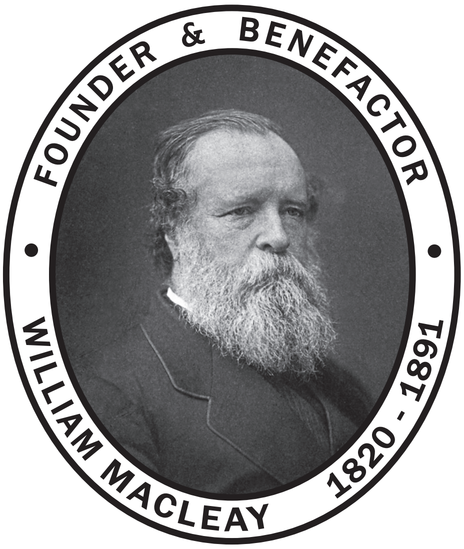
PROCEEDINGS
of the
LINNEAN SOCIETY
of
NEW SOUTH WALES

VOLUME 141

NATURAL HISTORY IN ALL ITS BRANCHES

THE LINNEAN SOCIETY OF NEW SOUTH WALES

ISSN 1839-7263



Founded 1874
Incorporated 1884

The society exists to promote the cultivation and study of the science of natural history in all branches. The Society awards research grants each year in the fields of Life Sciences (the Joyce Vickery fund) and Earth Sciences (the Betty Mayne fund), offers annually a Linnean Macleay Fellowship for research, and publishes the *Proceedings*. It holds field excursions and scientific meetings including the biennial Sir William Macleay Memorial Lecture delivered by a person eminent in some branch of natural science.

Membership enquiries should be addressed in the first instance to the Secretary. Candidates for election to the Society must be recommended by two members. The present annual membership fee is $45 per annum.

Papers are published at http://escholarship.library.usyd.edu.au/journals/index.php/LIN and access is free of charge. All papers published in a calendar year comprise a volume. Annual volumes are available to any institution on CD free of charge. Please notify the Secretary to receive one. “Print on demand” hardcopies are available from eScholarship.

Back issues from Volume 1 are available free of charge at www.biodiversitylibrary.org/title/6525.

The postal address of the Society is P.O. Box 291, Manly NSW 1655, Australia.
Telephone and Fax +61 2 9662 6196.
Email: linnsoc@iinet.net.au
Home page: www.linneansocietynsw.org.au/

Cover motif: Kaputar Pink Slug, *Triboniophorus* sp. nov. “Kaputar”. Photo: M.J. Murphy.

PROCEEDINGS
of the
LINNEAN SOCIETY
of
NEW SOUTH WALES

For information about the Linnean Society of New South Wales. its publications and activities, see the Society’s homepage
www.linneansocietynsw.org.au

VOLUME 141
December 2019

Two Centuries of Botanical Exploration along the *Botanists Way*, Northern Blue Mountains, N.S.W: a Regional Botanical History that Reflects National Trends

Doug Benson

Honorary Research Associate, National Herbarium of New South Wales, Royal Botanic Gardens and Domain Trust, Sydney NSW 2000, AUSTRALIA.
doug.benson@rbgsyd.nsw.gov.au

Benson, D. (2019). Two centuries of botanical exploration along the *Botanists Way*, northern Blue Mountains,N.S.W: a regional botanical history that reflects national trends. *Proceedings of the Linnean Society of New South Wales* **141**, 1-24.

The *Botanists Way* is a promotional concept developed by the Blue Mountains Botanic Garden at Mt Tomah for interpretation displays associated with the adjacent Greater Blue Mountains World Heritage Area (GBMWHA). It is based on 19th century botanical exploration of areas between Kurrajong and Bell, northwest of Sydney, generally associated with Bells Line of Road, and focussed particularly on the botanists George Caley and Allan Cunningham and their connections with Mt Tomah.

Based on a broader assessment of the area's botanical history, the concept is here expanded to cover the route from Richmond to Lithgow (about 80 km) including both Bells Line of Road and Chifley Road, and extending north to the Newnes Plateau. The historical attraction of botanists and collectors to the area is explored chronologically from 1804 up to the present, and themes suitable for visitor education are recognised. Though the *Botanists Way* is focused on a relatively limited geographic area, the general sequence of scientific activities described - initial exploratory collecting; 19th century Gentlemen Naturalists (and lady illustrators); learned societies and publications; 20th century publicly-supported research institutions and the beginnings of ecology, and since the 1960s, professional conservation research and management - were also happening nationally elsewhere. The broader view of the *Botanists Way* concept is considered to provide a valuable basis for expanded visitor interpretation of science and conservation in and around the Greater Blue Mountains World Heritage Area, botany being a significant element of nature tourism.

Funding for public-good science through largely government funded institutions is a relatively recent development. It has been particularly influential in the last 50 years (i.e. essentially in the lifetimes of current researchers). However, despite recognition of its obvious successes, public-good science should not necessarily be assumed to be a permanent feature of our culture, and remains vulnerable to political climate.

