allow it to be fitted into Stage 2, the calibrated radiocarbon age predates this by 4 to 5 thousand years (Voelker et al. 2000). The lack of a continuous, dated pollen record through the Late Pleistocene from any site in southeastern Australia prevents further assessment of the validity of the sample age based on pollen stratigraphy.

Thunder Point

Figure 2 gives the TL ages for five units exposed in the cliff section at Thunder Point. The sediment ages form a consistent progression from the oldest unit at the base of the sequence to the youngest at the surface. The basal aeolianite continues below sea level, indicating it was formed during a period of lower sea level. Its TL age indicates a late Last Interglacial (LIG) formation, possibly marine isotope substage 5.0 or 5.1 of Martinson et al. (1987).

The last bleaching of the quartz in sample WTPA5 occurred after this dune-building period and prior to the Last Glacial maximum. A younger age for this aeolianite is consistent with the distinctively different appearance of the undated soil (WTPS4) underlying WTPA5. The appearance of this strongly leached leptic tenosol suggests different climatic conditions existed during its formation to those which formed the poorly developed palaeosols within the LIG dune. For the unit WTP5, the equivalent dose (D) of 20.6 ± 0.9 Gy, and the dose rate (DR) of 0.639 ± 0.036 Gy/ka gives a maximum age for the Tower Hill eruption of 32±3ka. The TL age of 0.67 ± 0.96ka for the uppermost unit (sample WHD) was obtained for an active modern calcarenite dune and is effectively zero demonstrating the effectiveness of solar bleaching at this location.

Davison's Quarry Site

Radiocarbon ages for the two plant specimens are given in Table 1. The agreement between the two determinations, based on two types of plant material located 10m apart, is excellent. The range of possible conventional radiocarbon ages indicated by the quoted uncertainties and based on a C14 half-life of 5568yrs (corrected for isotopic fractionation) is 32.5 – 33.6 ka. Based on this the calibrated radiocarbon age is 37.4 ± 1.0 ka BP.

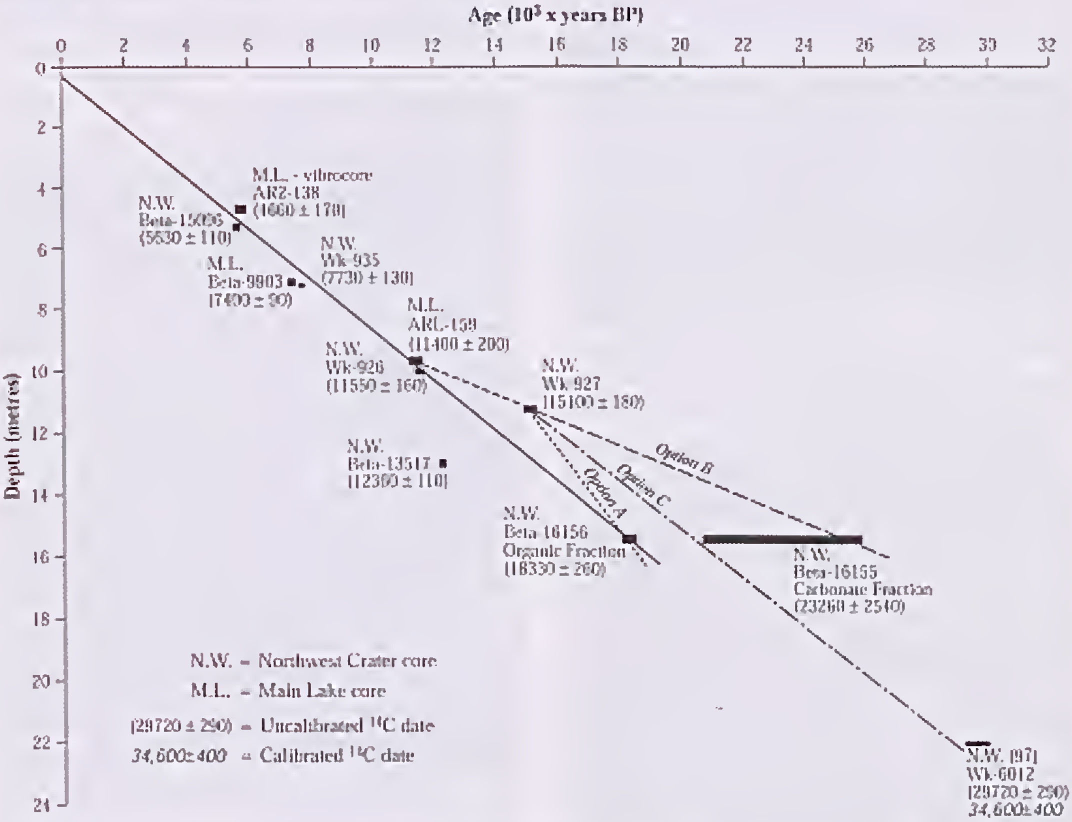

Fig. 3. Possible age-depth lines for sediment accumulation at sites from Tower Hill (modified from D'Costa et al. 1991)

Volcano	Age (ka BP)	Dating Techniques	Reference
Mt Schank (SA)	< 18.1 ± 0.35	C14^{+}	Polach et al. 1978
	4.93 ± 0.54	TL	Smith & Prescott 1987
Mt Gambier (SA)	~4.3	C14	Blackburn et al. 1982
	> 28	C14^{+}	Leaney et al. 1995
Mt Eccles (Vic)	< 19.3	C14^{+}	Gill 1980
	28 – 32*	C14^{+}, Cl36*	Head et al. 1991, Ollier 1981, Stone et al. 1997
Tower Hill (Vic)	35 ± 3	C14, TL	This Study
Mt Napier (Vic)	31.9 ± 2.4	Cl36	Stone et al. 1997
Mt Porndon	58.5 ± 5.0	Cl36	Stone et al. 1997

Table 2. Determinations of the eruption date for younger volcanoes in the Newer Basalt field
* Upper limit for age inferred from Cl - 36 dating of Mt Napier eruption.
$^{+}$ Uncalibrated ages, perhaps 3-4ka below the calibrated age.

DISCUSSION

Concordance of age determinations

Before discussing the concordance of the different age determinations, it is important to consider which event is being dated with each method. Both the radiocarbon dating of vegetation at Davison's Quarry and TL dating of sand at Thunder Point estimate a time pre-dating the eruption. Blanketing of the land surface by volcanic ash during eruption isolated its vegetation from the atmosphere and blocked sunlight from quartz grains. Dating of material in lake sediments should give ages that post-date the cessation of volcanic activity by an unknown period (the time for a lake to form after the final phase of scoria cone formation and then for sedimentation to commence). It should also be noted that, given the large uncertainties associated with each determination (up to 3ka), it may not be possible to resolve the times of commencement and conclusion of volcanic activity. It has been estimated, for instance, that the Tower Hill volcano could have been constructed within a few years and possibly even a few months (Orth and King 1990).

Despite these qualifications, however, the results of this investigation have given generally consistent ages for the Tower Hill eruption. The TL age for Thunder Point (32 ± 3ka) overlaps the calibrated C14 age from Northwest Crater (34.6 ± 0.4ka) based on the experimental uncertainties. The calibrated C14 ages for Davison's Quarry (37.4 ± 1.0ka) and Northwest Crater do not overlap but the date from the lake sediment is younger than that from the quarry, consistent with the sequence of eruption events. The apparent lack of any discontinuity between the scoria and base of organic sedimentation in the Northwest Crater core suggests that sedimentation began soon after the formation of the crater within the scoria cone. As the water levels in Tower Hill are controlled by ground water, there would be no requirement for basins to fill with rainwater before sedimentation commenced. If this argument is sound, the major factor contributing to the age gap between dates could be the elapsed time between initial maar formation and subsequent scoria cone activity i.e. two events of relatively short duration separated by a longer interval.

A mean eruption age, based on all three determinations is 35 ± 3ka. The uncertainty is calculated as the root mean square of the uncertainties quoted for each determination.

Palaeoecological considerations

The eruption of Tower Hill occurred just before the Last Glacial Maximum at a time when sea level was 80-90m lower than present. At this time the coast would have been at least 30km south of its present position and the volcano well inland as a consequence. Pollen analysis indicates a regional cover of steppe-type vegetation for which there is no present day analogue in Australia. In other parts of the world, steppe is associated with dry, cool conditions and these are consistent with most available evidence for the last glacial period in southeastern Australia (Kershaw 1998). It is difficult to imagine, however, temperatures and precipitation sufficiently extreme to exclude sclerophyll woodland or forest, considering the broad climatic adaptation of this type of vegetation. In addition, the presence of extensive *Banksia* around the site, probably shrubby *Banksia marginata,* as well as the regional survival of both sclerophyll forest and rainforest vegetation in the nearby Otway Ranges (McKenzie & Kershaw 2000), would suggest that temperatures were not too low to exclude trees from the area. Similarly, the fact that a lake could form within Tower Hill suggests that precipitation was not too low to exclude trees. In fact, considering the impact of lowered ground water with the marine regression, it is likely that effective precipitation was not much different to that of today. Consequently other factors, such as altered seasonality, extreme climatic events and the lowered concentration of CO$_2$ in the atmosphere during the last glacial period, have to be considered in an explanation of the landscape at the time of eruption.

One significant aspect of the vegetation preserved in Davison's quarry was its remarkably fresh appearance. Maar volcano eruptions are described as phraetomagmatic – explosive eruptions due to the combination of magmatic gases and steam derived from ground or surface waters (Joyce 1988). Basal surges accompanying these eruptions can travel at high speed and be highly destructive (Orth & King 1990). Cross-bedding in tuff around Tower Hill is evidence of such surges. It is possible that such violent events occurred later in the eruption and that initial phases were less violent. This is supported by observations during excavations to collect C14 samples. An intact clump of a sedge species and tuff-coated casts of grass stems were observed on the original ground surface. Burial of the original ground surface, apparently under low energy conditions, protected the buried vegetation from destruction during later, more violent eruptive episodes.

Ollier (1981) found a soil preserved in similar circumstances at the base of a quarry in volcanic tuff and scoria at Mt Eccles, approximately 80km northwest of Tower Hill. He collected small roots (up to 1mm in diameter) from the Mt Eccles palaeosol for radiocarbon dating. Similar small roots were common in the soil at Davison's Quarry but these were not used for dating purposes. Ollier (1981) also identified pollen from various taxa, predominantly Asteraceae, but with some *Casuarina*, *Eucalyptus*, grasses, *Grevillea*, *Haloragis*, *Beyeria* and fern spores. The excellent preservation of such plant remains suggested to Ollier that volcanic deposition was hot enough to kill microorganisms capable of decomposing organic matter but not hot enough to char the latter. Observations at Davison's Quarry are consistent with this hypothesis. Given this, it is possible that a detailed survey of vegetation and pollen preserved below volcanic deposits at such sites could provide valuable evidence for the nature of western Victoria's vegetation assemblages at the time of volcanic eruptions. This research could substantially refine reconstructions presently based on palynological studies of lake sediments.

Radiocarbon dating of the roots collected at Mt Eccles gave an uncalibrated age of 28,750 +11,700 /-4,600 yrs BP (Ollier 1981). This age was significantly greater than other eruption ages based on radiocarbon dating of peats supposedly formed when lava flows from Mt Eccles blocked drainage of nearby streams (Gill 1978; Gill 1980). Subsequently, Head et al. (1991) obtained an uncalibrated radiocarbon age for basal peat in Whittlebury Swamp of 27,510 ± 240 yrs BP, and in Condah Swamp of 26,240 ± 480 yrs BP. These authors argued that earlier, younger dates were based on peats formed well after drainage was first blocked. The agreement between radiocarbon ages for fossil vegetation and other techniques at Mt Eccles and Tower Hill suggests plant material obtained from original land surfaces may provide reliable ages. Since such material immediately pre-dates an eruption it should be preferable to material which post-dates one by an indeterminate period.

Regional volcanic activity

Recent determinations of the ages of several regional volcanoes considered to be "young" have shown them to be older, or potentially older, than previously thought. The studies have involved a range of techniques - radiocarbon dating of material in palaeosols and lake cores, thermo-luminescence dating of quartz grains in sands, palaeo-magnetism, and exposure dating of basalts using chlorine - 36. The majority of published ages for the Mt Gambier complex, derived from radiocarbon dating (Fergusson & Rafter 1957, Blackburn et al. 1982), palaeomagnetism (Barbetti and Sheard 1981) and thermoluminescence (Robertson et al. 1996) of tuff deposits and associated organic material, fall between 4 and 5ka, but radiocarbon dating of a Blue Lake sediment core suggests a very much older date of about 31ka (Leaney et al. 1995). It is considered possible by that the younger dates derive from renewed volcanic activity in the area that included the formation of Mt Schank. A cosmogenic chlorine-36 exposure age (32 ka) for the Harman Valley basalt flow from Mt Napier is consistent with the younger carbon-14 age found by Head et al. (1991) for overlying swamp sediments (Stone et al. 1997). An age for the Mt Eccles volcano is based on limits established by the age of peats in swamps formed when its lava blocked drainage channels and the age of older Mt Napier basalts on which these deposits sit (Stone et al. 1997). Mt Schank, and possibly Mt Gambier, are the youngest volcanoes on the Newer Basalt volcanic plain.

Interestingly, at least three volcanoes have given ages in the range 30 - 35ka BP – Tower Hill, Mt Eccles and Mt Napier (Table 2). It is possible that the closeness of these eruptions is due to a localised increase in mantle convective activity or crustal tectonic activity. Stone et al. (1997) have pointed out that the excellent preservation of volcanic features in these volcanoes and the failure of blocked streams to re-establish their courses, while originally suggestive of a young age for these volcanoes, may instead be due to extended periods of aridity.

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LATE PLIOCENE VEGETATION AND CLIMATE CHANGE AT STONY CREEK BASIN, WESTERN UPLANDS OF VICTORIA, AUSTRALIA

J. M. K. Sniderman[1], P. B. O'Sullivan[2], J. D. Hollis[3] & A. P. Kershaw[1]

[1]School of Geography and Environmental Science, Monash University, Clayton, Vic 3800
Australia
[2]Apatite to Zircon, Inc., 1075 Matson Road, Viola, Idaho 83872-9709 U.S.A
[3]The Australian Museum, 6 College St, Sydney, NSW 2000, Australia

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A high resolution pollen record from a small palaeo-lake in Victoria's western uplands provides evidence of vegetation and climate change during the latest Pliocene. A Late Pliocene age is indicated by both zircon fission track dating of lacustrine sediments, and comparison with regional palynostratigraphies. The 2.7m long sequence is dominated by fluctuating proportions of tree taxa indicative of a continuously forested environment, including rainforest taxa which are highly restricted or extinct regionally (*Phyllocladus*, *Podocarpus*, *Symplocos*, *Quintinia*, *Elaeocarpus*, *Macaranga/Mallotus*, Cunoniaceae) or Australia-wide (*Dacrycarpus*, *Dacrydium*). *Eucalyptus* forest including a mesotherm rainforest angiosperm component dominates early in the sequence. Subsequent regional drying is indicated by the loss of rainforest taxa, increased representation of *Callitris* and lower lake levels. Towards the top of the sequence, Podocarpaceae and ferns, representative of microtherm rainforest, become major pollen and spore components. Bioclimatic preferences of modern relatives of the fossil rainforest types indicate that mean annual temperature during the early warm 'interglacial' interval may have been 3°C higher than today, and summer rainfall during intervals of both meso- and microtherm rainforest was probably higher than today.

Keywords: Late Pliocene, pollen analysis, Australia, palaeoecology

THE TIMING and nature of the profound changes to climate and vegetation that marked the transition from the Tertiary to the Quaternary between about 6 Ma and 1.8 Ma remain poorly understood (Kershaw et al. 1994a; Williams et al. 1998). Worldwide, the transition involved major reorganisations of atmospheric and oceanic heat transport patterns, with consequent climatic disruptions and species losses (Webb & Bartlein 1992). Patterns of change typical of large parts of the temperate zones in both northern and southern hemispheres included loss or range contraction of mesic taxa and their replacement by frost-, drought- (and in some areas, fire-) tolerant species (Williams et al 1998; Huntley & Webb 1988). In southeastern Australia, evidence from fossil pollen shows the loss of formerly widespread rainforest communities palynologically dominated by taxa such as *Nothofagus* (subgenus *Brassospora* Read and Hill) and Podocarpaceae, and their replacement by taxa characteristic of open-canopied communities including *Casuarina* or *Allocasuarina*, *Eucalyptus*, Poaceae and Asteraceae (Kershaw et al. 1994a; Macphail 1997).

Much of our understanding of the vegetation before, during and after this transition is derived from either detailed 'snapshot' studies of stratigraphically discontinuous, poorly dated, terrestrial sedimentary horizons using micro- and/or macro-fossil plant assemblages (eg. Macphail et al. 1993, 1995), or fossiliferous terrestrial and shallow marine sedimentary sequences, such as found within the offshore Gippsland Basin (Stover & Partridge 1973; Macphail 1997) and the partly marginal marine Murray-Darling Basin (Martin 1987; Macphail & Truswell 1989, 1993; Macphail 1999) that provide long and better dated but coarse palynological records. Neither the 'snapshot' nor the stratigraphic approach has succeeded in elucidating the nature and composition of specific communities and their dynamic interactions in response to the pronounced cyclicity which was evidently a feature of global climate by the Late Pliocene (Shackleton et al. 1995).

This paper presents a pollen record from the upper part of a small Late Pliocene lake deposit in the western uplands of Victoria. The simple hydrological characteristics and small size of this palaeolake suggest that its pollen source area was quite limited (Jacobson & Bradshaw 1981; Prentice 1985; Jackson 1990), comparable in size to those of small lakes that have been important sources of high spatial and temporal resolution pollen data during the Late Quaternary on the western plains of Victoria (Kershaw et al. 1994a). Combined with this spatial resolution, relatively close sampling intervals used here allow the reconstruction of Late Pliocene vegetation history at a scale typical of Late Quaternary palaeoecology. Age determination has been facilitated by the presence within the basin of radiometrically datable zircons, allowing a comparison to be made with a biostratigraphic age estimate.

THE SITE AND ITS ENVIRONMENTAL SETTING

Stony Creek Basin (SCB) (37° 21' S, 144° 08' E) is situated at 550m above sea level (asl) in the western uplands of Victoria (Fig. 1). These subdued ranges, parts of the Delamerian and western Lachlan fold belts (Gray et al. 1997), are composed predominantly of steeply-folded early Palaeozoic marine sandstones and shales now elevated approximately 300-1000 m asl. The uplands, which divide the Victorian volcanic plains to the south from the Murray River plain to the north, have represented a topographic high since at least the Cretaceous (Jones & Veevers 1982). Although there is evidence for limited Pliocene-Pleistocene fault movement (Hughes et al. 1999), the uplands have occupied essentially their current altitudes since the Middle Miocene (Joyce 1992). Numerous Pliocene-Pleistocene basaltic lava and scoria cones form conspicuous geomorphic features of the southeastern corner of the western uplands (Joyce 1988); associated narrow valley lava flows, generally deeply weathered, interdigitate with the underlying folded Ordovician sediments. Phreatomagmatic maars are present but their tuffaceous deposits are typically partly or completely eroded (J. Hollis, unpub. data).

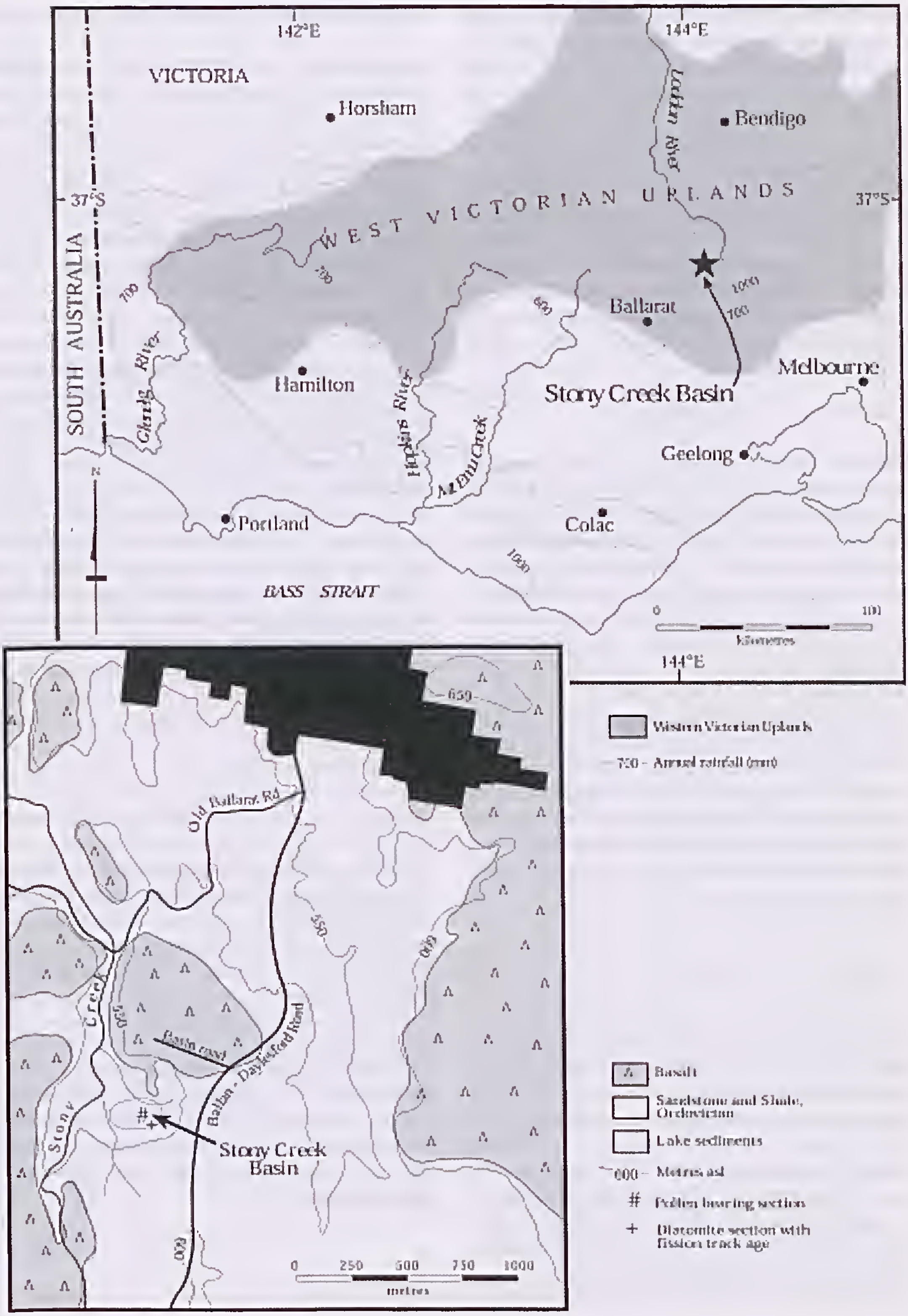
The climate of the region is controlled largely by the passage of subtropical high pressure anticyclones, which track over mainland southern Australia during autumn, winter and spring, but shift south of the continent during summer (Parkinson 1986). Low pressure fronts separating these anticyclones bring the majority of annual precipitation to the western uplands in the cooler months between April and November. The highest precipitation, up to about 1200 mm, falls on the most elevated parts of the continental divide in the southeastern corner of the western uplands, while as little as 400 mm falls on the northern and rainshadow parts of the southern margins. Annual rainfall and temperature at the Stony Creek Basin, seven km north of the continental divide, are estimated by BIOCLIM (Houlder et al. 2000) to be 870 mm, and 11° C, respectively.

Western uplands vegetation is predominantly *Eucalyptus* open woodlands and forests, with community type and species dominance controlled primarily by variations in altitude-dependent effective moisture budgets, and secondarily by soil type (Land Conservation Council 1987). Open box-ironbark woodlands in the driest, lowest areas give way to open gum-stringybark forests at better watered moderate elevations, and to damp sclerophyll forest (Conn 1993) in limited areas on and near the divide receiving more than 1000 mm annual precipitation. Tall open forest is nowhere well developed, and rainforest is absent entirely. Vegetation near Stony Creek Basin consists of *E. rubida-E. obliqua-E. radiata* open forests with grassy or heathy understoreys on duplex soils developed on Ordovician slopes, while deep krasnozems developed on basalt support *E. viminalis-E. obliqua* grassy open forests, most of which have been cleared for agriculture.

Stony Creek Basin is a flat-bottomed, roughly circular depression, its floor approximately 300 m in diameter. To the north and the west, rims 40 metres above the basin floor consist of erosional remnants of valley lava flows, while to the south and east they consist of ridges of Ordovician shale and sandstone. A small, seasonal stream, Stony Creek, flows along the western edge of the basin at the foot of the west rim and forms the only outlet from the basin.

The floor of the basin is partly mantled by ca. 2 m of mottled silt, sand and quartz gravel, much of which was removed during nineteenth century surface gold mining and later through development of the site as a motorcar racetrack. Beneath these mottled coarse textured deposits organic-rich, black, lacustrine silty clays containing wood fragments,

Fig. 1. Locality map of Stony Creek Basin within Victoria's western uplands (shaded), with rainfall isohyets. Stony Creek Basin relative to the town of Daylesford, height above sea level shown contoured and locations within the basin of the pollen- and diatomite-bearing sections.


142°E
144°E
37°S
37°S
VICTORIA
SOUTH AUSTRALIA
Horsham
Bendigo
Loddon River
WEST VICTORIAN UPLANDS
700
700
600
1000
700
Ballarat
Melbourne
Stony Creek Basin
Hamilton
Glenelg River
Hopkins River
Mt Emu Creek
Geelong
Portland
Colac
1000
N
BASS STRAIT
0
100
Kilometres
144°E
Western Victorian Uplands
700 - Annual rainfall (mm)
650
Old Ballarat Rd
450
600
Stony Creek
520
Basin road
Ballan - Daylesford Road
Stony Creek Basin
500
0
250
500
750
1000
metres
Basalt
Sandstone and Shale, Ordovician
Lake sediments
000 - Metres asl
Pollen bearing section
+ Diatomite section with fission track age

fossil leaf impressions, diatoms and sponge spicules attracted early scientific attention (Hart 1904; Orr 1927; Patton 1928; Coulson 1950). A vertical shaft lowered near the southern edge of the basin in 1864 encountered quartz gravels only after penetrating 35m of black clay (Hart 1904), which provides a minimum estimate of the depth of the lacustrine sequence.

The geological origin of the basin is uncertain. However, its simple circular outline, small size, depth of accumulated sediment and proximity to conspicuous eruptive centres in this volcanic region all suggest that the structure may be an explosion crater or maar, although no tuffaceous rocks are evident in the immediate vicinity (Orr 1927; JDH & JMKS pers. obs.).

METHODS

In March, 1999, a trench approximately 3 m in depth was excavated near the centre of the lake deposit. Samples were taken from the exposed vertical section (herein the pollen-bearing section) by hammering in and then extracting 10 x 10 cm metal boxes. Samples were wrapped with polyethylene, and transported to cold storage at the School of Geography and Environmental Science, Monash University.

Additional samples were collected from a 2 m high exposure (herein the diatomite section) of gravelly-mud overlain by 30 cm of diatomite, located in a drainage ditch approximately 50 m southeast of the trench. One sample was sieved and weight-separated to isolate its zircon fraction for analysis by the fission track dating method. The stratigraphic relationship between the diatomite and pollen bearing sections was investigated by augering down through the diatomite section.

Pollen and physical analysis

In the laboratory, 41 one cm^3 subsamples were taken at approximately 6.5 cm intervals for pollen analysis, and 5-10 cm^3 of sediment surrounding each subsample was taken for physical analysis. Organic and carbonate content were estimated by loss on ignition after combustion for two hours at 500° and 1000° C, respectively (Dean 1974). Pollen samples were spiked with a known quantity of exotic *Lycopodium* grains to allow calculation of pollen concentrations, and processed using standard chemical methods involving KOH, acetolysis, and HF (Moore *et al.* 1991), before being desiccated with ethanol and mounted in glycerol on microscope slides.

Pollen was counted routinely at 400x magnification with 1000x used for difficult identifications, under Olympus CH-2 and Zeiss Axiolab compound microscopes. In most cases at least 200 identifiable grains of dry land pollen and fern spore taxa were counted. These grains formed the pollen sum on which percentages of all taxa were calculated. Grains of aquatics, including the fern-ally *Isoetes*, were excluded from the sum. Charcoal particles, defined as angular, opaque particles greater than 10µ, were counted in relation to exotic *Lycopodium* spores on 20 slides.

Pollen identification was assisted by comparison with reference slides, and photos held in the School of Geography and Environmental Science, Monash University and contained in palynological publications on the Cenozoic of the Australian region. Pollen grains and fern spores were identified to the most refined feasible taxonomic level, usually genus or family. Identification of Myrtaceae pollen proved problematic. Despite the phytosociological importance and ecological diversity of the family, its pollen exhibits little morphological variation. Thus while most of the grains attributed to '*Eucalyptus* comp.' were clearly consistent with the modern pollen morphology of that genus, the type also includes grains that may represent both rainforest and sclerophyll genera including *Angophora*, *Melaleuca*, *Acmena* and *Syzygium*. Relatively distinctive verrucate pollen similar to that produced by the rainforest genera *Rhodomyrtus* and *Rhodamnia* was described as 'rainforest Myrtaceae', while psilate, syncolpate 15-20 µm grains of unknown generic affinity were described as 'other Myrtaceae'. Grains that were not clearly *Leptospermum* were attributed to 'myrtaceous shrubs' that may include genera such as *Baeckia* and *Callistemon* as well as some *Melaleuca* species. Within the Podocarpaceae, *Dacrydium* includes grains resembling both New Zealand *D. cupressinum* and New Caledonia *D. guillauminii*.

Zonation of the pollen diagram was carried out using dry land taxa with at least 5% representation in one or more samples. Four statistically significant local pollen zones were distinguished through optimal splitting by information content using PSIMPOLL (Bennett 1998).

Zircon fission-track analysis

Following mineral separation, zircon grains were mounted in FEP teflon, and, after optical-quality polishing, were etched in an eutectic KOH-NaOH melt (Gleadow et al. 1976) at 225°C for ~125 hours. Neutron irradiations were carried out in a well-thermalised flux in the HIFAR reactor, Lucas Heights, Australia. Fission track ages were measured using the external detector method (Gleadow 1981) with Brazil Ruby muscovite being used to record induced tracks. The muscovite detector was etched for 20 minutes in 48%HF at room temperature to reveal the induced tracks. The thermal neutron fluence was monitored by measuring the track density recorded in muscovite attached to pieces of the U3 standard glass. Fission tracks were counted in transmitted light using a dry 100x objective at a total magnification of 1600x. Only zircons with sharp polishing scratches were counted. A total of 64 individual grains were dated. The age of the sample was calculated using the standard fission track age equation using the zeta calibration method (Hurford & Green 1982) and errors were calculated using published methods (Green 1981). A personal zeta calibration factor (for POS) of 87.8±5 (U3) was determined empirically using zircon age standards with independently known ages.

RESULTS

Sediment stratigraphy

The pollen-bearing section exhibited massive to faintly microlaminated, very dark grey or black silty clays with organic content ranging from 10-25% (Fig. 2). Uniformly low (<3%) weight losses after combustion at 1000° C may be attributable to loss of clay lattice water rather than carbonate (Dean 1974) and are not presented. Augering of the diatomite section revealed grey, gravelly mud changing abruptly (over ~10cm) to fine, organic-rich black clay at a depth of 3.4 m below the base of the drainage ditch. Pollen analysis of this black clay suggested a correlation with local pollen zone S-2 or S-3(Fig. 3), implying that the diatomite section sits stratigraphically above the pollen-bearing section.

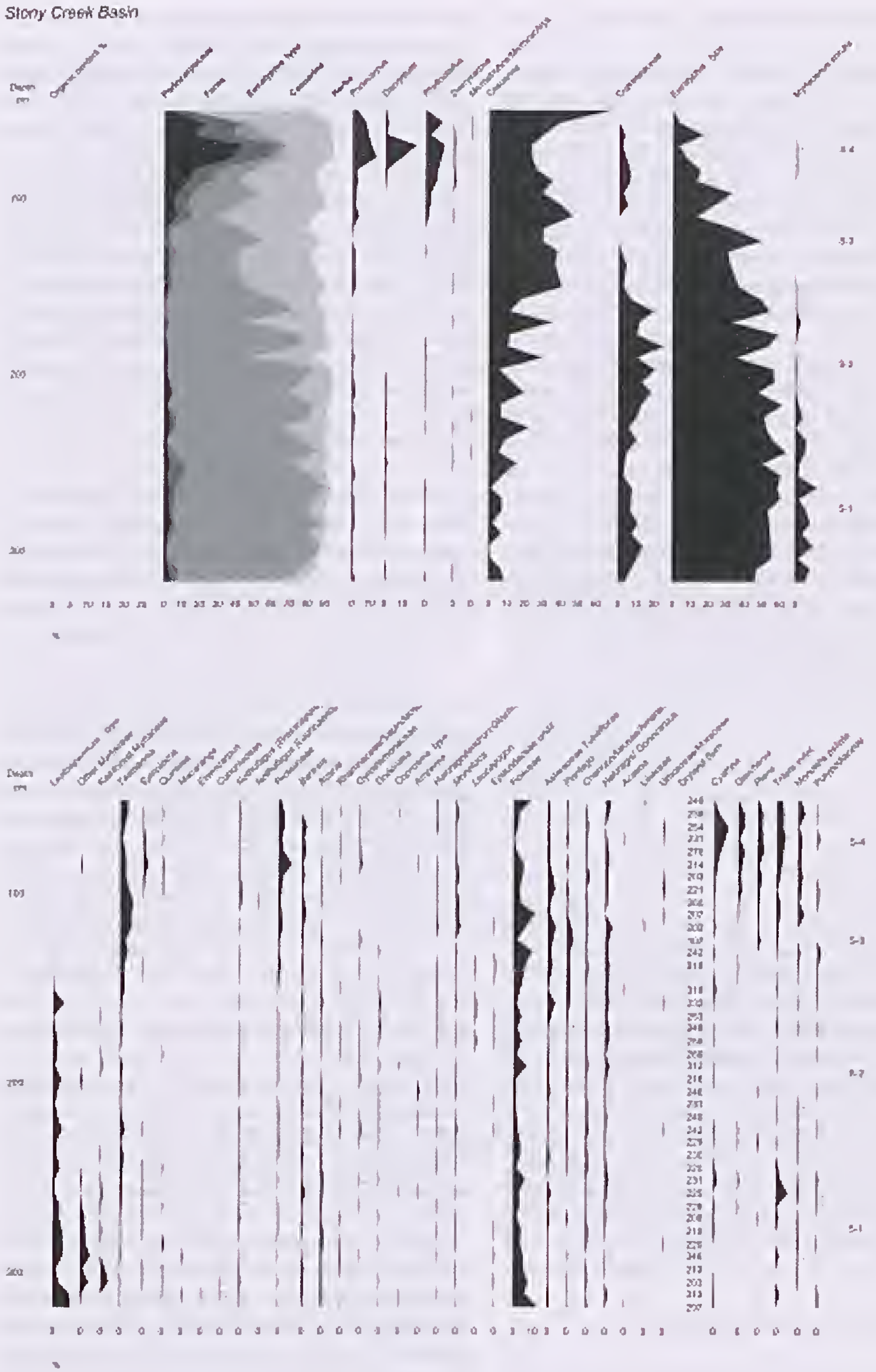
Description of the pollen diagram

Pollen and spore taxon percentages, organic matter and moisture content, charcoal and pollen concentrations, and charcoal/pollen ratios are shown in relation to the established zonation on Fig. 2. Also included is a summary diagram of ratios between Podocarpaceae, fern spores, *Eucalyptus* type, *Casuarina* and herbs including Poaceae.

Zone S-1 (318-235 cm): *Eucalyptus* type is consistently the dominant dry land pollen type, never falling below 45% of the sum. Non-eucalypt Myrtaceae are best represented, and most diverse, in this zone. Casuarinaceae and Cupressaceae have low percentages, and herbaceous taxa are poorly represented. *Acacia* is most consistently represented in this zone, and *Banksia* is represented by a small number of grains in most samples. Trace values are present for a variety of dry land shrubs and trees from both open forest and rainforest. Several rainforest taxa, viz. *Nothofagus* (Brassospora), *Symplocos*, *Quintinia*, *Macaranga-Mallotus* and *Elaeocarpus* have some representation. Herbaceous pollen, composed almost entirely of Poaceae, have relatively low values as do the aquatics, apart from a single peak in Cyperaceae. Charcoal and pollen concentrations are highest in this zone, and the charcoal:pollen ratio is erratic.

Zone S-2 (234-155 cm): *Eucalyptus* type remains the dominant type throughout, decreasing only slightly towards the top. Rainforest Myrtaceae and other Myrtaceae nearly disappear near the base of this zone, myrtaceous shrubs decrease to trace levels towards the top of the zone, while *Leptospermum* maintains values only slightly lower than those in zone S-1. Cupressaceae achieves its highest percentages within this zone (10-20%), while Casuarinaceae percentages rise steeply towards the top of the zone. Pollen values of herbaceous taxa remain low, but *Plantago*, Asteraceae (Tubuliflorae) and *Haloragis* are more abundant and more consistently represented than in zone S-1. Sclerophyll tree and shrub taxa, such as *Acacia*, *Banksia*, Proteaceae, *Haloragodendron*/*Glischrocaryon* and *Dodonaea*, are consistently represented. Aquatic values remain low. Both charcoal and pollen concentrations decline from zone S-1, but the charcoal:pollen ratio rises to its highest values in this zone.

Zone S-3 (154-95 cm): This zone is marked by a dramatic peak in the shallow-water aquatic *Isoetes* (which played no role in zone definition) accompanied by distinctly higher values in other aquatic and swamp taxa, namely Restionaceae, Cyperaceae and *Triglochin*/*Typha*. Dominance of the


Stony Creek Basin
Depth cm
Organic content %
Podocarpaceae
Eucalyptus type
100
200
300
S-4
S-3
S-2
S-1
%
Depth cm
Dryland Sum
Cyathea
Pinus
%

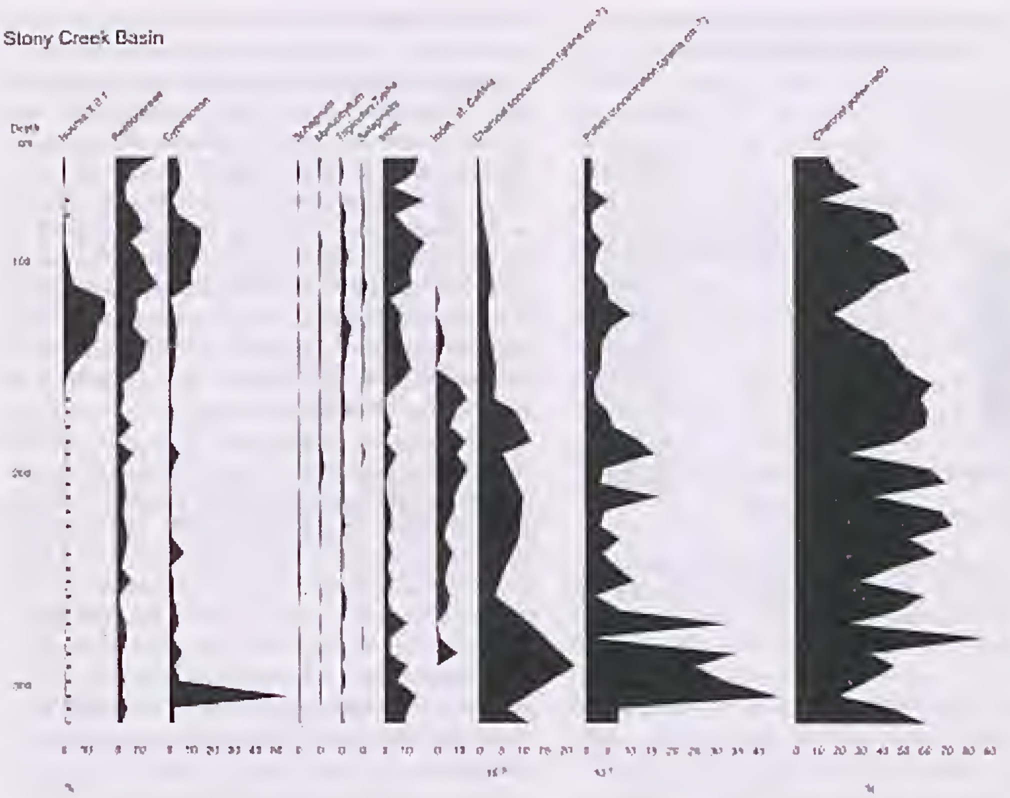


Fig. 2. Stony Creek Basin pollen percentage diagram plotted against depth. Percentages are relative to the total pollen and spore sum, excluding aquatic pollen.

pollen sum is shared by Casuarinaceae and *Eucalyptus* type, although the latter declines towards the top of the zone. Cupressaceae is very low at the base of the zone, then disappears from the record to return towards the top of the zone. *Podocarpus*, though still less than 5% of the pollen sum, is slightly better represented than at any time previously, while *Phyllocladus*, absent in the lower half of the zone, is increasingly represented in the upper half. The latter pattern is evident also in *Tasmannia*, *Monotoca*, Proteaceae and by most fern spores. The opposite trend is exhibited by Poaceae, Asteraceae, *Plantago* and *Haloragis*, which are all best represented in this zone, but then drop to low levels near the top of the zone. Concentrations of charcoal are low while pollen concentration peaks in the middle of the zone.

Zone S-4 (94-51 cm): Casuarinaceae dominates the pollen sum, while *Eucalyptus* type declines through the zone, vanishing completely in the uppermost sample. Podocarpaceae and Cupressaceae increase in importance, then decline to low levels or disappear near or at the top of the zone. Podocarpaceae, fern spores, Proteaceae, including *Banksia*, and *Symplocos* are all best represented in this zone. Herb and shrub taxa are poorly represented except for *Monotoca*. Of the aquatic and swamp taxa, Restionaceae and Cyperaceae are relatively well represented but at lower levels than in the previous zone. The uppermost sample at 51 cm is very distinctive, being marked by high values for Casuarinaceae, *Tasmannia*, Proteaceae, Poaceae, *Haloragis*, some fern types and Restionaceae, and the complete absence of *Eucalyptus* comp. and most Podocarpaceae. Pollen and charcoal concentrations, and the charcoal:pollen ratio, are generally low in this zone.

Fission track results

The zircon fission track ages for the sample from the diatomite section are presented in Fig. 4. Complete analytical results for the 64 grains analysed from this sample are shown in Table 1 and single-grain age

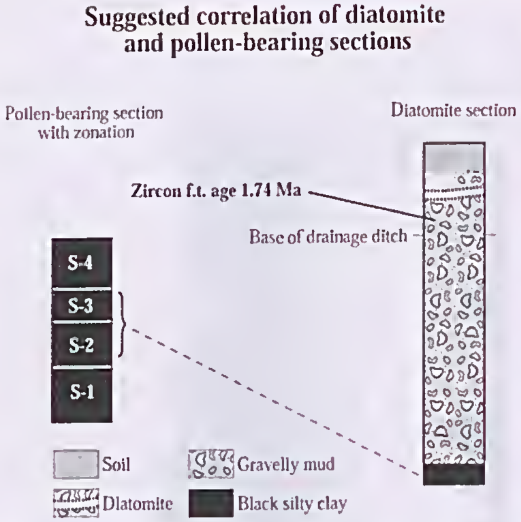


Fig. 3: Stratigraphy of the pollen-bearing section and the diatom section, showing the location from which detrital zircons were recovered, and suggested correlation of the diatomite section with zones S2-S3 of the pollen bearing section.

distributions (in the form of radial plots) are presented in Fig. 4A, B.

An overall age of 6.7±0.9 Ma was calculated for the 64 individual grains dated. However, as shown in Fig. 4A, the sample contained at least three distinct grain-age populations, indicating that the unit sampled from the diatomite section had been provenanced from multiple source terrains. Therefore, in order to best estimate the age of deposition of the diatomite section, the grains from the older two populations were statistically removed before a final age calculation was made. Following this, the sample yielded a date of ~1.74±0.16 Ma (Fig. 4B).

AGE AND DURATION OF THE SEQUENCE

The timing of sediment deposition in Stony Creek Basin can be estimated in two ways: interpretation of the fission track age from detrital zircons found within the diatomite section, and by comparison with southeastern Australian regional pollen and spore stratigraphies.

Fission track ages of detrital zircons from the diatomite section indicate that this unit probably was deposited around 1.74±0.16 Ma. As the pollen-bearing black clays underlie the diatomite, they must have been deposited prior to this time. The abrupt transition between the two units suggests that their contact may represent an erosional hiatus. Consequently the age of the pollen record is uncertain. It might be assumed, however, that any hiatus would be of short duration considering that small, deep maar lakes typically fill with sediment in only some 200-300 kyr, in tectonically relatively stable regions such as the western plains of Victoria (Wagstaff et al. 2001) and the Atherton Tableland of northeast Queensland (Kershaw et al. 1991a). Thus deposition of the pollen-bearing black clays is unlikely to predate deposition of the diatomite section by more than this, and probably occurred towards the end of the Late Pliocene (2.6-1.78 Ma).

Comparison with late Cenozoic pollen stratigraphies derived from the marginal marine Murray and offshore Gippsland Basins (Macphail and Truswell 1989, 1993; Macphail 1997, 1999) suggest deposition may have occurred as early as the Late Miocene-Early Pliocene, when SCB rainforest taxa such as *Dacrydium*, *Dacrycarpus* and *Symplocos* disappear from Murray Basin sequences, *Nothofagus* Brassospora first declines to trace levels, and some open forest taxa which contribute to the SCB record, such as *Amperea* (*Rhoipites ampereaformis*), *Monotoca* (*Monotocidites galeatus*) and *Leptospermum* first appear (Macphail and Truswell 1993). A minimum age of Late Pliocene is indicated by the consistent trace presence of Brassospora, which is absent completely from younger strata within both the Murray and Gippsland Basins, and by the absence from SCB of the *Cossinia arcuata*-type (*Tubulifloridites pleistocenicus*), the first consistent appearance of which defines the base of the Late Pliocene in both Murray and Gippsland Basins (Macphail 1997, 1999).

However, the dominance of SCB local pollen zones S-2 and S-3 by sclerophyll vegetation associated with herb and shrub genera including *Pimelea* (*Thymelaepollis* sp.) and *Plantago*, both first recorded for southeastern Australia in the Late Pliocene (Macphail *et al.* 1995; Macphail 1999), and *Pomaderris*, common in southeastern Australian modern pollen rain (Macphail 1981; Kershaw *et al.* 1994b) and Early-Late Quaternary records (D'Costa and Kershaw 1997; Wagstaff *et al.* 2001) but apparently unknown(?) from the Tertiary (Stover & Partridge 1973; Martin 1987; Macphail & Truswell 1993; Macphail *et al.* 1995), suggest that the sequence is no older than terminal Late Pliocene. Furthermore, the apparent close temporal juxtaposition of rainforest angiosperms and gymnosperms such as *Symplocos*, *Quintinia*, *Podocarpus*, *Phyllocladus*, *Dacrydium* and *Dacrycarpus* that are extinct or highly restricted in the region today, with *Callitris*-, *Eucalyptus*- and Casuarinaceae-dominated vegetation, evokes a period of 'transitional' Tertiary-Quaternary vegetation comparable to Casuarinaceae-Podocarpaceae dominated assemblages attributed to the Late Pliocene of the palaeomagnetically dated Lake George record (McEwan Mason 1989; 1991). These juxtapositions of extinct and extant taxa with contrasting ecologies cannot be explained by reworking of fossil palynomorphs because there are no known polliniferous older rocks in the catchment of the basin. The trace quantities of *Nothofagus* (Brassospora) at Stony Creek Basin contrast with Middle Pliocene assemblages from Lake George, and Late Pliocene assemblages from western Tasmania (Macphail et al. 1995), in which Brassospora was still a substantial component, suggesting that Stony Creek Basin is coeval with or younger than these assemblages.

If the age of the SCB sequence is considered latest Pliocene, the absence of the *Cassinia arcuata*-type (*T. pleistocenicus*) demands explanation. Given the small size of the Stony Creek Basin palaeolake, this absence may simply reflect the absence of source plants from a restricted upland pollen catchment. Similar contrasts between upland and lowland basins occur in the Late Quaternary where, for example, the *C. arcuata*-type is virtually absent from a swamp record spanning the last glacial cycle at Wyelangta, in the Otway Ranges (McKenzie & Kershaw 2000), despite the proximity of these ranges to the Victorian western plains where the pollen type constitutes up to 20% of pollen sums during glacial episodes ranging from the latest Early Pleistocene up to the last glacial maximum (D'Costa et al, 1989; Harle et al. 1999; Wagstaff et al. 2001). The absence at Stony Creek Basin of the *C. arcuata*-type may similarly reflect the inability of lowland pollen to significantly penetrate pollen assemblages within small, upland lakes with forested catchments.

The temporal resolution of the pollen record, and the length of the interval it represents, is uncertain. However, sedimentation rates in maar lakes possessing good chronological control, both in Australia (Kershaw 1986; Harle et al. 1999; Wagstaff et al.2001) and in Europe (Leroy & Seret 1992; Williams et al. 1996; Zolitschka and Negendank 1996; Willis et al. 1999) are relatively uniform, varying only between about 2 and 7 kyr m^{-1}. On this basis, the 270 cm of sediment analysed here may represent 6 kyr - 19 kyr.

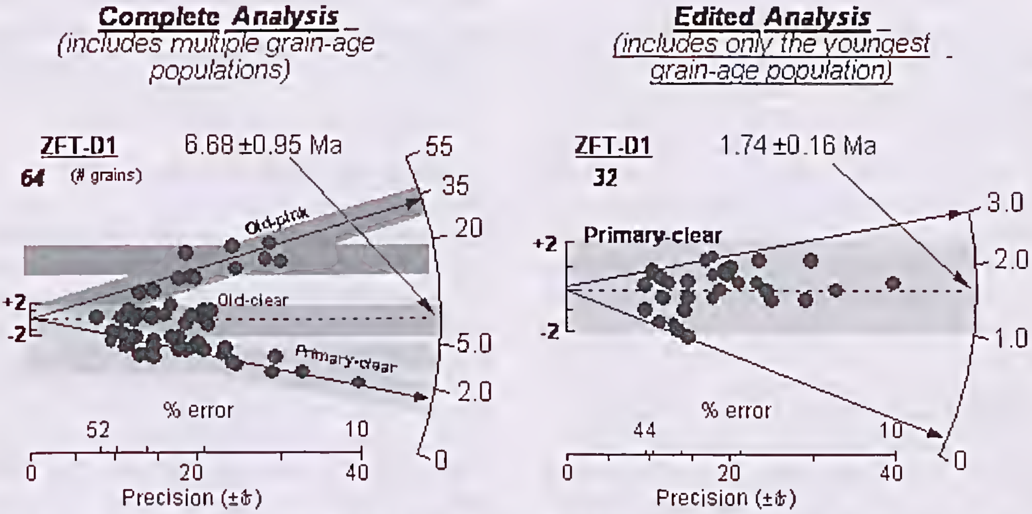


Fig. 4A, B. Single-grain age results in the form of radial plots from the sample dated from the diatomite section. The first plot (Fig. 4A) shows all of the single-grain ages for the sample. These break down into three distinct age populations: 1) old-pink grains, 2) old-clear grains, and 3) young-clear grains. The second plot (Fig. 4B) shows only the ages from the young-clear population of grains. The age of this population of grains of ~1.74 Ma is interpreted to represent the minimum age of deposition of the unit. On radial plots, each age has unit standard error (±2σ) on the y-axis, its actual precision is indicated on the x-axis, and its age is read by extrapolating a line from the 0-point through the plotted point to the logarithmic age scale on the right perimeter. Further details presented in the text.

PALAEOENVIRONMENTAL RECONSTRUCTION

Vegetation and environments

During zone S-1, the deposition of fine organic mud and low representation of aquatic pollen suggests a deep lake local environment with only a narrow fringe of swamp vegetation. Eucalypt forests, with other sclerophyll elements such as Casuarinaceae, *Callitris*, *Acacia* and *Banksia*, dominated the pollen catchment, while the presence of small quantities of poorly dispersed pollen similar to that of taxa such as rainforest Myrtaceae implies that these forests included a rainforest component or understorey. Modern climatic preferences of the rainforest trees *Rhodamnia*, *Rhodomyrtus*, *Macaranga-Mallotus*, *Symplocos* and *Quintinia* together suggest these contributed to warm temperature/subtropical (mesotherm) rainforest. Subsequent loss of most of these rainforest taxa in the upper half of the zone could reflect one or more of a number of climate changes including regional drying, temperature reduction, altered seasonality and increased climatic variability. The lack of response of aquatic pollen values together with the persistence of mesic understorey taxa such as *Tasmannia* and ferns, indicative of cool but moist conditions, suggests that a temperature reduction was a major cause.

Eucalypt dominance continued through zone S-2. Some change in the vegetation is indicated by the expansion of *Callitris* and to some extent Casuarinaceae, along with shrubs such as *Dodonaea*, *Coprosma*, *Haloragodendron* and the Epacridaceae, that could indicate some drying, although this is not supported by values of aquatic taxa and herbs that remain low, suggesting the maintenance of deep water conditions. Alternatively, increased lake level variability may have disrupted marginal swamp vegetation. Regional fire frequency and/or intensity was greatest during this time, which is perhaps consistent with some variability in the pollen representation of major taxa, and supports the proposal of more variable climatic conditions.

The dramatic increase in aquatics in zone S-3, notably *Isoetes* but also *Typha*/*Triglochin*, Restionaceae and Cyperaceae, indicates expansion of shallow water habitat most likely due to a substantial reduction in lake water level. The synchronous expansion of herbs, notably Poaceae, Asteraceae, *Plantago* and *Haloragis*, suggests this lowering of water levels was predominantly a response to regionally reduced effective precipitation. Eucalypt forests with associated shrubs were increasingly replaced by Casuarinaceae dominated communities. Decreasing charcoal and dryland pollen concentrations could reflect increased sediment deposition with greater aquatic plant productivity.

In the period represented by the latter part of zone S-3 and zone S-4, *Eucalyptus* forests declined and eventually disappeared from the area around the basin. Shrub and herb taxa characteristic of open vegetation also declined, in response to expansion of *Casuarina-Allocasuarina* forest and rainforest which included the gymnosperms *Podocarpus*, *Phyllocladus*, *Dacrydium* and perhaps also *Dacrycarpus*, despite its low pollen values. *Quintinia* and *Symplocos* also contributed to this western uplands rainforest, as did an understorey of ferns. The co-occurrence of *Casuarina* or *Allocasuarina* with diverse Podocarpaceae may reflect edaphic and topographic niche differentiation. The expansion of rainforest and reduction in more open eucalypt vegetation suggests increased precipitation, and/or reduced importance of fire. Support for high rainfall is also provided by a reduction in aquatic pollen, especially in the middle of zone S-4. The generally higher aquatic pollen component towards the top of the record may reflect general shallowing of the lake due to sedimentation rather than simply effectively lower rainfall. The absence of zone S-1 rainforest taxa of mesotherm affinities, and their replacement by Podocarpaceae dominated rainforest, suggests that zone S-4 rainforest was cool temperate (microthermal).

Quantitative palaeoclimate estimates

The Stony Creek Basin data provide evidence for the successive development of discrete climatic episodes during the Late Pliocene in Victoria's western uplands. Quantification of the climate prevailing during these episodes may be attempted by reference to the climatic tolerances of inferred nearest living relatives (Hill and Scriven 1997; Jordan 1997a) of the fossil pollen taxa. However, since the fossil pollen generally has not been identified below the genus level, the number of species with which a fossil type must be compared may be large, and the resulting inferred climatic space correspondingly imprecise (Martin 1997). This problem is especially acute in zones S-2 and S-3 where dominant genera or pairs of closely related genera (eg. *Eucalyptus*, *Callitris*, *Casuarina/Allocasuarina, Gonocarpus/Haloragis*) exhibit uninformative bioclimatic profiles as a consequence of extensive, continent-wide distributions. Quantification of palaeoclimate in these zones is therefore difficult. By contrast, rainforest genera or generic groups which contribute to zones S-1 and S-4 can effectively constrain Late Pliocene western uplands palaeoclimate. This is possible despite the large number of Australasian species in some of these genera (eg. *Macaranga/Mallotus*, *Podocarpus*) both because of the clear differentiation of southeastern Australian rainforest into microtherm (4-14°C mean annual temperature- MAT) and mesotherm (14-22°C MAT) types (Nix 1982) and because of the relatively high minimum precipitation requirements exhibited by Australian rainforest generally.

Rainforest pollen types present in zone S-1 (eg. *Rhodamnia/Rhodomyrtus* types, *Macaranga/Mallotus* and *Elaeocarpus*) suggest the occurrence of at least limited local stands of mesotherm rainforest. Using the structural/environmental rainforest typology of Webb (1968), these taxa imply the presence of evergreen notophyll vine forest, which can serve as an approximate vegetation model from which an estimate of climate can be made based on a bioclimatic analysis of Australian rainforests by Nix (1991). Climate averages for this rainforest type are MAT around 18°C, with precipitation around 1650 mm. A conservative climate estimate for zone S-1 suggests that MAT was at least the 14°C minimum for all Australian mesotherm rainforests, and annual precipitation was ≈ 950 mm (Nix 1982, 1991).

The rainforest pollen assemblage present in zone S-4 (*Podocarpus, Dacrydium, Phyllocladus, Dacrycarpus, Tasmannia*) implies the presence of microtherm rainforest, by comparison with the ecological and climatic habitats of Podocarpaceae in southeastern Australia, Tasmania and New Zealand (Kershaw & McGlone 1995; Ogden & Stuart 1995). The assemblage has no analogue in Australian vegetation today, but the climate during deposition of zone S-4 may be estimated by comparison with Webb's (1968) microtherm Evergreen microphyll fern forest. Although this forest type typically is dominated by *Nothofagus cunninghamii*, its widespread distribution from Tasmania to northern New South Wales, and the inclusion in Tasmania of *Phyllocladus aspleniifolius* and other Podocarpaceae, suggest that its bioclimate may provide a first approximation of the climate of zone S-4. Climate averages (Table 2) for this rainforest type include MAT around 12°C, with precipitation around 1250 mm. A conservative estimate for zone S-4 suggests that MAT did not exceed the 14°C maximum for all Australian microtherm forests, and annual

Table 1. Fission track analytical results.

Number of grains	Standard track density ($x10^5 cm^{-2}$)	Fossil track density ($x10^5 cm^{-2}$)	Induced track density ($x10^6 cm^{-2}$)	Chi squared probability	Uranium (ppm)	Fission track age (Ma±1σ)
Complete anaysis - includes all three zircon populations						
64	*6.982* *(2724)*	*9.713* *(1080)*	*4.091* *(4549)*	*0.0*	*304.7*	*6.68±0.95*
Oldest grain-age populatian (old-pink zircon grains)						
11	*6.982* (2724)	*36.25* (645)	*3.817* (679)	*3.1*	*284.2*	*29.2±2.3*
Middle grain-age papulatian (old-clear zircon grains)						
21	6.982 (2724)	8.779 (274)	3.310 (1033)	99.5	246.5	8.13±0.64
Youngest population (young-clear zircon grains)						
32	6.982 (2724)	2.589 (161)	4.562 (2837)	85.8	339.8	1.74±0.16

Brackets show number of tracks counted. Standard and induced track densities measured on mica external detectors (g=0.5), and fossil track densities on internal mineral surfaces. Zircon ages calculated using ζ=87.8±5 for dosimeter glass U3 (analyst: P. O'Sullivan) precipitation was ≥850 mm (Nix 1991).

Comparison of these estimates with modern climate at Stony Creek Basin (Table 2) suggests that during deposition of zone S-4, MAT was similar to today (11.1°C). By contrast, temperatures during deposition of zone S-1 were at least 3°C warmer (≥14°C) than today. The minimum estimates for annual precipitation during zones S-1 and S-4 suggest that modern precipitation at Stony Creek Basin (868 mm) may be marginally adequate to support some rainforest types, although the driest quarter (summer) rainfall of only 133 mm apparently is lower than summer minima for all Australian rainforest types (Nix 1991)(Table 2). Thus Late Pliocene western uplands climates appear to have been wetter than today, particularly during summer.

There are, however, additional potential constraints on acceptance of these quantitative palaeoclimatic estimates. First, rainforest taxa may overestimate regional precipitation if source plants were confined to sheltered, moist microclimates (Carpenter and Horwitz 1988; Demko *et al.* 1998). However, rainforest in southeastern Australia frequently is confined to sheltered microclimates in otherwise fire prone landscapes (Busby 1986; Bowman 2000), and such marginal stands are represented in the bioclimatic profiles (Nix 1991).

Second, extinctions of rainforest taxa are documented as recently as the Early-Middle Pleistocene in western Tasmania (Jordan 1995a,b; 1997a,b), where microfossil and macrofossil assemblages dominated by extant microtherm species also include extinct species belonging to higher taxa (e.g., *Quintinia*, *Austromyrtus*, *Symplocos*, Lauraceae) now confined in Australia to lower latitude, meso- and megatherm habitats. Jordan (1997a) showed that these "apparent" mesotherms were all extinct species and/or the bioclimatic profiles of their living mesotherm relatives were anomalous within predominantly microtherm assemblages. He thus argued that the apparent mesotherms were in fact microtherms with climatic tolerances similar to those of extant Tasmanian rainforest.

If this pattern is a general one, it is possible that the source plants of the apparently mesotherm pollen types at Stony Creek Basin were in fact microtherms, and their presence may not imply that Late Pliocene MAT was significantly different from modern microtherm MAT at SCB. However, in contrast to Jordan's (1997a) fossil assemblages dominated by extant microtherm species, the zone S-1 rainforest assemblage contains no obvious climate anomalies, but is composed of "apparent" mesotherms (e.g. rainforest Myrtaceae, *Macaranga-Mallotus*, Cunoniaceae, *Elaeocarpus*). Possible exceptions include *Symplocos* and *Quintinia*, which Jordan (1997a) believed may have included microtherm species in the Tasmanian Early Pleistocene. The occurrence of both genera in both zones S-1 and S-4 may reflect close altitudinal juxtaposition of meso- and microtherm communities, or may reflect the involvement of more than one species in each genus. Nevertheless, in the absence of macrofossil evidence identifiable to the species level, there appears no reason to reject the simplest interpretation that the assemblage reflects the presence of mesotherm rainforest taxa during the Late Pliocene in Victoria's western uplands.

Table 2. Selected bioclimatic attributes of the primary rainforest groups Evergreen notophyll vine forest, Evergreen microphyll fern forest, and modern climate at Stony Creek Basin (rainforest data after Nix 1991; Stony Creek Basin data generated in BIOCLIM).

	Annual mean temperature (·C)	*Wettest quarter mean temp.*	*Driest quarter mean temp.*	*Annual mean rainfall (mm)*	*Wettest quarter mean rainfall*	*Driest qtr mean rainfall*
Evergreen notophyll vine forest	17.9 ±2.8	21.8 ±2.3	14.7 ±3.9	1657 ±603	792 ±386	183 ±62
Evergreen microphyll fern forest	12.0 ±1.9	13.0 ±5.0	11.5 ±4.0	1255 ±430	429 ±211	214 ±44
Stony Creek Basin	11.1	5.8	16.5	868	296	133

It is noteworthy that marine oxygen isotope records provide little support for warmer than Holocene global mean temperatures for any time since about 2.6 Ma (Shackleton *et al.* 1990, 1995). If, as argued by Kershaw (1997), lower rainfall and temperature limits for many Australian rainforest taxa have been truncated by glacial aridity and fire, it may be possible that Late Pliocene growth of "mesotherm" rainforest taxa in Victoria's western uplands, rather than reflecting elevated Late Pliocene MAT, depended upon regional effects, perhaps related to rainfall seasonality and its effects on fire frequency.

IMPLICATIONS FOR REGIONAL VEGETATION AND CLIMATE RECONSTRUCTIONS

Implications of the Stony Creek Basin record for regional climate and vegetation reconstruction, combining pollen data associated with fission track dated sediment, are twofold:

In the first place, patterns of change in the record could suggest that the vegetation and aquatic environments of Stony Creek Basin are very sensitive to climate changes of broad regional significance. While it may be premature to attribute concepts of glacial climate stages to the pollen assemblages, it is possible that the sequence represents part of a climate cycle resulting from orbital forcing, with zone S-1 representing a moist, mesothermal 'interglacial' assemblage, S-2 and S-3 representing cooling 'glacial' conditions peaking in S-3, and S-4 representing a moist, microthermal 'interstadial' period. Preliminary analysis of an extended 40m long core collected recently from the basin (JMKS, unpublished data) does confirm the cyclic nature of vegetation succession observed in these top three metres.

Secondly, the presence of rainforest taxa outside the modern range of rainforest in the SCB record implies the persistence of high, particularly summer, rainfall, at least during "interglacial" or "interstadial" intervals, in Victoria's western uplands during the latest Tertiary. Bowler (1982) suggested that evolution of Australian Cenozoic climate involved a late Neogene shift from summer-dominant to winter-dominant rainfall across southern Australia. Kershaw *et al.* (1991b) and Truswell (1993) considered this shift may partly explain the final demise of many rainforest taxa in southern Australia which are now extinct or confined to Australia's east coast. The Stony Creek Basin data imply that such a shift may have been more protracted, and more complex, than previously considered, as it apparently had not fully run its course near the end of the Pliocene.

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THE LAST MILLION YEARS AROUND LAKE KEILAMBETE, WESTERN VICTORIA

A. Peter Kershaw[1], Donna M. D'Costa[1*], John Tibby[1+], Barbara E. Wagstaff[1] & Henk Heijnis[2]

[1]Centre for Palynology and Palaeoecology, School of Geography and Environmental Science, Monash University, Vic 3800
[2]Environmental Radiochemistry Laboratory, Australian Nuclear Science and Technology Organisation, PMB 1, Menai, NSW 2234
*Present address: School of Environmental and Marine Science, Tamaki Campus, University of Auckland, PB 92019, Auckland, New Zealand
+Present address: Department of Geographical and Environmental Studies, University of Adelaide, SA 5005

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Pollen records from sediments preserved in the older volcanic crater maars of Lake Terang and Pejark Marsh, situated close to the more recent and intensively researched younger maar containing Lake Keilambete, provide a basis for understanding the development of the present landscape of western Victoria in relation to past vegetation evolution, climate change and volcanic activity. Despite dating uncertainties and discontinuities, the record from Lake Terang may cover much of the last five hundred thousand years (500 ka) while that from Pejark Marsh is fission track dated to between about one million years (1 Ma) and 700 ka. An analogue method is used to provide measures of past vegetation and precipitation. Overall, the Early Pleistocene vegetation was dominated by herbaceous taxa with an open canopy of trees composed of more *Callitris* and fewer eucalypts than today. The climate was drier, never achieving rainfall levels higher than present. Since this time the vegetation and climate displayed greater variability, probably in relation to global shifts between glacial and interglacial conditions, with interglacial peaks often showing the development of eucalypt forest and expansion of cool temperate rainforest. Through the whole period, climate appears to have been the dominant influence on vegetation with no detectable impact of volcanic activity.

Key words: Quaternary, pollen analysis, palaeoclimates, analogue matching, volcanic plains, Victoria

LAKE Keilambete has been a major focus of palaeoenvironmental research for over 30 years. Past lake and salinity records derived from the study of sediments (Bowler 1981; Bowler and Hamada 1971), ostracodes (De Deckker 1982), ostracod chemistry (Chivas et al. 1993; 1985) and aquatic pollen (Dodson 1974) and hydrological modelling based on the calibration of these records (Jones et al. 1998), have combined to provide an unprecedented, high resolution record of effective precipitation over approximately the last 10,000 years (the Holocene period) in Australia. Calculated precipitation/evaporation ratios varied from less than 0.7 around 10,000 years ago when the lake was dry to at least 1.1 about 7000 years ago when the depth of the lake reached 40 m and overflowed (Jones et al. 1998). Presently the lake is at an intermediate level but, like many lakes within the region, the level has been falling rapidly in the last 100 years, probably due to a combination of reduced precipitation and increased temperatures (Jones et al. 1998).

In contrast to the marked changes in environmental indicators derived from the lake basin, the pollen record of terrestrial vegetation from this site is bland (Dodson, 1974; Tibby et al. this volume). The domination by Poaceae with consistently low levels of *Eucalyptus* and Casuarinaceae through the whole of the last 10,000 years, indicates a little varying open woodland, apparently insensitive to the substantial changes in climate. Both the lack of variation in regional vegetation through time and the absence of forest at the present day have been the subject of some debate as elucidated by Dodson (1974) and Jones (2001). A mean annual rainfall of about 800 mm, and substantially more during the mid Holocene, is adequate to support sclerophyll forest vegetation throughout much of southeastern Australia and, consequently, other factors such as soil and fire have been proposed as limiting forest development. Certainly the heavy clay soils derived from some basalt parent material are not conducive to tree growth due to swelling and shrinking of clay minerals and poor drainage capacity (Dodson 1974). Sclerophyll forests may also be less competitive on such substrates, having evolved on much older soil landscapes. However, very recent, little weathered basalt flows do support forest, most likely because of their coarse, well drained, structure. Fire, on its own, is unlikely to have resulted in the exclusion of forest as this factor is an integral component of most forest systems in Australia.

A greater understanding of the nature of the vegetation around Lake Keilambete and its relationship to soils, fire and climate can perhaps be gained by a longer term history of vegetation and environments. Although evidence of past environmental conditions from Lake Keilambete itself, prior to the Holocene, is very limited and does not include pollen data (Bowler and Hamada 1971), other nearby crater lakes, geologically older than Lake Keilambete, have recently revealed much longer records. Here we present evidence of vegetation and environmental change from Lake Terang and Pejark Marsh that together are considered to cover much of the last million years, a significant portion of the lifetime of the volcanic province. Details of the record from Pejark Marsh are contained in Wagstaff et al. (2001) while the more recent part of the record from Lake Terang is presented in D'Costa and Kershaw (1995). The whole of the existing Terang record formed the MA thesis of D'Costa (1989) but uncertainty over its chronology has discouraged formal publication. A Holocene pollen record from Lake Keilambete is contained in Kershaw, Tibby et al. (this volume).

THE PALAEOECOLOGICAL SITES AND THEIR REGIONAL SETTING

Lake Keilambete, Lake Terang and Pejark Marsh lie within 2-4 kilometres of each other around the town of Terang (Fig. 1). All originated as maar craters formed by explosions resulting from rising magma coming into contact with ground water within the Tertiary sedimentary limestone rocks, underlying the basalt (Birch 1994). The basins filled with water and acted like natural rain gauges, with sediments and biological indicators reflecting variation in lake water level and hence effective precipitation. Lake Keilambete still acts as a rain gauge lake but Lake Terang was drained by early European settlers and sediment infilling converted Pejark Marsh from a lake to a swamp a long time prior to subsequent drainage by Europeans. The Lake or 'swamp' surfaces of the sites all lie between 100 and 140 m ASL, only slightly lower than the general landscape that is relatively flat apart from volcanic structures such as Mt Noorat and Mount Terang, the former reaching above 250 m ASL (Fig. 1).

The area experiences a temperate climate with warm summers and a winter rainfall maximum. Rainfall averages 800 mm with 260 mm falling in winter. Mean annual temperature is around 13^0 C with means of about 9^0C and 18^0C for the coolest and warmest months respectively. The regional open *Eucalyptus* woodland with a grassy ground layer that existed at the time of European arrival was interrupted by a mixed woodland of *Allocasuarina verticillata, Banksia marginata* and *Acacia* in better drained areas, particularly scoria cones, that could have included Mts. Noorat and Terang, and scrub dominated by *Leptospermum lanigerum* in swamps such as that of Pejark Marsh. More distant, eucalypt open forest occurs on recent basalt 'stoney rise' country and on sedimentary parent materials within and around the basalts, while tall open eucalypt forest and patches of cool temperate rainforest dominated by *Nothofagus* are found in the Otway Ranges to the southeast, where rainfall can exceed 1500 mm per annum.

FIELD, LABORATORY AND NUMERICAL METHODS

Pejark Marsh is geomorphologically old with the original lake having filled with sediment and the tuff ring, that would have surrounded the crater, having virtually eroded away. A core was extracted from the swamp surface by the Geological Survey of Victoria in 1991 to a depth of 99 m. This core encountered lake sediments, peats and volcanic ashes above basal marl of Tertiary age, the latter preserved below the explosive maar structure. Unfortunately the construction of a continuous record from the sediments of the lake basin has been prevented by failure to recover all core material. The sequence is capped by a volcanic ash deposit that is likely to have helped prevent erosion or oxidation of the underlying sediments.

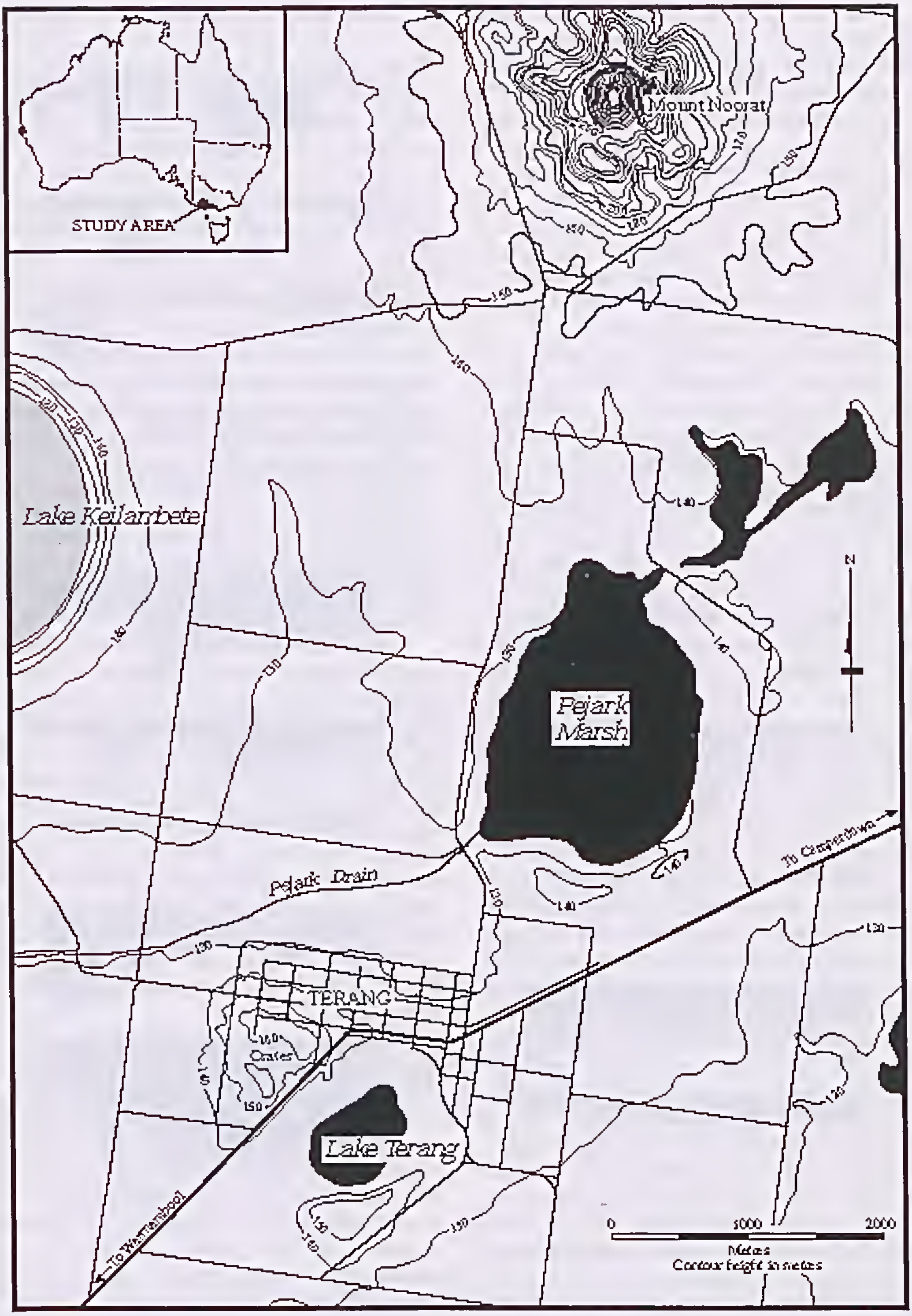

Fig. 1. Location of study sites

Lake Terang is geomorphologically much younger than Pejark Marsh with a well-preserved tuff ring and still contained shallow water at the time of European settlement. Initial analyses were undertaken on samples collected from a 20 m core taken from the centre of the drained lake by the Australian National University in 1985. The record was extended subsequently from cores taken from a similar location by Monash University in 1987. One core focused on the topmost sediments that were not adequately sampled originally while the other core reached to 38 m although it failed to penetrate to the base of the contained lake and swamp sediments.

Samples from available lake and swamp material in both cores were taken at 20 cm intervals for pollen and charcoal analysis and processed by standard procedures (Moore et al. 1978). Either a minimum of 200 pollen grains from terrestrial vegetation per sample (Terang) or the total number of pollen from one whole microscope slide per sample (Pejark) was counted where pollen was preserved. All charcoal particles with a diameter of greater than 10µm were counted as a measure of past fire activity. As charcoal values were calculated using slightly different techniques in the two records (at Lake Terang as the concentration of particles per sample and at Pejark Marsh as the area of charcoal per sample) values were standardised by dividing the values in each record by their maximum value.

For this study, emphasis is placed on those pollen taxa that have been demonstrated to reflect variation in regional vegetation of southeastern Australia (Kershaw et al. 1994; D'Costa and Kershaw 1997). They include the woody plants *Eucalyptus* and Casuarinaceae as the dominants of sclerophyll forest and woodland, *Acacia*, *Banksia* and *Dodonaea* as other notable and widespread woody representatives of sclerophyll vegetation, *Pomaderris* (specifically the *P. aspera/apetala* pollen type) that characterizes the understorey of many tall open forest communities and *Nothofagus*, *Podocarpus*, *Phyllocladus* and *Lagarostrobos* that typify cool temperate rainforest and scrub in Victoria and more especially in Tasmania. They also include Poaceae, Asteraceae and native *Plantago* that predominantly form the understorey of open sclerophyll forests and woodlands but, in the case of the first two mentioned taxa, can dominate treeless communities such as grasslands and herbfields under extreme environmental conditions. These form the pollen sum on which all percentages for each sample in the constructed pollen diagrams (Figs. 2 and 3) are based.

Additional taxa that contribute to a general picture of regional vegetation include Chenopodiceae, *Callitris*, Araucariaceae, *Cyathea/Dicksonia*, but each is excluded from the pollen sum for different reasons; Chenopodiaceae because saltbushes may sometimes dominate local saline swamps; *Callitris* because its delicate and indistinctive pollen may not always be recognized and recorded, at least in some sediment types; Araucariaceae because it no longer occurs in southeastern Australia and therefore, although of potential stratigraphic and palaeoclimatic value, is absent from modern comparative data; and *Cyathea/Dicksonia* because they have spores rather than pollen that may have different dispersal characteristics. It is also very possible that components of *Cyathea*, like Araucariaceae, have disappeared from the landscape in relatively recent times providing a no analogue situation. The same may apply to one component of Asteraceae that produces blunt rather than sharp spined pollen grains (Asteraceae type b). There is uncertainty as to whether there are extant parent plants that could have given rise to Asteraceae type b pollen that is recorded predominantly in glacial-aged sediments (Macphail and Martin 1991).

An estimate of mean annual rainfall (RANN) for each point in time represented by a pollen spectrum was calculated by analogue matching (Overpeck et al. 1985). The methodology followed that detailed in Penny et al. (this volume). Essentially, each fossil pollen spectrum was compared with recent (pre-European) pollen spectra from a collection of sites in southeastern Australia (Kershaw et al. 1994; D'Costa and Kershaw 1997) for which rainfall estimates had been derived from BIOCLIM (Busby, 1991) using the dissimilarity measure, squared chord distance (d^2), and the pollen sum taxa. The estimated RANN for each fossil spectrum is the weighted average of RANN in the three sites with lowest squared chord distance.

The pollen sum taxa were also used as the basis for a stratigraphically unconstrained classification of all fossil pollen spectra from the two sites, undertaken to characterize the range and types of vegetation represented and to see if there were systematic differences between the spectra from the two cores. Bray-Curtis similarity was calculated on the untransformed relative abundances of taxa in the south-east Australian pollen sum (D'Costa and Kershaw 1997) in PRIMER for windows v. 5.2.7 (Clarke and Gorley 2001). A similarity value of 70% was used as a cut off to define the groups shown in Figs. 2 and 3.

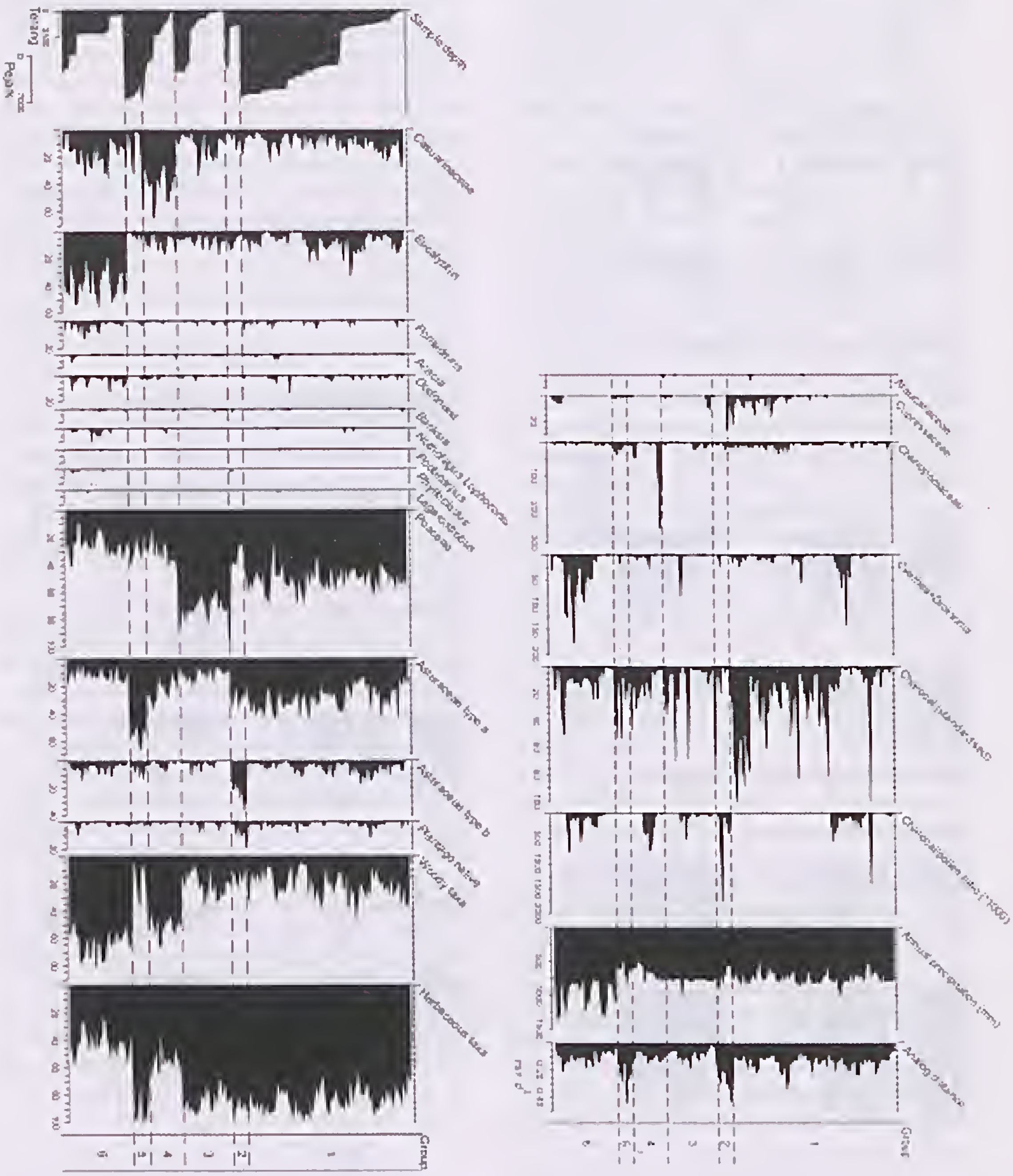

Fig. 2a and b. Pollen spectra from Lake Terang and Pejark Marsh grouped according to Bray-Curtis similarity rather than stratigraphic position. Pollen taxon values are expressed as percentages of the common taxon pollen sum of the appropriate sample. Precipitation estimates are derived from comparison of fossil spectra with precipitation values of closest modern pollen samples. Charcoal values are standardized in relation to maximum values for both records.

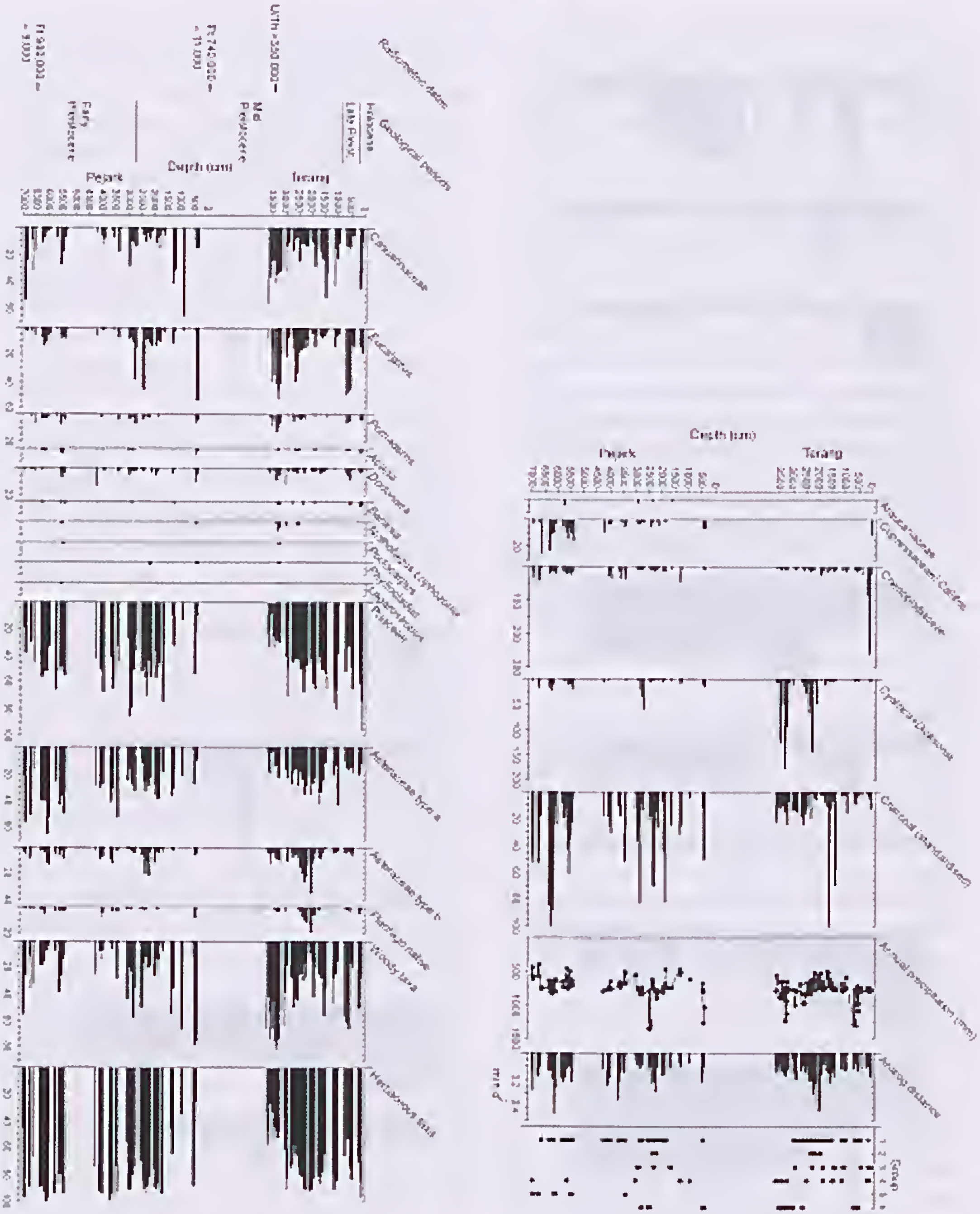

Fig. 3A and B. Pollen spectra from Lake Terang and Pejark Marsh stratigraphically ordered in relation to depth below swamp surface for individual sites. Pollen taxon values are expressed as percentages of the common taxon pollen sum of the appropriate sample. Precipitation estimates are derived from comparison of fossil spectra with precipitation values of closest modern pollen samples. Charcoal values are standardized in relation to maximum values for both records. Groups are those derived from the stratigraphically unconstrained classification of spectra as shown in figure 2.

Accurate dating has been, and continues to be, a major problem with long records. Research into these older sediment sequences was delayed for many years because of a lack of suitable radiometric dating methods beyond the limit of radiocarbon dating, somewhere between 30,000 and 55,000 years BP. Early radiocarbon dates did indicate that most of the Lake Terang sequence was probably beyond this limit (Alan Chivas pers. comm.) and that the whole of Pejark Marsh was beyond the limit. Uranium/thorium dating was undertaken on lake sediment from close to the base of Lake Terang and from close to the top of Pejark Marsh as part of a more general program incorporating the dating of long Australian palynological records by the Australian Nuclear Science and Technology Organisation and several universities. Although most of this research is not yet published, results from the Western Plains site of Lake Wangoom (Harle et al. 1999; 2002) provide some confidence in general age estimation from a sequence of dates derived from Western Plains organic sediment, but they also demonstrate that individual dates have to be treated with a great deal of caution. The methodology is detailed in these papers.

Ash bands in the Pejark core were examined for their potential for zircon fission track dating. Two samples were successfully dated by this method (see Wagstaff et al. 2001 for methodology), one from close to the base of the sequence and the other from the ash capping the sequence.