Manuscript received 22 July 2018, accepted for publication 13 March 2019.

KEYWORDS: Bells Line of Road, botanical collecting, botanical history, Greater Blue Mountains World Heritage Area, learned societies, public-good science, National Herbarium of New South Wales, nature tourism.

INTRODUCTION

> *But it is a form of romance to trace too close a parallel between a long lifetime and events belonging to local and national history, Most people exist with only the occasional peripheral thought they, personally, are part of an age or an epoch.*
> Ronald Blythe (1979)

The inscription of the Greater Blue Mountains World Heritage Area (GBMWHA) on the World Heritage List in 2000 has led to a demand for information not only on its biodiversity, but also on its scientific history, and particularly its botanical exploration and discovery. These stories provide background for interpreting the flora and vegetation in displays and exhibitions such as at Blue Mountains Cultural Centre at Katoomba, and for guides and

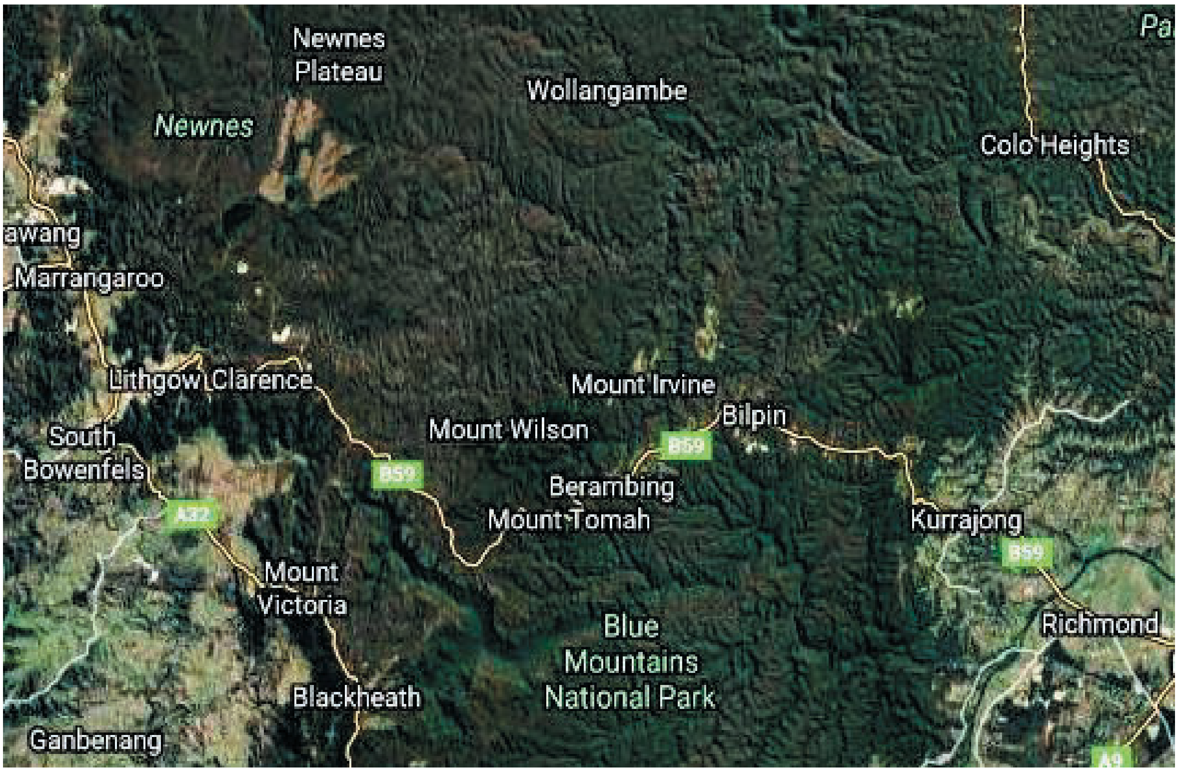


FIGURE 1 The route of the Botanists Way from Richmond to Lithgow along Bells Line of Road, a distance of about 80 km. The Newnes Plateau is immediately north of Clarence. (Source: Google maps).

tourist leaders, as well as the general public. The *Botanists Way* is a particular promotion by the Blue Mountains Botanic Garden at Mount Tomah to celebrate the botanical exploration of the Bells Line of Road and Chifley Road between Kurrajong and Lithgow (Figure 1). It has featured in its exhibitions and is shown on the maps of the Greater Blue Mountains Drive (DECC 2008), a series of routes traversing the GBMWHA.

In Australia the story of botany weaves in and out of the national history. During the 1950s N.S.W. primary school social studies classes devoted considerable energy to the discovery of the Australian continent and exploration of the interior. This included reference to the part that botanists and scientists played: a brief mention of William Dampier - though better known as a buccaneer, he collected the first documented Australian plant specimens (now at Oxford University) and described vegetation at Shark Bay in Western Australia in 1699 (Groves 2017); then of course James Cook's visit to Botany Bay in 1770 and the plant collections made by Joseph Banks and Daniel Solander that stunned the scientific world. Banks' later recommendations to the British Government were instrumental in the founding of the convict settlement of Botany Bay in 1788. Later he also selected, and largely funded, a series of botanists including George Caley, Robert Brown and Allan Cunningham. So influential was he in the development of the early colony of New South Wales that the 1821 Inscription Plaque at Botany Bay described him as *Maecenas of his time* (an influential arts patron under Roman emperor Augustus), and a later Australian botanist, Joseph Maiden, was convinced that he should be regarded as the *Father of Australia* (Maiden 1909).

Allan Cunningham was one of the intrepid explorers of the interior, and as well as collecting plants (this was not generally emphasized in classrooms) he discovered Pandoras Pass (northeast of Coolah) and the Darling Downs in southeast Queensland – neither meant much to N.S.W. students at the time. Botany appears to have then disappeared from Australian history, both in its impact on events and its significance in the N.S.W. primary school curriculum.

That is, until the late 1960s when the need for better general education led to an increasing interest in the natural world, particularly its biodiversity (a holistic term first used in 1985). At the same time establishment of the N.S.W. National Parks and Wildlife Service (in 1967), nature-focussed conservation of natural areas, and the funding of science in institutions such as botanic gardens by the Whitlam Government's Australian Biological Resources Study (ABRS), gave new impetus to botanical research nationally.

The *Botanists Way* promotion concentrates mainly on early botanical history and exploration and was developed in 2008, focusing particularly on the early 19th century botanist/collectors George Caley and Allan Cunningham, and their collecting excursions from Richmond to Mt Banks and Mt Tomah. However the area's botanical history is much richer than presented in tourist promotion: the route of the Bells Line of Road and Chifley Road (its continuation from Bell into Lithgow) has many more historical botanical associations. George Caley is certainly important from the Mt Tomah point of view, but his fellow botanist Robert Brown played a bigger role in describing the Australian flora. At the other end of historical time is the discovery of the Wollemi Pine in 1994 (to the north of this route) and the inscription of the Greater Blue Mountains on the World Heritage List in 2000. Many botanists and botanical collectors have been involved; there is not space to describe fully all their contributions but further biographical details for most can be obtained from various websites (e.g. the Australian Dictionary of Biography). A chronological summary of people historically associated with the *Botanists Way* is provided in the appendix.

This account takes the geographical corridor of the *Botanists Way*, and expands some of its other important connections with botanical history, research, exploration, conservation biology and wildlife management. The major trends in the science world at the time are treated chronologically. Similar events to those described for the *Botanist Way* were also occurring elsewhere in Australia; the story is therefore a good example of how regional botanical history has unfolded to provide the diverse individual components that make up our current level of national knowledge.

THE *BOTANISTS WAY*: from Richmond to Lithgow along Bells Line Of Road

Bells Line of Road is a major connecting route providing an alternative to the Great Western Highway to cross the Blue Mountains. From Richmond (at the Hawkesbury River bridge) on the north western outskirts of Sydney, the road passes through Kurrajong, Bilpin and Mt Tomah to Bell, in the upper Blue Mountains, whence the route continues to Lithgow as Chifley Road (this road was only continued to Lithgow during World War II). The distance from Richmond to Lithgow is about 80 km. The route from Richmond to Bell and into Hartley Vale was pioneered by 19-year old Archibald Bell in 1823 and was later used as a stock route. Elevation along the route ranges from near sea-level at Richmond to about 1000 m at Bell. The area is partly within both the Central Coast and Central Tablelands Botanical Subdivisions. The *Botanists Way* is currently interpreted by the Blue Mountains Botanic Garden as the Bells Line of Road from Kurrajong to Mt Tomah, but is marked on the Greater Blue Mountains Drive maps (DECC 2008) to include the Chifley Road. URL http://www.greaterbluemountainsdrive.com.au/the-drive-in-detail/themed-touring-routes/botanists-way

Early botanical exploration along the *Botanists Way*: the influence of Sir Joseph Banks

Although **Sir Joseph Banks** (1743-1820), botanist, science patron and president of the Royal Society in London for 41 years, came no closer to the Blue Mountains than Botany Bay, he is a figure of international scientific standing. It is fitting that a major geographical feature on the *Botanists Way,* Mt Banks, was named in his honour. He had a significant influence on the selection of Botany Bay for the penal colony. His influence on the administration continued through selection of the first governors, but his personal scientific interests were promoted through his employment and patronage of naturalists, in particular George Caley, Robert Brown, and Allan Cunningham (O'Brian 1987).