Approximate timescales for the sequences are provided from the few available radiometric dates and by comparison of patterns of change in pollen and precipitation with those in the marine oxygen isotope stratigraphy (MIS) of Shackleton et al. (1990) (see Wagstaff et al. 2001; and Urban et al. 1996; for the Pejark and Terang chronologies respectively). The validity of this procedure depends upon the relationships demonstrated between Western Plains pollen records and the MIS stratigraphy over the last one or two glacial cycles (Harle et al. 1999; 2002) having been maintained over the whole of the later part of the Quaternary period.

RANGE OF VEGETATION AND ENVIRONMENTS REPRESENTED

Six major groups emerged from the classification of pollen spectra. The groupings form the basis of Fig 2, with spectra ordered stratigraphically within each group. Based on available evidence, the whole of the Pejark sequence is older than that of Terang and therefore the samples from this site are shown, in stratigraphic position, below those of Terang within each group. Terang spectra cover the depth of samples from 0 cm (the sediment surface) to 3650 cm while Pejark spectra extend from 350 to 7000 cm. Some indication of associated environmental conditions can be gauged from RANN estimates and charcoal values.

Group 1 is the largest and appears to cover spectra that are geologically young, back to nearly the oldest. The vegetation was open with a predominance of herbaceous taxa within which both Poaceae and Asteraceae (generally containing and Asteraceae type b component) were well represented. Casuarinaceae and *Eucalyptus* are the major woody taxa though they seldom have greater than 20% representation. *Pomaderris* and *Dodonaea* are conspicuous while *Acacia* is poorly represented, as it is through almost the whole record, except for a one small group of samples, close to the base of the sequence. Of the taxa outside the sum, Chenopodiaceae is consistently present, with relatively low values in the younger spectra and consistently higher values in the older spectra. A similar, but more exaggerated pattern is shown by *Callitris* that is virtually absent in younger samples yet abundant in older ones. The tree fern spores have erratic representation (as they do through the whole diagram) with high values tending to occur in small clumps. Inferred rainfall generally varies from present day values of about 800 mm down to about 500 mm, matching the lowest rainfall levels recorded on the basaltic plains today, while charcoal levels, although variable, probably indicate greater burning in this type of vegetation than in any other.

Group 3 also indicates the regional presence of open woodland. It is distinguished from group 1 by exhibiting relatively higher values for Poaceae and relatively lower values for Asteraceae, including Asteraceae type b. It is represented in both sequences although is not present in the older part of the Pejark Marsh sequence. Inferred rainfall levels are remarkably consistent, around 750 to 800 mm, very similar to those of today. In fact the high Poaceae values are consistent with the domination of the plains vegetation by grassy woodland. The lack of group 3 spectra in the oldest part of the record suggests that this assemblage may have developed relatively recently.

Two other small groups display high percentages of herbaceous taxa, group 2 that is composed of spectra having highest Asteraceae type b percentages and generally highest percentages of *Plantago,* and group 5 that has the largest values of Asteraceae type a. Poaceae values are surprisingly low in both groups. The low rainfall estimates are consistent with what were likely to have been both cool and dry conditions. It is difficult to suggest what was responsible for the differences between these groups, especially as Asteraceae type a features so prominently and that these groups have the highest minimum d^2 values, indicating poor present day analogue matches.

Only two groups are dominated by pollen of woody taxa. Group 4 is charactersied only by high values of Casuarinaceae and there is no positive response in any other woody taxa within the sum. The group contains by far the highest value of Chenopodiaceae but this is not supported by higher values overall. Despite the high woody values, estimated rainfall is lower than for most other groups. Rainfall estimates generally increase through time suggesting a gradually changing assemblage and possibly an evolving vegetation type. Group 6 is dominated by *Eucalyptus* and represents sclerophyll forest with highest values for *Pomaderris, Nothofagus* and tree ferns together with most occurrences of the minor cool temperate rainforest taxa, indicating high rainfall. This is borne out by rainfall estimates that reach about 1300 mm and do not fall below 750 mm. This assemblage is best represented in more recent spectra and is not recorded at all in the oldest spectra.

CORE SEQUENCE CHRONOLOGIES

The combined record from the three Lake Terang cores and the Pejark Marsh core are shown on Fig. 3. The Terang component of the record is positioned above that of Pejark Marsh to illustrate its relative youth.

The top part of the Terang pollen sequence is discontinuous due to an absence of pollen in some sections, presumably because conditions were too dry to allow pollen preservation. The top set of pollen samples are radiocarbon dated to Holocene, while the set below them can be correlated with spectra of MIS 5 (last interglacial) age from Lake Wangoom. Consequently, it appears that there is no evidence preserved of the last glacial period. The time scale of the remainder of the Terang sequence is uncertain. There are two more phases lacking pollen that may represent glacial or stadial conditions, and indicate that the base of the sequence may be some antiquity. The suggestion of a relatively old age is supported by the date of > 350 ka from the U/Th date near the base of the sequence. It is proposed that the basal phase of the Terang sequence with its high woody plant values could well correspond to MIS 11 (dating to 360-425 ka), which is considered globally to be the most pronounced interglacial period.

The spasmodic presence of Araucariaceae through the Pejark sequence is indicative of the relative antiquity of this sequence compared with Lake Terang, a suggestion confirmed by the two fission track dates from Pejark which indicate that the sequence could range in age from about 1000 ka to 740 ka. Attempted correlation of variations in the pollen record with those in the orbitally-tuned marine oxygen isotope record of Shackleton et al. (1990) suggests that the age range might be somewhat greater, from about 1030 to 680 ka embracing MIS 17 to 30 (Wagstaff et al. 2001), but this correlation is fraught with uncertainty, especially as core recovery was so discontinuous.

More certainty about the antiquity of Pejark relative to Terang could be obtained by analysis of the composition of the tuff layers evident within the cores, especially that capping the Pejark Marsh sequence. Walcott (1919) undertook an investigation of the surrounding volcanic vents, i.e. Mount Noorat, Lake Keilembete and Lake Terang in an attempt to determine the source of this capping ash. Although all have an associated tuff ring and any of them could have been the source of the ash, he considered that Lake Terang was the most likely source as, from excavations and wells dug between Pejark Marsh and Lake Terang, the tuff was present in every excavation and increased in thickness towards Lake Terang. This suggested association remains to be tested but it is consistent with existing dates. It also suggests that, if a core was taken to the base of the Lake Terang sediments, the missing period between the two records could be almost fully filled.

PATTERNS OF VEGETATION AND ENVIRONMENTAL CHANGE

Regardless of the uncertainties regarding the ages and degree of continuity of the sequences, a general picture emerges of vegetation and environmental changes through the last million years from the proxy data. There is a great deal of variability in the pollen data, which, at this scale, is most likely dominated by Milankovitch-forced glacial-interglacial cyclicity.

The basal part of the Pejark sequence, to about 30 m, is the least variable for many taxa especially *Eucalyptus*, and this low level of variability is reflected in the pollen assemblage groups with only three (1, 4 and 5) recorded. As noted previously, group 5 is restricted to this period and may well represent the last phases of a vegetation type, dominated by Asteraceae type a, which no longer exists. Group 1 spectra are also distinct within this group as a whole in that *Callitris*, rather than *Eucalyptus* or Casuarinaceae, is the major woody taxon, although high values for Casuarinaceae are characteristic of group 4 spectra. The lack of spectra from group 6 suggests that reduced variation is the result mainly of relatively dry conditions and this is supported by inferred precipitation that ranges only between about 400 and 800 mm. This dampened variability is consistent with global evidence for low amplitude oscillations dominated by the 40 ka obliquity orbital signal in the Early Pleistocene (c 1.8 – 0.8 Ma) and extending into the Early-Middle Pleistocene transition (Shackleton et al. 1990).

The change to greater environmental variability in the Middle Pleistocene, as a result of higher peaks in woody plant pollen values, is also marked by higher values for *Eucalyptus* suggesting the development or expansion of sclerophyll forests as opposed to woodlands within the region. The disappearance of Araucariaceae (presently restricted in Australia to rainforests in the northeastern part of the continent – apart from wollemi pine that possesses a different and distinct pollen type), that had been an important component of southeast Australian vegetation during the Pliocene (Macphail, 1997), may seem inconsistent with a general increase in precipitation. However, the Araucariaceae have their greatest development in drier rainforest and it may be that increased variability, perhaps in combination with altered seasonality, rather than dryness, was the major influence on their demise (Kershaw and Wagstaff 1991). Any alteration of fire regimes may well have also been important because of the fire sensitivity of component taxa, although there is no evidence of increased burning from the charcoal data. In fact, charcoal values are generally lower within the Terang sequence, but this may be an artifact of standardization of the charcoal record.

Characteristically high amplitude, low frequency oscillations are demonstrated for the Terang and for the Pejark sequence above the Lower Pleistocene/ Middle Pleistocene boundary by occasional 'interglacial' peaks in the eucalypt forest assemblage of group 6, where rainfall at times is estimated to have exceeded 1250 mm. These rainfall values have been clearly influenced by regional expansions of wet sclerophyll forest and cool temperate rainforest indicated by notable values of *Pomaderris* and *Nothofagus*, respectively. As these expansions may have been largely confined to the Otways rather than extending over the Western Plains, the inferred rainfall values for the pollen sites may be exaggerated.

In contrast to peak rainfall during interglacials, there are no deep rainfall troughs during glacial periods. However, the emergence of group 2 samples, with high Asteraceae type b and *Plantago* values, may indicate glacial extreme conditions, with low temperatures perhaps compensating any rainfall lowering. It is interesting that this group disappears towards the top of the Terang sequence, most likely due to the lack of pollen preservation within drying lake sediments.

DISCUSSION AND CONCLUSIONS

The reconstruction of this record of past vegetation and environments around Lake Keilambete has, despite major gaps and dating uncertainties, provided an interpretable picture of past conditions. It is one of the few records from terrestrial sedimentary environments to cover the last million years. Consequently the record does have global as well as local significance, a feature illustrated by the importance of Milankovitch forcing on the recorded variations and changes in both climate and vegetation.

The record provides some useful insights into the evolution of the present vegetation. The occurrences of Araucariaceae pollen in the early part of the record most likely indicate the remaining remnants of drier rainforest that was widespread in southeastern Australia during the Late Cenozoic, including at least parts of the Western Plains during the Lower Pliocene (MacPhail, 1996). The demise of this vegetation and probably also *Callitris* communities (Jones, 1998) may have resulted from the extreme, particularly cold and dry, conditions that characterized subsequent Middle Pleistocene climates. Increased climatic variability, by contrast, is likely to have facilitated the spread of eucalypt-dominated communities, especially during warm-wet 'interglacial' periods. It is notable that eucalypt expansion has been much greater than that of the associated woody taxa *Dodonaea*, *Pomaderris* and *Acacia* suggesting the development of 'new' eucalypt community types. In contrast to the demise of dry rainforest, cool temperate rainforest remnants containing taxa such as *Nothofagus cunninghamii* and particularly *Cyathea* survived and even expanded during favourable conditions. Trace values for the present day cool temperate rainforest Tasmanian endemics *Phyllocladus* and *Lagarostrobos* may indicate that these taxa also survived well into the Middle Pleistocene in western Victoria. Conversely, the pollen may have derived by wind-transport from Tasmanian forests. However, it has been established that *Phyllocladus* at least was present in the Otway Ranges during the early part of the last glacial/interglacial cycle (McKenzie and Kershaw 2000).

In relation to the question of apparent insensitivity of the vegetation around Lake Keilambete to Holocene changes in climate, this extended record certainly demonstrates that the vegetation has changed dramatically within the region, apparently in response to climate change. Even during the Holocene there is significant vegetation change in the area. Although Poaceae is dominant and *Eucalyptus* values are generally low, indicating the regional presence of an open woodland vegetation, values for Casuarinaceae are high, up to 40% in the early Holocene, falling to less than 10% in the late Holocene. This degree of change, which is not evident in the Lake Keilambete record, might be explained by an early Holocene colonisation of the scoria cones around Terang and their subsequent contraction due to factors such as fire and increasingly impeded drainage as rainfall increased. The lack of vegetation response around Keilambete could then be explained by the lack of relief within its vicinity. In general terms, the variability around both Terang and Pejark in the past might be a result of local topographical and soil variability providing suitable habitat for a range of community types, whereas the flat plain around Keilambete did not allow the development of such diversity.

If it is the case that local vegetation distributions were having such an influence on pollen assemblages derived from the centre of large lake basins, it is very possible that the indicators of tall open forests and rainforests might also have similarly local signatures and did expand onto the Western Plains during interglacial periods or expanded from small pockets on the plains during these times. It seems improbable that *Nothofagus*, with its limited dispersal ability (Howard 1973), was able to freely move on and off the plains or was able to survive on the plains through the recorded period under such low and variable rainfall. Consequently, this suggestion of a pollen response to very local influences has to be treated with some caution.

Even though the Holocene record from Lake Terang shows a great deal more variation than that from Lake Keilambete, and covers three assemblage groups, the inferred rainfall does not indicate significant change, nor is there any representation of the group 4 assemblage as there is in some previous interglacials. It is possible that the vegetation and perhaps, as a result, also the climate have been systematically altered since the Last Interglacial period. It has been suggested that the impact of people, with their arrival at some time during the last glacial period, resulted in increased burning and a change to more open or sclerophyllous vegetation (see Kershaw et al. 2002; for an Australian overview and Jones 1998; for a Western Victorian perspective). Unfortunately there is no evidence of the last glacial period in this record to determine the existence or nature of any transitions (but see Harle et al. this volume). Certainly there doesn't seem to have been any major change in charcoal values, although no clear relationship between charcoal and fire regime has been established (Kershaw et al. 2002). Although there may have been significant regional reductions or extinctions in some taxa and human impact through burning may have been involved, the weight of evidence suggests that fire has been a conspicuous feature of the environment for a long period of time and there was no major human-induced landscape 'transformation' in southeastern Australia.

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PATTERNS OF VEGETATION CHANGE IN SOUTHWEST VICTORIA (AUSTRALIA) OVER THE LAST TWO GLACIAL/INTERGLACIAL CYCLES: EVIDENCE FROM LAKE WANGOOM

Harle, K.J.,[1,2,4] Kershaw, A.P.[1] & Clayton, E.[3]

[1]School of Geography and Environmental Science, Monash University, Victoria 3800, Australia
[2]Environment Division (Bld 34), Australian Nuclear Science and Technology Organisation, PMB 1, Menai, NSW 2234. Australia
[3]Information Management Division, Australian Nuclear Science and Technology Organisation, PMB 1, Menai, NSW 2234, Australia
[4]Current address: CSIRO Sustainable Ecosystems GPO Box 284 Canberra ACT Australia 2601
email: Kate.Harle@csiro.au

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Multivariate statistical techniques and modern analogue analysis of the Lake Wangoom pollen record were used to reconstruct vegetation change in western Victoria (Australia) over the last 200,000 years. Stratigraphically unconstrained correlation coefficient analysis was used to compare the representation of pollen taxa throughout the sequence. Ten *pollen associations* have been determined, from which it is possible to identify vegetation community types represented in the record. These include elements of warm temperate rainforest not previously suspected as having occurred in the region during the Late Quaternary. A stratigraphically unconstrained dissimilarity coefficient analysis was used to compare pollen spectra in the sequence. From this, thirteen key *pollen assemblages* have been identified. Inverse analysis of pollen taxa was undertaken to produce *pollen associations* representing the mosaic of vegetation types present in the region at the time of sediment deposition. Interpretation of the *pollen assemblages* was assisted using modern analogue analysis.

The record reveals a complex pattern of cyclical shifts in the composition of the vegetation in the region overlain by long term trends in vegetation composition. Three major and distinct phases of forest and woodland expansion, which chronologically equate to the Holocene, Last Interglacial and latter part of the Penultimate Interglacial, have been identified. In addition, an apparently short phase of *Eucalyptus* and rainforest expansion occurred during the Penultimate Glacial period. This is distinguished from the other forest phases by its high representation of a distinctive type of Asteraceae, which is commonly associated with glacial complexes. Open grassland, heath and herbfield communities were widespread during the driest glacial phases, with limited occurrences of semi-arid woodland and scrub. Dry sclerophyll forest, woodland and temperate grassland communities expanded during climatically intermediate phases. A trend to more open-canopied vegetation in the last ca 50 kyrs may be related to increased levels of burning, possibly anthropogenic and/or volcanic in origin.

Key words: Quaternary, vegetation, pollen, southwest Victoria, multivariate statistical analysis, modern analogue

THE PRESENT native vegetation of the Western Victorian volcanic plains is characterised by sweeping grasslands, scattered stands of eucalypt-dominated woodland and dry sclerophyll forest and remnant patches of Casuarinaceae woodland. Palynological records from the region indicate that this has not always been the case, with evidence for short term as well as long term shifts in the composition and relative importance of various vegetation types (see Kershaw et al. this volume). Even within the recent past there is clear evidence in these records that colonial settlers had a drastic effect on the regional vegetation. Sharp decreases in arboreal taxa associated with increases in Poaceae provide evidence for tree clearance and establishment of open pasture, whilst the appearance of exotic species, such as *Pinus*, attest to the establishment and spread of introduced species (D'Costa et al. 1989; Dodson, 1974a; Edney et al. 1990; Gell et al. 1994; Kershaw et al. this volume). Going further back in time, Holocene sequences indicate that open *Eucalyptus* woodland was dominant in western Victoria during the middle to

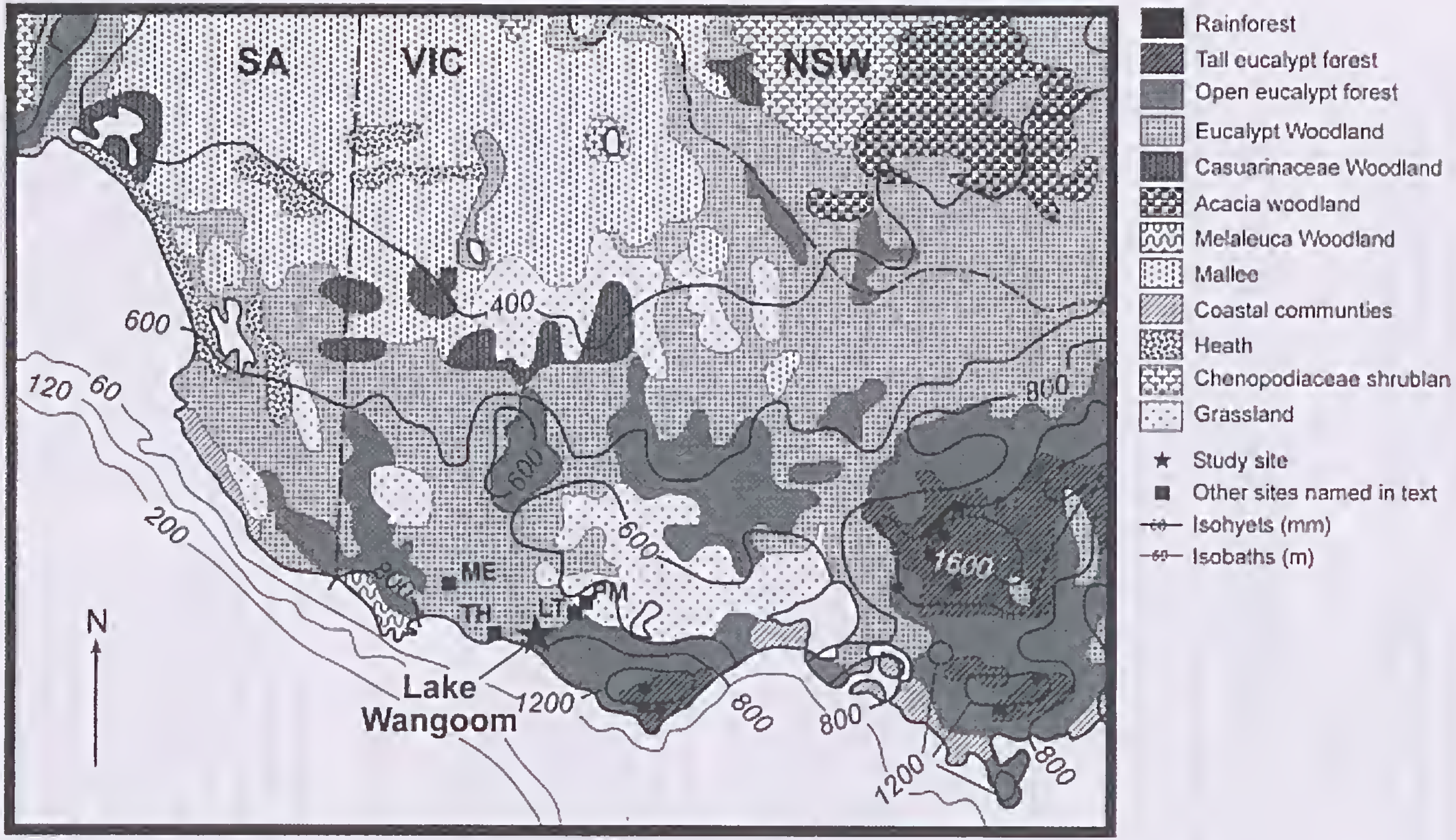

Fig. 1. Map of the study region showing pre-European regional vegetation (after the Australian Surveying and Land Information Group, 1990), mean annual precipitation (mm/yr) (Parkinson, 1986), the study site and other sites mentioned in the text. (ME) Mount Eccles, (TH) Tower Hill, (LT) Lake Terang, (PM) Pejark Marsh.

late Holocene, whilst Casuarinaceae dominated communities were more widespread during the early Holocene (eg. Crowley & Kershaw 1994; D'Costa, et al. 1989; Dodson 1974a; Edney et al. 1990; Head 1988; Luly 1993). In contrast, trees were sparse during the height of the Last Glacial period, with open semi-arid steppe, herbfield and scrub communities dominant (D'Costa et al. 1989; Crowley & Kershaw 1994; Dodson 1979; Edney et al. 1990; Harle et al. 1999). Unfortunately, there are very few pre-Holocene records from the region. Of these, the Lake Wangoom sequence provides the longest and most continuous late Quaternary record, extending from the Penultimate Interglacial to the present (Harle et al. 2002; Harle 1998). Other records from the region of similar or longer duration are either very discontinuous (Lake Terang, D'Costa & Kershaw 1995) or do not extend into the Late Pleistocene (Pejark Marsh, Wagstaff et al. 2001; Kershaw et al. this volume). The Lake Wangoom record, therefore, is extremely important to the reconstruction of late Quaternary environments in western Victoria.

Previous interpretation of the Lake Wangoom record has been largely based on the representation of a limited number of significant taxa, with the focus on broad-scale vegetation changes in response to climate fluctuations as well as on questions of chronology (Edney et al. 1990; Harle et al. 1999; Harle et al. 2002). This paper presents a much more detailed analysis of a 41 m long pollen record from the site, utilising the full range of dryland palynomorphs identified. The interpretation of this large dataset is complicated by uncertainty over the relationships between pollen spectra and source vegetation as well as the difficulty in recognising many Australian palynomorphs beyond generic or even family level. These uncertainties have implications for the reconstruction of vegetation communities. The problem is exacerbated in long records, such as the Lake Wangoom sequence, where questions over species and community extinction become apparent with influences such as long-term climate change and anthropogenic activities, including use of fire.

Two approaches have been adopted in this study in an attempt to overcome some of the difficulties associated with interpreting such a complex dataset. Firstly, multivariate statistical analyses have been applied to the Lake Wangoom palynostratigraphy, based on the assumption that pollen taxa with frequent co-occurrence in fossil assemblages are more likely to have been associated in life than those that are not (Harris and Norris 1972). From this analysis, pollen associations and assemblages were identified, the former being used to provide evidence of source vegetation communities (including those now locally extinct) and the latter to determine the mosaic of communities making up the regional vegetation. To enhance these findings, a second approach was also adopted using modern analogue analysis. This entailed the quantitative identification of closest modern analogues for each fossil pollen assemblage using the Southeast Australian Recent Pollen Database developed by Kershaw et al.(1994a) and D'Costa & Kershaw (1997). The combined results are used to provide a detailed reconstruction of dryland regional vegetation in western Victoria over the last 200,000 years.

SITE LOCATION AND REGIONAL VEGETATION

Lake Wangoom (142°36' E 38°21'S, altitude 100 m asl) is located on the southern margin of the western Victorian volcanic plains, 9.5 km from the coast (Fig. 1). It is a simple volcanic maar approximately 1200 m in diameter (Ollier 1967) which has been partially filled by sediment (Edney et al. 1990). Prior to European settlement in the 1840s, Lake Wangoom had a water depth of around 8 m (Bonwick 1970). It is currently drained and is dry in all but the wettest winters.

Regionally, Lake Wangoom is located within a broad climatic and vegetation gradient trending southeast to northwest (Fig. 1). Variation in the vegetation is influenced by climate, soils and human impact. Drier communities generally occur in the western and north-central areas. Wet forest communities, largely dominated by *Eucalyptus*, are widespread in the east and southeast. Temperate rainforest, dominated by *Nothofagus cunninghamii*, grows in isolated patches in the Otway Ranges and the Central Highlands. Since European settlement in the 1840s (Sayers 1972), the natural vegetation of western Victoria has been extensively cleared, mainly for pasture, and exotic species (eg. *Pinus radiata* and *Cupressus* spp.) have been introduced.

METHODOLOGY

Core collection and sampling

The Lake Wangoom pollen record has been constructed from a combination of cores extracted from the centre of the site. The majority of the sequence described is based on a 41.5 m long core (LW87) collected in 1987 using a Speedstar percussion drilling rig. Unfortunately, the top 1.8 m and sediments between 8.5 and 11 m were not recovered. These gaps were filled using samples from a 20.6 m core (LW84) originally analysed by Edney (1987), and collected in 1984 using a Gemco drilling rig and a Livingstone sampler.

The LW87 core was sampled for sediment, pollen and charcoal analyses at 20 cm intervals. The top 1.8 m of the LW84 core was sampled at 10 cm intervals and sediments between 8.5 and 11 m at 20 cm intervals.

Dating

A chronology for the record has been established using radiocarbon and uranium/thorium disequilibrium techniques. Sampling, methods and results of the application of dating to this record are described and discussed in Harle et al. (2002). Dates acquired are shown in Fig. 4.

Sediment analyses

The sediments of the Lake Wangoom 41.5 m core were analysed for organic, inorganic and carbonate contents through combustion of oven dried samples in a muffle furnace at 550 °C and 1000 °C respectively, with the residue after ignition representing the inorganic and carbonate content.

The magnetic susceptibility of the sediments was measured using the Bartington Magnetic Susceptibility Meter (Bartington 1983). Susceptibility readings were corrected for magnetic drift, diamagnetism and sample mass. Results are plotted in Fig. 4.

Pollen and charcoal analyses

Samples (1 cm^3) were prepared for pollen and charcoal analyses using the standard methods of potassium hydroxide digestion, hydrofluoric acid treatment and acetolysis (Faegri & Iverson 1989). The palynological residues were mounted on microscope slides in silicon oil (AK2000) and counted on a BH Olympus microscope at x600 magnification until a minimum of 150 pollen grains and spores of taxa included in the pollen sum was achieved. Based on studies of pollen dispersal in southeast Australia (eg. Hope 1974; Macphail 1979; Dodson 1982/83, Hill & Macphail 1985; Kershaw et al. 1994a; D'Costa & Kershaw 1997), the pollen sum was designed to reflect the regional vegetation and consisted of the following taxa: *Lagarostrobos, Phyllocladus, Nothofagus cunninghamii, Cyathea, Dicksonia, Eucalyptus*, Casuarinaceae, *Dodonaea, Pomaderris*, Gyrostemonaceae, Asteraceae and Poaceae.

Size Class (μm)	Possible Species
> 28m	*Alloeasuarina verticillata,* *Alloeasuarina littoralis,* *A. luehmannii,* *A. muellerana* and *Alloeasuarina nana*
23-27m	*Alloeasuarina paludosa,* *A.pusilla, Casuarina cristata*
<23m	Possibly *C. cristata*?

Table 1. Subdivision of Casuarinaceae pollen (after of Kershaw, 1970; Dodson, 1974b, 1975)

For the majority of taxa, identification was restricted to genus or family level. One species of eucalypt was tentatively distinguished (*Eucalyptus spathulata* type) with the remainder being divided into *Eucalyptus* spp. and a large *Angophora* like type (*Eucalyptus/Angophora*). *Melaleuca* was divided into a general species group (*Melaleuca* spp.) and the distinctive *Melaleuca squamea*. Adapting the classifications of Kershaw (1970), Dodson (1974b, 1975) and Edney (1987), three size classes of Casuarinaceae were separated on measurements of the equatorial diameter. These are outlined in Table 1. Two tribes of Asteraceae were recognised: Tubuliflorae and Liguliflorae. The former was subdivided into a type possessing sharp, generally long echinae (type A) and a type with short, blunt echinae (type B) (see Edney 1987). The Asteraceae Liguliflorae identified in the sequence is of the *Taraxacum*-type (see Head 1984; Feuer & Tomb 1977; Wodehouse 1935). *Taraxacum*-type species occurring in Australia today are the introduced species *Taraxacum officinale*, the possibly native *Picris hieracioides* var. *squarrosa* and the native species *Microseris scapigera* and *Taraxacum aristum* (Hnatiuk 1990). In addition to extant mainland taxa, a number of palynomorphs were identified that are likely to be derived from Tertiary sediments. These include: *Dacrydiumites*, *Cupanieidites orthotheichus*, *Nothofagus* subgenus *Brassospora*, and *Nothofagus* subgenus *Fuscaspora*-type

Charcoal was identified as opaque black or dark brown particles with irregular from. It was counted using the Point Count Method of Clark (1982).

The pollen data were expressed as percentages of the pollen sum using the TILIA pollen statistical program (Grimm 1991). TILIAGRAPH (Grimm, 1991) was used to construct the pollen diagrams. Pollen concentrations were calculated against volume of sediment and charcoal was expressed as area per cubic centimetre as well as a ratio of the pollen concentration (based on the pollen sum).

To overcome possible differences in counting techniques and taxon identification, samples used from Edney's (1987) LW84 pollen record were recounted. Unfortunately, Edney (1987) used different methods to those outlined above to determine charcoal and pollen concentrations and the information necessary to recalculate these (eg. volumes of silicon oil added) was not available. Consequently, it was not possible to fill in the gaps in the charcoal and pollen concentration records from core LW87 using data from the LW84 core.

Statistical analyses of the Lake Wangoom pollen data set

Statistical analyses of the dryland taxa were used to identify dryland vegetation *associations* and *assemblages*. The analyses were conducted on a stratigraphically unconstrained data set. The aquatic and ground fern taxa were excluded in order to reduce the impact of local pollen and spore signals.

Following the recommendations of Overpeck et al. (1985) and Prentice (1980), a correlation coefficient method was used for the comparison of the pollen taxa whilst a dissimilarity coefficient approach (using a Manhattan metric) was used to compare the pollen spectra of each of the samples. The data were pre-processed by adding one to the count value and taking the log of the result in order to eliminate problems associated with 0 values as well as increasing, without overweighting, the importance of minor taxa. It should be noted that the associations are based on the strongest alliances rather than all the possible associations, as the classification technique only allows for a single group allocation of each taxon.

Identification of nearest modern vegetation analogues

Modern analogues in the Southeast Australian Recent Pollen Database (SEAPD) (Kershaw et al. 1994a: D'Costa & Kershaw 1997) were determined for the Lake Wangoom *pollen assemblages* using a dissimilarity coefficient analysis (Prentice 1980; Overpeck et al. 1985; Baker et al. 1989). As with the analyses of the pollen taxa and pollen spectra, the data were log transformed. The modern analogue analysis was based on pollen taxa selected according to the following criteria:

1) presence in both the Lake Wangoom record and the Southeast Australian Recent Pollen Database;
2) representation greater than or equal to 10% in any one sample; and
3) strong association with specific pollen assemblages.

The pollen sum used in the SEAPD (D'Costa & Kershaw 1997) was extended to include *Cyathea* and *Dicksonia*, both of which have widely dispersed spores (Hill & Macphail 1985). Modern sites with significant fluvial input were excluded from the database as fluvial transported pollen is likely to create an over-representation of vegetation communities growing some distance from the site. Following the recommendations of Kershaw et al. (1994a), taxa effectively representing local site communities, such as the aquatic taxa, most fern spores and taxa with poor pollen dispersal (eg. *Melaleuca* and Ericaceae) were omitted. [The family Epacridaceae has recently been included as Styphelioideae within the Ericaceae (Kron et al. 2002)]. This included Apiaceae as many researchers had failed to separate the frequently aquatic *Hydrocotyle* genus from this family. Also excluded were Chenopodiaceae (which is commonly over-represented in saline environments) and taxa with ambiguous or inconsistent identification in the samples contributing to the SEAPD (eg. Apiaceae, Myoporaceae and Gyrostemonaceae). Pollen percentages in the database were subsequently recalculated, using raw data where available.

In all, the following twenty-one taxa were selected for the modern analogue analysis: *Acacia*,

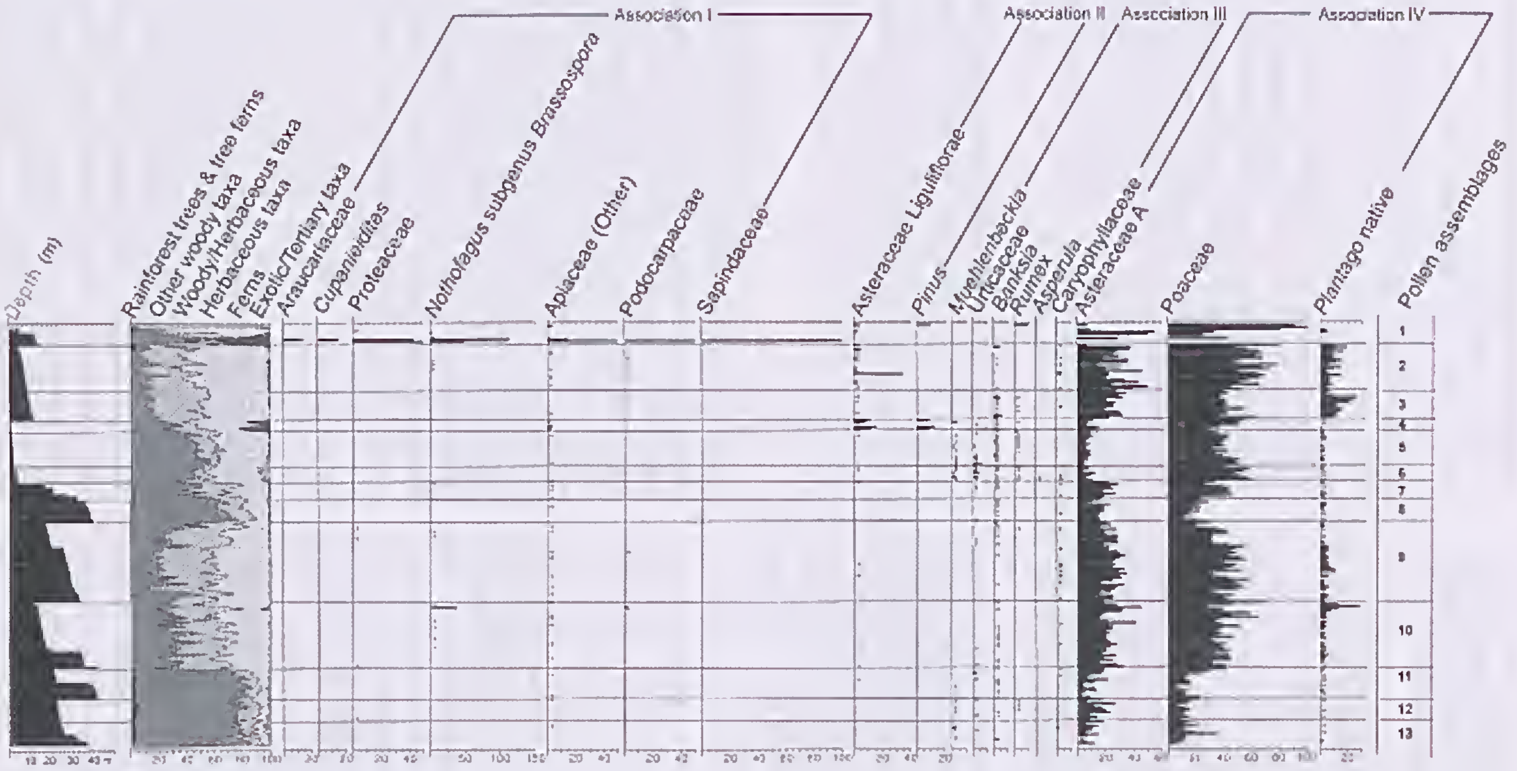

Figure 2a

Fig. 2. Plot of the dryland pollen associations against the dryland pollen assemblages derived from the stratigraphically unconstrained multivariate analyses of the occurrences of individual pollen taxa and pollen spectra in the Lake Wangoom record. Pollen representation is expressed as percentages of the pollen sum. The graph demonstrates the representation of pollen associations in each pollen assemblage. The depths of the pollen spectra making up each pollen assemblages are plotted against a horizontal axis. See text for further explanation.

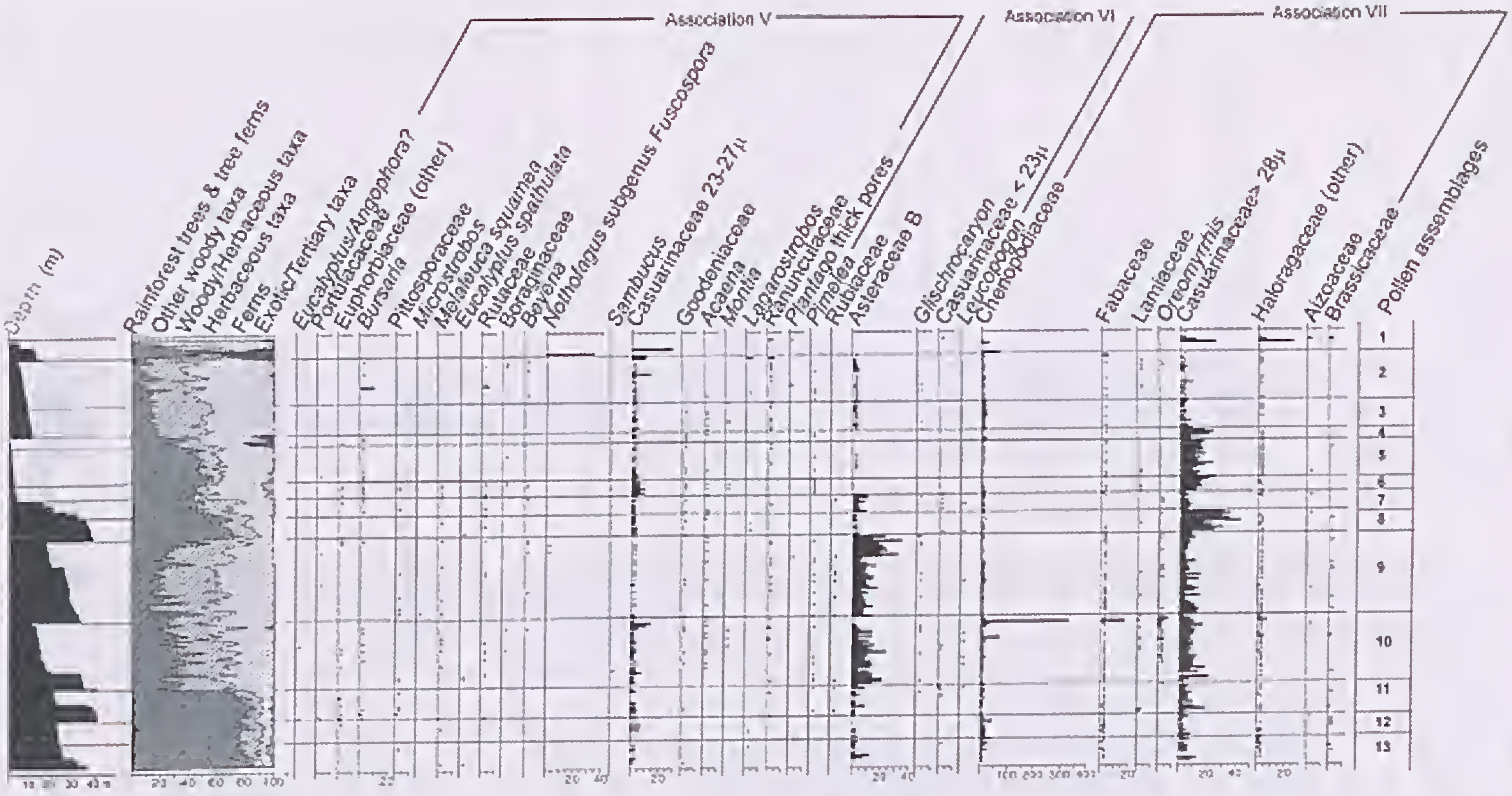
Depth (m)
Rainforest trees & tree ferns
Other woody taxa
Woody/Herbaceous taxa
Herbaceous taxa
Ferns
Exotic/Tertiary taxa
Eucalyptus/Angophora?
Portulacaceae
Euphorbiaceae (other)
Bursaria
Pittosporaceae
Microstrobos
Melaleuca squamea
Eucalyptus spathulata
Rutaceae
Boraginaceae
Boyena
Nothofagus subgenus Fuscospora
Sambucus
Casuarinaceae 23-27μ
Goodeniaceae
Acaena
Monita
Lagarostrobos
Ranunculaceae
Plantago thick pores
Pimelea
Rubiaceae
Asteraceae B
Glischrocaryon
Casuarinaceae < 23μ
Leucopogon
Chenopodiaceae
Fabaceae
Lamiaceae
Oreomyrrhis
Casuarinaceae> 28μ
Haloragaceae (other)
Aizoaceae
Brassicaceae
Pollen assemblages
Association V
Association VI
Association VII
1
2
3
4
5
6
7
8
9
10
11
12
13

Figure 2b

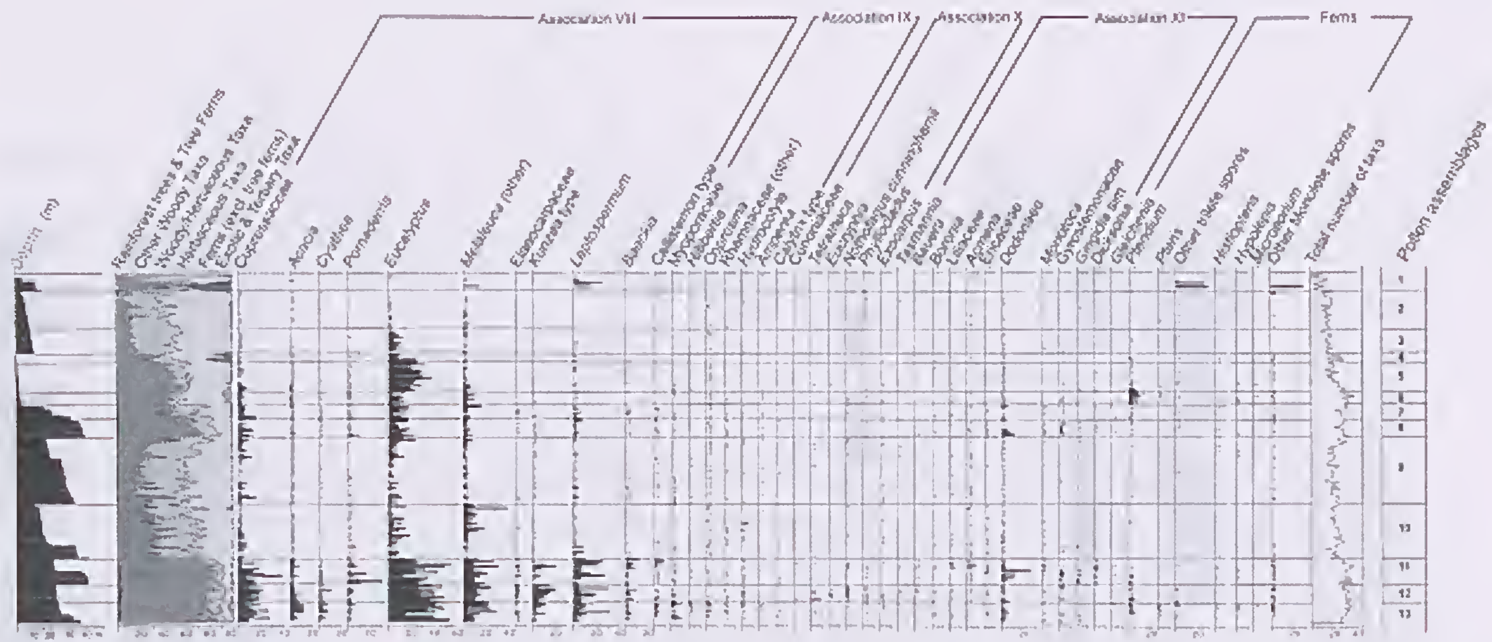
Depth (m)
Rainforest trees & Tree Ferns
Other Woody Taxa
Woody/Herbaceous Taxa
Herbaceous Taxa
Ferns (excl. tree ferns)
Exotic & Tertiary Taxa
Casuarinaceae
Acacia
Cyathea
Pomaderris
Eucalyptus
Melaleuca (other)
Elaeocarpaceae
Kunzea type
Leptospermum
Banksia
Callistemon type
Myoporaceae
Haloragis
Olearia
Rhamnaceae (other)
Hydrocotyle
Angiosperma
Calytrix type
Cunoniaceae
Tasmannia
Euphorbia
Nothofagus cunninghamii
Phyllocladus
Exocarpus
Tasmannia
Baeckea
Boronia
Liliaceae
Apiaceae
Ericaceae
Dodonaea
Monotoca
Gymnostomaceae
Gleichenia
Dicksonia
Gleichenia
Pteridium
Plants
Other trilete spores
Histiopteris
Hypolepis
Microsorum
Other Monolete spores
Total number of taxa
Pollen assemblages
Association VIII
Association IX
Association X
Association XI
Ferns
1
2
3
4
5
6
7
8
9
10
11
12
13

Figure 2c

Acmena, Asteraceae (Tubuliflorae) type A, Asteraceae (Tubuliflorae) type B, *Banksia*, *Banera*, Casuarinaceae, *Coprosma*, *Dodonaea*, Elaeocarpaceae, *Eucalyptus*, *Eucryphia*, *Exocarpos*, *Nothofagus cunninghamii*, *Phyllocladus*, native *Plantago*, Poaceae, *Pomaderris*, *Cyathea*, *Dicksonia* and *Pteridium*.

RESULTS OF THE STATISTICAL AND MODERN ANALOGUE ANALYSES

Eleven dryland taxon associations and thirteen dryland pollen assemblages were identified from the correlation coefficient analysis of all dryland pollen taxa and the dissimilarity coefficient analyses of the core spectra. These are plotted against each other in Fig. 2.

The nearest modern analogue sites and their surrounding vegetation determined for the pollen spectra in each dryland assemblage are presented in Table 2. For location of these sites see D'Costa and Kershaw (1997). The statistical distances between the pollen spectra in these assemblages and the identified modern analogue sites are given in Fig. 3 according to both sample group and depth. These provide a measure of the dissimilarity between the analogue and the fossil pollen spectra - thus the smaller the distance, the closer the match.

Dryland pollen associations

Dryland pollen association I: This association is composed principally of taxa that have been identified as Tertiary. Araucariaceae, *Nothofagus* subgenus *Brassospora*, *Cupanieidites* and Podocarpaceae are common in Tertiary sediments from southeast Australia (Cookson 1957; Cookson & Pike 1953,1954; Dettmann et al. 1990; Hekel 1972; Stover & Partridge 1973). The inclusion of Podocarpaceae, Proteaceae and Apiaceae at first appears incongruous. However, all these families have fossil forms in the Tertiary flora: *Podocarpus* - *Podocarpidites* (Cookson 1947; Hekel 1972) and *Parvisaccites* (Stover & Partridge 1973); Proteaceae - *Proteacidites* (Cookson 1950); and there are many Tertiary tricolporate pollen grains which are similar to modern Apiaceae (eg. *Santalumidites cainozoicus* in Cookson and Pike 1954, Fig. 68, 69, Plate 2).

Dryland pollen association II: *Pinus* and species of Asteraceae (Liguliflorae) were introduced to Australia by Europeans. This association appears, therefore, to be determined by the presence of exotic taxa, although there are native species of Asteraceae (Liguliflorae) species also represented.

Dryland pollen association III: All of the taxa represented in this association are native or include native species. Potential source plants are predominantly herbaceous, except for *Banksia* (a small tree or shrub) and *Muehlenbeckia* (a shrub or vine). *Banksia*, *Asperula* and Caryophyllaceae are widespread through a range of habitats and climates (Costermans 1989; Hnatiuk 1990; Robinson 1997; Walsh & Entwisle 1996). *Urtica* is also found in a range of vegetation communities within the cooler and wetter areas of southeastern Australia (Curtis 1956; Walsh & Entwisle 1996), while *Muehlenbeckia* occurs in woodland and heath communities and on the margins of water courses, swamps and saline lakes (Hnatiuk 1990; Walsh & Entwisle 1996). *Rumex*, which includes exotic species, grows on the margins of water courses, swamps and lakes within temperate regions of southeastern Australia (Hnatiuk 1990; Walsh & Entwisle 1996). Many of the pollen types in this association have poor pollen dispersal and are therefore likely to have been derived from a local source (Dodson 1977; Dodson 1982/83, Hope 1974; Hill & Macphail 1985; Kershaw et al. 1994a; Macphail 1979). It seems probable, especially with the importance of *Banksia* in this group, that this pollen association represents heath (possibly in the understorey of temperate woodland) and lake-side communities growing in and around the Lake Wangoom crater.

Dryland pollen association IV: The three taxa represented in this association (Asteraceae A, Poaceae and the native *Plantago*) are all common in open vegetation communities, such as grasslands and grassy woodlands. Asteraceae type A pollen has a number of additional major sources, including semi-arid, coastal and forest communities (Costermans 1989). All three pollen taxa are well to over-represented in pollen surface samples.

Dryland pollen association V: With the exception of Casuarinaceae 23-27m, the taxa in this association all generally have trace to very low percentages. Potential source plants for the Casuarinaceae 23-27m palynomorph include *Allocasuarina paludosa*, *A. pusilla* and *Casuarina cristata* (Kershaw1970;

Dryland pollen assemblage	Modern analogue sites	Surrounding vegetation
1	Lake Ranfurlie	- mallee & Casuarinaceae woodland
	Boomer Swamp	- eucalypt woodland
	Bolobek*	- dry sclerophyll forest & eucalypt woodland
2	Lake Jaka	- Casuarinaceae woodland
	Lake Ranfurlie	- mallee & Casuarinaceae woodland
	Lake Crosby	- mallee (tall shrubland)
3	Sheet of Water	- dry sclerophyll forest & eucalypt woodland
	Lake Jaka	- Casuarinaceae woodland
	Lake Ranfurlie	- mallee & Casuarinaceae woodland
	Lake Cartcarong	- eucalypt woodland
4	Sheet of Water	- dry sclerophyll forest & eucalypt woodland
	Lake Terang	- eucalypt woodland
	Lake Gnotuk	- mixed eucalypt woodland & grassland
	Boomer Swamp	- eucalypt woodland
5	Lake Wangoom	- eucalypt woodland
	Sheet of Water	- dry sclerophyll forest & eucalypt woodland
	Long Swamp	- dry sclerophyll forest & eucalypt woodland
	Mt Burr	- dry sclerophyll forest & eucalypt woodland
	Lake Terang	- eucalypt woodland
6	Lake Wangoom	- eucalypt woodland
	Lake Terang	- eucalypt woodland
	Blue Lake (G)	- dry sclerophyll forest & eucalypt woodland
	Salt Lake	- dry sclerophyll forest & eucalypt woodland
	West Basin	- dry sclerophyll & grassland
7	Caledonia Fen	- dry sclerophyll forest
	Tiger Snake Swamp	- eucalypt woodland
	Lake Terang	- eucalypt woodland
	Egg Lagoon	- wet coastal scrub/heath
	Cobrico Swamp	- border of dry sclerophyll forest & grassland
	Lake Flannigan	- coastal scrub heath

Table 2. Nearest modern analogue sites for the dryland pollen assemblages based on modern analogue analysis of the pollen spectra. Analogue sites are listed in order of similarity, i.e. closest analogues are listed first. * indicates high dissimilarity (i.e. poor analogue)

Dryland pollen assemblage	Modern analogue sites	Surrounding vegetation
8	Greens bush	- eucalypt woodland
	Lake Terang	- eucalypt woodland
	Long Swamp	- dry sclerophyll forest & eucalypt woodland
	Lake Flannigan	- coastal scrub heath
	Lake Crosby	- mallee (tall shrubland)
9	Lake Crosby	- mallee (tall shrubland)
	Tiger Snake Swamp	- mallee (tall shrubland)
	Caledonia Fen	- dry sclerophyll forest
	Lake Ranfurlie	- mallee & Casuarinaceae woodland
	Lake Lascelles	- eucalypt woodland
10	Lake Crosby	- mallee (tall shrubland)
	Breadlebane NW	- eucalypt woodland
	Lake Jaka	- Casuarinaceae woodland
	Lake Ranfurlie	- mallee & Casuarinaceae woodland
	Sheet of water	- dry sclerophyll forest & eucalypt woodland
11	Lake Curlip	- dry sclerophyll near coastal *Banksia* scrub
	Carlisle State Park	- wet forest & dry sclerophyll
	Lake Lascelles	- mallee (tall shrubland)
	West Basin	- border of dry sclerophyll forest & woodland
	Egg Lagoon	- wet coastal scrub/heath
	Powel Town	- wet forest & dry sclerophyll
12	Lake Tarlikarng	- wet forest, euc. woodland & dry sclerophyll forest
	Lake Flannigan	- coastal scrub heath
	Chappel Vale	- wet forest near dry sclerophyll forest
	Caledonia Fen	- dry sclerophyll forest
	Jacksons Bog B	- grassland & eucalypt woodland
	Lake Terang	- eucalypt woodland
	Lake Curlip	- dry sclerophyll near coast
13	Egg Lagoon	- wet coastal scrub/heath
	Killiecraigie	- wet coastal scrub/heath near wet forest
	Lake Crosby	- mallee (tall shrubland)
	Lake Elusive	- dry sclerophyll forest
	Lake Wangoom	- eucalypt woodland
	Long Swamp	- dry sclerophyll forest & eucalypt woodland

Table 2. continued

Dodson 1974b, 1975; Edney 1987). *Allocasuarina paludosa* is common in heath and scrub in coastal areas, *A. pusilla* in heath in coastal and drier regions and *C. cristata* in dry inland woodland communities (Costermans 1989; Hnatiuk 1990). Potential source plants for the other pollen taxa included in this association grow in a range of environments, from semi-arid woodland to subalpine (Costermans 1989; Hnatiuk 1990; Walsh & Entwisle 1996). Nearly all of them have representatives in drier woodland, mallee and semi-arid communities. The exceptions are the *Eucalyptus/Angopohora* type (if it is indeed *Angophora*), *Nothofagus fuscospora* type, *Melaleuca squamea, Lagarostrobos* and *Microstrobos. Angophora* is restricted to dry forest communities, *M. squamea* occurs in heath on damp ground, *Microstrobos* occurs in alpine areas, *Lagarostrobos* occurs in cool temperate rainforest in Tasmania, and the only extant Australia *N. fusca* type is *N. gunnii* - a Tasmanian endemic occurring in wet subalpine communities. It is possible that the *N. fuscospora* type could be reworked Tertiary pollen or, as is potentially the case with *Lagarostrobos*, derived by long distance transport from Tasmania. Given its preference for damp ground, such as occurs in swamps and bogs, it is possible that *M. squamea* was derived from communities within the Wangoom crater.

Although there is a potential range of communities for this association, the dominance of Casuarinaceae 23-27μ suggests the source of much of the pollen may have been open woodland, heath and semi arid shrubland. The possible presence of long-distance dispersed pollen provides support for relatively sparse, open vegetation.

Dryland pollen association VI: Unfortunately the source, and in turn the ecology of the dominant pollen type in this association, Asteraceae B, is unknown. Of the other taxa in this association, *Pimelea* occurs in a range of environments, from wet forest to alpine formations; Rubiaceae (excluding *Asperula,* which is analysed separately) grows in dry forest and coastal scrub and occasionally rainforest; *Gliscltrocaryon* is restricted to mallee and heath communities; and *Leucopogon* grows predominantly in coastal, dry woodland and mallee communities but can occur in montane forest (Costermans 1989; Hnatiuk 1990). There has been some debate over the source of the Casuarinaceae <23μ pollen type (Singh & Geissler 1985), although Kershaw (1970) speculated it may be derived from *Casuarina cristata,* which grows in semi-arid woodland (Costermans 1989). Overall, the uncertain source of some taxa combined with the broad geographical spread but limited abundance of other taxa suggests that the assemblage may not be represented in the present landscape. However, the presence of a number of taxa currently growing in drier areas suggests the source community was probably dry.

Dryland pollen association VII: Apart from Casuarinaceae >28μ, Chenopodiaceae and Haloragaceae, the percentages of the taxa included in this association are trace to low. There are a number of Casuarinaceae species in southeastern Australia that have pollen in the > 28μ size class (see Table 1). Of these, *Allocasuarina muellerana* and *A. leuhmannii* occur in heath, mallee and semi-arid woodland in which Chenopodiaceae is a significant component (Costermans 1989). Of the other Casuarinaceae species in this size class, *A. littoralis* and *A. verticillata* grow in coastal to more inland forest, woodland and scrub communities whilst *A. nana* is a sub-alpine species (Costermans 1989). Crowley (1994a) argues that the species generally represented in southern Australian pollen records by Casuarinaceae >28μ pollen is *Allocasuarina verticillata,* which is one of the most salt sensitive species of the family. She suggests that its generally inverse relationship with Chenopodiaceae in these records reflects this salt sensitivity (Crowley 1994a, b). There is some evidence of this inverse trend in many sections of the Lake Wangoom record, particularly in Pollen Assemblages 12 and 13, which are described later. However, Chenopodiaceae and Casuarinaceae exhibit similar trends in representation in Assemblages 1, 9 and 10 (described later), suggesting a salt tolerant source plant. Other taxa in this association (Aizoaceae, Brassicaceae, Fabaceae, Haloragaceae, Lamiaceae and *Oreomyrrhis*) occur in a range of environments, although all are found in mallee and heath communities. Several species also grow in and adjacent to wetlands, with members of the Aizoaceae and Brassicaceae families tolerating fairly saline conditions (Walsh & Entwisle 1996).

Overall, this association most probably incorporates communities of generally dry environments including heath, woodland and perhaps communities growing adjacent to brackish or saline water.

Dryland pollen association VIII: The pollen taxa in this association are all derived from trees and shrubs, most of which have representatives in forest communities. *Eucalyptus* is the dominant taxon in tall

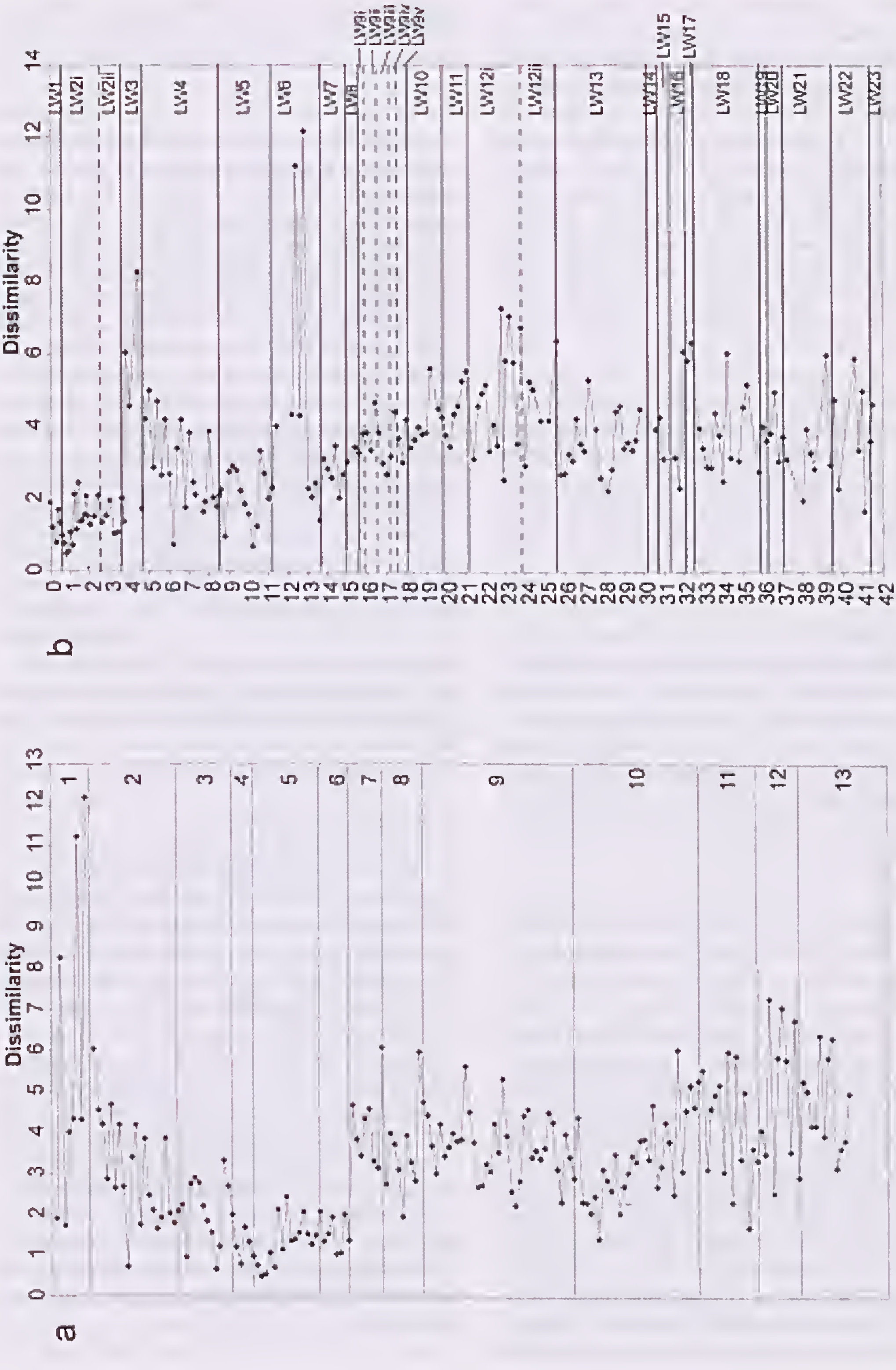

Fig. 3. Dissimilarity curves for the modern vegetation analogues determined for the Lake Wangoom record (a) Dissimilarity for pollen assemblages, which are indicated by numbers 1-13, (b) Dissimilarity vs core depth (m).

shrubland and woodland as well as sclerophyll forest communities throughout southeast Australia, often in association with *Acacia*. *Pomaderris* occurs in both wet sclerophyll and dry sclerophyll forest communities, whilst *Cyathea* and *Elaeocarpus* are restricted to wet forest types. The only native genus of Cupressaceae in Victoria is *Callitris*. It is largely restricted to drier communities, such as open forest and woodlands, although one species, *Callitris rhomboidea*, grows in relatively high rainfall areas along the eastern seaboard and in eastern Tasmania. In western Victoria, *Callitris* is currently restricted to low open forest in the Grampians and in adjacent mallee communities (Costermans 1989). *Callistemon*, *Leptospermum* and *Melaleuca* frequently fringe water courses and swamps (Costermans 1989) and therefore could be representative of sclerophyll vegetation growing around the margins of Lake Wangoom. *Baeckea* and *Kunzea*, both of which have relatively poor pollen dispersal, could also be part of communities growing within the Wangoom crater.

Dryland pollen association IX: The source plants of most of the pollen taxa in this association are shrubs occurring in heaths, open woodland and scrub on sandy soils, particularly in areas of low rainfall areas and physiological dryness. The exception is the herb *Hydrocotyle*, which although found in a range of vegetation communities, the poor dispersal of its pollen suggests a predominantly local aquatic and/or semi-aquatic (eg. swamp) source.

Dryland pollen association X: With the exceptions of *Tetratheca* and *Exocarpos*, the taxa represented in this association are from wet forest communities, in particular cool temperate rainforest. Two of the taxa (*Eucryphia* and *Phyllocladus*) are no longer extant in Victoria, the latter being confined to temperate rainforest in Tasmania and the former being confined to temperate rainforest in both New South Wales (*Eucryphia moorei*) and Tasmania (*E. lucida* and *E. milliganii*). *Tetratheca* species in western Victoria are small shrubs of dry forest and heath communities (Curtis 1956; Hnatiuk 1990). The parasitic small tree, *Exocarpos*, occurs in dry forest, semi-arid woodland and mallee and as a shrub in subalpine regions of Tasmania and Victoria (Costermans 1989). Overall, this association probably gives evidence of vegetation communities in the wetter southern and eastern areas of the region and dry sclerophyll forest in inland areas towards the drier end of the rainfall gradient.

Dryland pollen association XI: This association includes species occurring in or marginal to temperate rainforest communities. Several species, such as *Acmena smithii*, *Boronia muelleri* and *Codonocarpus attenuatus* (Gyrostemonaceae), are now predominantly confined to East Gippsland and coastal NSW, where warm temperate rainforest is found. Indeed, *Acmena* is a frequent dominant canopy taxon of this rainforest type whilst *Dicksonia* is an important component of the understorey (Cameron 1992; Costermans 1989). Codonocarpus also grows in Queensland (Bodkin 1990). Gyrostemonaceae, *Dodonaea*, *Boronia*, Ericaceae and Liliaceae are recorded in a much wider range of habitats, including semi-arid communities. However, their inclusion in this association strongly suggests that the major occurrence of these palynomorphs within the sequence, particularly where other members of this association also occur, are indicative of more humid communities. Ericaceae and Liliaceae have limited pollen dispersal, so it is likely that they were derived from plant communities, possibly heath and/or bog communities, growing around the margins of Lake Wangoom.

Dryland pollen assemblages

Dryland pollen assemblage 1: The nine samples in this assemblage are characterised by high inter-sample variation, low diversity and frequent dominance by otherwise poorly represented taxa, many of which are considered to be of Tertiary origin or are introduced. Apart from associations I and II, representing the Tertiary and introduced species, there is high representation of associations IV (grassland/herbfield) and VII (open woodland, heath and saline communities). It is considered that this assemblage consists of two sub-assemblages: i) a European modified vegetation with introduced taxa and ii) an assemblage containing a significant proportion of Tertiary pollen flora, most likely reworked from the Tertiary sediments in the Wangoom tuff. The difficulty of separating out reworked pollen significantly reduces the ability to reconstruct prevailing vegetation and climate.

Dryland pollen assemblage 2: This assemblage consists of twenty-one samples from between 380 and 850 cm. They are dominated by taxa in dryland pollen association IV (Asteraceae A, Poaceae and the native *Plantago* type), which are considered to represent grassland and herbfield communities. Consistent with this is the continuous presence of Asteraceae (Liguliflorae), which, given the lack of introduced taxa in this assemblage, is most likely either *Microseris scapigera* and/or *Taraxacum aristum*, both being common in grassland and herbfield communities (Scarlett et al. 1993). The representation of arboreal taxa is the lowest for the diagram, with only minor presence of trees and shrub pollen, predominantly from dryland pollen associations V, VII (open woodland, heath and saline communities) and VIII (sclerophyll forest/woodland). The sporadic trace presence of rainforest trees and tree ferns would most likely have been from long distance dispersal with their representation facilitated by the comparatively open nature of the regional vegetation. Trace percentages of *Nothofagus* subgenus *Brassospora* and Podocarpaceae in three samples are probably derived from minor erosion of Tertiary sediments from the Wangoom crater.

The dominance of this pollen assemblage by dryland pollen association IV coupled with the minimal occurrence of taxa from other associations, in particular the forest associations (associations VIII, X and XI), is consistent with the occurrence of extensive grassland/steppe and herbfield communities. Sparse arboreal cover (less than 10%) is indicated, which in turn suggests the presence of very open woodland and/or shrubland communities. Some support for this interpretation is provided by the modern analogue analysis which suggests the presence of open Casuarinaceae woodland and tall eucalypt shrubland (Table 2).

Dryland pollen assemblage 3: This assemblage, which includes thirteen samples from 860 to 1100 cm, is dominated by dryland pollen association IV, indicating a significant presence of grassland/steppe and possibly herbfield. It is very similar to pollen assemblage 2, although differs in having a higher proportion of *Eucalyptus* and Chenopodiaceae, a lower representation of Poaceae and a slightly different array of minor taxa. The greater proportion of *Eucalyptus* suggests a denser arboreal cover than in assemblage 2, although still low at less than 30%. Chenopodiaceae may have been derived from semi-arid communities, coastal communities or saltmarsh growing within the Wangoom crater. The lower values of Poaceae may represent a real reduction in the landscape and/or may simply be an artefact of its proportional pollen representation being affected by the rise in other taxa, eg. *Eucalyptus*.

The nearest modern analogues for this assemblage are sites in mixed dry sclerophyll forest and eucalypt woodland, eucalypt woodland and shrubland, and Casuarinaceae woodland (Table 2). It is most likely that this assemblage represents a mosaic of grassland/steppe and eucalypt and Casuarinaceae woodland and shrubland.

Dryland pollen assemblage 4: This assemblage, which incorporates samples from 10 to 60 cm, is dominated by dryland pollen association II, indicating the presence of exotic plants. Also important is dryland pollen association IV, with moderate to high percentages of Poaceae. Values of between 10 and 25 % for *Eucalyptus* and Casuarinaceae >28μ suggest they have some importance, although representation of other arboreal associations, in particular the forest associations (X and XI) is minimal. Trace percentages of *Acacia, Banksia, Leptospermum* and *Melaleuca,* all of which have poor pollen dispersal capabilities, suggest they occurred within the Wangoom crater.

Overall, this assemblage is indicative of vegetation modified by Europeans, with the presence of introduced taxa and a mosaic of open eucalypt and Casuarinaceae woodland and widespread grasslands. This reconstruction is supported to some degree by the modern analogue analysis, which suggests the occurrence of a mixture of eucalypt woodland and dry sclerophyll forest (Table 2).

Dryland pollen assemblage 5: Samples from 70 to 240 cm are included in this assemblage. They are dominated by *Eucalyptus* and Poaceae and to a lesser extent Casuarinaceae >28μ. The three most important pollen associations are III (heath and lake margin communities), VIII (sclerophyll forest components) and IV (grassland/steppe), although the latter is really only represented by Poaceae with consistently low values of Asteraceae A and native *Plantago*.

As with assemblage 4, the existence of open woodlands with grassy understoreys is implied. The moderately high percentages of *Eucalyptus* and the consistent representation of other taxa from dryland pollen association VIII suggest that eucalypt forest may also have been present. Corroboration is provided by the closest modern analogues, which occur in eucalypt woodland, dry sclerophyll forest and in mixed eucalypt woodland/grassland communities. Low dissimilarity values indicate that these are close analogues (Fig. 3).

The continuous presence of pollen association III suggests heath/wetland communities may have existed around the site, with *Banksia*, *Muehlenbeckia*, *Rumex* and minor occurrences of *Urtica* and perhaps *Melaleuca* and *Leptospermum*.

Dryland pollen assemblage 6. Incorporating seven samples between 260 and 370 cm, the palynoflora of this assemblage is similar to that of Assemblage 4. It is dominated by Poaceae, has low to moderate percentages of *Eucalyptus* and Casuarinaceae >28µ, low but consistent representation of Asteraceae A and Chenopodiaceae and an absence of Asteraceae B. The major differences from assemblage 4 include the absence of exotic pollen association II, a more consistent representation of taxa from dryland pollen association III (heath and lake margin communities) and higher, more consistent representation of dryland pollen assemblage VIII (sclerophyll forest) in particular Cupressaceae, *Pomaderris*, *Melaleuca*, as well as ferns, especially *Pteridium*.

This assemblage appears to represent a mosaic of vegetation types including woodland (dominated by *Eucalyptus*, Casuarinaceae and Cupressaceae), grassland (including as understorey to open woodland), dry sclerophyll forest and a relatively well developed swamp around the margins of Lake Wangoom. The closest modern analogues occur within woodland and dry sclerophyll communities (Table 2).

Dryland pollen assemblage 7. This assemblage includes eight samples from a variety of depths (1640, 1660, 2020-2060, 2700, 3160 and 3200 cm). Dryland pollen association IV (grassland/steppe) is the best represented with moderate percentages of Asteraceae A and Poaceae. Dryland pollen association VIII (sclerophyll forest/woodland) is of some significance, with moderate to low values of Cupressaceae, *Eucalyptus*, *Leptospermum* and *Melaleuca* and the low but consistent presence of *Acacia*, *Baeckea*, *Callistemon*, *Cyathea* and *Pomaderris*. Also important are Asteraceae B (pollen association VI), which has moderate percentages, and the low but continuous presence of *Pteridium*. The overall representation of arboreal taxa is moderately high, principally due to the number of arboreal taxa present rather than large percentages of any one type. The lack of any clear dominant taxa or community types suggests that the regional vegetation was composed of a mosaic of types, including dry sclerophyll forest (dominated by *Eucalyptus* and perhaps), open *Eucalyptus* and Casuarinaceae woodland, grassland, herbfield and some minor occurrences of wet sclerophyll (indicated by the presence of wet forest taxa such as *Pomaderris* and *Cyathea*). This mixed pattern of vegetation is certainly apparent in the modern analogue analysis, with closest analogues including wet coastal scrub/heath, tall shrubland (mallee), eucalypt woodland and dry sclerophyll forest (Table 2).

Dryland pollen assemblage 8. Dryland pollen assemblage 8 is composed of ten samples close to the base of the core (3580, 3600, 3700-3860, 3940, 3960 cm). It is dominated by Casuarinaceae >28µ (dryland association VII - dry heath/woodland), which has its highest percentages for the sequence, although other taxa from this association are not well represented. Dryland pollen association VIII (sclerophyll forest/woodland) has some importance, with moderate percentages of Cupressaceae and *Eucalyptus* and consistent but low values of *Acacia*, *Leptospermum*, *Melaleuca*, *Pomaderris*, *Cyathea* and *Kunzea*. Dryland pollen association XI (wet forest/temperate rainforest) is moderately well represented. There is some presence of dryland pollen association IV (grassland/steppe), with moderate percentages of Asteraceae A, moderate to low values of Poaceae and low values of the native *Plantago*. Overall, the herbaceous taxa are relatively poorly represented.

The dominance of this assemblage by Casuarinaceae >28 µ pollen suggests the widespread occurrence of Casuarinaceae (most probably *Allocasuarina verticillata*) woodland and/or forest. *Eucalyptus* and Cupressaceae may have been subdominants or could have formed more restricted occurrences of other woodland and forest types.

The proportionally high percentages of *Dodonaea* and Gyrostemonaceae may have been derived from relatively dry communities, such as semi-arid woodland or heath. However, the presence of other taxa from pollen association XI suggests that their source was wet forest possibly marginal to temperate rainforest. Indeed, the presence of wet forest components from dryland pollen associations VIII, X and XI (eg. *Cyathea*, Elaeocarpaceae, *Pomaderris*, *Acmena and Phyllocladus*) indicate that small patches of wet sclerophyll and perhaps rainforest communities occurred within the region.

The closest modern analogues (Table 2) exhibit a moderately high dissimilarity to this assemblage. The analogues selected by the analysis consist of a mix of eucalypt woodland, dry sclerophyll forest, coast scrub/heath and mallee shrubland. The latter were probably selected because of their reasonably important Casuarinaceae component.

Dryland pollen assemblage 9. This assemblage includes thirty-six samples between 1740 and 3360 cm. It is dominated by dryland association IV (grassland/steppe) and Asteraceae B (pollen association VI). There are moderate percentages of taxa from dryland association VII (dry heath/woodland). Taxa from the dryland pollen associations indicative of forest communities have low to trace representation. Casuarinaceae >28μ is the best represented of the arboreal taxa, with moderate percentages. Cupressaceae representation ranges from moderate to absent, whilst *Eucalyptus* percentages are generally low. There is an array of other trees and shrubs, such as *Acacia*, *Banksia*, *Baeckea*, *Kunzea*, *Leptospermum* and *Dodonaea*, but all with very low to trace values.

The palynoflora of this assemblage indicates the widespread occurrence of grassland/steppe and herbfield communities. The presence of *Acaena* suggests that some at least of this grassland was temperate rather than semi-arid. The presence of open woodland, mainly Casuarinaceae dominated, and some heath is also implied. Trace percentages of wet forest taxa, such as *Cyathea*, may have been derived from small isolated patches of wet forest communities in the region, although probably some distance from the study site. It is a pity that the ecology of Asteraceae B is unknown, as its high percentages in this assemblage indicates that it was a significant component of the landscape.

The modern analogues analysis indicates a range of open forest, woodland and shrubland communities, including mallee, Casuarinaceae and eucalypt woodland and to a lesser degree dry sclerophyll forest (Table 2).

Dryland pollen assemblage 10. Thirty samples, ranging in depth from 1120 cm to 4150 cm, are included in this assemblage. Overall, it is very similar to dryland pollen assemblage 9, being dominated by the herbaceous and woody/herbaceous taxa, in particular dryland pollen association IV (grassland/steppe), Asteraceae B and Chenopodiaceae. However, it has a higher representation of pollen associations V and VI as well as *Eucalyptus* (slightly), *Melaleuca*, *Oreomyrrhis* and Chenopodiaceae. It also includes two taxa from dryland pollen association I (*Nothofagus* subgenus Brassospora and Podocarpaceae), suggesting some possible minor contamination by Tertiary sediments.

This assemblage indicates a regional vegetation composed largely of grassland/steppe, herbfield and dry heath with scattered stands of scrub and woodland in more sheltered and higher rainfall areas. The drier communities are implied by the combination of reasonably high percentages of Casuarinaceae 23-27μ and Chenopodiaceae together with the presence of a suite of taxa found in semi-arid environments, such as *Beyeria*, *Bursaria*, *Leucopogon*, *Boraginaceae* and *Gliscluocaryon*. *Melaleuca* may also have been derived from such communities. The modern analogue analysis provides support for the presence of dry communities, with analogues generally consisting of open and semi-arid woodland and shrubland (Table 2). Heath communities are likely to have included *Banksia*, Rhamnaceae and perhaps *Hydrocotyle* and *Oreomyrrhis*.

Dryland pollen assemblage 11. Incorporating fourteen samples from between 2080 and 4140 cm, this assemblage is dominated by arboreal taxa, in particular those in dryland association VIII (sclerophyll forest/woodland). Also important are taxa from dryland pollen association XI (wet forest, especially warm temperate), with the highest percentages in the sequence of *Acmena* and *Dicksonia*. There are trace to low percentages of most taxa from dryland pollen associations IX (heath/woodland shrubs) and X (wet forest, especially cool temperate), including *Nothofagus cunninghamii* and *Phyllocladus*. The woody/herbaceous and herbaceous taxa are poorly represented, with very low percentages of Asteraceae, Poaceae and the native *Plantago*.

The dominance of this assemblage by dryland pollen association VIII implies eucalypt forest was widespread, with much higher proportions of Cupressaceae and *Acacia* than is evident today. High percentages of *Pomaderris* coupled with the presence of other wet forest components, such as the tree ferns (*Cyathea* and *Dicksonia*), indicate that a significant component of the eucalypt forest was wet sclerophyll forest. Low but consistent percentages of rainforest trees (eg. *Nothofagus cunninghamii* and *Phyllocladus*) and the presence of taxa in dryland pollen association XI strongly suggests that stands of cool temperate rainforest and elements of warm temperate rainforest also existed in the region. It is not clear whether the latter actually formed communities of warm temperate rainforest or were merely relict components within other wet forest communities, such as cool temperate rainforest.

Support for forest domination, including the occurrence of wetter forest types, is provided by the closest modern analogues, which include both wet and dry sclerophyll communities (Table 2).

The sources of the high percentages of *Leptospermum* and *Melaleuca* are likely to have been heath and shrubland in the Wangoom crater. Such communities may also have included other Myrtaceae (eg. *Baeckea* and *Kunzea*) and various heath species (eg. Ericaceae and *Monotoca*). The ferns, with the possible exception of *Pteridium*, which may have been widespread in the understorey of open forest and woodland communities, were also likely to have been local.

Dryland pollen assemblage 12. This assemblage covers a continuous sequence of samples from 2220 to 2380 cm. It is very similar to dryland pollen assemblage 11 in that it is dominated by arboreal taxa, in particular those occurring in dryland pollen association VIII (sclerophyll forest/woodland). However, it has a higher representation of Asteraceae A, Chenopodiaceae, *Kunzea* and taxa from dryland pollen association (X). It also has a lower representation of Casuarinaceae, Asteraceae B, *Pomaderris* and taxa from dryland pollen association XI, most significantly *Acmena*, *Dodonaea* and *Dicksonia* (the latter being absent). This assemblage has a greater presence of cool temperate rainforest than in assemblage 11 with a much reduced occurrence of warm temperate rainforest components. The widespread occurrence of wet sclerophyll and some dry sclerophyll forest is also implied, perhaps with some occurrence of woodland communities.

As in dryland pollen assemblage 11, the source of high percentages of *Melaleuca*, *Leptospermum* and other myrtaceous and heath taxa may have been heath and scrub communities occurring within the Wangoom crater. The reduced representation of Asteraceae B within this assemblage suggests that environmental conditions suitable for the expansion of cool temperate rainforest were detrimental for the source species of this palynomorph. The overall impression of a mosaic of wet and dry forest communities and woodland is reflected in the closest modern analogues (Table 2).

Dryland pollen assemblage 13. Eleven samples, from a range of depths between 2400 and 3640 cm, make up this final assemblage. As with the previous two assemblages, *Eucalyptus* and other taxa in dryland pollen association VIII (sclerophyll forest/woodland) are dominant. The highest values for *Acacia* and *Eucalyptus* are recorded. Taxa in dryland pollen association IX (heath/woodland shrubs) are also well represented. There are markedly lower values, however, of rainforest taxa. Dryland pollen association IV (grassland/steppe), Casuarinaceae and Chenopodiaceae have moderately low percentages.

This pollen assemblage indicates eucalypt forest dominated the region, a significant proportion of which was likely to have been wet sclerophyll. High percentages of Cupressaceae suggest it was also important, most likely as a co-dominant with *Eucalyptus* in forest and woodland communities. Some presence of dry sclerophyll forest is suggested by the moderately high values of *Pteridium*. The presence of woodland, heath and scrub communities are also implied, particularly by the high percentages of *Melaleuca*, *Leptospermum* and taxa in dryland pollen association IX. The relatively high influence of scrub and heath communities probably reflects the vegetation within the Wangoom basin. General support for this pattern of regional vegetation is provided by the closest modern analogues (Table 2).

RECONSTRUCTION OF THE LATE QUATERNARY VEGETATION AND ENVIRONMENTS OF WESTERN VICTORIA FROM THE COMPOSITE LAKE WANGOOM RECORD

The composite Lake Wangoom dryland pollen record is plotted against core depth in Fig. 4. It has been zoned with the assistance of the results from the dissimilarity coefficient analysis of the pollen samples. Biostratigraphic zones implied by the pollen assemblages were ignored where they involved the isolation of an individual sample. The main assemblage(s) represented in each zone are plotted along with the ferns, total percentage of aquatic taxa, pollen concentrations, area of charcoal, ratio of charcoal to pollen concentration and radiometric dates acquired for the sequence to assist interpretation and establishment of the chronology. Where possible, the zones have been related tentatively to the marine isotope stratigraphy of Martinson et al. (1987).

Interpretation of the charcoal record

Interpretation of charcoal evidence can be problematic as no direct relationship between vegetation, fire and the charcoal produced by it has been established (Clark 1982; McKenzie 1989; Winkler 1985). Expression of the area of charcoal as a ratio of the pollen concentration potentially reduces variables associated with sediment accumulation rates and sediment compression. It is more difficult, however, to assess variation in the influx of charcoal into a closed basin caused by the filtering effect of local vegetation. Examination of the Lake Wangoom charcoal record (Fig. 4) reveals that through most of the record, the highest raw charcoal concentrations are associated with the lowest representation of aquatic taxa. There is a visible reduction in the area of charcoal at the beginning of zone LW 14 in association with a sharp increase in percentage representation of aquatic taxa. This strongly suggests that the presence of aquatic vegetation in the lake had a filtering effect on the quantity of charcoal deposited in the lake sediments and hence in the core. For this record, therefore, high charcoal concentrations will only be taken as evidence of increased fire frequency or intensity where they are obviously not influenced by aquatic plant representation of changes in particle concentration.

Zone LW23. Consisting of a single sample from the base of the core (4150 cm), this zone is quite distinct from those above both on a palynological and sedimentalogical basis. The sharp sedimentary boundary between this sample and the one above raises the possibility of a hiatus. It is therefore difficult to place an age on the sample.

The pollen of this sample falls into dryland pollen assemblage 10 and together with the closest analogues, suggests the regional vegetation consisted of a mosaic of grassland, Casuarinaceae woodland, open shrubland and a limited extent of open eucalypt woodland. Conditions, therefore, appear to have been drier than today. Moderately high charcoal values (very high when expressed as a ratio to pollen concentration) provide evidence for fire in the region.

Zones LW22-19 (The Penultimate Interglacial). Uranium/thorium disequilibrium (UTD) dates and sustained high arboreal representation suggest that zones LW22 to LW19 occurred during the Penultimate Interglacial. Overall, this period is characterised by the presence of rainforest trees, tree ferns and ground ferns, high values of trees and shrubs and low representation of woody/herbaceous and herbaceous taxa. The regional vegetation appears to have been dominated by forest and woodland communities, with a significant presence of wetter forest types. However, the composition of the forest varied throughout the period, with alternating dominance of Pollen Assemblages 11, 8 and 13.

Zone LW22, dominated by Pollen Assemblage 11, indicates the widespread occurrence of wet sclerophyll and dry sclerophyll forest as well as temperate woodland, with Cupressaceae (likely to be *Callitris*) as well as *Eucalyptus* forming the canopy. There is some hint of the presence of remnants of warm temperate rainforest with the occurrence of Pollen Association XI. There may also have been very minor occurrences of cool temperate rainforest. Both of these rainforest types may have grown in sheltered locations, probably within the Otway Ranges. *Leptospermum* and *Melaleuca* heath and scrub communities most likely grew within and around the Wangoom crater.

Pollen Assemblage 8 dominates zone LW21, indicating that the regional vegetation became more open, with Casuarinaceae (probably *Allocasuarina*) open forest and/or woodland largely replacing *Eucalyptus* and Cupressaceae (most likely *Callitris*) forest communities. Some trace presence of wet sclerophyll forest and rainforest is indicated. The lack of good modern analogues for this assemblage implies that the vegetation landscape was rather different to any extant in the region.

Zone LW20 shows a return to vegetation similar to that in zone LW22, although evidence for wet sclerophyll forest is reduced with lower values of *Pomaderris*. In contrast to zone LW22, where *Eucalyptus* gives way to Cupressaceae, Cupressaceae is prominent early, with *Eucalyptus* becoming dominant in the latter stages.

The return to dominance in zone LW19 of Pollen Assemblage 8 indicates the return to the more open, Casuarinaceae dominated vegetation present during the period represented by zone LW21.

The shifts in vegetation evident during the Penultimate Interglacial were most likely caused by fluctuations in climate, in particular effective precipitation. The transition from the dominance of wet sclerophyll and dry sclerophyll forest in zone LW22 to more open Casuarinaceae dominated forest and woodland in zone LW21 implies a decrease in effective precipitation. The reverse is suggested with the re-expansion of wetter forest types in zone LW20. Effective precipitation then appears to have decreased again with the re-emergence of Casuarinaceae dominated communities at the expense of *Eucalyptus* and Cupressaceae (probably *Callitris*) dominated communities in zone LW19. These apparent climatic shifts do not seem to have substantially affected the incidence or intensity of fire in the region, as revealed by the consistently low charcoal to pollen ratio. Given this low ratio, the moderately high and variable charcoal values are likely to be the product of particle concentration in a deep water lake rather than any significant burning in the region.

Zones LW18-13 (The Penultimate Glacial). There appear to be three major phases within this period – two indicating very open canopied vegetation separated by a middle phase with fluctuation between woodland and forest communities and drier more open canopied vegetation. The earliest phase, zone LW18, is dominated by Pollen Assemblages 9 and 10, indicating the widespread expansion of grassland and herbfield, as well as dry open woodland, shrubland and heath, most probably in response to a decrease in annual effective precipitation. The communities containing woody taxa were dominated by Casuarinaceae (at least two species) with *Eucalyptus* and Cupressaceae (*Callitris*) possibly in areas of slightly higher annual effective precipitation. Small, isolated stands of dry sclerophyll forest may also have occurred in higher rainfall areas, such as the slopes of the Otway Ranges. Asteraceae B is significant in both these assemblages. However, the lack of knowledge about its source prevents interpretation of its ecological or climatic significance. Slightly elevated charcoal to pollen ratios during this phase suggest a higher incidence and/or intensity of fire in the region than experienced during the Penultimate Interglacial.

The second phase is identified by dramatic and short-term fluctuations of Pollen Assemblages 13, 7 and 9. The stratigraphy suggests a fairly rapid and marked regional expansion in zone LW17 of *Eucalyptus* and Cupressaceae (likely *Callitris*) dominated forest and woodland communities, including a minor component of wet sclerophyll forest (Pollen Assemblage 13). This was followed by an opening up of the regional vegetation in zone LW16, with the expansion of grassland and herbfield, either as understorey in woodland and scrub and/or as discrete communities (Pollen Assemblage 7). This trend continued into zone LW15, with a return to the open grassland, herbfield, woodland and shrubland communities of zone LW 18 (Pollen Assemblage 9). There appears to have been a brief re-expansion of forest and closed woodland communities (Pollen Assemblage 13) in Zone LW14. However, this evidence is based on one sample and would require analysis of intervening samples in order to confirm it as being a real event, rather than potential contamination. Asteraceae B remained important throughout. Overall, this phase appears to have been one of fluctuating effective precipitation, with an initial rise (zone LW17) followed by a gradual decline (zones LW16 to LW15) and then a possible sharp increase (zone LW14). The charcoal/pollen ratio suggests low levels of burning in the region at a slightly reduced scale than in the previous phase.