George Caley was employed by Banks as a natural history collector and arrived in Sydney in 1800. For nearly 10 years he worked out of Parramatta and took a particular interest in eucalypts, noting species hybridization, and in Aboriginal plant use. His attempt to cross the Blue Mountains in November 1804 (with convict assistants but no aboriginal guides) took him from Richmond, through Kurrajong, across Burralow Swamp and then the rugged country along the northern side of the Grose Valley, which he called *The Devil's Wilderness* (his route is much further south of the current Bells Line of Road), to Mount Tomah (his *Fern Tree Hill*), and Mt Banks (which he named after his employer). Alan Andrews (1984) transcribed and annotated Caley's account of this journey and his descriptions of some of the plants. He was the first naturalist to journey into this part of the Blue Mountains, and some of his observations deserve highlighting.

On the native currant, presumably *Leptomeria acida* - Nov 7 1804 The Devil's Wilderness - *As* *a substitute for water, we made use of the native* Currant*, which we found to be in tolerable plenty in some places, upon the barren hilly ground, and which in great measure alleviated our thirst. Yet though the shrub was so common, the fruit might be said to be scarce, seemingly by being devoured by birds.*

First description of mallee eucalypts - Nov 13 1804 southwest of Mt Tomah - (*The ground down hill we found to be nakedish of trees, of a very barren nature, but in some places thickly covered with a bush like species of* Eucalyptus*, which much resembled young trees in growth.*

Similarities with Sydney vegetation - Nov 14 1804 Mt Charles - *We arrived at a barren piece of land, destitute of trees, and much like some places in the vicinity of Sydney, such as South Head etc*.

The contrast between the vegetation on barren sandstone and that on the Wianamatta Shale - 21 Nov 1804 returning near Little Wheeny Creek - *The first sight of forest land had great effects on our minds, which had the appearance of a paradise, in comparison to that which of late we had been accustomed to* [i.e. sandstone vegetation]. *As we came through the brush, on the lower part of the hills we noticed a deal of* Currijon *(a species of* Hibiscus*) in flower, which had a grand and beautiful appearance.* It is clear from this and Caley's separate description of *Currijon* (Appendix in Andrews 1984) that Caley's *Currijon* refers to the shrub/small tree *Hibiscus heterophyllus*, and not the well-known tree Kurrajong *Brachychiton populneus*, commonly associated with the placename Kurrajong. Both species could have provided fibre, which the Aboriginal word apparently refers to. Caley clearly indicates the abundance of *Hibiscus heterophyllus,* but he does not mention *Brachychiton*. Both species could have occurred in the Kurrajong area; both occur at the interesting botanical site at nearby Grose Vale (Benson 2012).

Caley's plant descriptions (Appendix in Andrews 1984) are difficult to identify to species now, but recent research indicates that, for example, his *Viola* from *The Devils Wilderness* area is a new and undescribed taxon (Louisa Murray pers. comm. 8/2/2018).

Robert Brown (1773-1858) was selected by Banks as naturalist to accompany Matthew Flinders on the *Investigator's* survey of the Australian coast (1801-1805) (the expedition also included the artists Ferdinand Bauer and William Westall). Vallance et al. (2001) transcribed Brown's journal of the expedition. During his time in Sydney Brown met with Caley, and in 1804-05 he explored the Richmond-Windsor area, then known as the Green Hills, and the Lower Grose River. From here he collected and described a small shrub *Epacris sparsa*, which was subsequently overlooked until the 1990s, when it was found in the Grose near the Vale of Avoca (Powell & James 1993), probably very near where Brown originally collected it. Brown returned to Britain to work on his material, later (1805) becoming Bank's librarian, and subsequently (1827) Keeper of the Botanical Department of the British Museum, when the collections were transferred there. He published descriptions of 3500-4000 Australian species.

The appointment of **Allan Cunningham** (1791-1839) as botanical collector for the Royal Botanic Gardens Kew was one of Banks' last significant contributions to Australian science. Cunningham, had Brown's acquaintance at Kew and after more than a year in Brazil, arrived in Sydney in 1816 with substantial botanical expertise. He collected locally around Parramatta and in April 1817 joined John Oxley exploring westward to Wellington and the Lachlan River. Over the next four years he sailed with Philip Parker King on coastal hydrographical surveys and collected widely in north-western Australia. Back in Sydney in 1822, he set out to collect specimens and explore the country between the Macquarie and Cudgegong Rivers, resulting in the discovery of Pandoras Pass through the Liverpool Range to the Liverpool Plains (though much better access across the range was soon found to the west). In 1827 he made a major exploratory journey north from the upper Hunter through the Gunnedah and Bingara areas to the Condamine River, a potentially rich pastoral area which he named the Darling Downs. He made many local trips around Sydney including to Mount Tomah in 1823 following Bell's survey line and described the rainforest and treeferns at Mt Tomah. His journals contain a wealth of botanical and landscape descriptions, as well as observations on ecology and early impacts of settlement. While extracts of Cunningham's writings are available (e.g. Lee 1925), his journals are yet to be fully transcribed and published, though this is being gradually done by various people (R.O. Makinson pers. comm.). See also Heward (1842)-obituary, McMinn (1970)-general biography and Orchard and Orchard (2015)-letters.