The final phase within the Penultimate Glacial, zone LW13, appears to have been a sustained period dominated by Pollen Assemblage 9. The lack of Pollen Assemblage 10, in comparison to zone LW18, suggests a more open regional vegetation, with widespread grassland and herbfield communities and pockets of open woodland in sheltered locations. The latter were dominated by Casuarinaceae, although *Eucalyptus* and Cupressaceae (probably *Callitris*) were also present. As with the previous zones in the Penultimate Glacial, Asteraceae B remained important. The evidence suggests effective precipitation was low. The incidence/intensity of fire in the region during this phase does not appear to have changed much from the low levels recorded in zones LW17 to 14.

Zone LW12 (The Last Interglacial). Based on UTD dates and the significant and sustained dominance of arboreal taxa, zone LW12 is interpreted as spanning the Last Interglacial. Unfortunately the large uncertainties of the UTD dates (see Harle et al. 2002) prevent a definite assessment of the exact relationship this zone has to marine oxygen isotope stage 5 (OIS 5), in particular the number of substages it includes. The height of the Last Interglacial (corresponding to substage 5e; Martinson et al. 1987) is certainly present. This period is divided into two phases (subzones LW12ii and 12i) based on changes in the nature of arboreal communities represented.

Defined by Pollen Assemblage 13, subzone 12ii represents a phase where increased effective precipitation caused a rapid expansion of forest communities, in particular eucalypt-dominated wet sclerophyll and dry sclerophyll forest with a significant Cupressaceae (most likely *Callitris*) component. Woodland communities are also suggested as being present in the region. Heath and scrub are indicated as being important, with pollen probably being derived mainly from within the Wangoom crater. A peak in the charcoal to pollen concentration ratio in the middle of this phase suggests a short phase of increased frequency in burning. Higher fuel loads associated with the expansion of forest communities may have contributed to this.

Subzone 12i is dominated by dryland pollen assemblages 12 and 11 (the latter towards the top). The former indicates the expansion of cool temperate rainforest in the region whilst the latter suggests a subsequent expansion of warm temperate rainforest elements. Both probably expanded from sheltered moist gullies in the Otway Ranges and perhaps in isolated and sheltered locations along the coast and in river valleys (such as at the Hopkins River). The rainforest expansion, although limited in extent, was probably in response to an increase in effective precipitation, with levels well above those of today. There are also some possible temperature implications for the increase in warm temperate rainforest elements towards the top of the zone. Woodland communities were probably also present, although the lower representation of Pollen Association IX suggests a reduction in heath and scrub components. *Leptospermum* and *Melaleuca* probably continued to dominate the vegetation on the margins of the Wangoom crater. There appears to have been a drop in the level and/or intensity of burning in the region, indicated by the decrease in the area of charcoal and most significantly by the reduced charcoal/pollen ratio.

Zones LW11-3 (The Last Glacial). More open canopied and drier vegetation within zones 11-3 suggest a period of significantly reduced effective precipitation, which most likely equates to the Last Glacial period.

The early part of this period is characterised by reduced effective precipitation, with the expansion in the region of dry sclerophyll forest, eucalypt woodland, scrub and grassland communities (zone LW11, Pollen Assemblage 7). This was followed by the replacement of forest and closed woodland with open grassland, herbfield and scattered semi-arid woodland/scrub (zone LW10, Pollen Assemblage 9). Percentages of Asteraceae B increased during this phase, becoming significant in zone LW10, indicating its importance in the early Last Glacial flora of the region. The local vegetation around Lake Wangoom also appears to have become progressively more open, with lower values for *Melaleuca* and *Leptospermum*. Both charcoal curves suggest that the level of burning in the region remained moderately low.

Some climatic recovery is suggested by the minor re-expansion of woodland and scrub communities at the base of zone LW9. This heralds the commencement of a complex phase (zones LW9 to LW6) where the expansion and contraction of woodland and scrub, and in particular the changing importance of *Eucalyptus*, provides evidence for fluctuations in effective precipitation. This phase is interpreted as an interstadial within the Last Glacial. Open grassland and herbfield, as well the source of the Asteraceae B pollen, appear to have remained widespread throughout the interstadial, whereas the expansion of woodland and scrub communities peaked at the beginning (subzone LW9v). This suggests highest effective precipitation occurred at the beginning of the interstadial. Following this peak, a cyclical trend of expanding and contracting woodland and scrub communities was overlain by an apparent general decline in the representation of arboreal taxa. This pattern is best illustrated by decreasing representation of *Eucalyptus*, with its possible replacement by *Melaleuca* and the source of the Casuarinaceae 23-27m palynomorph (potentially *Allocasuarina paludosa, A. pusilla or Casuarina cristata).* In turn, this implies the expansion of semi-arid communities in response to decreasing effective precipitation. Evidence for two extremely dry episodes (zones LW8 and LW6), separated by a return to slightly wetter conditions (zone LW7), is provided by marked decreases in arboreal taxa and the occurrence of very low pollen concentrations and barren samples. These zones are dominated by Pollen Assemblage 1, suggesting the regional vegetation was

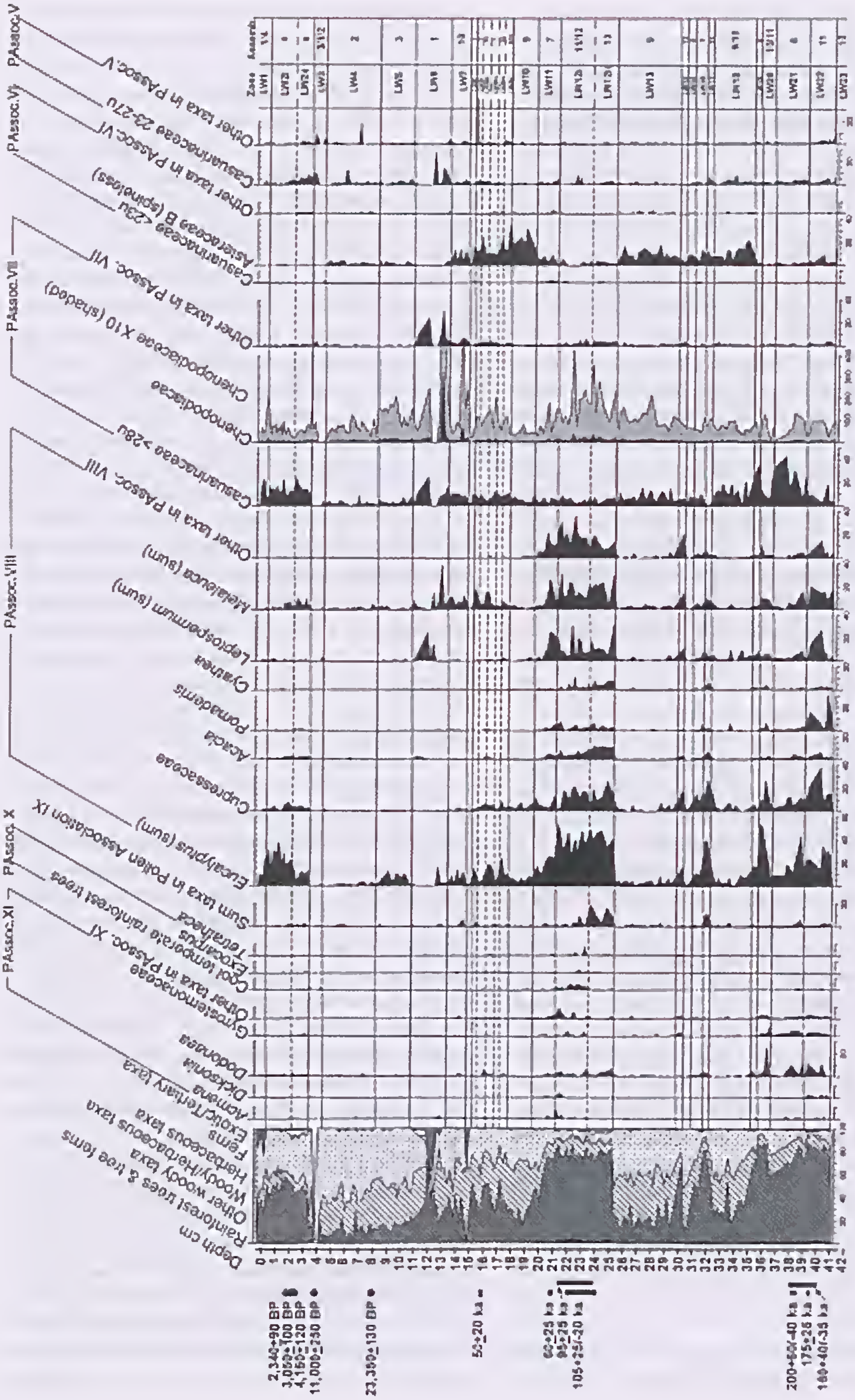

Figure 4a

Fig. 4. The Lake Wangoom percentage pollen diagram against depth. The dates are derived from uranium-thorium disequilibrium ( ) and AMS radiocarbon ( ) analyses (Harle *et al.*, 2002). Taxa are arranged according to their representation in the *dryland pollen associations.*

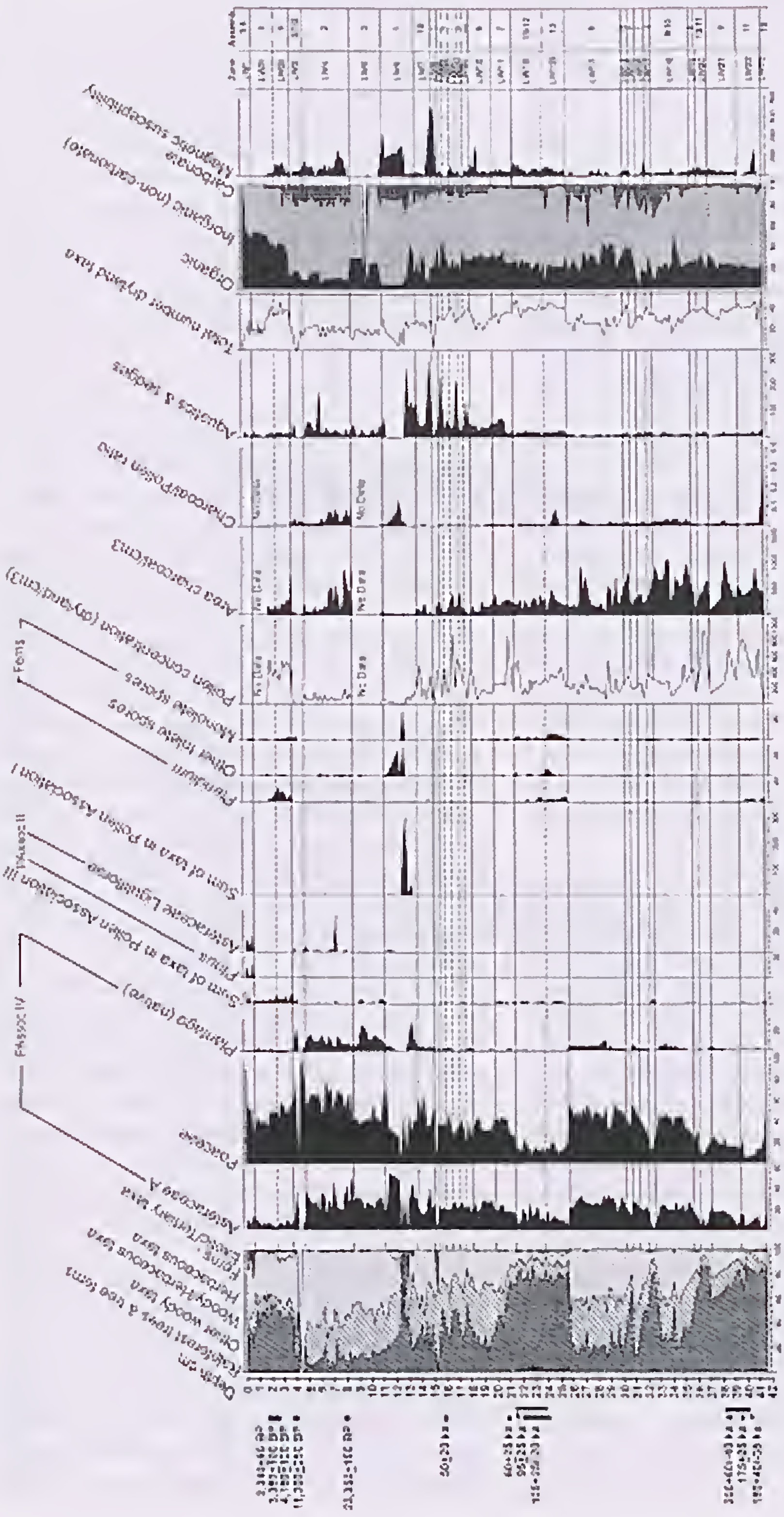
Depth cm
Eucalypt trees & tree ferns
Other woody taxa
Herbaceous taxa
Ferns
Exotic/Tertiary taxa
Asteraceae A
Poaceae
Plantago (native)
Assoc IV
Sum of taxa in Pollen Association III
Pinus
Asteraceae Liguliflorae
Assoc II
Sum of taxa in Pollen Association I
Pteridium
Other trilete spores
Monolete spores
Ferns
Pollen concentration (grains/cm3)
Area charcoal/cm3
Charcoal/Pollen ratio
Aquatics & sedges
Total number dryland taxa
Organic
Inorganic (non-carbonate)
Carbonate
Magnetic susceptibility
Zone
Assemb.
No Data

Figure 4b

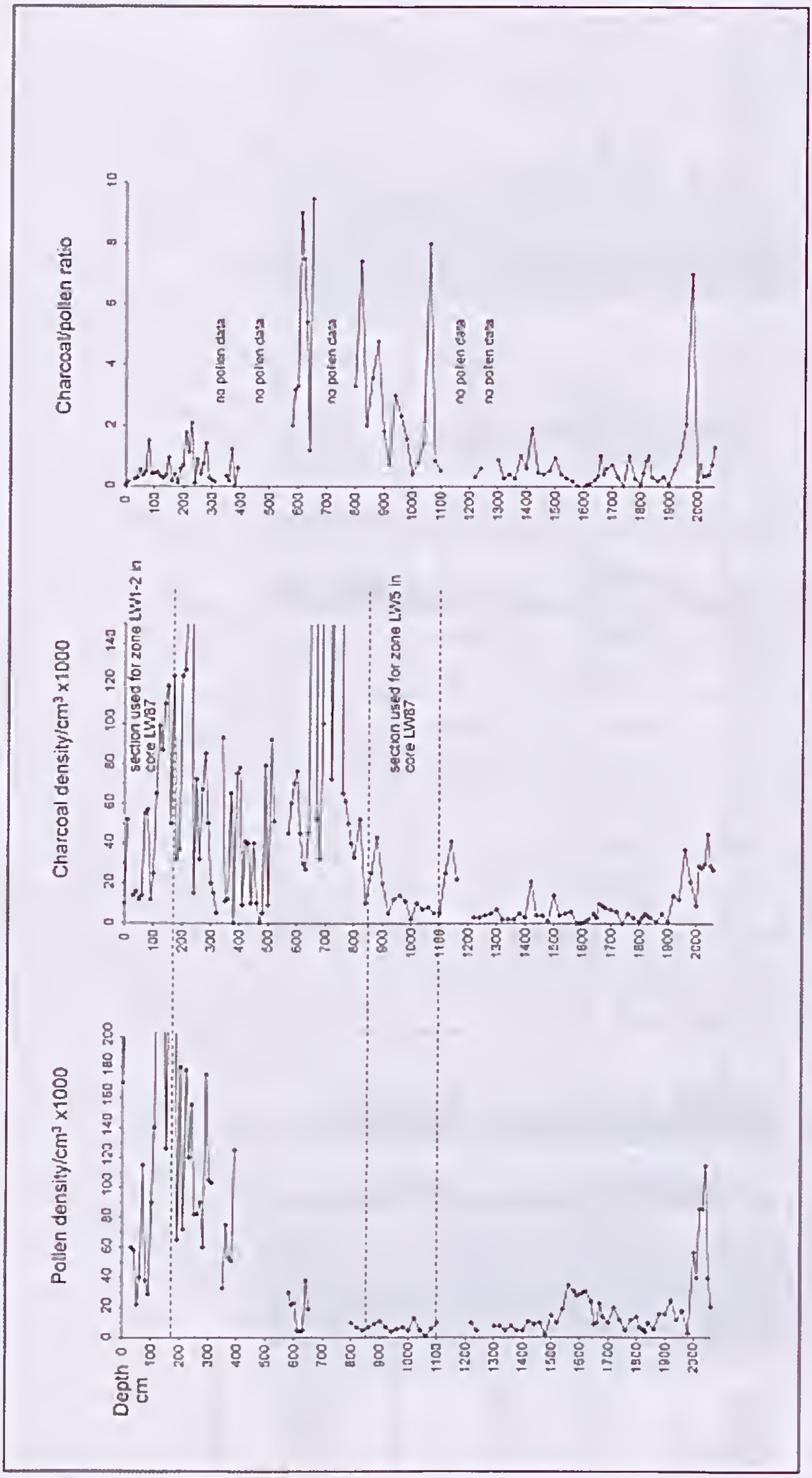

Fig. 5. Pollen and charcoal density curves from core LW84 as derived from Edney (1987) Figure 6.1. The ratio of charcoal to pollen density is also shown to identify the effects of particle concentration on charcoal representation. The section used from this core to fill gaps in zones LW1, LW2 and LW5 in the LW87 core re bracketed by dashed lines.

composed of a mosaic of open Casuarinaceae woodland, scrub, heath and steppe. Chenopodiaceae dominated saline wetland communities possibly existed in and around Lake Wangoom. The presence of Tertiary taxa in this assemblage (including the fern spores) may indicate erosion from the crater rim under a sparse vegetation cover resulting from extremely dry conditions. Support for this interpretation is provided by the high inorganic content and magnetic susceptibility in these samples (Fig. 4). Alternately, the Tertiary taxa and ash material may actually have been fallout from nearby volcanic eruptions. One potential source is the Tower Hill eruption, which now has a minimum age of 30 ka (Sherwood et al. this volume). This is younger than the mean 50 ka UTD age determined for sediments within zone LW7 (Harle et al. 2002), although it does fall within its uncertainty range. High charcoal levels in zone LW6 may also have been derived from volcanic ash, whether from the Wangoom crater or from external sources. They may also indicate increased fire frequency and/or intensity in the region.

Following the arid period of zone LW6, eucalypt-dominated woodland appears to have once again expanded (zone LW5), implying a rise in effective precipitation. The dominance of this zone by Pollen Assemblage 3 suggests the regional vegetation consisted predominantly of open grassland and scattered stands of open eucalypt woodland with a grassy understorey. Interestingly, the significantly reduced values of Asteraceae B suggest the source plant of this palynomorph was no longer an important component of the regional flora. Indeed, levels are similar to those recorded for the previous two interglacials. The regional vegetation present during this phase appears to have been remarkably different to those of previous periods in the Lake Wangoom record. A possible explanation for this is that climatic conditions were unique in comparison to those experienced previously. However, other factors also needed to be considered, in particular the potential influence of fire. There is evidence in the previous zone (LW6) for possibly increased burning in the region, which may have contributed to opening of the regional vegetation. The charcoal evidence from the LW84 core (Fig. 5), from which data for this section was used, also indicates comparatively higher charcoal levels during the zone LW5 phase. Data from both the LW84 and LW87 cores indicate that this trend continued into the following phase (zone LW4), corresponding with evidence for an even more open canopied regional vegetation (Pollen Assemblage 2). The apparently close association of higher charcoal proportions and the presence of more open plant communities provides support for the argument that increased fire frequency and/or intensity had a significant impact on the regional vegetation from around 50 ka to the end of the Last Glacial period.

The final phase in the Last Glacial period (zone LW3) appears to have been extremely dry, with very low pollen concentrations (some samples are barren) implying the lake frequently dried up. It is difficult to determine if this was the most arid period in the record, given that Wangoom basin would have been markedly shallower than during the Penultimate Glacial due to over 20 m of sediment having been deposited in the intervening time. With a much smaller lake capacity, the probability of the lake becoming dry during the late Last Glacial would have been higher than during the Penultimate Glacial, when the lake reservoir would have been considerably greater. General shallowing of the lake is supported by the increasing abundance of aquatics through the record indicating the expansion of swamp. The palynostratigraphy of zone LW3 suggests the regional flora was dominated by open grassland/steppe and herbfield, with scattered occurrence of open semi-arid woodland and scrub, dominated by Casuarinaceae (Pollen Assemblages 2 and 3). Overall arboreal representation is extremely low, with *Eucalyptus* being largely absent.

Zones LW2-1 (The Holocene). A radiocarbon age of 11,000±250 BP marks the commencement of a dramatic and apparently rapid expansion of trees in the region, with a mosaic of dry sclerophyll forest, *Eucalyptus*, Casuarinaceae and Cupressaceae (*Callitris*) woodland and temperate grassland becoming established (Pollen Assemblage 6). The latter most probably formed a significant component of the understorey of woodland communities. Heath may also have been important in the understoreys of forest and woodland communities. It also possibly grew within the Wangoom crater and around the lake margins. This vegetation mosaic was widespread in the region throughout the early to mid Holocene (Zone LW2ii). The drop in the ratio of charcoal to pollen concentration suggests a reduction in the level of burning in the region.

A shift in the dominance of the regional vegetation occurred around 4, 000 BP - eucalypt woodland and open forest probably replacing that dominated by the Casuarinaceae 23-27m species (either

Allocasuarina paludosa, *A. pusilla* or *Casuarina cristata*) and possibly *Melaleuca*. Communities dominated by the source of Casuarinaceae >28m (probably *A. verticillata*) appear to have remained important as does grassland. Unfortunately comparative charcoal data is not available for the whole of this period, due to the use of samples from the LW84 core. Data that is available (Fig. 5) suggests fire was not an important component of the landscape, although little can be said about the period form ca 3,000 BP to the present.

Zone I contains clear evidence of the impact of European settlers on the regional vegetation with the establishment of Pollen Assemblages 4 and 1. Widescale clearance of forest and woodland for pasture is evident in the sharp decrease in arboreal pollen percentages and corresponding increase in Poaceae. The reduction in the number of pollen taxa present is testament to the loss of native floristic diversity in the region and the appearance of *Pinus*, *Plantago lanceolata* and Asteraceae Liguliflorae (probably *Taraxacum officinale* and/or *Hypochoeris radicata*) signifies the spread of introduced plants. Low values of Cupressaceae pollen in this zone may be indicative of the presence of the introduced genus *Cupressus*.

DISCUSSION

Multivariate analysis has proved extremely valuable in the interpretation of the Lake Wangoom pollen record. It has allowed the identification of pollen associations and assemblages, including communities like warm temperate rainforest, which would perhaps otherwise have gone unnoticed or their relationships unrecognised. The identified taxon associations for the most part make ecological sense given the present range of potential source plants. However, in a few cases the associations are somewhat puzzling, particularly where they include taxa that appear to be in ecological conflict. In these cases it is likely that a mosaic of vegetation communities are represented, with the common factor being a similar response to climate change or that, due perhaps to extinction at a species level, associations have changed through time. The region incorporates a range of vegetation communities occurring along a distinct climatic gradient from the coast inland. Climate change would result in different responses across this gradient. For example, an increase in effective rainfall would likely cause an expansion of dry forest in central western Victoria paralleling cool temperate rainforest expansion in the wetter areas around the Otways. This would have been complicated by the role of soils, with spatial differences in soil properties contributing significantly to floristic and structural diversity of vegetation communities within climatic boundaries (Beadle 1981). A further complication would be the response of vegetation communities within the Wangoom crater, particularly in association with the local hydrology. Separating local from regional pollen can at times be an impossible task, particularly in the case of widely dispersed pollen taxa.

In general, the modern analogue analysis supports the multivariate analysis. There is a good match between the closest modern analogues and the dryland pollen assemblages in many parts of the record, with the highest degrees of correlation occurring in dryland pollen assemblages 4, 5 and 6. This is not surprising given that they consist of the most recent samples and hence are most likely to contain vegetation akin to modern communities. Where there is no clear match, the fossil pollen spectra suggest the presence of communities no longer extant in the study region. For example, the modern analogues for most of the samples in dryland pollen assemblage 1 are not particularly close due to the significant proportion of Tertiary pollen they contain. The modern analogues determined for samples in dryland pollen assemblage 8, although much closer and exhibiting the general trends apparent in this assemblage, do not adequately reflect the high proportion of Casuarinaceae, also suggesting that no close modern analogue exists.

Multivariate and modern analogue techniques proved valuable not only in determining the composition of vegetation mosaics growing in the region through the record, but also in identifying repeated occurrences of these mosaics throughout the sequence. From this it was possible to recognise both cyclical as well as long term shifts in vegetation community and species composition in western Victoria over the last 200,000 years. Major, broad-scale changes in the regional vegetation were associated with the cyclical climatic fluctuations driven by global orbital forcing and most clearly reflected in interglacial and glacial periods - the former being characterised by the expansion of woodland and forest communities and the latter by the regional dominance of dry open steppe, herbfield and scrub communities. Superimposed on this is evidence for long term changes in the regional vegetation, with a significant reduction in rainforest taxa in the last 100,000 years and a trend to more open vegetation. This is highlighted when a comparison is made between the composition of the forest and woodland communities in each of the three interglacials. Both the Penultimate and Last Interglacials are characterised by a dominance of forest communities (including elements of temperate rainforest) and very restricted representation of grassland. In contrast, the regional vegetation throughout the Holocene was more open, with grassland communities having greater significance and closed forest communities being very limited in their extent. Rainforest and wet sclerophyll understorey taxa appear to have been particularly reduced. Possible reasons for this apparent long term shift towards more open vegetation include: increasing aridity through the Quaternary; long term changes in soil fertility, possibly associated with volcanic activity; and anthropogenic impact.

Several lines of evidence indicate a trend of increasing aridity from the Tertiary through the Quaternary. Lacustrine records suggest lakes became seasonally dry from the mid Miocene (Bowler 1986; Singh et al. 1983), with the establishment of saline, evaporative lakes (playa lakes) between 0.9 and 0.5 Ma (An et al. 1986; Bowler 1982; Bowler & Teller 1986; Chen & Barton 1991). The initiation of dune formation has been dated to between 0.98 and 0.5 Ma (An et al. 1986; Bowler 1982; Chen & Barton 1991) whilst there is a marked rise in aeolian dust content in cores from the Tasman Sea towards the end of the Pleistocene (Hesse 1994). Evidence for vegetation change also appears to support the concept of increasing aridity, with pollen records from Australia demonstrating a shift from closed-canopied rainforest to more open, sclerophyll vegetation (eg. Kershaw 1985; Longmore & Heijnis 1999; Singh & Geissler 1985). This trend appears to have accelerated in the late Tertiary (Kershaw 1988; Kershaw et al. 1994b; Martin 1989, 1990; McEwan-Mason 1991) and continued through the Quaternary, culminating in the reduction and disappearance of rainforest from many regions of Australia towards the end of the Pleistocene (Bohte & Kershaw 1999; Colhoun & van de Ger 1998; Colhoun et al. 1977; Colhoun et al. 1982; D'Costa 1997; Kershaw 1976, 1985, 1993; Kershaw et al. 1993; Longmore 1997; Longmore & Heijnis 1999). In southern Australia, evidence for the local extinction of rainforest taxa includes: the presence of *Nothofagus cunninghamii* (which no longer exists on King Island) in the Egg Lagoon pollen record between 90 and 120 ka (D'Costa 1997); the disappearance of rainforest taxa in the Lake Terang record from western Victoria after the last major wet phase (D'Costa & Kershaw 1995); and the disappearance of rainforest taxa in the Lake Wangoom record itself. However, maximum rainforest expansion in the Wangoom record occurred during the Last Interglacial, not in the Penultimate Interglacial as would be expected if a long term trend of increasing aridity was the major cause of rainforest extinction in the region. Furthermore, the representation of other key taxa in the sequence do not appear to exhibit any long term trends. For example, values of Casuarinaceae are highest in the Penultimate Interglacial and the Holocene whilst *Eucalyptus* has greatest representation in the Last Interglacial. Indeed, the evidence suggests that of the three interglacials represented in the Lake Wangoom record, the Last Interglacial was the wettest, with the greatest and most sustained expansion of wet forest communities, including wet sclerophyll and temperate rainforest.

Fire has also been invoked as a major factor in the expansion of sclerophyll taxa and demise of rainforest communities, with many records exhibiting a corresponding increase in charcoal content (Kershaw 2002). To what extent this increase in fire was a result of increasing aridity or by the arrival of people on the continent is the subject of much debate. In the Lake Wangoom record, evidence for increased burning in the region between 50 ka and 23 ka is associated with the opening up of the regional vegetation, in particular the expansion of grassland and open woodland communities. The implication is that fire was the cause of this vegetation change. What distinguishes this phase from previous episodes of increased fire in the record, is the higher charcoal/pollen ration, suggesting more extensive and/or more frequent burning, coupled with the significant loss of woody taxa. None of the pre-Last Glacial phases of increased burning appear to be associated with comparable shifts in regional vegetation composition. A charcoal peak early in the Last Interglacial (zone LW12ii) occurs when eucalypt forest was widespread in the region, with no significant vegetation changes before or after. A less pronounced but more sustained phase of burning during the Penultimate Glacial appears to be associated with an expansion of more open vegetation at the expense of woodland and forest communities. However, there was not the same degree of loss of woody taxa as evident during the Last Glacial burning phase. Furthermore, the level of burning appears to have been less during the Penultimate Glacial, despite the greater abundance of woody taxa and with it higher available fuel loads. The elevated levels of burning during both glacial phases may have been a natural response to the onset of more arid conditions. Fire frequency is known to increase as precipitation decreases, due to the drying out of fuel sources and subsequent increased flammability (Ashton 1993). Certainly, the rise in charcoal concentration during the Penultimate Glacial post-dates the shift in vegetation, suggesting drier conditions promoted the apparent increase in fire around this time. Unfortunately the lack of a comparable charcoal record for zone LW5 prevents a similar assessment of the relationship between timing of fire and vegetation change during the Last Glacial burning phase. The apparent differences in burning levels between the two glacials cannot be explained by drier conditions, particularly when charcoal levels remained high during the Last Glacial for some time after the vegetation became very open and fuel availability would have been reduced. An alternative explanation for increased burning is that increased volcanic activity in the latter part of the Last Glacial was responsihle, with ignition by eruptions and lava flows sweeping across an already dry landscape. Certainly, elevated magnetic susceptibility levels (although not as high as in zones LW8 and LW6) could point to an increased component of volcanic ash being deposited in Lake Wangoom. Eruptions in the region are dated as occurring during this period, including Tower Hill (Sherwood et al. this volume). However, such eruptions were relatively infrequent relative to climate variation and successional adjustment to vegetation. They were also spatially scattered, making a substantial impact on the regional vegetation unlikely. Another potential cause is the anthropogenic use of fire. It has been argued (Flood 1995; Jones 1969, 1975; Nicholson 1993; Tindale 1959) that Aborigines frequently used fire to aid hunting, promote the growth and regeneration of economically useful plants and to extend the range of more open vegetation rich in both faunal and plant food reserves. Increased levels of burning during the Last Glacial, therefore, may have been the result of the implementation of 'fire stick farming' practises by Aboriginal people. This explanation has been invoked for other records where there is evidence of major shifts in vegetation coinciding with increases in charcoal concentration (eg. Singh and Geissler, 1985; Kershaw, 1976, 1986; Moss and Kershaw, 2000). Clearly, more refined dating of the burning increase in relation to proven evidence for the timing of Aboriginal presence on the continent is needed before a firmer link can be demonstrated. Whatever the cause, it is probable that the sustained incidence of fire in the region during the last Glacial contributed to the disappearance of temperate rainforest communities from much of western Victoria and its current limited distribution to sheltered locations in the Otway Ranges.

CONCLUSIONS

Together, the use of multivariate and modern analogue techniques have allowed an objective and comprehensive reconstruction of vegetation change over the last 200,000 years in western Victoria from the Lake Wangoom pollen record. Application of a correlation coefficient analysis to the occurrence of pollen taxa throughout the sequence enhanced the recognition of community types represented, with eleven *pollen associations* being identified. Amongst these is an association including elements of warm temperate rainforest, which does not currently grow in the region and which has not been identified in other late Quaternary records from the area. Several taxa included in this association have a broad ecological range (eg. Gyrostemonaceae) and without the statistical analysis, would not necessarily have been suspected as being part of a rainforest complex. The use of a stratigraphically unconstrained dissimilarity coefficient technique to compare each pair of pollen spectra in the sequence enabled thirteen key *pollen assemblages* to be identified. Each of these assemblages consists of a unique combination of *pollen associations* and represents a mosaic of vegetation types present in the region at the time of sediment deposition. In general, these reconstructions are supported by modern analogue analysis carried out on each of the pollen assemblages. However, in some cases the match between the modern analogues and the reconstructions was poor, implying the presence of vegetation communities and/or species no longer extant in the region. An extreme situation occurred with Tertiary taxa during dry phases in the Last Glacial, most likely indicating erosion of Tertiary material from the Wangoom crater, as well as the occurrence of Casuarinaceae dominated assemblages during the Penultimate Interglacial which appear to have no modern equivalents in the region. Not unexpectedly, the closest correlation between the modern and fossil spectra occurred toward the top of the record.

The statistical analyses also improved the recognition of repetition of vegetation mosaics through time. From this it was possible to identify not only vegetation change associated with interglacial-glacial climatic cycles, but also fluctuations within interglacial and glacial periods. Broadly speaking, interglacials were characterised by an expansion of forest communities; glacial periods by the dominance of open semi-arid to arid grassland, herbfield and scrub; and interstadials by the expansion of woodland, grassland and some dry sclerophyll forest. This cyclical pattern appears to have been overlain by a long-term trend towards more open vegetation, with a reduced presence of woody understorey taxa and increased dominance of grassland during the Last Glacial and Holocene periods. There also appears to have been an accompanying demise in the representation of rainforest taxa in the region. Increasing aridity through the Quaternary provides one possible explanation, which is supported by other evidence from the region. However, this is not supported by the evidence for variation between the interglacials in the Lake Wangoom sequence, with the Last Interglacial exhibiting greatest expansion of rainforest and wet sclerophyll taxa and therefore likely to have had highest effective precipitation.

Fire provides an alternative or additional explanation for the opening up of the regional vegetation during the last ca 50 kyrs. Higher relative charcoal concentrations are associated with this apparent shift in vegetation, suggesting that either increased fire frequency and/or intensity during the late Last Glacial and Holocene periods was a major contributing factor. Such a change in fire regime may have been the result of the use of fire by Aborigines, possibly enhanced by increased volcanic activity.

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LATEST PLEISTOCENE AND HOLOCENE VEGETATION AND ENVIRONMENTAL HISTORY OF THE WESTERN PLAINS OF VICTORIA, AUSTRALIA

A. PETER KERSHAW[1], JOHN TIBBY[1,2], DANIEL PENNY[1,3], HABIB YEZDANI[4], RHYS WALKLEY[1], ELLYN J. COOK[1] & ROCHELLE JOHNSTON[1]

[1]Centre for Palynology and Palaeoecology, School of Geography and Environmental Science, Monash University, Vic. 3800, Australia
[2]Geographical and Environmental Studies, University of Adelaide SA 5005, Australia
[3]School of Geosciences, University of Sydney, NSW 2006, Australia
[4]School of Natural Resource Sciences, Queensland University of Technology, Brisbane, Qld. 4001, Australia

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Major pollen taxa from 11 records constructed from the basaltic Western Plains of Victoria are examined to provide a regional picture of vegetation and environmental change through the latest Pleistocene and Holocene (i.e. the last 20,000 years). Analogue matching of recent and fossil pollen spectra is employed to determine the degree to which past vegetation is relatable to any communities present today and to make quantitative estimates of past rainfall. The plains were virtually devoid of trees during conditions of the Last Glacial Maximum but rainfall was lowest between about 14,000 and 12,000 years ago within the succeeding late glacial period. Woodland expansion is evident from about 12,000 years ago. There are marked differences between the western, northern and eastern parts of the plains in woodland composition and timing of development within the early Holocene, possibly due to an atmospheric circulation pattern different to that of today. Around 8000-7000 years ago, the vegetation cover present at the time of European arrival was established and, despite evidence for substantial changes in water levels within Western Plains lakes, the vegetation has remained resilient to apparent significant climate change. The pollen data reflect the major impact that recent land use changes have had on the landscape.

Key words: Late Quaternary, crater lakes, volcanic plains, quantitative climate reconstruction, regional vegetation history, Victoria

THE BASALTIC Western Plains of Victoria have long held a fascination for palaeoecologists. The presence of small enclosed lakes provides one of the few opportunities in Australia to produce records that are continuous and free of the many complications that plague interpretations from sub-optimal sites of investigation such as riverine swamps and shallow saline lakes, so characteristic of the Australian environment. The first pollen records from the area were produced by Yezdani (1970). Since that time, the area has been revisited a number of times for purposes such as testing and refining initial interpretations (Dodson 1974), temporally extending the existing record (D'Costa et al. 1989; Dodson 1979; Edney et al. 1990; Harle et al. 1999; Wagstaff et al. 2001; Kershaw et al. 2004), dating times of volcanic eruption (Head et al. 1991; Sherwood et al. 2004) and examination of impacts of Aboriginal and European people on the landscape (Head 1989; Dodson et al. 1994). Recently, there has been a focus on the production of high resolution records in order to examine sub-millennial changes in climate, and their relationships to vegetation dynamics and fire regimes (Mooney 1997; John Dodson pers. comm.; Rochelle Johnston pers. comm.; Penny & Tibby unpublished data; Chris White pers. comm.).

This paper attempts a regional reconstruction of vegetation for the latest Pleistocene (c 18,000 to 10,000 radiocarbon years BP) and the Holocene period (the last 10,000 radiocarbon years or the present interglacial) by bringing together available pollen records, some of which have not previously been published. The latest Pleistocene to early Holocene marks the approximate time when the majority of sites began to accumulate sediments continuously or to preserve pollen. Results from 11 sites are presented, and nowhere else in Australia is there such a concentration within an equivalent area.

There are several reasons why a regional synthesis is of value. In the first place, individual pollen diagrams are heavily biased towards the vegetation around one spot in the landscape with dilution of both vegetation and taxon representation with increasing distance from the site (e.g. Jacobson and Bradshaw 1981). Consequently, local vegetation patterns and influences may detract from the production of a regional picture. Furthermore, the actual area of pollen representation is largely unknown and a number of records can assist in greater definition of pollen source areas as well as provide a clearer picture of patterns of representation over the landscape. In terms of vegetation change, a regional overview can indicate broad scale vegetation dynamics, including the timing, nature and causes of distributional spread or replacement of taxa and communities that can be used in future community management and conservation. Finally, and most relevant to the Western Plains, is the question of suggested vegetation inertia in the face of independent evidence, from pollen records elsewhere in southeastern Australia (Kershaw 1995) and lake level and water quality reconstructions from the Plains (e.g. Bowler and Hamada 1971; De Deckker 1982; Chivas et al. 1993; Gell et al. 1994; Jones et al. 1998) for substantial Holocene climate change.

THE SITES AND THEIR ENVIRONMENTAL SETTING

The pollen sites are shown in relation to the physiography and mean annual rainfall of southwestern Victoria on Fig. 1 while some features of individual sites are presented in Table 1. All sites, apart from Lake Turangmoroke, fall along the southern boundary of the volcanic plains, and, with the exception of Northwest Crater that occurs within the scoria cone complex of Tower Hill, all southern sites are volcanic maars. In fact they encompass almost all maars that contained a lake at the time of European settlement although Cobrico Swamp, like Northwest Crater, was largely covered in swamp

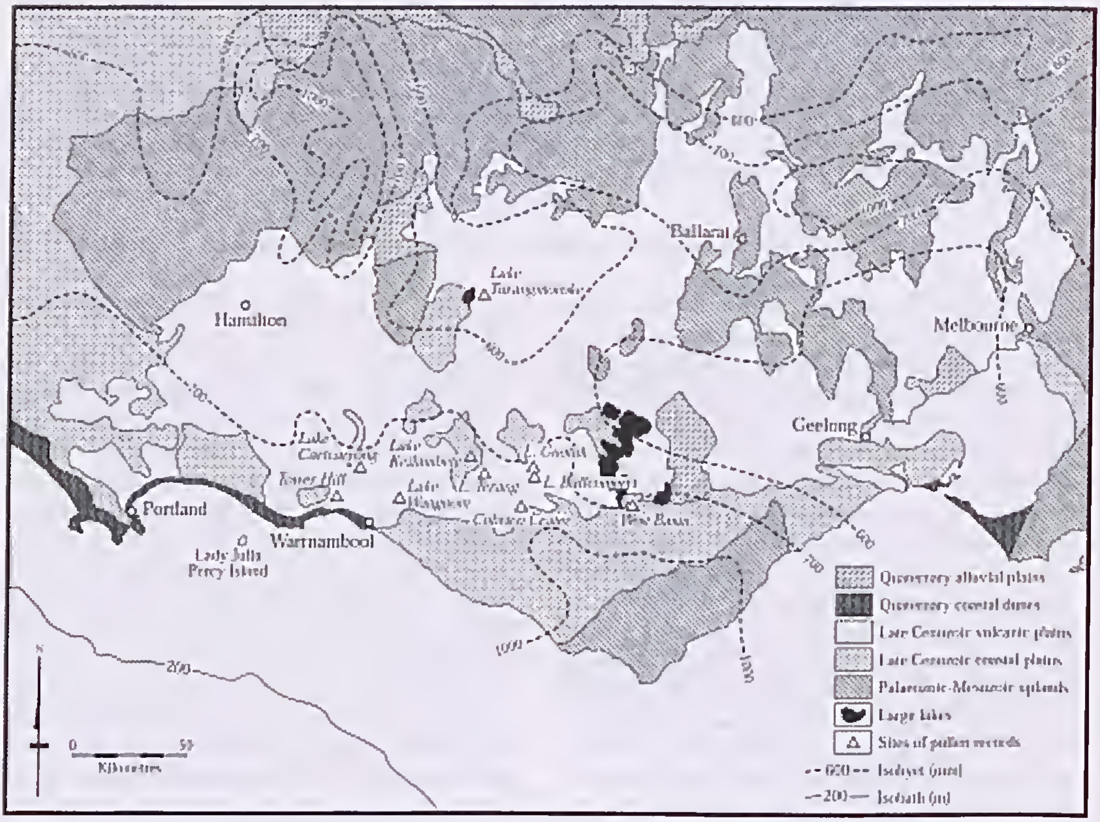


Fig. 1. Location of sites of pollen records in relation to major physiographic features and rainfall of southwestern Victoria. Adapted from maps in Atlas of Victoria (Duncan, 1982). Site names are shown in italics.

scrub, and the shallow water maars of Lake Wangoom and Lake Terang have been drained. These volcanic lakes and swamps cover a mean annual rainfall range of about 690 to 810 mm per annum, with a winter maximum, but due to the low altitude of the sites, there is little variation between them in mean annual temperature (13.0°C to 13.8°C). Although rainfall variation is small, it is within a critical range with regards to salt accumulation. The lakes range from fresh to hyper-saline but there is no direct correlation with rainfall as other factors, including ground water influence, basin size and depth and the propensity of

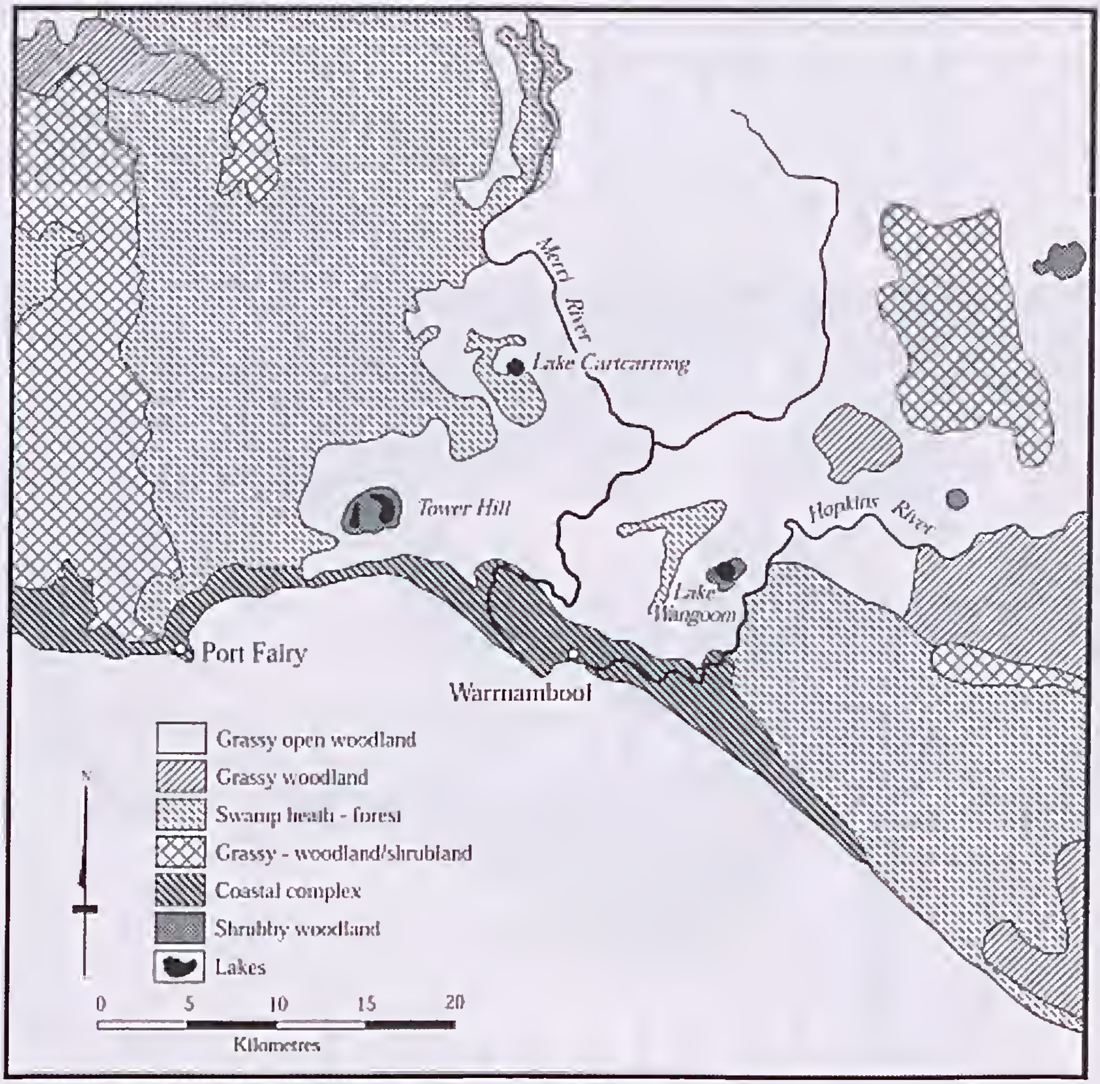
Table 1. Site location and selected attributes

Site	**Lat. (S)**	**Long. (E)**	**Alt.(m)**	**Rainfall**	**Sources of raw pollen data**
Tower Hill NW Crater	38° 19’	142 ° 22’	20	721	D’Costa et al., 1989; Rochelle Johnson, unpubl. data.
Tower Hill Main Lake	38° 19’	142 ° 22’	20	721	D’Costa et al., 1989;
Lake Cartcarrong	38° 15’	142° 27’	75	727	Rhys Walkley, unpubl. data
Lake Wangoom	38° 21’	142° 36’	100	810	Edney et al., 1990
Lake Keilambete	38° 13’	142° 53’	120	759	Dodson, 1974
Lake Terang	38° 15’	142° 54’	130	796	D’Costa and Kershaw, 1995
Cobrico Swamp	38° 18’	143° 02’	140	847	Yesdani, 1970
Lake Gnotuk	38° 13’	143° 06’	200	820	Yesdani, 1970
Lake Bullenmerri	38° 13’	143° 06’	210	820	Yesdani, 1970; Dodson, 1979
West Basin	38° 19’	143° 27’	110	689	Gell et al., 1994
Lake Turangmoroke	37° 42’	142° 45’	220	516	Crowley and Kershaw, 1994; Ellyn Cook, unpubl. data

lakes to overflow, also influence salinity levels.

Lake Turangmoroke, in the northern part of the volcanic plains, differs in most respects from sites to the south. It is a shallow (c. 1m) hyper-saline lake formed in a depression within the basalt. Studies of sediments within and around the lake suggest that it was originally part of the Lake Bolac Basin that has been separated from Lake Bolac and defined by the formation of lunettes on the easterly sides of each lake (Jim Bowler pers. comm.). The Lake Turangmoroke lunette has also severed contact with Fiery Creek that skirts the southern shore and then flows through Lake Bolac. Precipitation is much lower (540 cm per annum on average) than around the southern sites and, although it is the site at the highest altitude, falls within the temperature range of the other sites.

In general terms, the pre-European vegetation of the volcanic plains was composed predominantly of either grassland with a sparse but variable cover of eucalypts with *Eucalyptus camaldulensis* (red river gum) usually the most conspicuous, and perhaps including *Allocasuarina verticillata* (drooping sheoak), on the heavy clay soils weathered from older basalt



Figs 2a-c. Location of sites of pollen records in relation to reconstructed vegetation at the time of European arrival. Simplified from Anon (2000). Site names are shown in italics.

flows, and woodland dominated by a variety of *Eucalyptus* and *Acacia* species, *Allocasuarina verticillata* and *Banksia marginata* on younger, more pervious volcanic surfaces such as scoria cones and stoney rises. Both vegetation types show variation in relation to degree of drainage impedance. The volcanic plains are surrounded by a variety of parent materials that generally produce soil textures that are conducive to the development of open forests with grassy or heath understoreys. In the higher rainfall areas of the western highlands around Ballarat and particularly in the Otway Ranges, wet sclerophyll forest (or tall open forest) has developed. It is dominated by tall eucalypts with a distinctive understorey layer that includes tree Asteraceae and *Pomaderris aspera*. Small patches of *Nothofagus cunninghamii* rainforest occur in the highest rainfall part of the Otway Ranges.

As the location of sites in relation to particular communities has a major bearing on pollen representation, the vegetation within at least 20 km of each site is shown on Figs. 2a-c. Community distributions are based on the maps contained in Anon

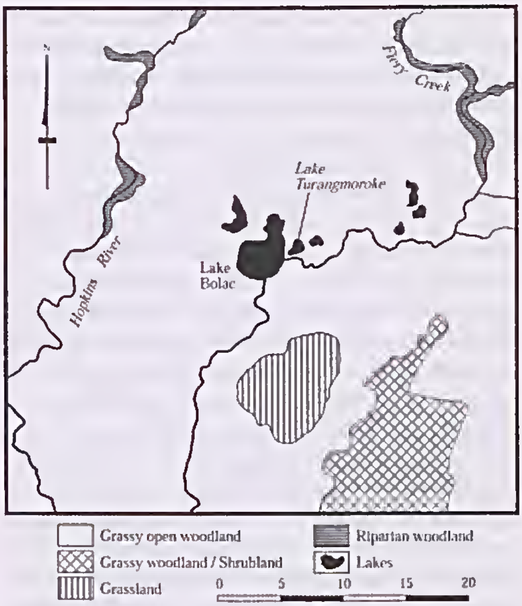


Fig. 2c.

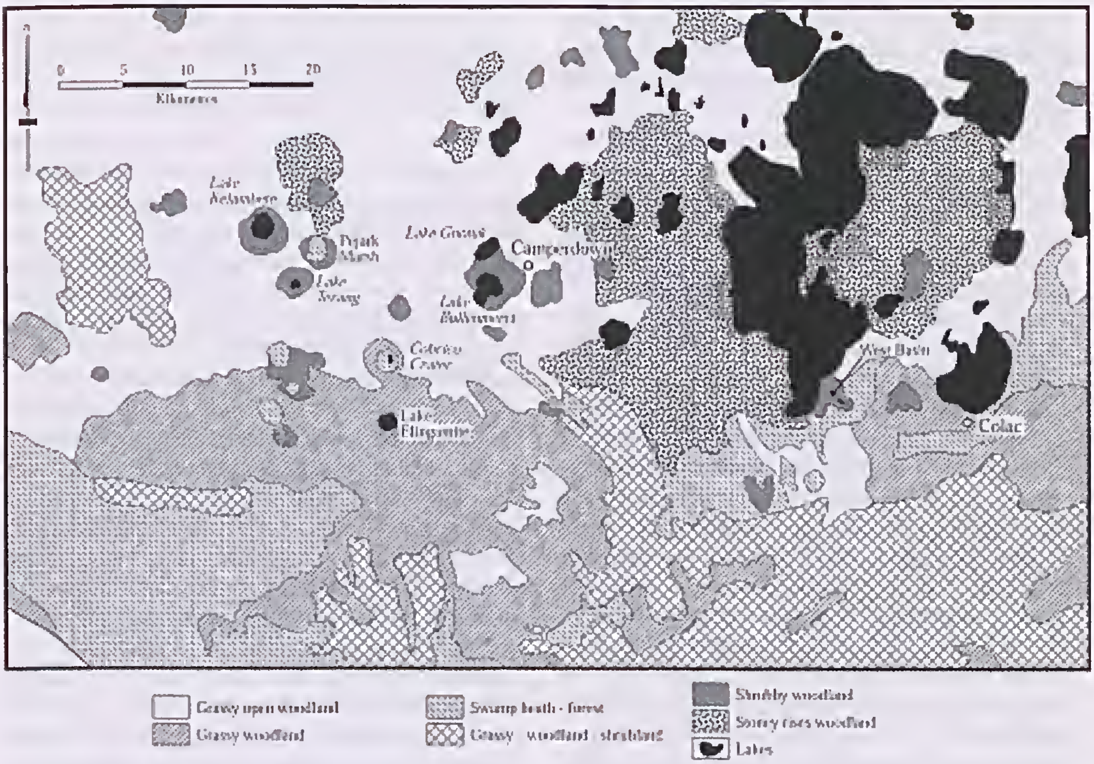


Fig. 2b.

(2000) and have been simplified for clarity and to emphasise the structural and floristic features that may strongly influence pollen representation. The three illustrated areas that incorporate all the sites are together representative of vegetation variation over most of the Western Plains.

Four sites are located on the Warrnambool Plain (Fig. 2a). In this area, a combination of coastal dune barriers and low-lying basalt flows, that have impeded the formation of coherent drainage, have resulted in extensive wetland or seasonal flooded vegetation communities away from the centrally-located Hopkins River catchment. These communities are grouped on Fig. 2a as swamp heath-forest. Tree canopies are composed of a variety of species with *Eucalyptus ovata, E. camaldulensis, E. viminalis* and *Acacia melanoxylon* predominant on basalt and *E. viminalis, E. baxteri* and *E. ovata* important on the less fertile and texturally lighter soils derived from Cenozoic marine and non-marine sediments. Understoreys are characterized by a significant sedge component within basalt communities, and a variety of heath and scrub species, including *Leptospermum* and *Melaleuca* spp., the heath form of *Banksia marginata* and *Allocasuarina paludosa,* as well as sedges, on lighter soils. Where drainage is sufficiently impeded to have formed peatlands and on low fertility soils, scrub and heath communities without a tree canopy can be found.

On the better drained parts of the basalt plain area, predominantly in the Hopkins catchment, grassy open woodland is the major natural vegetation type, as it is over the Western Plains as a whole. Canopy species are the same as those in more swampy basalt areas, but the ground layer is mainly composed of tussock grasses. Within this open woodland area are many small swamp areas that have not been included on Fig. 2a. A third major type of vegetation on basalt is shrubby woodland that characterizes the skeletal soils of well drained scoria and cinder cones as occur in association with Tower Hill and Lake Wangoom. Mapping of this vegetation type also appears to include tephra derived from explosion of the maars that may be largely derived from underlying limestone rather than scoria (Anon. 2000). It is debatable whether such deposits carried a similar type of vegetation. *E. viminalis, A. melanoxylon, Allocasuarina verticillata* and possibly the tree form of *Banksia marginata* were important components of the canopy layer above shrubs including *Bursaria spinosa* and *Hymenanthera* spp. and a ground layer of tussock grasses and/or *Pteridium esculentum* (bracken). Some topographically more variable parts of the plains, possibly the result of differential weathering of relatively recent basalt flows, are mapped as grassy woodland-shrubland and contain an intimate mix of grassy woodland, grassy wetland and shrubby woodland.

Other vegetation types within this Warrnambool area include *E. viminalis* woodland, *Leptospermum lanigerum* swamp scrub and aquatic herblands. These form the coastal grassy woodland complex, essentially on Cenozoic sediments, that is considered to have had a canopy composed of a number of eucalypt species, but insufficient remains to fully describe its composition. There is also a small incursion of eucalypt-dominated open forest that is best represented in the overlapping map of Fig. 2b where most sites are located.

It is clear from Fig. 2b that, although pollen sites are concentrated on the open woodland basalt plains as in the Warrnambool area, this area has vegetation types indicative of additional environments. Swamp communities have reduced representation but open lakes, many of them saline to hyper-saline, are a major feature. This indicator of a poorly developed drainage system is largely the result of extensive recent extrusion of basalt flows that form a landscape of stoney rises. The woodland that has formed on this highly irregular terrain is dominated by a single species of eucalypt, *E. viminalis,* though often accompanied by *A. melanoxylon,* while woody Asteraceae are prominent in the shrub layer and tussock grasses and bracken are the common ground cover. To the south of the sites, on largely marine and coastal Cenozoic sediments, extensive grassy woodlands occur and give way to open forests as rainfall increases towards the Otway Ranges. These forests are dominated by *E. obliqua* with a number of other eucalypts including *E. willsii, E. aromaphloia* and *E. baxterii* variously present, while the understorey is usually rich in shrubs. Swamp heath-forest occurs in patches on both basaltic and non-basaltic soils, and is or was present in some maar crater swamps such as Cobrico Crater, Pejark Marsh and probably Lake Terang. Shrubby woodland is considered to have existed around all the maar pollen sites though most sites lack substantial scoria sediment.

The largely basaltic area around Lake Turangmoroke (Fig. 2c) is dominated by grassy open woodland but dotted with depressions supporting freshwater wetlands with sedges prominent beneath the open eucalypt canopy, and brackish to saline lakes or saltpans of which Lakes Bolac and Turangmoroke are among the most conspicuous. Occasional rises support shrubby woodland, while riparian woodland of *E. camaldulensis* with an understorey of grasses, sedges and aquatics, is prominent along stream channels including Fiery Creek that flows into and out of Lake Bolac. Other communities include grassland where trees are extremely scattered due to a combination of the heavy soils and seasonal waterlogging, and grassy woodland-shrubland where there is increased topographic variation.

Throughout the Western Plains there has been substantial alteration of vegetation since the arrival of Europeans and, with the exception of a few environments such as the stoney rises where technology for substantial agricultural production is only just developing, the representation of intact native communities is rare. As a result of agricultural activities, combined with the high degree of variation in this geologically recent landscape, reconstruction of the 'natural' vegetation is very tentative. Of particular concern for this paper is the uncertain location of some key taxa, although examination of the pollen records may contribute to some better understanding of their natural abundance and distribution.

METHODS

Pollen data selection

For each pollen record, values of selected taxa of the dry land component were extracted from available raw data or, in the cases of Lake Keilambete, Lake Bullenmerri and West Basin, measured from published diagrams and recalculated on a 'common' taxon pollen sum for each spectrum (see Figs. 4a-k). These common taxa are demonstrated to reflect variation in the regional vegetation of southeastern Australia (Kershaw et al. 1994; D'Costa & Kershaw 1997). They include the following: *Eucalyptus* and Casuarinaceae as dominants of sclerophyll forest and woodland; *Acacia, Banksia* and *Dodonaea* as other notable and widespread woody representatives of sclerophyll vegetation; *Pomaderris* (specifically the *P. aspera/apetala* pollen type) that characterizes the understorey of many tall open (wet sclerophyll) forest communities; *Nothofagus* and *Phyllocladus* that typify cool temperate rainforest; and Poaceae, Asteraceae (Tubuliflorae) and native *Plantago* that are major components of the understorey of open sclerophyll forests and woodlands and are dominants of treeless communities such as grasslands and herbfields. Within the Asteraceae (Tubuliflorae) a distinction is made between plants producing pollen with conspicuous spines, that embrace almost all extant forms within the region, and those producing pollen grains with very short spines (Asteraceae type b). The plant sources of Asteraceae type b are uncertain and are recorded mainly in glacial-aged sediments (Macphail and Martin 1991). Chenopodiaceae and *Callitris* values were also calculated for some diagrams as these can contribute substantially to the regional pollen rain. However, they have been expressed as percentages relative to, rather than as a component of, the pollen sum because, in the case of Chenopodicaeae, there can be major over-representation from saltmarsh vegetation growing within or around saline basins and, in the case of *Callitris*, the pollen grain has not been recognised in a number of studies. In addition, *Callitris* pollen cannot be separated from that of introduced Cupressaceae species, including the commonly planted Cypress pine. In several early diagrams (i.e. the records from Cobrico Crater and Lake Gnotuk and last 8000 years from the Lake Bullenmerri record) comparability is reduced by the failure to identify grains of one or more of the taxa native *Plantago, Dodonaea* and *Pomaderris* that together may make up around 10% of the pollen sum in other diagrams. It is also notable that Asteraceae type b was not separated from other Asteraceae throughout the Bullenmerri record.

Analogue matching

Analogue matching, using the techniques of Overpeck et al. (1985), is employed to provide a measure of the degree to which past vegetation relates to vegetation represented at the time of European settlement and to provide estimates of precipitation changes through time. The latter will be used in an assessment of the relative importance of climate in vegetation change while the former will provide some measure of community integrity through time and a basis for assessment of the validity of the climatic estimates. With the analogue technique, each fossil spectrum is compared with a data base of recent pollen spectra, in this case those spectra derived from just prior to evidence for European settlement within sites included in the southeastern Australian pollen data base (SEAPD) (Kershaw et al. 1994; D'Costa & Kershaw 1997) but excluding 24 sites considered inappropriate for climate reconstruction (*sensu*

D'Costa & Kershaw 1997). These excluded sites included those where fluvial influences are significant or where the uppermost sediments were disturbed. Following this process the SEAPD consisted of 112 sites. Modern precipitation estimates for all sites have been determined from climatic prediction system BIOCLIM (Busby 1991).

Canonical Correspondence Analysis (CCA), a multivariate technique which assesses the explanatory power of multiple environmental variables (Palmer 1993), was implemented to provide closest recent analogues for fossil spectra and to assess the suitability of annual precipitation for climate reconstruction. The computer program MAT (Juggins 1995) was used to compare the predictive power of 20 (dis)similarity measures for assessing the degree of similarity between assemblages (with varied emphasis on abundant vs. poorly represented taxa), including all those measures outlined in Overpeck et al. (1985). The program was also used to determine the optimal number of analogues to use in predicting modern climate. The predictive power of similarity measures was assessed using the Root Mean Square Error (RMSE) between modern and pollen predicted climate.

Although mean annual rainfall (RANN) was the variable chosen for palaeoclimatic reconstruction, all other BIOCLIM generated precipitation variables, with the exception of their range, were highly correlated (r^2>0.85) for sites in the SEAPD and as a result mean annual rainfall can be regarded as a proxy for other measures, that are essentially different estimates of rainfall seasonality. CCA showed that RANN explains 17.9% of significant (p<0.005) variance in the SEAPD, which is marginally less than that explained by the most important variable, precipitation of the driest quarter (18.6%), with which it is highly significantly correlated (r^2=0.94, p<0.005) (Tibby et al. 2001). This level of explained variance is comparable to, or exceeds that in many other transfer function studies and therefore RANN is an appropriate variable for which to derive a transfer function. As a result of the aforementioned strong co-variation between precipitation variables, other precipitation measures explain little variance (<3.5%) not already explained by annual precipitation. Similarly, mean annual temperature (and other temperature measures) explain only a small proportion of variance (3.4%) in addition to annual precipitation. As such the SEAPD is unsuitable for reconstructing temperature parameters independent of precipitation with any confidence.

Kershaw et al. (1994) suggested that chi-squared distance would be the most appropriate to infer past climates from the SEAPD since it places less emphasis on rare taxa (which may have been inconsistently identified by the multiple contributors to the data base). Tibby et al. (2001) showed, in terms of its ability to predict modern climate from pollen assemblages, that squared chord distance (SCD) has errors which were marginally lower (≈3%) than those associated with the chi-squared technique and has the highest predictive ability of 20 (dis)similarity measures compared.

Tibby et al. (2001) also assessed the effect of number of analogues used on model predictive error. They showed that errors declined with addition of sites up to between 3-6 sites, but that the addition of subsequent sites (which presumably were poorer analogues to the site being estimated) increased errors in the model. Where SCD is the similarity measure used, lowest errors occur when three sites are used (providing support for the approach adopted by D'Costa (1997) and Harle (1998). Hence for the purposes of reconstruction (and reporting of model errors), the weighted average of RANN in the three sites with lowest SCD was used. Comparison of modern RANN with pollen predicted RANN in the 112 site data set showed that, although there was a reasonable relationship between the observed and predicted data (r^2=0.70), RMSE, was substantial (398 mm). As a result we excluded seven sites with the greatest residual difference between observed and inferred values. The removal of these sites led to substantial improvement in the model with the RMSE

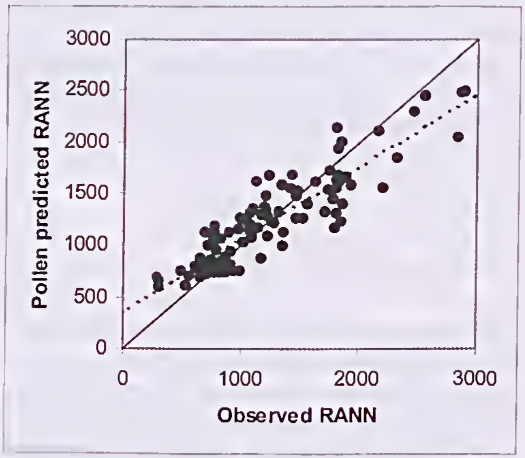


Fig. 3. Observed v. pollen predicted annual precipitation (RANN) in the 105 site south-east Australian pollen data base. Shown is both the line of equivalence (solid) and the linear trend (dotted) in the data.

almost halved to 244 mm and the r^2 increased to 0.84. As can be seen from an examination of Fig. 3, there is reasonable agreement between pollen predicted and observed RANN although, as illustrated by the trend line, there is a tendency for RANN to be overpredicted at the low values and underpredicted at high values. This is the case with many transfer function models (Birks 1998) and is a product in part of an edge effect where the environmental gradient is truncated before the full breadth of a taxon's distribution is sampled.

The relatively small error highlights the importance of precipitation in influencing the distribution of dryland vegetation in south-eastern Australia. This low level of error is particularly pleasing since the source of much of the 1 - r^2 error may be derived not from a poor biological relationship to the environment, but rather from inadequate characterisation of the environment. This is particularly relevant in this situation since the BIOCLIM derived estimates of RANN at the site selected have errors of their own. Furthermore, the BIOCLIM estimated of RANN represent a contemporary estimate, while the pollen estimates are derived from pollen data often > 200 years old. Given that precipitation may have considerably altered in south-east Australia over that period (Jones et al. 2001), pollen predictive errors may derive from the mis-match between biological and environment sampling.

Establishment of chronologies

Radiocarbon dates, together with the first presence of exotic pollen (considered to have occurred approximately 150 years BP), provide the basis for establishment of chronologies. In those records containing several radiocarbon dates and where the nature of the sediments suggests continuous and relatively constant deposition, radiocarbon timescales have been estimated from linear interpolation between dated points. These independent timescales are valuable for temporal comparison of changes between records. In parts of records where dating is uncertain, comparison with more certainly dated records is employed to provide general estimates of regional change, though this circularity restricts assessment of spatial variation in the timing of particular events. In the case of Lake Turangmoroke, where periods of non-deposition are suspected, no attempt has been made to estimate a timescale. In the longest dated record, that from Northwest Crater, the radiocarbon timescale has been calibrated (Stuiver & Reimer 1993) to provide a calendar year timescale for those interested in comparisons with calibrated records from other areas.

VEGETATION AND ENVIRONMENTAL RECONSTRUCTION

Pre-Holocene

Three records, Northwest Crater (Fig. 4a), Lake Bullenmerri (Fig. 4i) and Lake Turangmoroke (Fig. 4k) provide substantial evidence of Late Pleistocene vegetation. Other sites either contained sediments too consolidated to core or revealed essentially inorganic sediments that did not preserve pollen. In either case substantially drier conditions than today may be inferred. It is not difficult to explain the persistence of the record at Lake Bullenmerri because, being the deepest lake in Victoria, lower water levels would have been insufficient to dry the basin, but the situation is not as simple at the other two sites. There is certainly evidence for lower, variable lake levels at Northwest Crater and presumably here the ground water level remained sufficiently high to just maintain a lake despite an absence in the surrounding Main Lake of Tower Hill, with which it has a ground water connection (D'Costa et al. 1989). It is very surprising that there is a record from the shallow, hyper-saline Lake Turangmoroke, the site experiencing the lowest rainfall. However, it is the only site potentially river fed, if Fiery Creek did flow into the basin, and it is unlikely that the record is continuous as a date of 12,640 years BP from the neighbouring Lake Bolac lunette indicates deflation of lake sediments from the Bolac basin, at least around this time (Crowley & Kershaw 1994). The date is consistent with a proposed break in deposition of the lake sediments at 132 cm (Crowley & Kershaw 1994).

The vegetation of the Late Pleistocene phase is characterised by a predominance of herbaceous and woody/herbaceous taxa with Poaceae and Asteraceae dominant and *Plantago*, Chenopodiaceae and Asteraceae type b, where separated from Asteraceae (i.e. Northwest Crater), conspicuous. Woody taxa have total percentages of around 20-25% or less. The vegetation has been described as predominantly steppe-grassland with no modern analogue (Kershaw & Bulman 1996), and this interpretation is supported here by the high analogue distance values. Trees may have formed an open canopy cover or, most likely, were restricted to isolated, sheltered pockets.

There is both temporal and spatial variation in the pollen data. Those samples beyond about 15,000 years ago in Northwest Crater and Bullenmerri, and perhaps the basal 3 samples of Turangmoroke, represent the Last Glacial Maximum. Here Asteraceae is predominant at Turangmoroke, equal with Poaceae at Northwest Crater and subordinate to Poaceae at Bullenmerri. These data indicate variation in grassland steppe vegetation but its significance is unknown. The much lower values of *Eucalyptus* around Lake Turangmoroke than around the other two sites may suggest greater survival in the southern part of the plain. Conversely, higher values for Casuarinaceae at this site may indicate more substantial regional survival of woodland trees (represented in this area by *Allocasuarina verticillata*). However, the high proportion of small Casuarinaceae grains suggests a heath source, probably *Allocasuarina paludosa* growing around the lake. The relatively high values for *Banksia* at Northwest Crater more certainly indicate a more local source, as *Banksia* pollen is poorly dispersed. In this largely treeless landscape, it is likely that the shrub form of *Banksia* formed a major component of a heathland on the scoria cones. The fact that there is little representation of this taxon at the other sites could be due to an inability to disperse into the centre of larger lakes, but its poor representation relative to Holocene assemblages at these sites suggests that conditions were not suitable for the formation of local *Banksia* heath. *Callitris* pollen forms a higher proportion of Pleistocene than Holocene assemblages at both Bullenmerri and Northwest Crater. One interpretation is that the well dispersed pollen type is derived from Wimmera and Mallee sources to the west and north of the area and its representation is increased because of low production from a sparse tree coverage on the plains. However, it might be expected that values would be highest at Turangmoroke, and the record from here (supported by more recent work by one of us – EC) indicates very low pollen representation during the latest Pleistocene. If the *Callitris* values are a true indication of parent plant representation in the landscape and not an artefact of preservation, then perhaps the taxon did have a presence on the plains at this time. The existence of isolates of *Callitris* today on the eastern fringes of the basalt plains indicates the possibility of a more extensive past distribution on basalt, and the fact that rainfall on the eastern fringes is about 200 mm less than at Bullenmerri today is consistent with a presence there during the last glacial period (or perhaps more especially the very late Pleistocene).

The evidence for existing vegetation supports sedimentological data for conditions, on average, being drier than today. However, lowest estimates from analogues, ranging from about 100 mm lower than today at Turangmoroke to perhaps 200 mm lower than today at Northwest Crater, would not result in treeless conditions. Conversely, the estimate of a mean annual rainfall of only 250 mm derived from fossil material of the red kangaroo, *Macropus rufus*, at Lake Bolac within this period (Horton 1984) would be a different proposition. The pollen records from the Western Plains reveal little about temperatures but both a general palaeoclimate model for south-eastern Australia (Harrison & Dodson 1993) and palaeoecological data (Kershaw 1998) indicate that temperatures are likely to have been about 4°C lower than today, again insufficient, even in combination with lower rainfall, to account for the scarcity of trees. In fact, lower temperatures would have increased the effectiveness of precipitation. Consequently, other factors such as higher wind speeds and incursions of cold polar air (McGlone 1998) and, more recently, low carbon dioxide levels that increase the competitive advantage of grasses (Huang et al. 2001), have been invoked to explain the paucity of trees at these latitudes. The expansion of the continental shelf with glacial low sea levels would also have impacted on climate with the area suffering greater continentality, so greater variation between summer and winter may have been an additional important factor. It has been suggested for a similar situation during the glacial period in the Mediterranean region, where there was sufficient water to form lakes but within a treeless landscape, that excessive rain during the winter filled the lakes and that evaporation in the relatively warm but extremely dry summers resulted in a water deficit sufficient to exclude tree growth (Prentice et al. 1992).

After about 15,000 years BP there is evidence of some change within the vegetation. The pollen of woody taxa essentially maintains its representation

Fig. 4a-k. Major features of Late Quaternary pollen records from the Western Plains of Victoria and results of analogue matching. All taxa are expressed as percentages of the 'common' taxon sum for each sample. The horizontal dashed line marks the first presence of exotic pollen while vertical dashed line indicates the present day mean annual precipitation of the site, on each diagram. Min d^2 is the distance between each sample and its numerically closest recent analogue. Chronologies derived by interpolation between radiocarbon dates.

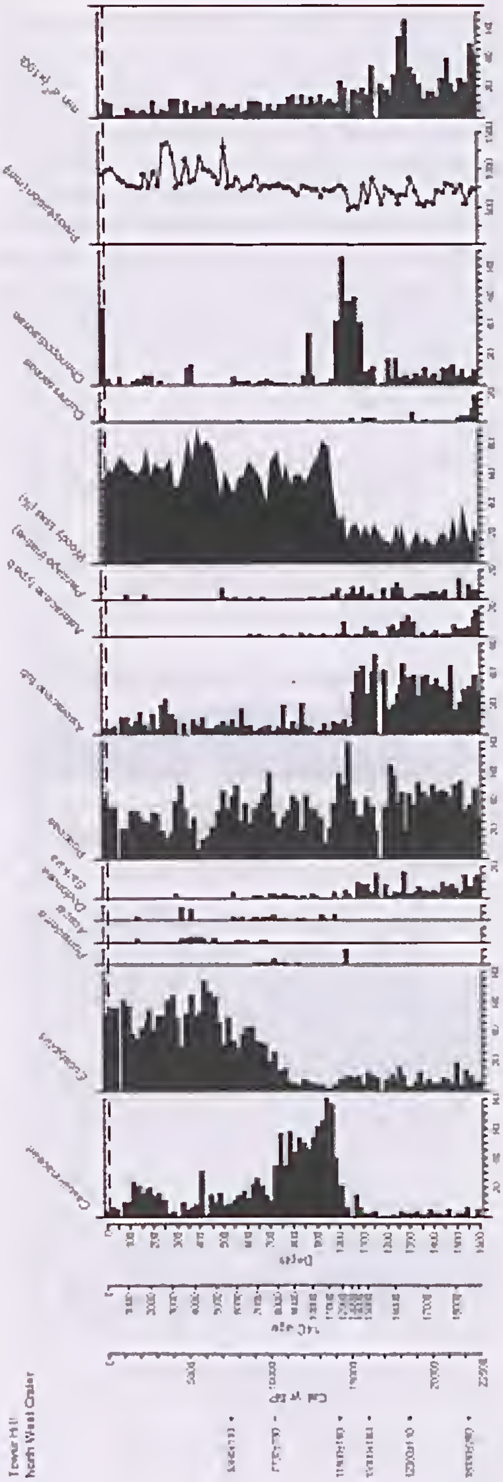

Tower Hill
North West Crater
Casuarinaceae
Eucalyptus
Poaceae
Asteraceae
Chenopodiaceae
Depth
14C age
Cal yr BP

Fig. 4a.

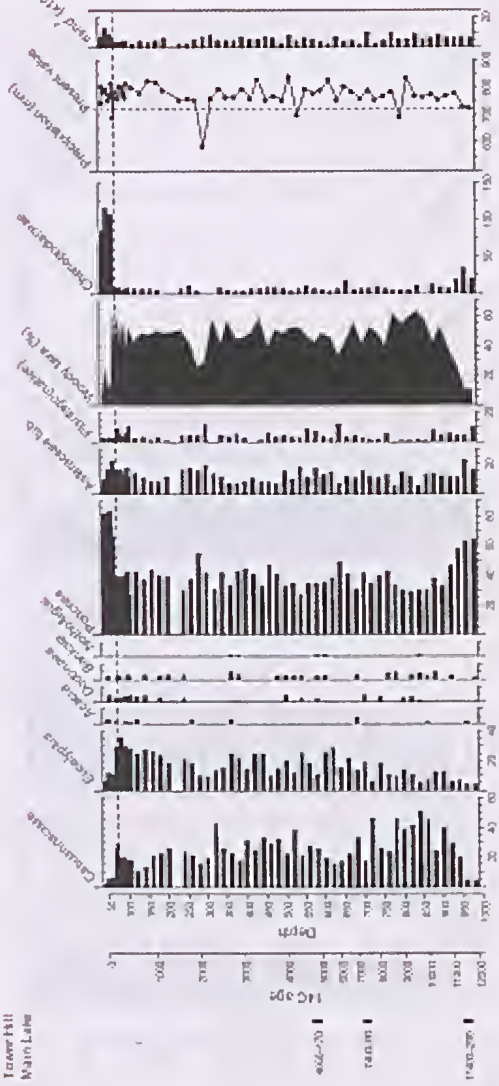

Tower Hill
Main Lake
Casuarinaceae
Eucalyptus
Acacia
Poaceae
Asteraceae
Chenopodiaceae
Depth
14C age

Fig. 4b.

at Northwest Crater, falls a little at Bullenmerri but perhaps increases at Turangmoroke, although the dating is uncertain at this site. This increase, though, is largely in heath Casuarinaceae (Crowley & Kershaw 1994) and does not indicate a regional increase in trees. In all diagrams there is a rise in Poaceae values relative to those of Asteraceae, gradually at Bullenmerri, more abruptly at Turangmoroke, and sharply at Northwest Crater. The change at Northwest Crater is dated to between 13,000 and 12,000 years BP and falls within a major peak in Chenopodiaceae. The two events are likely to be connected. The relative increase in grasses relative to Asteraceae is likely to reflect an evolution of steppe vegetation into grassland with temperatures increasing towards present levels while the Chenopodiaceae indicate an effective reduction in moisture in response to the temperature increase. Any rise in precipitation would have lagged that of temperature because of a slow response of sea surface temperatures and ice sheet melting (and hence sea level rise) to global warming. The extent of the

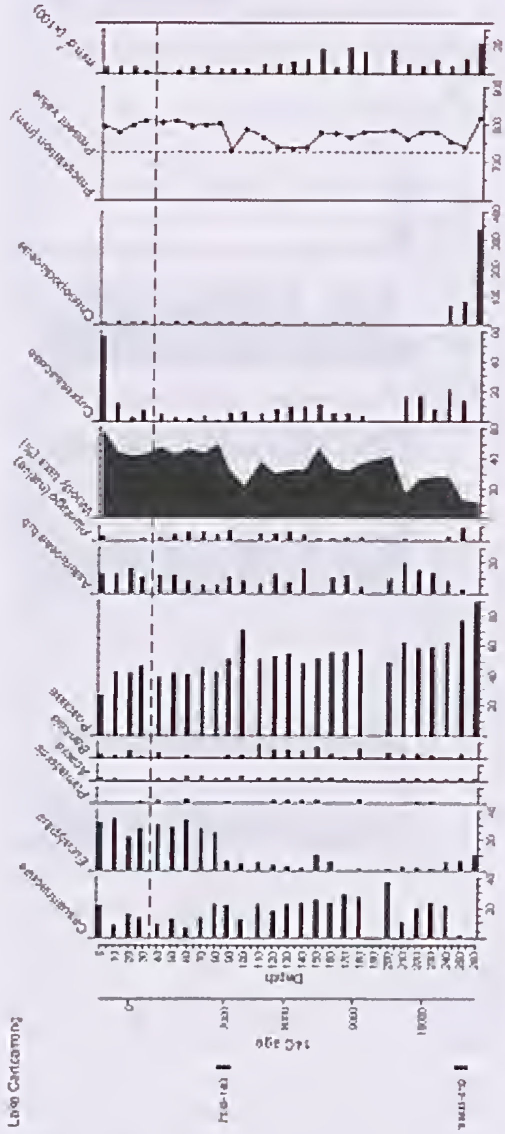


Fig. 4c.

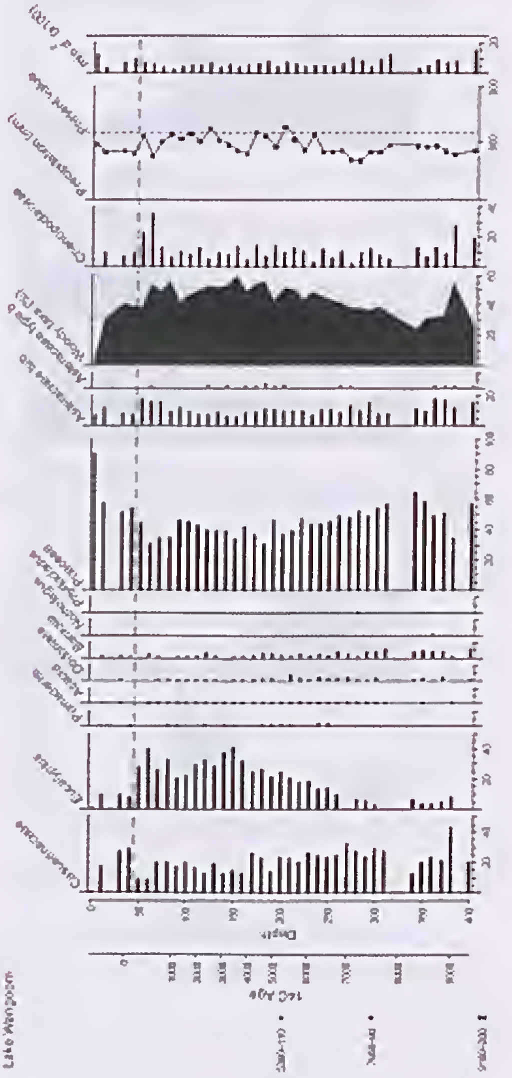


Fig. 4d.

Chenopodiaceae rise at Northwest Crater indicates largely the establishment of salt marsh species within the basin as salts were concentrated by lake drying, although the more limited response of the taxon in the other records is more indicative of regional colonisation of shallow saline depressions and perhaps also the encroachment of salt bush onto the plains. Dry conditions, centred on 13,000 to 12,000 years ago are also indicated by a reduced sediment accumulation rate at Northwest Crater, presumably due to frequent drying, the achievement of lowest precipitation estimates at Northwest Crater from analogue matching, and achievement of lowest levels of woody plants in the Bullenmerri diagram indicating a further regional reduction in tree cover. The date of 12,640 years BP from the Bolac lunette falls neatly within this period and demonstrates erosion rather than deposition of lake sediments at this site, consistent with its drier location and the shallow nature of its basin. The Turangmoroke complex is probably representative of the timing of lunette formation associated with many shallow Western Plains lakes.

The Pleistocene/Holocene transition

Although the Pleistocene/Holocene boundary is formally placed at 10,000 years BP, major climatic

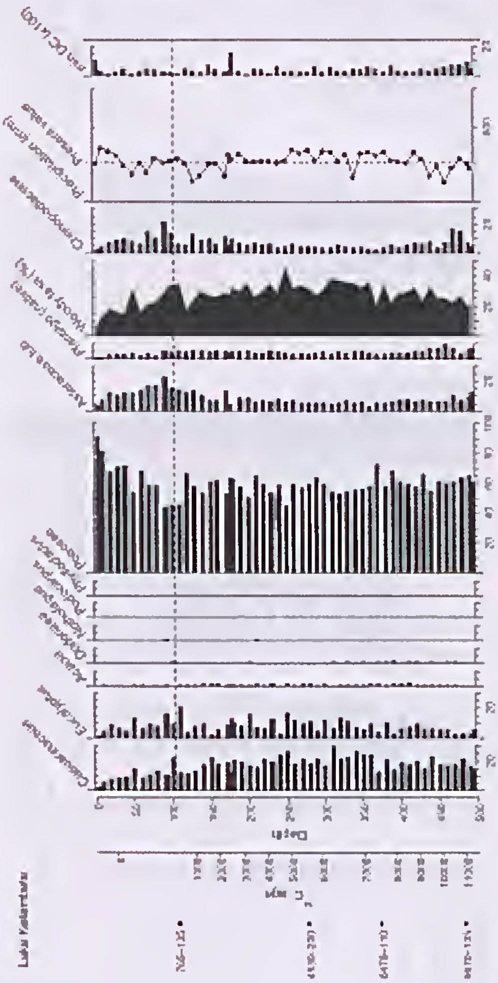


Fig. 4e.

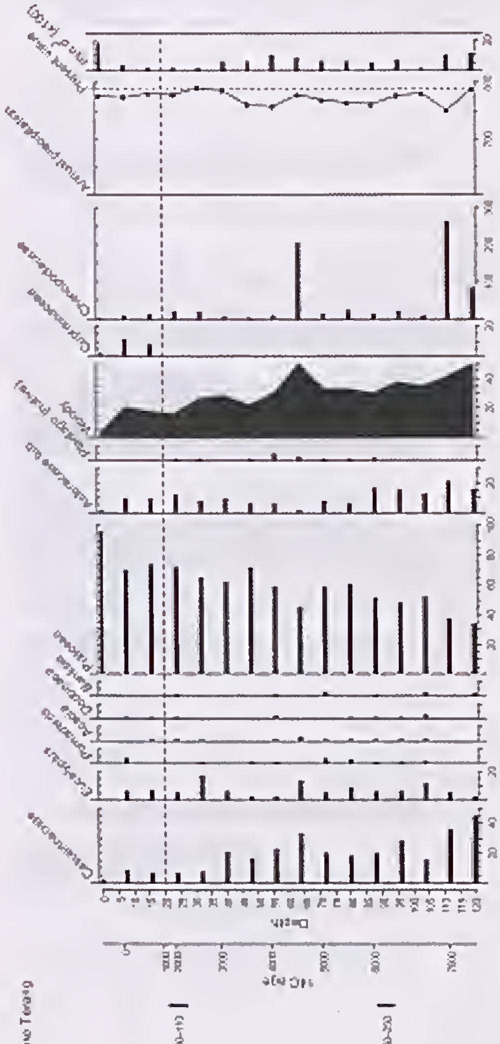


Fig. 4f

'amelioration' is indicated by initiation of a forest or woodland cover in the region from about 12,000-11,500 years ago. At Bullenmerri, there are notable increases in Casuarinaceae and *Eucalyptus* at this time with an increase in total woody plant representation from about 20% to at least 30% while at Northwest Crater Casuarinaceae percentages rise sharply to over 60% with eucalypts actually having reduced values. The base of the record in Tower Hill Main Lake shows a presumably synchronous increase in Casuarinaceae to 40%. Climatic estimates show a sustained increase in precipitation at this time and some support for a rainfall increase is provided by the initiation of organic sediment accumulation and a reduction in Chenopodiaceae values at Main Lake, but high chenopod values are maintained at Northwest Crater, and also Bullenmerri. It could be suggested, especially in light of reductions in Asteraceae values, that the Casuarinaceae expansion could have been triggered as much by temperature as by precipitation related factors.

The subsequent beginning of organic sedimentation, and hence permanent lake establishment, at sites provides some indication of the nature of effective precipitation increase within the transition. Those sites with relatively reliable basal dates indicate a progressive rise in effective rainfall from 11,400 years BP to 8000 years BP. Basal ages generally relate to basin depth with deeper lakes such as West Basin (c10,600 years BP) and Lake Keilambete (c 9700 years BP) being older than the shallow basins of Lake Wangoom (c 9200 years BP) and Lake Terang (c 8000 years BP). The basal age determination for Lake Gnotuk (c 9000 years BP), of similar lake depth to

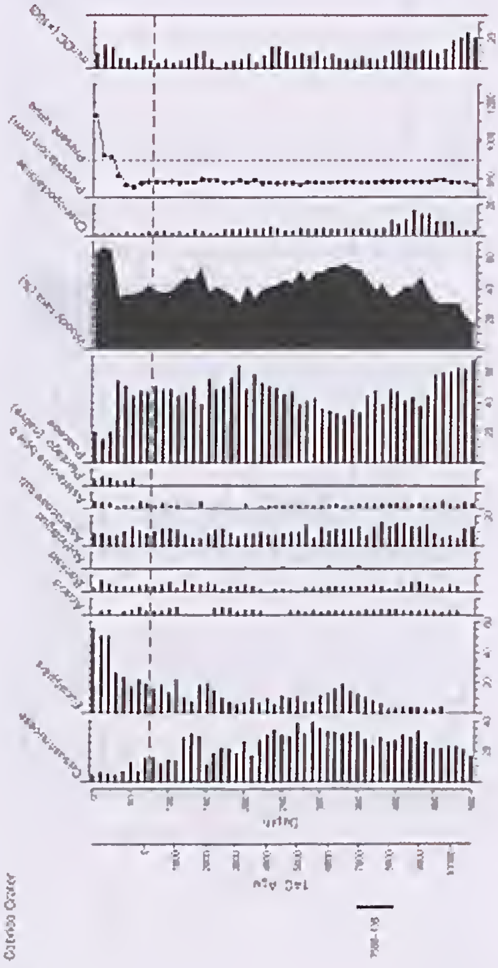


Fig. 4g.