An awareness of Australian identity: the beginnings of formal scientific research

The second half of the 19th century brought the cessation of convict transportation, the wealth from the gold rushes, and an increasing population regarding Australia as its home. These led to the development of civic pride in the Australian colonies, particularly highlighted by the 100th anniversary of the Foundation of the Colonies in 1888. The excitement of science and discovery in a new continent drove scientific research. From Melbourne the internationally recognized scientist Ferdinand Mueller (1825-1896) kept Australia in touch with world botany. The monumental *Flora Australiensis* by George Bentham, seven volumes published in London in 1863-1878, was made possible by the specimens collected by Banks, Caley, Brown, Cunningham, Mueller and many others. It provided the definitive resource for identifying Australian plants in Australia, but it also ended the era of needing to send specimens to Britain/ Europe for major work on Australian botany. There was now an increasing interest in local organisations and scientific institutions. Local networks of men with common interests developed. Colonial scientists formed the *Australasian Association for the Advancement of Science* in 1888.

Networks of learned men: opportunities provided by the Linnean Society of New South Wales

Natural history scientific institutions in 19th century Sydney were the Sydney Botanic Gardens (established in 1816), the Australian Museum (1827), the Technological Museum (1878) and University of Sydney (established in 1852, but the Botany Department was only established in 1913). These institutions were essentially storehouses for specimen collections overseen by a few professional scientists. The majority of scientific research in the 19th century was done by networks of educated and often influential enthusiasts, Gentleman Naturalists (Augee 2010), connected through learned scientific societies which provided opportunities for correspondence, meetings, field visits and publication of results (Fig. 2). Though modelled on those of London, they were not exclusive in their membership and catered for a wide variety of interests. The networks did include some ‘lady’ illustrators. Their illustrations which often disclose considerable understanding and original natural history observations, accompanied scientific papers but they were rarely included as authors. For those

**FIGURE 2 Rather formally attired members of the Linnean Society pose for Henry King’s camera during an excursion to the Nepean River, on Saturday, 29 September 1888.
Seated, from left: Henry Deane, Ernst Betche, J.H. Maiden (with plant press), John Brazier, Dr James C. Cox, Sir William Macleay. Standing, from left: Prof. W.J. Stephens, Frederick A. Skuse, Frank Meyrick de Meyrick, Joseph Fletcher. Many were authors of Linnean Society publications over the following decades. (Source: Henry King; State Library of New South Wales).**

with natural history interests there was the Linnean Society of New South Wales (which accepted women as Associate Members from 1885 and as full members from 1909). Others were the Royal Society of New South Wales with primarily geological interests, and the Royal Zoological Society with a major interest in acclimatisation.

The Linnean Society of New South Wales was founded in 1874, to promote the "Cultivation and Study of the Science of Natural history in all its Branches", with the support and patronage of Sir William Macleay (major interest entomology) and supported by other leading Gentleman Naturalists including Sir William Macarthur (botany, horticulture). Robertson (1974) summarised the first hundred years of the Society, emphasising that '*One of the characteristics of natural history in the nineteenth century was that the work — including work of great distinction — was often carried out by people to whom it was more of a hobby than a profession…Macleay and the clergyman -geologist W. B. Clarke.* [In the early 20th century]- *the Reverend H. M. R. Rupp working on the orchids, Mr. G. A. Waterhouse " the butterfly man ", Mr. S. J. Copland the herpetologist who used to be the night crime reporter for the Sydney Morning Herald.* [and] *Mr. A. H. S. Lucas, Headmaster of Sydney Grammar School… the only person in Australia then to undertake a systematic investigation of our marine algae'*.

The Society also provided meeting rooms (most recently Science House) and important library resources up until their dispersal in the early 1980s (Martin 2015). However, the lasting value of these societies was, and is, their publications. The journals of the learned societies such as the *Journal and Proceedings of the Linnean Society of New South Wales* published much of the work of this period. In 1890, for example, 50 papers were published in Volume 5 of the *Proceedings*, the majority by Gentleman Naturalists, though seven were written by people who were professional biologists or had biological training (Augee 2010); a new trend in the "professionalism" of natural history studies was emerging.

Based in Richmond, the **Reverend** Dr William Woolls (1814-1893), a Church of England clergyman and a knowledgeable botanical Gentleman Naturalist, published papers on both native and exotic plant species, particularly for Parramatta and western Sydney (Woolls 1867) (see biography by Thompson 1986). He sent specimens to botanist Ferdinand Mueller in Melbourne and on meeting young botanist **Louisa Atkinson** (1834-1872) who was living with her mother at *Fernhurst* at Kurrajong in the 1860s, introduced her to William Macleay and encouraged her to correspond with Mueller. She published articles in the *Sydney Morning Herald* on the flora of the Kurrajong area, particularly ferns, and planned an illustrated fern guide, but died too young to finish it (Lawson 1995). *I wish you had known Louisa Atkinson*, Woolls wrote to his botanist-engineer friend Henry Deane fourteen years after her death (Gilbert 1980). In the 1880s Woolls gave botanical lessons to a young mining surveyor Richard H. Cambage (1859–1928) who made plant collections for him. Cambage later authored papers on geological influences on vegetation and the routes of the early explorers in the *Journal and Proceedings of the Royal Society of N.S.W*.