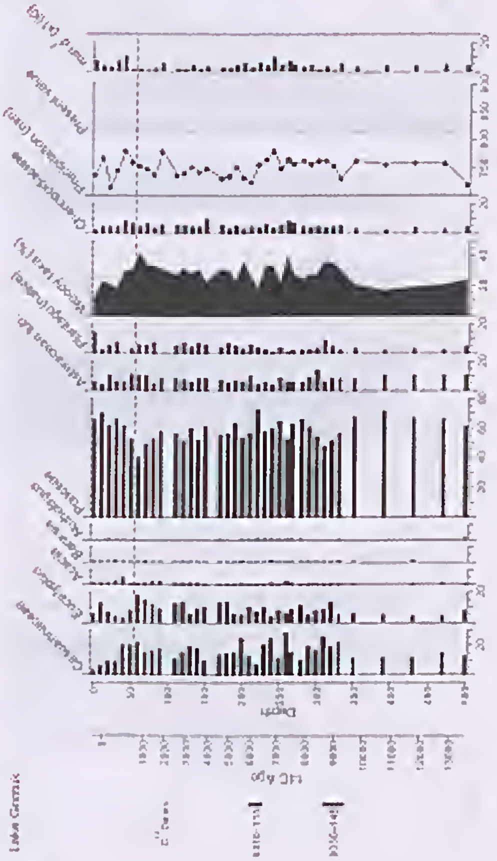


Fig. 4h.

Lake Keilambete, is problematic in that there appears to be mixing of sediment with volcanic ash below this date. Other exceptions to this pattern are the shallow lake sites of Tower Hill and Lake Cartcarrong whose older dates could suggest that the southwestern part of the plains experienced relatively higher rainfall than the southeastern part in the late Pleistocene, a situation that might have arisen through closer proximity to the sea. Alternatively, there may have been a higher ground water table. The progressively wetter conditions though are not reflected in the analogue precipitation estimates that show, on average, constant rainfall levels through the transition period.

In line with the lake establishment data, there is variation in the timing and extent of development of Casuarinaceae, presumably *Allocasuarina verticillata,* between sites during the transition. Of those sites where values of the taxon rise substantially, those at Tower Hill are clearly the earliest,

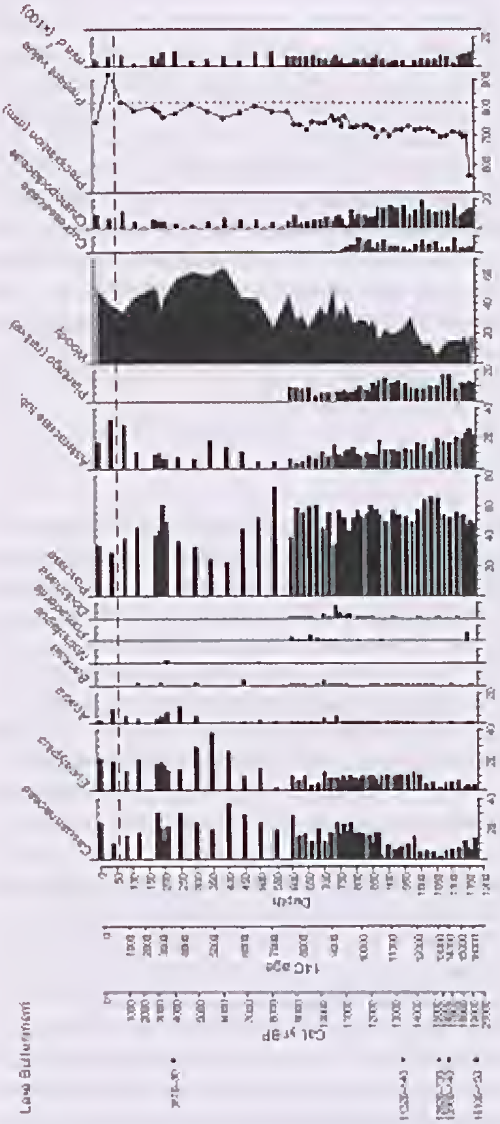


Fig. 4i.

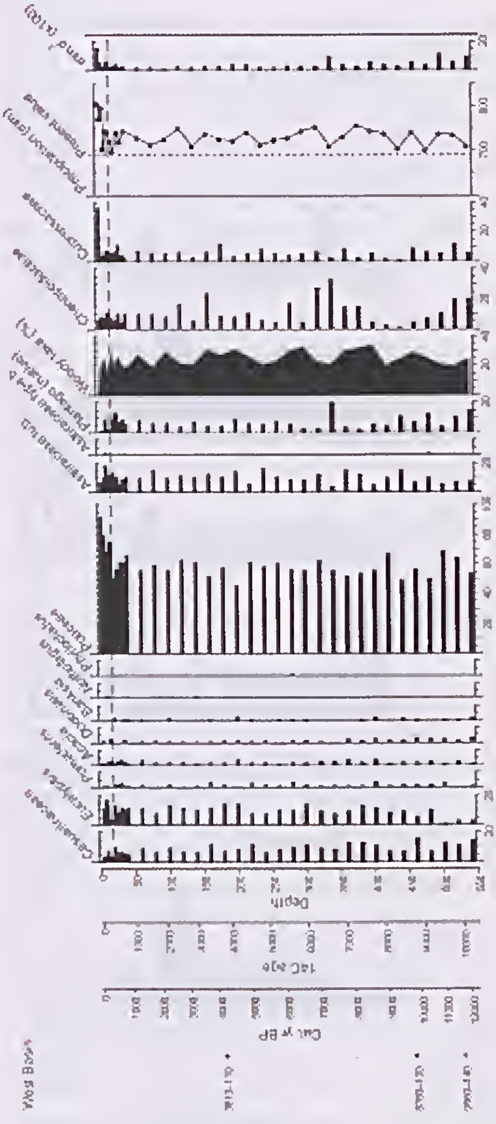


Fig. 4j.

about 11,500 years BP, followed by Cartcarrong (c 10,500 years BP) and Lake Turangoroke (c 9000 years BP). These sites are also the only ones where Casuarinaceae forms a major peak in the transition or early Holocene. Lake Bullenmerri shows a second and more notable rise in Casuarinaceae about 10,500 years BP. Casuarinaceae values have presumably risen at all other sites before record commencement and, considering the geographical proximity of these sites to Lake Bullenmerri, increases around the same time (c 10,500 years BP) might be expected. With respect to the reason for this pattern of expansion, the proposed existing rainfall gradient may have been important, as may have been centres of taxon survival during the last glacial period. *A. verticillata* appears to prefer well drained sites, including dune systems and basalt rises, but is also widespread within grassy woodlands in the region, in association with eucalypt species. The low values for pollen that can be attributable to *A. verticillata* during the last glacial period would suggest an absence on the plains, despite availability of well drained scoria material around some sites, especially those of Tower Hill. It might appear then that the early expansion around Tower Hill was from refugia within the dune systems in the Warrnambool area, primarily as a result of an increase in temperature, with subsequent migration, from this source, over the southeastern part of the plains. In the case of Lake Turangmoroke, late colonisation but marked representation may have been a result of a combination of time for migration from the southern margin of the plains and optimal conditions for establishment. Alternatively, the source of Turangmoroke populations may have been the uplands to the north and north-west of the area.

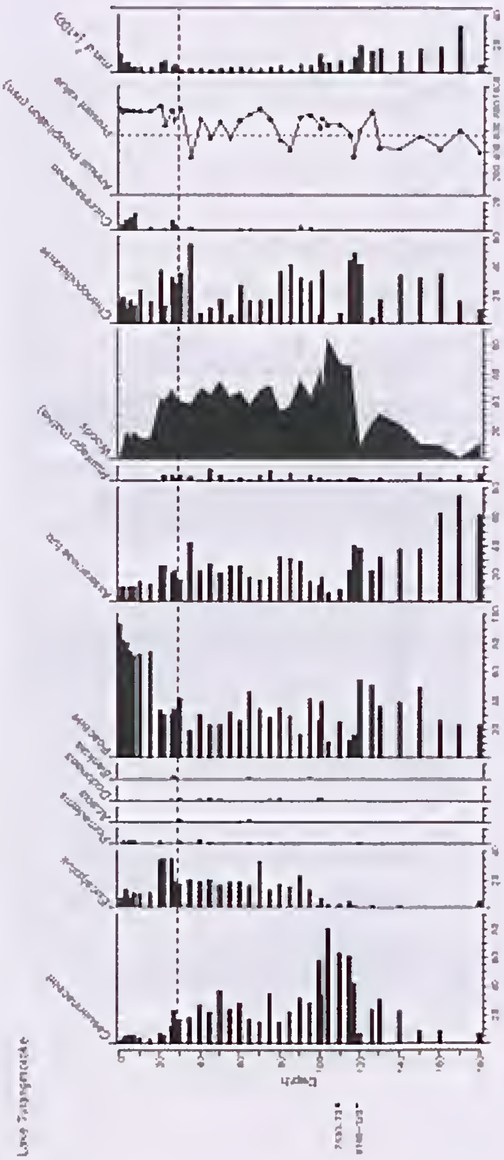


Fig. 4k.

The Holocene

By the beginning of the Holocene, pollen values suggest that woody plants were as well established on the southern part of the plains as they were at the time of European arrival, except perhaps in the north where, if the dating in the Lake Bolac basin is accurate, full development was delayed for about 1000 years. In the case of the Bullenmerri record, the ratio of woody to herbaceous plants is distorted by the lack of recognition of native *Plantago* within the Holocene sequence. In addition to the noted representation of Casuarinaceae, *Banksia, Eucalyptus* and *Callitris* in the Pleistocene, *Dodonaea* gained a regional representation around 10,000 years ago, suggesting some increase in diversity. There is evidence also of forest expansion in wetter areas, with fairly consistent representation of the wet sclerophyll taxon *Pomaderris,* and occasional representation, at a number of sites, of the rainforest taxon *Nothofagus*. The highest values or most frequent occurrence of these taxa at West Basin suggests an Otway Ranges source but the presence of *Phyllocladus* pollen in a few records, whose parent rainforest plants are not present today on the

Australian mainland, may indicate also longer distance transport from Tasmania. Within the Lake Bolac region, there is little indication of the local presence of *Eucalyptus* until about 10,000 years BP and a lack of evidence for *Acacia* or *Dodonaea* until about 7000 years ago.

The average value of woody plant pollen through the Holocene varies from site to site, but does generally reflect regional tree or shrub cover. Some variation can be accounted for by regional differences, but, despite significant pollen transport ability of the major tree taxa, much of it relates to the nature of individual sites. With the twin lakes of Gnotuk and Bullenmerri, the latter has an average woody pollen value of 45%, 20% above that at Gnotuk. This difference can at least partially be explained by higher dispersal ability of tree pollen and hence higher representation in a core from the centre of the larger lake. Conversely at Tower Hill, the small basin of Northwest Crater has 65% woody pollen, the highest average percentage of any site, while Main Lake less than 1 km away, averages 50%. In this case the fact that Northwest Crater is surrounded by scoria cones with a substantial woodland cover and Main Lake is exposed to the open woodland of the plains, has probably been the dominating influence on pollen representation. It is perhaps surprising that West Basin, along with Keilambete and Gnotuk, has the lowest woody plant pollen percentages, despite having closest proximity to forest vegetation. Although there are notable percentages of wet forest taxa indicating forest as a pollen source, the predominant westerly winds may have generally limited its overall representation. Also unexpected is the relatively high value of 40% for woody plant pollen at the driest site, Lake Turangmoroke. Here, a relatively high representation in the landscape of Casuarinaceae, a taxon that depends on wind as the sole mechanism of pollen dispersal and consequently has high pollen production, may have been important.

The substantial differences in proportions of woody plant pollen between sites do not appear to have unduly impacted on the quantitative precipitation estimates, at least for the records from the southern part of the plains. In fact Holocene averages for all sites, excluding Lake Turangmoroke, fall within 80 mm of present day estimates with half within 20 mm. Overall, spatial variation in rainfall between site extremes is reduced from 160 mm at the present day to a Holocene average of 50 mm. Overestimates are recorded for sites within the Warrnambool region (Main Lake, Northwest Crater and Cartcarrong) and West Basin and these could be due to high regional ground water tables that increase effective moisture availability to plants and proximity to forest vegetation of the Otway Ranges, respectively. All sites in the middle of the southern plains show rainfall underestimates, perhaps because of some impedance to tree growth by the heavy textured soils. The estimate from Lake Turangmoroke (680 mm) is substantially higher than the present day value of 540 mm. The reason for this discrepancy may be statistical since the method overestimates values for sites with lower rainfall and there are few sites with similar rainfall characteristics from which to draw analogues. The regional importance of Chenopodiaceae around Lake Turangmoroke, that is excluded from the pollen sum, together with a more open grassy understorey, may also contribute since it has resulted in a higher relative abundance of pollen from woody plants than is the case generally within the SEAPD.

The most notable change in the vegetation over much of the plains within the Holocene is an increase in *Eucalyptus* relative to Casuarinaceae. This change is marked in the records from the western part of the region (Tower Hill, Cartcarrong, Turangmoroke and Wangoom) where there is some clear, partial replacement of Casuarinaceae by *Eucalyptus* beginning around 8000 to 7000 years ago. Most other records show a similar but more subdued change around the same time. The exceptions are Keilambete, Gnotuk and West Basin where there is little change in the representation of these two taxa after the initial rise in *Eucalyptus* in the very early Holocene.

The reasons for the partial replacement of Casuarinaceae by *Eucalyptus* can be debated. If taken in combination with the general evidence for increased woody plant diversity through the early Holocene, it is possible that this change was the result of an increase in rainfall. There is also the possibility that there was a critical reduction in temperature around 7500 years BP as, from the SEAPD, Casuarinaceae percentages are highest under present day warmer as well as drier environments than are those of *Eucalyptus*. An increase in effective precipitation, whatever the contributions of absolute rainfall and temperature, are certainly indicated in reconstructions and models of lake levels within the region (see Jones et al., 1998). These indicate a rapid increase in effective rainfall between 8000 and 7000 years ago that would explain the degree of synchroneity of change within the various records. However, it is still surprising that there was similar and synchronous response at the drier site of Lake

Turangmoroke and this may suggest the involvement of other climatic, or non-climatic influences. It has been proposed, from an application of the analogue technique to Northwest Crater (Kershaw & Bulman 1996), that there was a shift in partial-analogues from sites within the more western part of southeastern Australia, that experience a Mediterranean type of climate, to those in the east where seasonality is reduced. Consequently, the early Holocene may have seen some alteration in atmospheric circulation that resulted in the westerly contraction of a Mediterannean climate, which had dominated the western part of plains and extended inland to Lake Turangmoroke and facilitated the expansion of Casuarinaceae. An additional factor may have been an increase in waterlogging over the plains with an increase in precipitation, whether annually or seasonally, and waterlogging is a feature that has been shown to be widespread today. Both a decrease in seasonality and increase in water table height would be consistent with a replacement of *Allocasuarina verticillata* by eucalypt species in some areas (Crowley, 1994a) as *A. verticillata* has greater drought tolerance as a result of its deep root penetration (e.g. Withers 1978) while some *Eucalyptus* species have relatively high transpiration rates that allow them to survive high groundwater tables (e.g. Biddiscombe et al. 1985). Another explanation would be that an increase in burning, possibly resulting from more intensive Aboriginal occupation and use of the plains, would have favoured eucalypts over the relatively fire sensitive casuarinas. However, there are few charcoal records available for testing this idea and, those that exist, provide no support for it. In fact, evidence for occupation of this region by people suggests a reduction at this time with major intensification occurring after 4000 years BP (Lourandos & David 2002). Although a climatic cause for the increase of *Eucalyptus* relative to Casuarineceae appears most likely, the quantitative climatic reconstructions fail to provide any supporting evidence. Incorporation of measures of seasonality may have been useful, but, as mentioned, these are highly correlated with mean annual precipitation in the SEAPD.

There is little indication of sustained variation in regional vegetation, from the pollen data, between 7000 years BP and the arrival of European people. Despite the evidence for highest water levels in lakes between about 7500 and 5500 year ago (Jones et al. 1998), only a few records from the central part of the plains (Keilambete, Cobrico and Bullenmerri) reflect the higher precipitation levels through a minor peak in woody plant values, while a number of sites show maximum representation of *Eucalyptus* within the last 5000 years. Precipitation curves, despite some fluctuations, are also stationary, apart from those at Bullenmerri and Northwest Crater that display overall higher values. The latter record also shows a high level of variation in the last 5000 years. The change here corresponds to a replacement of open water by swamp vegetation in the basin that could be construed as indicating a reduction in water level and therefore evidence for decreased rather than increased precipitation. It is possible that the apparent precipitation increase is an artefact of the altered pollen deposition surface. The displayed climate variation may indicate the sensitivity of the vegetation around the site to El Niño-Southern Oscillation (ENSO) variability that has been suggested to have become more pronounced in the last 5000 years from other proxies on the Western Plains and from other parts of eastern Australia (McGlone et al. 1992). Alternatively the variability may simply reflect changing analogue matches between recent sites in the SEAPD with similar pollen spectra but somewhat different climates, as is probably the case with many of the fluctuations in rainfall curves in all records. Higher resolution records with greater dating control are needed to see if there is systematic climatic variation during this period.

European settlement period

The first presence of exotic pollen, particularly *Pinus*, is used to indicate European settlement, dating from about 1840 AD, though landscape impact is likely to have preceded the establishment of these plants. From a detailed study of the topmost sediments at one site, Cobrico Crater, it can be seen that the effects of European settlement included tree clearance and planting and establishment of pastoral and arable agriculture. Dodson et al. (1994) found that *Eucalyptus*, Casuarinaceae and Poaceae were the only regional taxa to show significant change between the historic and immediate prehistoric periods. The data set considered here suggests that these taxa, with the addition of *Plantago*, are also the ones that were most affected regionally although patterns of change are variable between sites. This variability is presumably related mainly to different degrees of impact and history of land management, but sample resolution will also influence event recognition. All sites except Bullenmerri and Wangoom show a sustained decline in Casuarinaceae, and many sites indicate that this decline occurred early in the settlement phase. This decline is attributed to preferential selection of *A. verticillata* for firewood and its vulnerability to fire (Crowley & Kershaw 1994). There is evidence from Turangmoroke for an increase in charcoal in the early settlement period while higher charcoal levels are indicated for the settlement period generally at the Tower Hill sites and Cobrico. Dodson et al. (1994) suggest that the impact of burning was increased by a change from the low intensity, frequent burning regime of Aboriginal people to a less frequent but more intense fire regime that developed after settlement.

Eucalyptus tends to decline after Casuarinaceae, where sample resolution allows separation, and is generally associated with an increase in Poaceae. This combination can be best attributed to woodland removal with the development of more intensive agriculture, often cultivation in the early days. At Turangmoroke and Gnotuk, there is evidence for an initial increase in eucalypt values before the decline, and this may have been a response of eucalypts, either in terms of increased regeneration or flowering, to the reduction of Casuarinaceae. At Cobrico, the strong increase in eucalypts in the late European period may result from recent planting, as suggested by Dodson et al. (1994), while much variation in records could result from a combination of clearing for agriculture and establishment of windbreaks. High values for Cupressaceae pollen in some records indicate the extensive planting of Cypress pine rather than any increase in native *Callitris.*

Despite the creation of more extensive grasslands, there is a reduction in native *Plantago.* The demise of this herbaceous taxon is probably indicative of the degree of alteration to the composition grassland vegetation types generally on the plains, and their status as probably the most threatened of Australia's major temperate ecosystems (Jones 1998). There is clear evidence for establishment of introduced species of *Plantago* in almost all records, suggesting that direct competition may have played a big part in the loss of the native species.

Alteration of dry land vegetation appears also to have impacted on the aquatic environments of individual sites. At both Tower Hill sites and Turangmoroke there are marked increases in Chenopodiaceae, indicating increasing salinity levels that are most probably linked to clearing induced salinisation. At Tower Hill, total deforestation of the volcanic structure would have had a major influence, as would the damming of the outlet of the lake. In almost all records, sediment accumulation rates appear high compared to average rates for the Holocene as a whole and this suggests that disturbance has resulted in substantial erosion of catchment sediments and their deposition within the basins. However, Dodson et al. (1994) attributed the dramatic increase at Cobrico Crater to lower consolidation of recent sediments. This may be the case at this site, where the lake is surrounded by vegetated peat capable of trapping eroded material, but in lakes lacking marginal swamp there is evidence that material has eroded into the basins. At Keilambete, for instance, previously accumulated sediment along the lake margins has been washed into the basin as a result of a substantial fall in water level over the last century (Jones et al. 1998). The eroded material may be indistinguishable from freshly depositing lake mud. Of concern here is that pollen contained within the old sediments may be being redeposited and contaminating and distorting the pollen signature for the most recent time of European occupation.

It has been hypothesised by Crowley (1994b), from examination of a number of pollen records from southeastern Australia, that salinization, indicated by regional increases in Chenopodiaceae, was a major contributing factor to the substantial decline in salt intolerant Casuarinaceae. However, although there is good evidence for such a relationship between the two events at a few sites, salinity does not appear to have been a contributing factor at many other sites.

The impact of Europeans on the landscape has significantly influenced dissimilarity measures. Appropriately, squared chord distances have increased suggesting the creation of a landscape that has no close analogue in the pre-European vegetation. In line with this alteration, precipitation estimates become erratic with some records indicating highest or lowest values for the Holocene and one record (Bullenmerri) indicating both. The results are meaningless and provide graphic support for the decision to use pre-European rather than modern pollen spectra for quantitative palaeoclimatic reconstruction.

CONCLUSIONS

There has been marked temporal and spatial variation in the vegetation of the Western Plains over the last 20,000 years or so, but much of this variation is contained within the latter part of the Pleistocene and early Holocene. The plains were probably almost treeless during the Last Glacial Maximum, which extended to about 15,000 years ago. Most woody taxa would have been of shrub rather than tree form although *Callitris* may have been a more important component of the regional vegetation than it is today. The predominant vegetation type is inferred to have been steppe grassland dominated by Poaceae and Asteraceae that varied in composition across the plains. The lack of modern analogues in southeastern Australia inhibits more exact determination of the structure and composition of this vegetation. Calculated rainfall values suggest that mean annual rainfall was about 100-200 mm lower than that of today although estimates may be influenced by globally lower temperatures during this glacial period as well as statistical uncertainties. Neither mean temperature nor precipitation lowering would have led to the exclusion of trees and other factors such as incursions of cold polar air, globally lower carbon dioxide levels in the atmosphere, and altered seasonal distribution of rainfall, may also have been important influences.

During the late glacial period (15,000 to 10,000 years ago) available evidence suggests a further decline in woody plant representation, despite rising temperatures globally. The major influence appears to have been a reduction in effective moisture, most likely a result of rising temperatures, with expansion of saline environments and lunette formation. Maximum 'aridity' occurred between about 14,000 – 12,000 years BP. After this time there are suggested increases in both temperature, indicated by a reduction in the Asteraceae/Poaceae ratio that likely represents a switch from steppe-grassland to grassland, and rainfall, indicated by reductions in Chenopodiaceae, the beginning of sediment accumulation at many sites, cessation of lunette formation and expansion in the distribution of trees, largely *Allocasuarina verticillata*. Marked regional variation is indicated by much higher representation of *A. verticillata* values in sites within the Warrnambool area and later in the north of the plains than in the Camperdown-Colac area suggesting either eastern and northeastern expansion from glacial refuges off the basalt or more seasonal Mediterranean climatic conditions in the western and northern areas.

By the beginning of the Holocene (10,000 years ago), the tree cover over much of the Western Plains had virtually achieved present day levels, although there may have been a delay of about 1000 years in the north. Community composition continued to change in the early Holocene with increased diversity of woody plants and, around 8000-7000 years BP, a sustained increase in *Eucalyptus* relative to Casuarinaceae except in the southeastern area where *Eucalyptus* had been the predominant taxon since at least the beginning of the Holocene. These changes are explained by a continued rise in rainfall combined with the establishment of a less seasonal climate, especially in the west and north. Despite lake level evidence for substantial subsequent changes in climate, including a maximum in effective precipitation between about 7500 and 5500 years BP, there has been little vegetation response and consequently little variation in constructed palaeoclimatic estimates. The sensitivity of the small Northwest Crater basin may be registering variation related to increased ENSO activity within the last 5000 years.

In contrast to the relative stability of the vegetation through much of the Holocene, marked changes are evident after European settlement with tree removal and planting and establishment of agriculture. Sites reveal a great deal of regional variation in impact but most common features are an early decline in Casuarinaceae, presumably due to alteration of the fire regime and selective cutting for firewood, a subsequent decline in *Eucalyptus* combined with an increase in Poaceae with major land clearance, and a severe decline in native *Plantago* and its replacement with exotic *Plantago* species. This latter change is probably a good indicator of the massive alteration to grassland habitats on the plains that is otherwise invisible because of the difficulty in separating native from introduced members of the dominant families Poaceae and Asteraceae on pollen morphological grounds, and the lack of pollen representation of most other herbaceous taxa. More local impacts included abrupt rises in Chenopodiaceae around some sites indicating a rise in salinity levels and increased erosion of sediments into lake basins.

The regional picture presented here does not totally support the idea that the vegetation of the basalt is largely insensitive to climate change (see Jones 1998, Dodson 2002). There appears to have been significant vegetation response to climate on a glacial-interglacial timescale although the limited variation in pollen representation around Bullenmerri suggests relatively minor vegetation change within at least some parts of the plains. It is certainly true that, in almost all records, there has been little change in vegetation through much of the Holocene despite evidence for significant variation in lake levels. Here, it is probably appropriate to consider factors such as the heavy texture of the soils and perhaps frequent burning by Indigenous people as factors limiting tree growth. However, the proposed changes in the precipitation/evaporation ratio that have a critical influence on lake levels under the precipitation regime experienced over the plains would not necessarily be expected to have a major impact on vegetation composition. A proposed Holocene range of 450 mm (Jones 1998) would still place the region consistently under a dry sclerophyll forest/woodland cover dominated by essentially the same species. Furthermore, the proposal of soil as a limiting factor to vegetation development is not supported by the extended record from the Terang area, that clearly shows much greater variation during previous glacial /interglacial cycles and greater forest development during some inferred interglacial periods (Kershaw, D'Costa, Tibby et al. 2004). Similarly, there is no consistent inverse relationship between Casuarinaceae and Chenopodiaceae to support the proposition (Crowley 1994a, 1994b) that soil salinity has impacted severely on casuarina populations during the Holocene from the data presented here or through the late Quaternary period (Kershaw, D'Costa, Tibby et al. 2004; Harle et al. 2004) although waterlogging may have had an influence on the Casuarinaceae (Crowley 1994a) In relation to the question of Aboriginal burning, it is possible that alteration of fire regimes since the time of arrival of people, perhaps 45,000 years ago, may have had some impact on vegetation development during the Holocene (see Harle et al. 2004).

The use of analogue methodology for reconstructing past rainfall has been of some benefit although actual quantitative values have to be treated with some caution. In most records the standard error is greater than the range of RANN so that it is the trends in precipitation that are most useful. Precipitation estimates for the last glacial period seem realistic, despite the lack of close recent vegetation analogues from which estimates were derived, but the method failed to reflect dry conditions during the late glacial period. Analogue matching has, however, contributed to the consideration that a temperature increase, as much as a precipitation decline, was a contributing factor. The lack of notable rainfall trends within the Holocene is consistent with visual interpretation of the data, while the suggestion of slightly drier climates in the Pleistocene/Holocene transition and early Holocene in most diagrams exhibiting high Casuarinaceae percentages reinforced interpretation from visual interpretation. The data were not sufficiently refined to allow assessment of the significance of fluctuations in most rainfall curves although high variability in the last 5000 years at Northwest Crater may be indicative of vegetation response to increase ENSO activity. High analogue distances in those spectra deposited within the period of European occupation generally indicate that the present vegetation landscape is very different to any experienced previously within the Holocene period. There is greater potential for more refined and accurate reconstructions with a denser network of recent pollen spectra, better chronological control on fossil sequences, and perhaps consideration of pollen taxa additional to the selected, common taxa considered in this review.

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MT ECCLES LAVA FLOW AND THE GUNDITJMARA CONNECTION: A LANDFORM FOR ALL SEASONS

HEATHER BUILTH

School of Geography and Environmental Science, Monash University, Vic. 3800, Australia

BUILTH, H., 2004:11:14 Mt Eccles lava flow and the Gunditjmara connection: a landform for all seasons. *Proceedings of the Royal Society of Victoria* 116(1):163-182 . ISSN 0035-9211.

An archaeological investigation of the Tyrendarra Flow of Mt Eccles in temperate Southwest Victoria has demonstrated that the Indigenous occupants, the Gunditjmara, developed a socio-economic system based on the environmental characteristics of the lava flow. Basalt stones, the reliable rainfall, the shortfin eel *(Anguilla australis)* and the *Eucalyptus viminalis* woodland all contributed to the development of an aquaculture system covering 100 sq km. Manipulation of the landscape resulted in large-scale management of the wetland resources by the time of British colonisation. Resource specialisation including processing formed the basis of sedentary settlement.

Key words: Mt Eccles lava flow, Gunditjmara, Southwest Victoria, landscape archaeology, Shortfin eel, aquaculture, wetlands.

PIONEERING research in certain localities in Southwest Victoria, Australia, in the late 1970s led to hypotheses that, prior to the arrival of Europeans, Indigenous groups had achieved social cohesion and an economic system based on water control and eel trapping (Presland 1976, 1977;Coutts, Frank & Hughes 1978; Lourandos 1976, 1980a & b). New archaeological evidence supports the hypothesis that Gunditjmara settlement on the Mount Eccles lava flow in Southwest Victoria was based on the management and control of the Shortfin eel, *Anguilla australis* (Builth 2002b). This management regime incorporated modification of the landscape so as to ensure that spring and surface water were directed via channels into water bodies which were interconnected. The water bodies became the long-term habitat of the growing eels. The natural, modified or artificial channels that connected them ensured mature migrating eels access from the ponds through the laval landscape to the Darlots Creek and so to the ocean. Development of techniques for the trapping, processing and preservation of the migrating eels ultimately led to a Gunditjmara socio-economy analogous to so-called complex fisher-hunter-gatherer societies that existed elsewhere in the world (Builth 2002b).

The research was premised on human cultural potential being conditional upon the environment and human socio-economic potential being conditional on technological achievements (Hayden 1992). The landform known as the Tyrendarra Flow features environmental attributes that provided Gunditjmara with the basic means to develop their technology and economy.

Following Lourandos (1976:176), Presland (1976, 1977) and Coutts et al. (1978) in their interpretation of prehistoric Aboriginal land and resource use in this area of Southwest Victoria, and questioning the orthodox concept of the Australian Aboriginal hunter-gatherer economy based on an arid or semi-arid model of survival (Lourandos 1980a, 1980b), Lourandos' 1980b hypothesis was tested by this present study.

The archaeological finds support Lourandos (1980a & b) hypotheses and have initiated renewed enquiry into socio-cultural patterns in pre-contact Aboriginal Southwest Victoria leading to a re-interpretation of occupation patterns and the subsistence economy.

THE TYRENDARRA LAVA FLOW

The landform that constitutes the Mount Eccles lava flow is known geologically as "the Tyrendarra Flow". The Tyrendarra or Mount Eccles lava flow is one of the longest, most spectacular and distinct in Victoria (see Fig. 1). The Eccles landform has a geological signature known as "the stony rises" which is the weathered remains of the laval episodes. This geology consists of Pleistocene basalt that has produced red-brown, shallow, stony, gradational soils and supports woodland or open forest dominated by manna gum (*Eucalyptus viminalis*), blackwood (*Acacia melanoxylon*), and native cherry (*Exocarpus*

Fig. 1. Satellite image of Mt Eccles lava flow (LizardTech 2001).

cupressiformis). The physical characteristics can be steeply contorted and the boulder-strewn stony rises are prone to seasonal inundation (CONTEXT 1993:14). The Mount Eccles and Mount Napier (20km to the north east) eruptions, between them, "contain the most extensive and diverse collection of volcanic features in south-eastern Australia". The wetlands of the Tyrendarra Flow are of considerable significance in terms of examples of the effects and succession of volcanism on drainage (CONTEXT 1993:12,36).

Prior to the Mt Eccles' eruptions, the drainage of the gently south-sloping topography was via the ancestral valley and tributaries of Darlots River, at that time a "weakly incised" system to the west and north. The ensuing lava flows blocked and diverted the existing system causing the formation of lakes and swamps such as Whittlebury Swamp and the previously 30 km long Condah Swamp, also known as the Great Swamp in early ethnohistorical literature (Clark 1998-2000, Critchett 1990:54). Gorrie Lake and Swamp are situated on the eastern side of the lava flow, a result of the blocked Eumeralla River drainage. Homerton Swamp was formed by the blocking of the Fitzroy River (CONTEXT 1993:34.)

Mt Eccles lava flow is physically situated adjacent to four separate landforms which include the extensive Condah Swamp (now drained); the Heywood well-watered plains; Bessiebelle plains of swamps and woodlands; and Whittlebury Tertiary deposits (Williams 1988:33; CONTEXT 1993:14).

Mount Eccles consists of a main mound of scoria, 179 m a.s.l. with a flooded crater, Lake Surprise. The eruption points of the volcanic complex are situated along a 2 km crest - the product of numerous lava flows. There are lava channels associated with these features, and "a line of smaller spatter and cinder cones and craters" which extend to the southeast from the main crater (ASF 1995:46). The nature of this volcano is its "small number of eruption points which eject large volumes of basaltic lava from craters or elongated fissures", known as "effusive volcanicity" (CONTEXT 1993:28). It would have provided spectacular viewing. The lava from Mount Eccles "formed the great basaltic lake of the Stony Rises" (Boutakoff 1963:64). The 'lake' measures 16 km by 8 km (Rosengren in Context 1993:28-9). At its western end, an approximately 3 km wide flow travelled south along the valley of Darlots River, past Tyrendarra township, to the coast. The 50 km long flow ended at what is now Julia Reef, 15 km offshore in the Southern Ocean.

The terrain of the Eccles landform is dominated by lava surfaces that, at its northern beginning, stand up to 20 metres higher than the bordering wetlands. Apart from Mt Eccles, the highest terrain is only about 60 metres above sea level. Further south, nearer the coast, there is less variation in surface elevations. At Tyrendarra township to the south the lava-derived terrain is only 8 metres above sea level (see Fig. 1).

The age and frequency of the flows has been debated since the initial dating by Boutakoff (1963) of a Mount Eccles eruption between the end of the Pleistocene and before the sea advanced to its present level in the Holocene (Gill 1979, Ollier 1981). The most recent dating of the eruption is 27,000 years BP (Head et al. 1991) based on radiocarbon dating of sediment cores taken from the swamps of Condah and Whittlebury. Evidence from sediment cores supports the claim that Lake Condah did not exist prior to 8000 years BP (Head 1989, Head et al. 1991:303), and the adjacent Condah Swamp shows a transition from lake mud to peat occurring between 8000 and 9000 years BP. Prior to European drainage, Lake Condah was perennial although water levels would have seasonal variation. Condah Swamp could have had a greater seasonal variation.

Climate

The temperate climatic conditions are a product of the latitudinal position. The lava flow is situated between 38° 05' south and 38° 40' south, and extends from the coast inland for approximately 40km. The Mount Eccles lava flow receives high and regular rainfall. Today, the climate of this region is considered mild. However, there is a marked seasonality with a high variance in temperature, light and rainfall. The rainfall is seasonal, falling predominantly during autumn, winter and spring months as a product of westerly winds and cold fronts. Over the 50 km of the Tyrendarra Flow, the annual rainfall varies from 660-860 mm. Winters are cool to cold, mostly wet and on these plains near the ocean are prone to cold winds from the south-west. Average daily winter temperatures very between 5° and 13° C. Summers are warm to hot and much drier: average daily temperature ranges between 12° and 26° C, and with days over 38° C not unknown (CONTEXT 1993:12).

Natural Drainage

Running in a north to south direction, run-off from the Tyrendarra Flow drains into the southern ocean. Darlots Creek is the western boundary river and the Eumeralla drains the area to the east. Both rivers evolved into larger water bodies during times of high rainfall and run-off in some autumn, winter and spring months and were fed from natural drainage further to the north. In the case of the Darlots Creek, the catchment included the extensive Condah Swamp, at the northern limit of which is the present day township of Branxholme. The nature of the "open trap scoriae" at Lake Condah ensured a continual underground drainage which surfaced further south as Darlots Creek and sub-surface fed sinkholes and springs occurring south of Lake Condah (Ingram in Kenyon 1912:110). Outside of the Tyrendarra Flow, on all sides, were naturally extensive wetlands consisting of both permanent and seasonal swamps. Darlots Creek is currently listed as significant for both its aquatic and riparian qualities (Scott 1989:305; CONTEXT 1993).

The characteristics of the natural drainage from Condah Swamp and Lake Condah were critical environmental factors in the Gunditjmara wetland-use model presented in this paper.

Cultural Significance of Eruption

That the eruption of Mount Eccles was spectacular, there can be little doubt. The total formation of Mount Eccles itself happened rapidly, perhaps over a brief three month period (Ken Grimes, pers. comm. 1998).

Mount Eccles, known as *Budj Bim*, and its stones, has immense cultural significance for both the past Gunditjmara population and their present descendants. Their continued ties with the lava flow and the volcanic episode(s) that created it, illustrates the nexus between the geology and the culture.

To the Gunditjmara, and indeed many other Australian Aboriginal Language groups, *Budj Bim* is known to be part of a larger "Creation Ancestor" of enormous power, and therefore something to be highly respected (Keith & Theo Saunders, John Lovett, pers. comm..1998). Investigation into the *Dhauwurd wurrung* language name for Mount Eccles reveals something of its significance and meaning. *Puutch beem* means "High head", and is the word for the volcanic cone. *Tung att* means "teeth belonging to it", and is the word for the scoriae that occur at this site (Dawson 1881:lxxxii). The mounds of scoria can therefore be realised to be the teeth of the Ancestor.

There is little doubt that local Aboriginal groups had been witness to volcanic activity. There are local language words for both active and extinct volcanoes (Dawson 1881). The word for active volcano literally translates as "burning hill": *walpa kuulor* in *Chaap wuurong*, and *baawan kuulor* in *Kuurn kopan noot* dialect (Dawson 1881:xliv). In 1870 the Portland Guardian published a Gunditjmara local oral history that revealed witness of volcanic activity and the associated tsunami that was said to have drowned most of the people. The volcanoes of the Mount Vandyke group are named as appearing after a few days of volcanic activity. Mount Richmond was also erupting. It is predicted that "when Mount Gambier begins to burn and the earth to shake the tidal wave will come again" (Kerley 1981:144).

The esteem and respect given to the local volcanoes and their "stones" reflects their cultural significance. An understanding of this relationship between Gunditjmara and their volcanic landscape can be appreciated in the development of their culture and economy.

The proximity of parallel lava flows, from Mounts Eccles, Napier and Rouse to the east, made it easier for the Aborigines to retain occupation and defend their position against the British squatters in this area. It took much longer at this place for the Europeans to gain control and displace Gunditjmara. The defence of the Stones has become known as the Eumeralla Wars (Kiddle 1967, Boldrewood 1969, Christie 1979, Clark 1989, Cannon 1990; Critchett 1990; Builth 1996, 2002b). The reputation of the Stones, as a consequence and nature of the European invasion and Gunditjmara defence, has resulted in our present lack of knowledge regarding Gunditjmara socio-economy. Mt Eccles lava flow was not generally known to Europeans. Its reputation was such that it was avoided (Bonwick 1857). However, there were exceptions to the total isolation of the stones from ethnographic records. There were some brief documented visits to its eastern edge at Lake Gorrie in the early 1840s by Robinson (Clarke 1998), Westgarth (1846:8) Sievwright and Fyans (quoted in Gerritsen 2000:17), and later surveyor Ingram (Worsnop 1897:105-6).

Ecological Context

The formation of numerous wetlands with associated species within a matrix of weathered basalt and varying densities of *Eucalyptus viminalis* woodlands and grassland (CONTEXT 1993) has provided a biologically-productive environment. It provided high resource potential for human exploitation.

The cool, wet winters, combined with the clay-rich soils and impeded drainage of the basalt flows, results in a large area of this region being saturated if not swampy (Williams 1988). Lourandos (1980:30) has described almost the entire Gunditjmara territory as an area of "water excess", being the consequence of perennial streams, lakes and swamps. This situation ensured almost continual run-off which had evolved specific ecosystems centred on wetland and river species. The resulting high productivity, with seasonal species differentiation, makes this an attractive environment for exploitation of natural resources (Dinnin and van de Noort 1999). The environmental conditions provided unique opportunities for the local Indigenous people, the Gunditjmara.

Flora

A plethora of plant resources was available in wetlands and the woodlands of the stony rises. Plants as staple food sources in the southeastern part of this continent consisted in the main of bulbs, roots and tubers. In addition there were some fruits and berries, leaves and shoots, seeds, nectar and pith. As a group, plant foods peaked in the months from spring to early summer and were in lower quantities during autumn and winter (Lourandos 1980b:34). However, it is in the autumn and winter months that the floral and faunal resources of the wetlands are at their most productive. Gott (1985, pers. comm. 1996,) suggested that the environment had a direct effect on Indigenous economies: "the vegetation of the tribal area was central to such ecological differences, because it determined above all the daily food supply, whether of plant or, frequently, of animal kind." Her studies have illustrated how reliance on seeds, being a seasonal resource, prevents permanent settlement; whereas occupation of cooler, wetter environments rich in perennial root plants supports a more sedentary occupation (Gott 1982; Clarke 1985). It has been estimated that 50% - 80% of an Indigenous family's food in these environments of Southwest Victoria was obtained by women, and the staple vegetable diet consisted of tubers, corms, rhizomes and roots obtained by systematic and predictable foraging (Gott 1982, 1983, 1985; Gott and Conran 1991:1-3, Zola and Gott 1992:6). This almost certainly led to a high regeneration for the species concerned (Kirkpatrick 1994).

One of the most widespread vegetable food resources in Victoria, was the Murnong or Yam Daisy (*Microseris lanceolata*). Underground tubers were baked in different regional styles of oven (Kenyon 1928:141, Coutts 1981, Gott 1982, Gott and Conran 1991:11-25).

There are many species of tubers, roots, rhizomes, and bulbs growing on the stony rises that were used as the staple food resource, rich in starch and other carbohydrates (Gott 1982; Williams 1988:29). Many of these consisted of different species of lilies and orchids. Several wetland species can be termed "ecologically flexible" due to their occurrence as permanently submerged aquatic, amphibious, and dryland plants depending upon the seasonal conditions. The tolerance of these species to wet, dry and damp conditions is significant for humans as these characteristics allow sustainability of sedentary human groups (Builth 2002b). This difference between dryland and wetland tubers illustrates the significance of wetlands as a permanent habitat for indigenous foraging groups.

Fauna

The Mount Eccles lava flow, with its many environmental zones, supports a wide variety of fauna including now rare mammals, reptiles, birds and fish. The large variety of faunal species that was present on the lava flow prior to European settlement served as a rich resource base available to Gunditjmara throughout the seasonal cycles. As a consequence of European farming practices the stony rises are habitat to many species that have now become rare, including the Tiger Quoll and some species of bats (Belcher 2003). Past studies have under-reported amphibians, reptiles and bats (CONTEXT 1993:70). The close proximity of the riparian habitat of Darlots Creek makes the wetlands particularly species-rich and biologically productive in comparison to other more simple categories of lake or swamp. One hundred and five indigenous birds species have been recorded, including six now threatened species. All but one of these is classified as a wetland bird (CONTEXT 1993:70). However, the key wetland species that inhabited Southwest Victoria, it can be argued, was the Shortfin eel, *Anguilla australis* Richardson (Builth 1996, 2002b).

SHORTFIN EELS AND GUNDITJMARA

The Shortfin eel was the most consequential Gunditjmara food resource. It is a reliable provider of high quality protein and lipids. It is seasonally predictable and abundant and, as it is highly territorial, its availability is assured throughout the year. This knowledge was utilised efficiently and to great effect by Gunditjmara. Technology was developed to ensure its efficient exploitation and processing. The staples of tubers combined with eel satisfied basic nutritional requirements for many Indigenous groups in western Victoria (Lourandos 1980a). The eel's capacity for preservation further meant it was ripe for long-distance trading (Builth 2002b).

The Shortfin eel is one of four species of eel endemic to Australian coastal catchments. It is a temperate species but this includes a territorial range extending from southeast Queensland to Victoria, Tasmania and the Murray River in South Australia (Gooley et al. 1999).

Eels are harvested by humans in two different ways: large numbers are caught in creeks or channels over a short period of time by the use of fixed weirs and net fish traps during their annual migration back to the spawning grounds in the Pacific Ocean, or smaller numbers can be caught in wetlands or lakes etc on a more regular basis throughout the year using spears, lines or nets. These methods have been used the world over by many different Indigenous groups throughout the Holocene (Moriarty 1978, Pedersen et al. 1997, Builth 2002b). Eels have always offered a high return for energy expended due to their nutritional composition and high oil content. This is also the situation today on many continents, with eels remaining a desirable and prized catch. There is an unsatisfied export market for Shortfin eels from Australia presently. Australia is currently conducting feasibility studies and researching the potential for more intensive eel aquaculture (Gooley et al. 1999).

The environment, resulting from specific geological, biological and climatic relationships, plays a major role in the subsequent human relationships that evolved with it (Dinnin & van de Noort 1999). In Australia, as elsewhere in the world, wetlands were "the richest of all food environments" (Zola & Gott 1992:10). In Southwest Victoria and in particular on the Tyrendarra Flow, the landscape exhibits a high ecological integrity. The Manna Gum woodland and forest is juxtaposed with wetland depressions, sinkholes and abutting swamps bordered by Darlots and Eumeralla Rivers. The result of this combination is a heterogeneous distribution of environmental zones with unique faunal and floral assemblages. The latitudinal and bio-physical conditions are a favourable destination for the Shortfin eel. Williams, while investigating an archaeological site on the eastern side of the Tyrendarra Flow, claimed that:

> Lakes and swamps contain higher numbers of eels relative to other habitats because they act as a nutrient sink. The largest numbers of eels are found in shallow lakes and swamps, such as those common in the study area, since these habitats trap a greater amount of energy in the form of sunlight (Beumer in Williams 1988:28).

The ethnographic and ethnohistorical records tell of an economy heavily dependent on exploiting eels, and the observations of the large-scale regional utilisation of fishtraps and eel weirs (Kenyon 1928; Lourandos 1980a &b; Clark 2000-2002; Builth 2002b). It is the potential of natural ecosystems to contribute to human economic systems (with subsequent social implications) that in the past has facilitated cultural complexity or the development of human societies (Hayden 1992, Coles et al. 1999, Builth in press).

Archaeological Investigation on Mt Eccles Lava Flow

In addition to eel exploitation, documented descriptions by explorers and squatters are testament to the many types and examples of Indigenous housing existing prior to European contact (Builth 2002b, Clark 2000). (The identification and interpretation of archaeological remains on the Mount Eccles lava flow supports the reliability of this archival material – see also Wesson 1981). The archaeological infrastructure underlies the hypothesis that, at the time of the British occupation of Southwest Victoria, a settlement existed on the Mount Eccles lava flow that was testament to a Gunditjmara socio-economy that was based upon wetland management and eel exploitation.

> The periodic return of Aborigines to regular camp sites, and their construction of durable huts, stone weirs and extensive channels indicate a situation of greater peace and security than has been envisaged by [some historians such as] Blainey (Christie 1979:19-20).

Environmental manipulation by Indigenous Australians for the purpose of trapping fish has been described before in the literature (Worsnop 1897; Robinson in Kenyon 1928; Smyth 1972a:201; Happ 1977; Coutts et al 1978; van Waarden and Simmons 1992; Clarke 1998; Lourandos (eg 1980a). However, the extent of this manipulation, it is suggested, has not been fully appreciated. Analysis of archaeological remains at a landscape level is viewed as the most appropriate means to investigate past economies and settlement patterns (Lourandos 1980b). Certainly evidence of large-scale environmental manipulation could be overlooked using a small-scale archaeological excavation. (It is highly likely that this may have occurred during Australian archaeological studies [Lourandos 1980b:353; Head 2000]). The patterns investigated during the study included ecological relationships on the Mt Eccles landform. By using suitable investigative methods it is possible to identify economic activities and ascertain their social repercussions on Gunditjmara society (Builth 2002a).

It can be demonstrated, using a Geographical Information System (GIS) to simulate past water flows through the now-drained landscape, that a coordinated system of land management had been put in place by Gunditjmara to take advantage of the ecological traits of the Shortfin eel. It is argued that more orthodox archaeological methods such as excavation are inappropriate for investigating Gunditjmara socio-economy on this landscape (Aldenderfer & Maschner 1996; Builth 2002a; Gillings, Mattingly & van Dalen, 1999). Without the use of GIS to interpret cultural footprints on this landscape, the study could not confidently be undertaken. Using GIS to reconstruct past water flows has determined the function of archaeological remains associated with hydrological activities (see van Waarden & Wilson, 1994). The results of this landscape analysis support a claim for eel aquaculture being the primary activity across this landform.

The GIS analysis of a Digital Elevation Model (DEM) of the southern study area near Tyrendarra reveals that water flow was maintained through channels so that migrating eels could make their way downstream to the ocean and be trapped in a series of weirs. Channel modification, including construction by excavation through the lava flow, had been carried out to ensure control of the migration routes – both upstream from the ocean and downstream back to the spawning grounds. In addition, the natural wetlandscape had been artificially extended spatially and temporally by the construction of dams to retain water channelled in from the river upstream.

Consisting of a series of wetlands interconnected by channels with additional side channels from the boundary river, the whole system was designed to raise and maintain wetland water levels, grow eels, and efficiently trap them in the eel traps built behind the weirs and throughout the channels when they eventually made their way back to the ocean to spawn some 7 to 20 years later. Via the simulated waterflows using GIS, it can be demonstrated that elvers were brought from the boundary river into a system of channels, pens and wetlands. During this time they were available for catching with spears, the "bob" method, or in individual traps (Builth 2002b). The weirs are also positioned to double-up as traps during the mature eel migration runs by incorporating the arrabines or woven traps into their structure. Other remains downstream from the weirs are also interpreted as eel trap remains.

Eels are highly territorial (Moriarty 1978). They also have definite requirements regarding a preferred location in which to live and grow before their return to the ocean (McKinnon & Gooley 1998; Gooley et al. 1999). Gunditjmara understood these requirements and provided a suitable habitat for them. At the same time these conditions also fulfilled the environmental needs of other wetland resources and nutritional staples, such as the bulbs and tubers, in addition to plant materials for organic-based artefacts (Gott 1982, 1993, Gott & Conran 1991, Zola & Gott 1990). Wetlands were the most exploited local environment for this Indigenous nation (Godfrey 1994:110). The result of the economic endeavour was a sustainable socio-economy based on a potentially sedentary settlement through wetland management. As a consequence of constructing and maintaining these systems, valuable resources were available throughout all seasons and over many years. In cases of extreme drought the eels could enter a state of torpor until the waters returned (Moriarty 1978).

Analysis of Study Areas

Both the north and south of the lava flow were the subject of archaeological investigations. However, the two study areas did not feature the same environmental characteristics and consequently a suite of archaeological features exist that are predicated on the particular environmental conditions. These reflect the environmental changes that occur over the length of the flow as a result of the volcanicity (Rosengren in Clarke 1991; CONTEXT 1993). A methodology was designed that established the basis of site identification (Builth 2002a, 2002b:Ch.3). Fig. 2 shows the separate study sites on the lava flow in relation to the Darlots Creek.

Within the northern area there are numerous small (<20 m dia.) natural water-filled sinkholes within a mainly flat basalt-strewn plain incised with major channels paralleling the Darlots Creek to the west. These channels enter and leave a series of swamps. The northern study area also features woodland with large individual trees of Stringy bark or Messmate (*Eucalyptus obliqua)*, Manna gums *(Eucalyptus viminalis)*, Swamp gums (*Eucalyptus ovata)* and Blackwood wattle (*Acacia melanoxylon)*. A survey of 59 mature *E. viminalis* and *E. ovata* trees confirmed that a high percentage had been culturally modified (Builth 2002a, 2002b:152-176). Attributes were collected and analysed in order to form a hypothesis regarding their cultural utilisation.

The 40 ha south study area consisted of large areas of potential waterbodies joined by relatively short channels, plus side channels that connected the boundary river, Darlots Creek, directly with the waterbodies.

Both sites, as representative of the whole lava flow, feature areas of well-drained land in the form of terraces or flat higher ground that enable the construction of dwellings and what has been identified as storage areas (Builth 1996, 2000). A schematic cross-section of the edge of the stony rise, modeled on that existing to the southeast of Lake Condah, is shown in Fig. 3. It represents a weathered "finger" of the flow, typical of the features that occur adjacent to swamps and lowlands of the Mt Eccles landform. Close examination of the flow reveals the weathering process and offers the means to discriminate between natural and cultural stone "circles".

A number of distance analysis functions were carried out to identify any spatial correlation between structures, and between the structures, natural features and the simulated water flow (Aronoff 1989). Proximity analysis using GIS was used in order to better understand spatial relationships between the archaeology and the landscape. In this way the two separate landscape analyses on different parts of the

Fig. 2. Positions of Northern and Southern study areas within lava flow (map: D.James).

2. survey of topography, including boundary river

A pattern or framework was formed from features that interconnected for resource allocation and resource optimisation. In order to decipher how the variables relate spatially, they were analysed with reference to:

1. each other.
2. their components.
3. other clusters.
4. other structures.
5. topographical features, including water bodies.

This involved investigating:

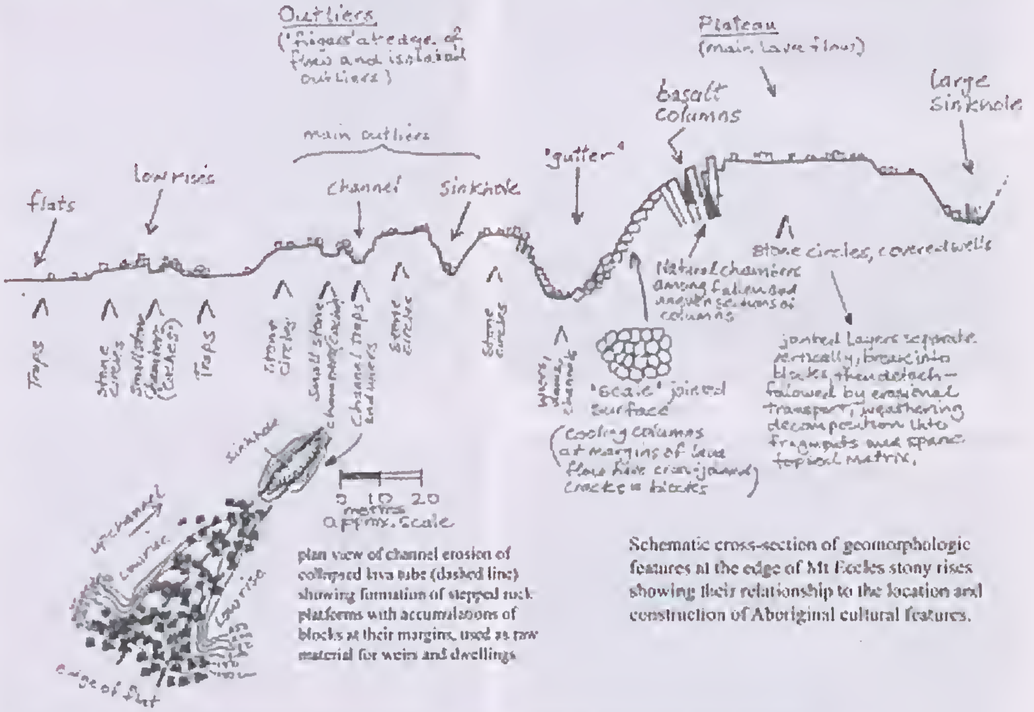
1. mean distances between features.
2. relationship of cultural stone circles to a simulated water level.
3. patterns of proximity.
4. clustering of stone circles.
5. water flows: their levels and contiguity.

It was anticipated that use of GIS, including spatial analysis, will show:

1. a map of the main data base.
2. patterns in the data base.
3. the function of, and clear relationships between, archaeological features.
4. the basis of the socio-economy on the Tyrendarra Flow prior to European arrival, given a specified set of characteristics from the data base.

In the northern area the DEM was used to analyse the proximity of a main channel featuring eel trapping complexes adjacent to trees and dwellings (see Figures 4 and 5). Following initial proximity analysis, the focus in the north study area became a study of culturally modified trees (CMTs) and eventually biomolecular analysis. The north study site has also been used to undertake specific analyses of stones, their positions and sizes, and the origins and formation of stone features (Builth 2002a). (Detailed measurements of the stones used in the construction of dwellings and storage caches have not previously been undertaken for archaeological studies on this landform; this may have contributed to presumptions of features being of natural rather than cultural origin [Clarke 1991, 1994].)

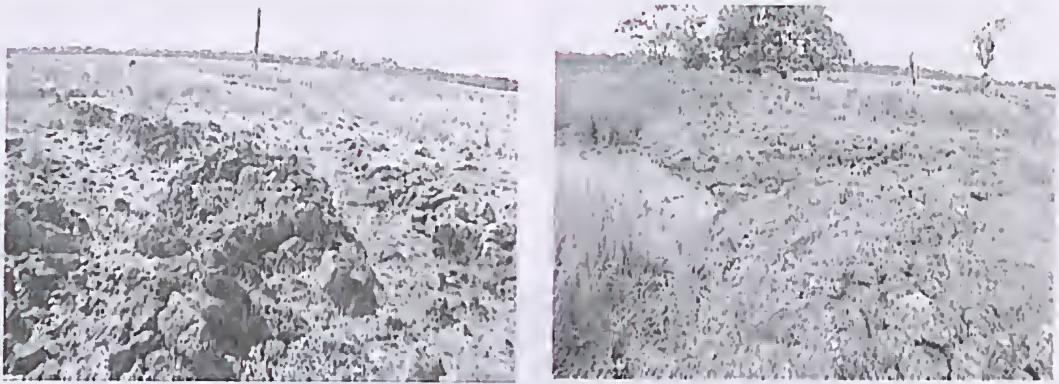
In the south study area, the European draining of the land and the subsequent loss of the large trees show a different environment with which to understand and interpret past land-use by Gunditjmara (Builth 2000). Previous large wetland areas still show



plan view of channel erosion of collapsed lava tube (dashed line) showing formation of stepped rock platforms with accumulations of blocks at their margins, used as raw material for weirs and dwellings

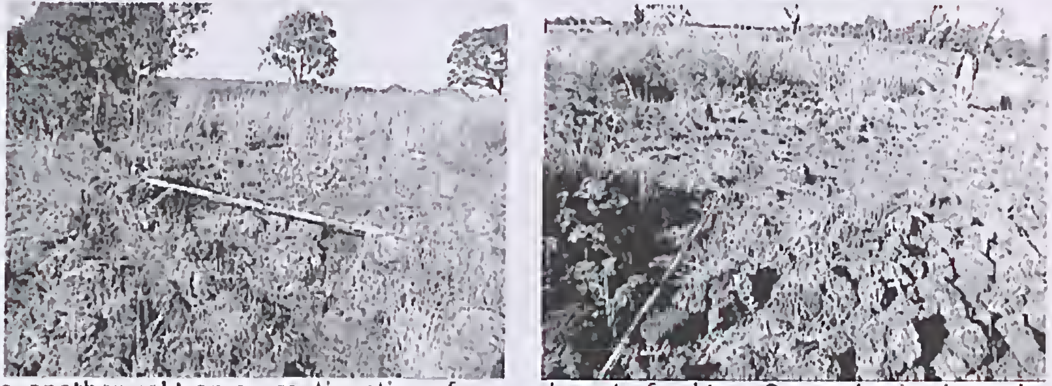
Schematic cross-section of geomorphologic features at the edge of Mt Eccles stony rises showing their relationship to the location and construction of Aboriginal cultural features.

Fig. 3. Schematic cross-section of lava flow adjacent to lower lying swamp area (drawn by Neale Draper)



a. part of eel trap 2 complex

b. part of eel trap 1 complex



c. another eel trap on continuation of channel running south from study area

d. part of eel trap 2 complex in channel

Fig. 4. Eel traps in Northern study area on one channel (photos H.Builth)

landform; this may have contributed to presumptions of features being of natural rather than cultural origin [Clarke 1991, 1994].)

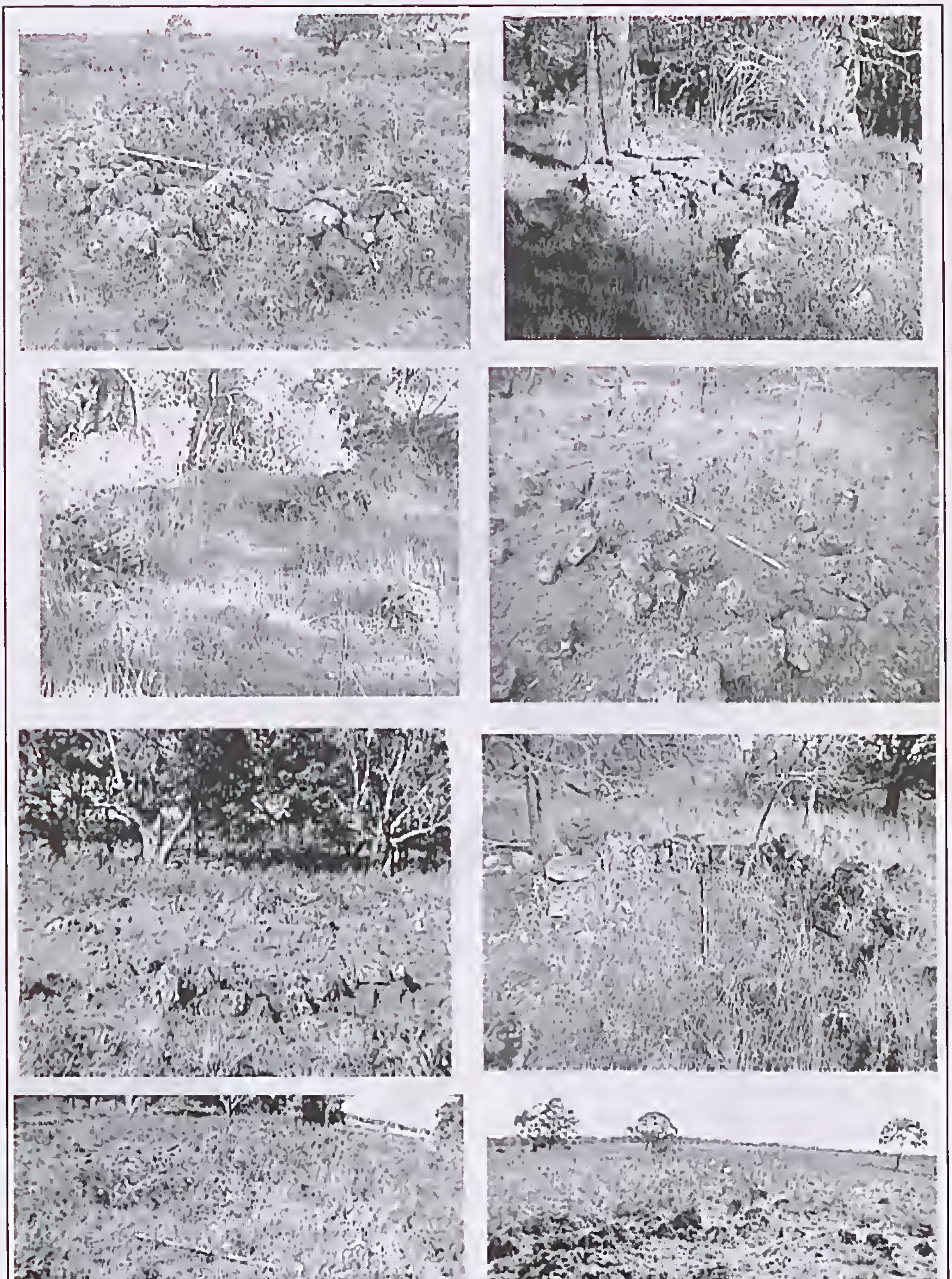
In the south study area, the European draining of the land and the subsequent loss of the large trees show a different environment with which to understand and interpret past land-use by Gunditjmara (Builth 2000). Previous large wetland areas still show evidence of having been dammed. There is a series of excavated parallel channels from the boundary river heading west to the dammed wetlands. A central main channel joins these wetlands. The presence of archaeological remains that have been interpreted as former dwellings and storage caches are in proximity to the wetlands. The GIS map showing the relationship of the archaeology and natural features can be seen in Figures 6 and 7.

Water bodies and Eel traps

Across approximately 100 sq kms of the Mt Eccles lava flow, an extensive area of water bodies feature the remains of dams constructed to maintain a perennial wetland regime. These water bodies are interconnected by channels that contained a series of traps along their length, commencing immediately downstream of the dam. Culturally constructed inlet channels from Darlots Creek to the dammed water bodies have been demonstrated as the means of bringing in elvers from the migration corridor into permanent wetland habitat (Builth 2000). It is argued that the archaeological remains of inlet channels, the dammed water bodies, and the traps, in combination demonstrate the previous existence of large-scale eel aquaculture (Builth 2000, Builth 2002b:211-274).

Directly upstream from the eel trap complex in

Fig. 5. Remains of dwellings in the Northern study area (photos H.Builth).



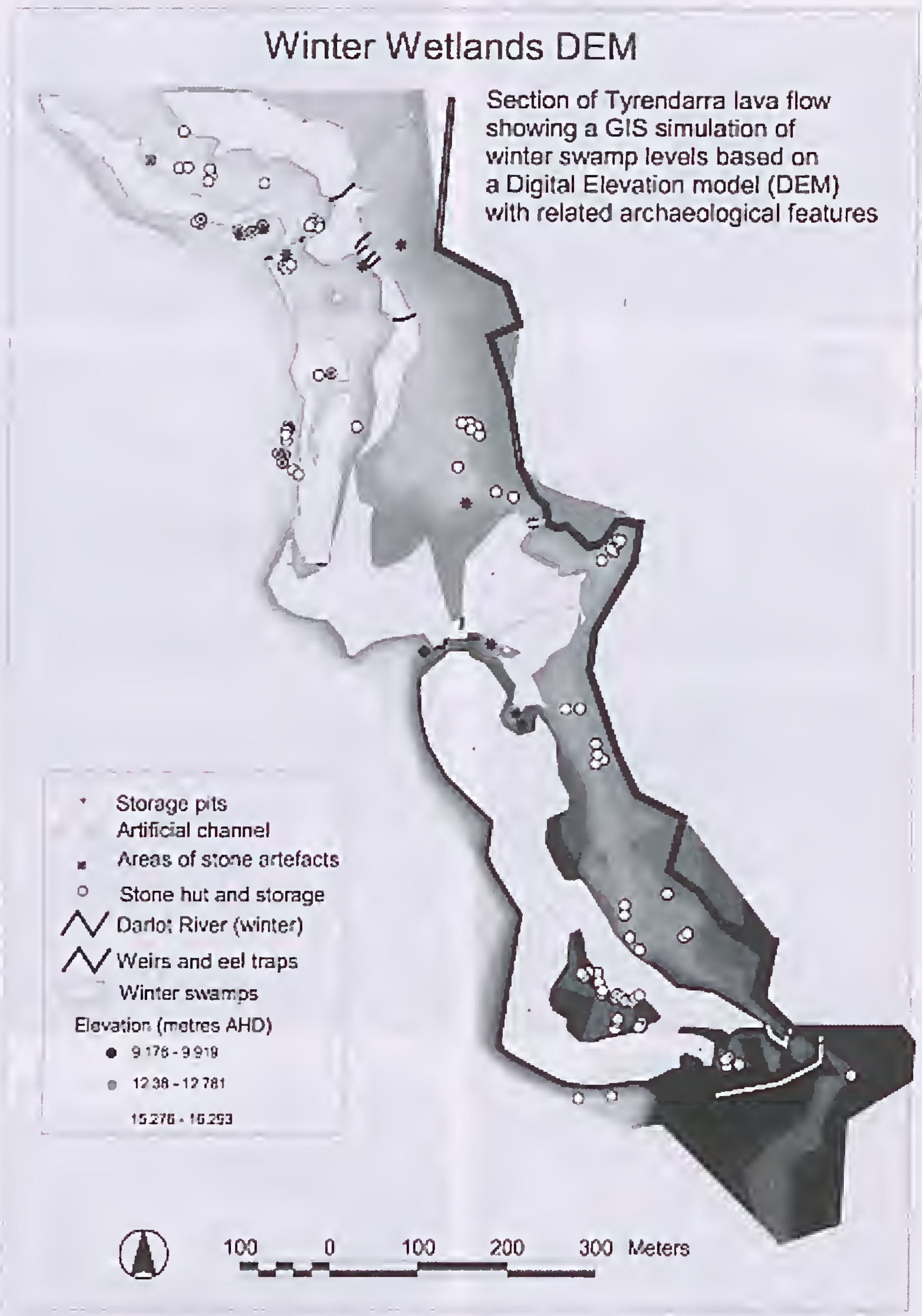


Fig. 6. GIS simulated winter wetlands for Southern study area

the northern study area it is suggested the channel has been formed into an area that has been used to hold or "grow" eels. All along the sides of this wider section of the channel are rocks that are black from being water-logged, and that have been positioned there (see Fig. 8). It is likely that these held in place woven lattice type "walls" to contain the eels, which, given the nature of the surrounding land, could have moved out to other wet areas.

In the north study area, immediately upstream of the eel trap complexes, it can be observed that water is held in the ponds by an edge or lip having been excavated for this purpose. It is suggested this was achieved by the application of fire and water to crack and excavate broken rock. (This method, it has been suggested, may have been used to quarry greenstone at Mt William in Victoria [McBryde 1984]).

In the south study area water is held in the wetlands by damming. The traps are also placed immediately downstream of the dams which demonstrate that seasonal flows are factored in by the height of the dam (see Fig. 7). When the autumn rains come and the migrating eels are on the move south to the ocean, they go over the dams and through the traps, but during summer and/or drier times water is held back to enable the wetlands to thrive and eels to grow.

The southern study area is topographically suited to the construction of a series of large water bodies that were able to contain, and grow to maturity, the highly territorial Shortfin eel, and so provide the daily requirements of eel protein and wetland vegetable staples. Adjacent well-drained terraces proved to be ideal residential locations. Activity areas and dwellings are closely related to the presence, seasonal or otherwise, of water bodies - be they channels or wetlands. Hundreds of dwelling and storage remains have been observed in such proximities. Fig. 6 shows the juxtaposition of dwellings, storage, water bodies with weirs and channels in the south study area.

The existence of a continuous series of large "growing ponds" or wetlands in the southern area, and the consequent availability of the resource on a daily basis, could mean there is less demand in this area for preserving eels and more for it as a residential site.

The north study area shows that even the smallest area of water was captured and used for the growing of eels. Each such area had a trap downstream that came into play when the eels were migrating and that also may have doubled as a weir or barrage to keep the water in during drier times. However, water flow through channels during heavy rain and migrations was always assured.

Culturally Modified Trees

After examination of trees in spatial association with archaeological features it was considered possible that a large number of hollow trees had been culturally modified. It was observed that the incidence of modified *Eucalyptus viminalis* and *Eucalyptus ovata* occurred in spatial association with both the dwelling/storage sites and the eel traps at this area, and that this pattern continued outside of the study area on the remainder of the lava flow. It was hypothesised that hollow trees, initially formed by the natural process of termite activity, were utilised to satisfy cultural requirements that enabled sedentary settlement on the lava flow.

Attributes were collected in an attempt to quantify the tree modification, and to ascertain the function of the trees (Builth 2002a:152-176). It was observed that entrances were made into hollow trees by cutting through the outer layer of bark, and/or burning

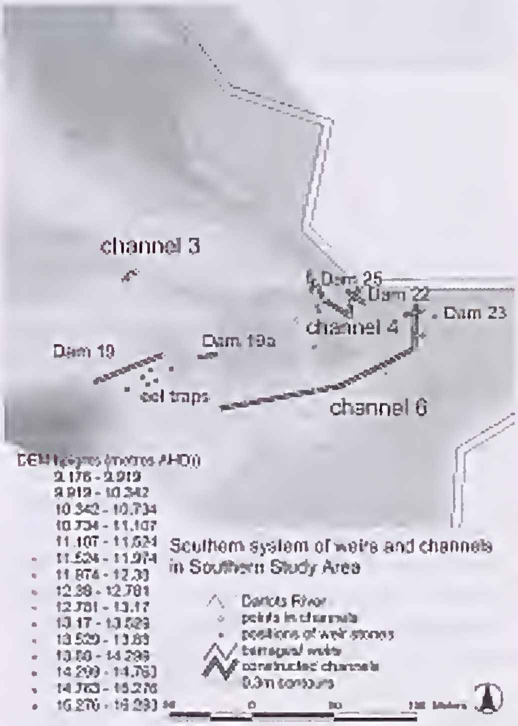


Fig. 7: GIS map of weirs/dams in relation to channels and elevation in south of Southern study area.

Fig. 8: Channel upstream from eel trap complex flanked by lines of rocks to contain growing eels (photo H.Builth).

through the remaining outer layers. Very often burnt scars were still visible. Examination of some of the culturally modified tree bases showed a bimodal differentiation by either containing broken pieces of basalt within an ash and charcoal matrix, or else charcoal and a "greasy" sediment.

The proximity analysis and statistical analysis of tree attributes led to the hypothesis that many trees had been culturally modified and were performing two significant separate functions within the settlement economy. These were

1. to carry out domestic family baking on the stones
2. to smoke, and therefore preserve, migrating eels caught in adjacent traps.

It can be further hypothesised that these two socio-cultural activities were gender divided with the women taking control of the family cooking and the men dealing with the resource processing.

The first function evolved from the necessity to carry out overnight domestic baking of the staple vegetable roots and tubers as it is not possible to construct a baking oven on the lava flow. It is hypothesised that the basalt pieces functioned as oven heat stones. Modifying mature eucalyptus trees to serve as ovens in order to carry out domestic baking was convenient and also innovative. It is of significance that the existence of sediment contained within the base of tree hollows is one of the few terrestrial situations on this landform where stratigraphy exists. Thus it is able to feature as a baking oven by containing the heat stones and tubers or roots that have been put in a woven bag within a matrix of sediment to bake overnight, as is the custom (Dawson 1881:103; Gott 1982).

Recognition of these trees as culturally modified infrastructure with which to perform domestic functions has not been recognised previously by archaeologists. (This may in some way explain the conclusions of Clarke (1994) that the hypotheses of villages and permanent occupation on the lava flow was an archaeological construction.)

The second function of the trees in close proximity to the traps as smoking chambers for processing the large annual eel catch explains how it was possible to deal with the large eel numbers and ensure their preservation (see Figure 9). Preserving the sea-

Fig. 9: *E. viminalis* used in GC/MS analysis (photo H.Builth).

sonally abundant resource would logically facilitate its storage or trade and the regional ethnographic record for eel trading contributed to the hypothesis that CMTs performed this function (Robinson in Kenyon 1928:141; Morgan 1852:55-56). A method was sought to test for this (Fankhauser 2001). A positive result would prove crucial in redefining Gunditjmara settlement and establishing a new socio-economic model.

GC/MS Analysis

The fact that only modified trees are found within 20 metres of the eel traps suggests that these trees were an integral part of the aquaculture system and especially high activity eel processing areas in close proximity to the traps. During the relatively short annual autumn migration, large numbers of eels would be making their way to the ocean along the channels and high density processing, including the smoking and preserving stage, would be expected to occur adjacent to the traps thus maximising energy efficiency. There is a need to preserve the eels for storage or trade, or else risk wasting them or the opportunity their migration offered.

The short-finned species, *Anguilla australis* from Victoria showed more than 55% greater fat content while migrating as compared to feeding eels (Sumner et al. 1984). The changes that occur in lipid content in growing eels (Sumner & Hopkirk 1976; Sumner et al. 1984) is significant when considering that their highest fat content is reached just prior to the annual autumnal migrations of mature individuals. Feeding eels had a fat content of 12.6% and migrating eels 19.0%. This is therefore the optimum time for their exploitation from a consideration of caloric content and the generic Indigenous desire for high energy-giving fats and oils. Capture and preservation of eels, therefore, at this particular point in their long lives would justify the great investment of human energy required for their harvesting and processing.

A decision was made to test for lipids, including fatty acids, as a means of ascertaining if the culturally modified trees (CMTs) had been used for the purpose as stated in 2, above. Identification of fatty acids emanating from the shortfin eel, *Anguilla sp.*, in samples taken from within the base of certain hollow trees, would provide strong evidence for this. Figure 9 shows one of the trees which contained sediment that was tested with GC/MS. Sediment from four trees have been tested.

Following GC/MS analysis, biomolecular evidence was obtained that supports eel processing having taken place (Builth 2002b:177-210). All sediment samples were positive and contained the crucial fatty acids that enabled them to be identified.

Although the residues extracted from sediments found in hollow trees were degraded there were still unsaturated fatty acids, 16:1, 18:1, 18:2, 20:4, and 20:5, present. Arachidonic acid, 20:4, and timnodonic acid, 20:5, are commonly found in aquatic animals in relatively high levels and are rare in plants. Given the large amounts of long chain fatty acids, an aquatic source is most likely. In addition, cholesterol was present which indicates an animal source and this coupled with the presence of cetyl alcohol gives an aquatic animal source for the origin of the residues. A relatively high amount of 18:2 fatty acid points to a freshwater fish source. Given the context of the samples the most likely source of the residues is eel processing (Fankhauser 2001:11).

Archaeological evidence of resource preservation supports a revised model of Gunditjmara settlement on the lava flow (Testart 1982).

DISCUSSION

The archaeological features, that were an integral part of the aquaculture system, occur in association with each other and particular natural features. The combination of the environmental requirements to carry out the eel aquaculture, processing and residential settlement – that is, stones, water and trees, were present in abundance on the same landform that the eels migrated to and through. The topographical and biological contrasts and similarities between the two study sites are reflected in the types of cultural usage that Gunditjmara had undertaken in these areas. Each shows how different environmental attributes have contributed to the particular Indigenous land usage.

The present interpretation of the archaeology of the Mt Eccles lava flow can be compared to the hydraulic manipulation documented by Lourandos near Toolondo to the north east of the present study area (1980b). Remains of weirs elsewhere in the region have been documented (Builth 2002b:56-69, 92-98). Certainly this technology existed throughout the region but the extent of wetlandscape manipulation in Southwest Victoria is not known.

The positive identification of eel lipids supports the hypothesis for smoking and therefore preserving and storing this species. It also supports the former identification of storage caches adjacent to dwelling remains (Builth 1996:114-122, Builth 2002b:211-258). This is the first time that trees have been identified as performing a vital role in Aboriginal socio-economic activities with significant ramifications for cultural development.

The topography, the channels – with their instream series of growing ponds and weirs for trapping, plus the presence of large mature trees, are the environmental evidence for the suitability of the northern study site and its surrounds, for exploiting the eel migrations during autumn. The weirs enable resource surplus; the modification and use of these trees is the means to preserve this seasonally abundant and nutritionally rich resource; and the culturally modified wetlands with their perennial staple foods makes it possible for a sedentary occupancy of this area. There are sufficient sinkholes and wetlands to guarantee daily availability of live specimens but it appears that the north area is highly suited to trapping and preserving eels. The quality and fat content of the eel during the migration season (Sumner and Hopkirk 1976; Sumner et al. 1984; Fankhauser 2001) makes the investment of energy in the trap construction, tree and channel modification worthwhile. This utilisation of this resource supports the claim for a resource specialisation which incorporates its preservation, storage and/or trading.

Ethnographic and archaeological research (Godfrey 1994) informs us that Gunditjmara visited the coast for the summer months. From the evidence it can be assumed that for the other three seasons, at least, certain clans would have occupied the stony rises of the Mt Eccles lava flow, managing the wetlands previously created by their ancestors, spearing or trapping eels, smoking, preserving and storing them for trade, later consumption by families, or by the large organised gatherings (Lourandos 1980a & b,1983, 1985, 1987, 1991,1997).

The nature of British colonisation and the huge loss of Indigenous numbers masked the extent of previous Gunditjmara landuse patterns and the resulting socio-economies. This occurred despite various ethnohistorical reports alluding to an economy based on the ownership of eel weirs and associated villages (Dawson 1881; Clark 1998). It was not in the squatter's interests to record the high population numbers or any Indigenous infrastructure. The squatters were initially unlawfully residing, and they had good reason to downplay the nature of Aboriginal occupation. The draining of the wetlands and lakes has disguised the landscape from its previous incarnation. The European perspective of their use of this landscape is summarised thus:

> The main theme of the history is the transformation of the Shire from forest, swamps and stones to highly productive pasture. The heroes of the story are the successive waves of squatters, selectors and soldier settlers who have accomplished this transformation...(Yule 1988:viii).

The irony is that under Gunditjmara management the Mt Eccles lava flow was far more productive in the numbers of people that it could sustain than those sustained under the subsequent European grazing regime.

When the eel traps and CMTs are investigated in combination, it is evident that the two form a nexus to efficiently exploit migrating eels. It demonstrates that the focus of Gunditjmara socio-economy is not merely built around the daily provision of food – which can be obtained from the growing ponds or culturally modified wetlands. This economy was based on wetland management specialising in the production of surplus resource and its preservation. Its physical manifestation can be read in the landscape of the Mt Eccles lava flow. The spatial relationships and economic nexus between wetlands, dwellings, channels and weirs remain as material evidence of a former Indigenous economy based on permanence and sustainability. Their system had socio-economic implications (Builth in press).

CONCLUSION

All of the above observations and its interpretation support the landscape as being the product of a sophisticated management regime. Indigenous people occupying the landscape of the Mount Eccles lava flow at the time of European contact had achieved sustainable development by adapting appropriate extractive technology to an enhanced local ecology. Subsequent European land-use focused on draining the area and establishing grazing regimes.

The potential of the Mt Eccles landscape to sustain the incumbent Aboriginal society based on its ecological potential and its anthropogenic utilisation has been investigated and supported by archaeological research. The question of whether the utilisation was seasonal or perennial can be ascertained by examining landscape productivity. The potential of the environmental management of the Mt Eccles lava flow coupled with the ecological traits of the shortfin eel means that it is feasible to have sedentary settlement on this landform. Human occupation patterns respond to resource availability.

The extent of Gunditjmara transformation of the landscape in order to exploit the shortfin eel has all the characteristics of it having been domesticated (Erickson 2000). The archaeology has revealed evidence of a landscape-scale fishery present throughout the entire southern portion of the landform – covering at least 100sq kms. It is argued that the "natural environment", existing at the time of European arrival, was an anthropogenic product reflecting human ingenuity. It had been created, maintained and managed by a collective multigenerational knowledge, and involved a cooperative, governed society (Builth in press). A mosaic of wetlands, stony rises and woodland had been integrated by environmental opportunism and technology to serve the socio-economic interests of Gunditjmara.

The cultural construction of an extensive aquaculture and processing system, with the built-in means to ensure its seasonal sustainability and perennial occupation, demonstrates technology hitherto unrecognised in Australian Aboriginal societies. The chronology associated with the development of the aquaculture system is presently under investigation. Further research is necessary to identify any relationship between palaeoenvironmental responses to climate change and possible Gunditjmara intervention. Ramifications of such anthropogenic activity may or may not have had social implications leading to the development of social complexity as outlined by Lourandos (1980a & b,1983, 1985, 1987, 1991,1997).

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Papers considered for publication may be: Reviews, Reports of experimental or descriptive research, or Short Communications. Length of papers may vary but Short Communications should not exceed 1500 words. When an author submits a manuscript for consideration, it is assumed that it has never been published nor is under consideration for publication elsewhere.

SUBMISSION

The original and two copies of the typescript and all tables and figures should be submitted to the Executive Officer, Royal Society of Victoria, 9 Victoria Street, Melbourne, Victoria, 3000. Use International A4 bond paper, printed on one side only. In a letter of transmittal, give the names and addresses (postal and email) of the author or co-authors, also give the names, addresses and email addresses of three persons not directly associated with the work and outside the author's institution, who could act as referees. For all papers, presentation of the final manuscript on word-processed floppy disk is essential as well as a hard copy. Authors or their institutions may be requested to contribute towards the cost of publication of the paper and in the case of very long papers, such contribution is mandatory.

It will assist reviewers if related papers recently published or submitted elsewhere accompany the submitted manuscript.

FORMAT

All manuscripts should be written in clear and concise English. Use double spacing throughout; leave 30 mm margins around the text; number all pages. All measurements are to be expressed in SI units (eg µm, mm, m, km but not cm) and standard symbols and abbreviations used. Note, Ma refers to a date (eg 25Ma) not a time interval, which is written as 25 million years. When a number does not refer to a measurement it should be spelt out except when it is greater than nine. Wherever possible fractions should be written in the form x/y.

Geological papers must follow the Australian Code of Stratigraphic Nomenclature and should cite geological maps in the text with italics for the 1:63 360 series and full caps for the 1:250 000 series. New stratigraphic names should be registered with the Geoscience Australia (GA) Australian Stratigraphic Names Database. The GA website "How to define a lithostratigraphic unit" (http://www.ga.gov.au/minerals/strat_names/) is a useful guide.

The *Proceedings* uses Australian spelling according to the latest edition of the *Macquarie Dictionary* and where there is optional spelling for words we use the form used by Victorians traditionally. For example we use the following spelling; color, honorary, program.

Authors should follow the layout of headings, tables and illustrations as presented in a recent issue of the *Proceedings*.

Papers should be organised as follows:

1. *A brief title*, capitalised and, if possible, beginning with a key word.
2. *The name and address of the author(s)*, with numerical superscripts to distinguish addresses of multiple authors.
3. *A full reference to the paper*, leaving space for the printer's additions.
4. *A short abstract* of not more than 200 words describing the results (rather than the contents) of the paper.
5. *Up to 5 key words.*
6. *The main text.* Capitalise the first word of the introductory paragraph; do not use the heading 'Introduction'. Within the text up to three grades of headings may be used, typed as follows:

GRADE ONE HEADING

Grade two heading

Grade three heading. Followed by running text on the same line.

Refer to the papers illustrations in the text as "Fig. 1A, B", "Figs 1, 2" or "Figs 1-4", and indicate in the margins where the illustrations should be placed. Cite references in the text as Archbold (1998), (Archbold et al 1998) or (Archbold 1998: 2, fig. 1); multiple citations should be arranged chronologically. All references cited in the text must be listed at the end of the paper. Footnotes in the main text are not allowed. Where there are multiple authors for a reference, "et al." is used, and is not italicised.

In taxonomic works, synonymies should be of the same format as the following examples, with a dash preceding authors' names except in the case of reference to the original description.

Eudendrium generalis Lendenberg 1885: 351, pl. 6. — Lendenberg 1887: 16.

Eudendrium generale. — Hartlaub 1905: 515. — Watson 1985: 196-200, figs 40-52.

non *Eudendrium generale.* — Watson 1982: 89, pl. 10, fig. 3.

Eudendrium lendenfeldi Briggs 1922: 150. — Rosler 1978: 104, 120, pl. 20, figs 1-3.

Note that plate and figure numbers, etc. originally given in Roman numerals should be transliterated into Arabic figures; this is also the case in the main text and in the references.

7. *Acknowledgements.* The source of finacial grants and other funding, as well as the contribution of colleagues or institutions, should be acknowledged. These should follow the main text and be as brief as possible.
8. *References.* These should conform in arrangement to the examples below. Journal titles must be cited in full as they appear on the title page.

Curtis, N.P., 2001. Germination of *Xanthorrhoea australis* using treatments that mimic post-fire and unburnt conditions. *Proceedings of the Royal Society of Victoria* 113(2): 237-245.

Bergson, H., 1928. *Creative Evolution.* MacMillan and Co., Ltd., London, xv+425 pp.

Rosen, B.R. & Turnesk, D., 1989. Extinction patterns and biogeography of scleractinian corals across the Cretaceous/Tertiary boundary. In *Proceedings of the Fifth International Symposium on Fossil Cnidaria including Archaeocyatha and Spongiomorphs*, P.A. Jell & J.W. Pickett, eds, Association of Australasian Palaeontologists, Brisbane, Queensland, 355-370.

Any other type, check previous recent copies of the *Proceedings*.

Personal communications and unpublished data are not to be listed in the reference list but should be mentioned in full in the text (eg P. Brown pers. comm. 2002).

9. *Tables and Figures*. Each table with its title should be typed on a seperate sheet. A separate sheet should also be used to list captions to figures in numerical order.

ILLUSTRATIONS

These must be designed for one or two column width (67 mm or 140 mm); maximum length is 193 mm. Composite Figures should be lablelled A, B, C, etc. (not a, b, c). Oversized illustrations, tables or maps may be accepted for publication as foldouts only if the author meets all costs involved in their production. Maximum size for foldouts is 193x285 mm.

Final submission of black and white figures electronically is encouraged as long as it is in a readily acceptable format (JPEG, TIFF, emf, wmf, pex, pct, wpg, cdr). These can be supplied on 3.5" floppy disks, zip disks or CD (especially for figures with any grey shades) and accompanied by a high quality hard copy. Digital files must be supplied at a resolution of at least 600 d.p.i. at full size.

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Authors will normally receive an 'Adobe Acrobat PDF' version of the mock page proofs; this is for the purpose of correcting printer's errors and not for altering the wording or substance of the paper. This should be returned, or comments emailed to the editor within 72 hours. If absent, authors should arrange for a colleague to check and return proofs to the editor on their behalf. Authors will be charged for excessive alterations at this stage.

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