The lush rainforests on the isolated basalt soils at Mt Wilson and Mt Tomah that had attracted Caley and Cunningham now attracted others. Woolls published (1887) *A glance at the flora of Mount Wilson,* Prosper N. Trebeck published a list of Mount Wilson ferns (Trebeck 1886), and in 1899 teacher Alexander G. Hamilton published notes on the Mt Wilson vegetation and climate, and listed the flora, combining his list with those of Trebeck, Joseph Maiden, and local residents Jesse Gregson and J.D. Cox. (Hamilton 1899). The botanical works of all these people were published in the *Proceedings of the Linnean Society of N.S.W.*

Gardeners at Mount Wilson

The rich red soil of the basalt-capped mountains also provided attractive sites for country houses, with extensive gardens set in surrounds of tree fern-filled forest (Fig. 3). The nearby railway station of Bell (opened in 1875 as Mt Wilson station) made Mount Wilson accessible. In 1880 **Jesse Gregson** (1837-1919) (Superintendent of the Australian Agricultural Company) constructed a holiday property *Yengo* at Mt Wilson, and developed gardens with assistance from Sydney Botanic Gardens director Charles Moore. Later, as his interest in botany developed, he sent specimens to botanist Joseph Maiden, Moore's successor. A friendship developed and Maiden accompanied Gregson on collecting excursions. An unpublished list of lichens collected at Mt Wilson by Jesse Gregson (Gregson 1902-3) (46 species determined by Edwin Cheel) is probably the first documentation of the non-vascular flora of the area. The fern *Blechnum gregsonii* was named for him by moss expert Reverend William Watts (Fig. 4). His son **Edward Jesse Gregson** (1882-1955) continued to live at *Yengo* and collect specimens (which were later given to the University of New England) and

FIG. 3 Cathedral of Ferns Mt Wilson; early 20th century postcard promoting the rich basalt vegetation as a tourist experience. (Source: Mt Wilson and Mt Irvine Historical Society)

published a paper on the eucalypts of Mt Wilson and Mt Irvine (Gregson 1952). The botanical contribution of the Gregsons was recognised in the naming of *Eucalyptus gregsoniana* in 1973 by another Sydney Botanic Gardens Director L.A.S. Johnson who had been accompanied in the field by Edward Gregson.

Other Mt Wilson retreats were J.D. Cox's *Balangra* (now *Sefton Hall*) and *Nooroo*, purchased in 1918 by George Valder, previously principal of Hawkesbury Agricultural College and later Undersecretary of the N.S.W. Department of Agriculture (he was Maiden's superior in the Public Service). His son continued to improve the historic garden, and the expertise of grandson **Peter Valder**, a Sydney University botanist and mycologist, made *Nooroo* an important collection of exotic, not least Chinese, plantings.

Commercial horticulture has also been important along the Bells Line of Road with orchards on the shale soils at Kurrajong and Bilpin, and nurseries on Mt Tomah, one of which the Brunet family donated in 1972 to become Mt Tomah (now Blue Mountains) Botanic Garden.

An example of the new professionals

In 1890 the Linnean Society included only a few professionals; notably J.H. Maiden (Curator of the Sydney Technological Museum), T. W. Edgeworth David (N.S.W. Department of Mines), W.A. Haswell (professor of biology Sydney University), and Baron F. von Mueller (National Herbarium of Victoria), but their number and influence was beginning to increase (Augee 2010). In 1891 Hawkesbury Agricultural College (HAC) was established at Richmond and began to employ trained science teachers, providing a base for science outside Sydney, often closer to interesting field study sites. **Charles Tucker Musson** (1856-1928) (Fig. 5) was a significant member of the Hawkesbury Agricultural College staff from its beginning until 1919, being, amongst other duties, Science Master and Lecturer in Botany and Entomology (see Lister 2017). Musson's career exemplifies the type of work being done in science and education at the time by a network of educated (mainly) men. Compared with the early 19th century exploration, this period has been generally overlooked; much of the progress at this time was made possible through the personal connections between the scientists through meetings and correspondence.

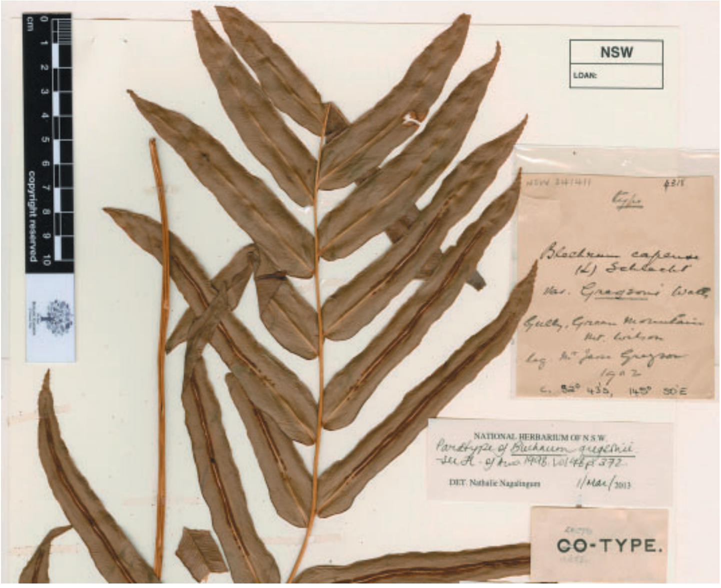


FIGURE 4 Type specimen of the fern *Blechnum gregsonii* (originally *Blechnum capense* var *gregsoni*) collected from Gully, Green Mountain, Mt Wilson by Mr Jesse Gregson in 1902. (Source: National Herbarium of NSW).

Charles Musson had broad interests in science and education, and a wide circle of friends and correspondents. He published his own botanical research on dioecy in the small lily *Wurmbea dioica,* and with his Hawkesbury colleague **Walter Mervyn Carne** researched adventitious roots on *Melaleuca linariifolia.* He worked on eucalypts and lignotubers with Joseph Fletcher (another teacher/scientist). **Joseph J. Fletcher** (~1850-1926) Councillor of the Linnean Society of N.S.W. from 1885 to 1919 and noted for his zoological research, maintained an interest in sandstone flora, in particular eucalypt and wattle seedling development. Fletcher had given a short account of the occurrence of what he believed were natural *Grevillea* hybrids amongst wild populations in the Blue Mountains to the Linnean Society in 1913, and in 1927, following Fletcher's death, Musson was asked by Fletcher's wife

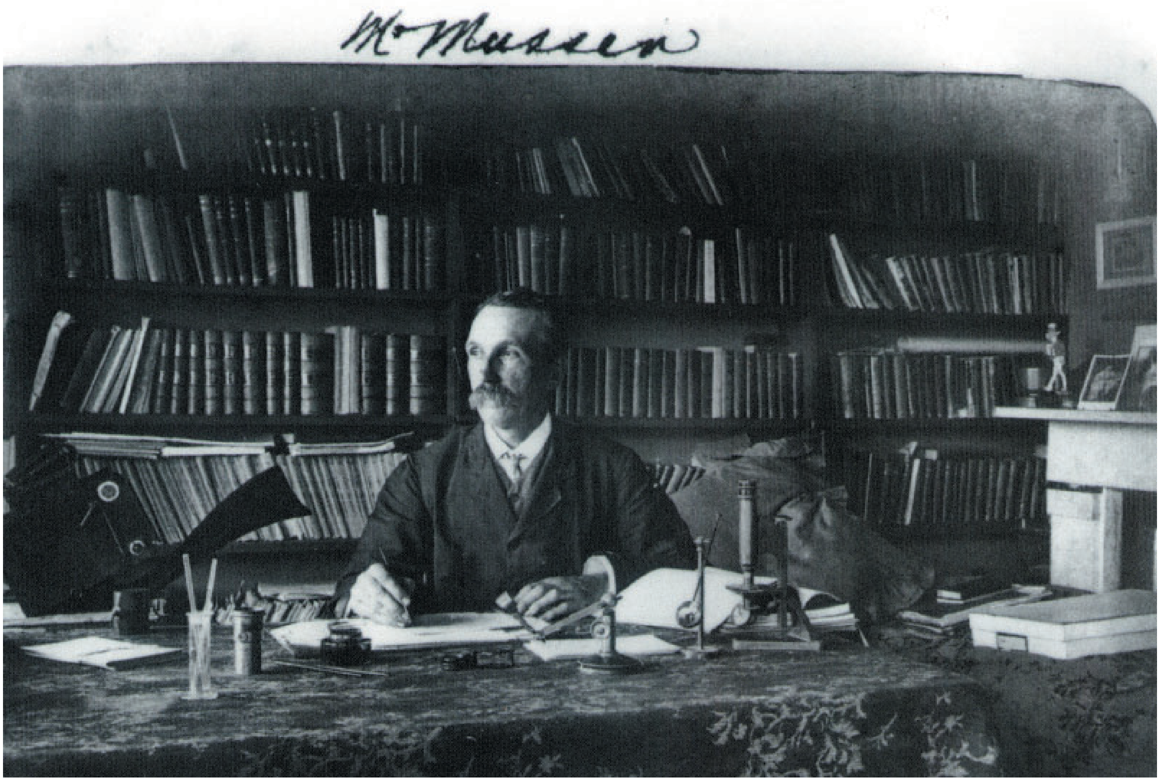


FIGURE 5 Charles Musson at his desk at Hawkesbury Agricultural College Richmond. Note the white herbarium boxes with black metal label holders on the right – these were still in use at the National Herbarium of N.S.W. until replaced with plastic boxes in 1982. (Source: Peter Lister).

Emma if he could do something with her husband's notes. Musson incorporated his own field observations and the resulting publication (Musson and Fletcher 1927) established that *Grevillea gaudichaudii* (as originally described by botanist Robert Brown in 1830), was actually a hybrid of *Grevillea acanthifolia* X *Grevillea laurifolia*. The characteristic plants of the hybrid growing to the present day on the edges of swamps on the Newnes Plateau, in intermediate microhabitats between the swamp inhabited by *Grevillea acanthifolia* and the dry woodland with *Grevillea laurifolia,* are always of interest to botanical enthusiasts (and reminds professional botanists that even Robert Brown, 'Jupiter botanicus' as he was described in his lifetime (Mabberley 1985) could make mistakes), though Brown would not have seen the plants in the field.

Near the end of his life Musson wrote a series of articles intended for a proposed *Introduction to the botany of N.S.W*. These, subsequently collected together in the HAC library and now reprinted (Lister 2017), provide an insight into botanical thinking of his time. Although the loss of species associated with land clearing was deplored, there was no consideration given to the idea of protecting areas for wildlife conservation. That was left to the bushwalking and conservation activists of the next generation.

The networks of the Linnean Society of N.S.W. and other learned societies allowed members with scientific interests, such as Charles Musson, to collaborate across disciplines: in botany, microbiology, pathology and zoology as well as history and education. Musson's colleagues for example also included Charles Hedley (on molluscs) and Sir John B. Cleland (pathologist and microbiologist). They also enabled valuable collaborations between amateur naturalists and professionals, but later as public institutions became more formal and professional, the role of the amateur became less important.

Walter Mervyn Carne, Musson's successor at HAC, was interested in the impact of geology on the distribution of species and plant communities. His attention was drawn to an interesting area of vegetation on limestone near Kurrajong (Carne 1910). Plant species lists for that site have been recorded on a number of subsequent visits documenting changes (Benson 2012). Currently (2019) the site is potentially threatened by the proposed Castlereagh Connection motorway corridor route from Castlereagh to Bells Line of Road at Kurrajong. At about the same time W.M. Carne's father **Joseph Carne** published his extensive geological surveys of the volcanic sites of the western Blue Mountains (Carne 1908). He was commemorated in the 1970s by the renaming of the eastern branch of the Wolgan River on the Newnes Plateau as Carne Creek.

The 20th century- national focus, public service science and herbaria

Most Australian capital cities set up botanic gardens early in their history, but for most of the 19th century these were mainly involved in importing seed and material of (exotic) overseas species and distributing or growing/acclimatising these, as well as sending Australian plant material overseas (especially for European gardens). Research on the Australian flora was mainly confined to sending Australian specimens to overseas herbaria. At the Sydney Botanic Garden, director Charles Moore (Director from 1848 to 1896), *in view of rendering the Public Herbarium of indigenous plants as complete as possible* travelled along Bells line of Road as far as *Mt Thomar* (sic), to collect *flowering plants and seeds* (according to Wilson 2004). He published *A Census of the Plants of New South Wales* (1884) and a *Handbook of the Flora of New South Wales* (with Ernst Betche in1893), but the next director **Joseph Henry Maiden** (1859-1925) found *a very poor herbarium* (Wilson 2004). Maiden established local collections and serious research programs and could be regarded as the first publicly-funded professional botanical research scientist in N.S.W. He had developed his botanical interests at the N.S.W. Technological Museum (later the Museum of Applied Arts and Sciences and then the Powerhouse Museum) (Gilbert 2001) where, inter alia, he used the collections to write *The Useful Native Plants of Australia* (Maiden 1889) (Fig. 6). A proud tradition of botanical research concentrated on essential oils was continued at the MAAS until the 1980s when the plant collections were transferred to the National Herbarium of NSW. In 1901, following his appointment as Director of the Sydney Botanic Gardens, Maiden opened a new Botanical Museum and National Herbarium building (known as the National Herbarium of New South Wales) in the Sydney Gardens. (As part of the 1970s injection of funding into science, this building was replaced by a new larger herbarium building in 1982, but the herbarium is now to be relocated from central Sydney out to the Australian Botanic Garden at Mount Annan in 2022).

From the end of the 19th century, enquirers sent plant specimens to the Sydney Gardens for identification, and for adding to the National Herbarium of N.S.W. institutional collections. A strong culture of public service science developed, enhanced by the Herbarium's position as part of the

FIGURE 6 *Actinotus helianthi* illustration from Maiden's 1895 Flowering Plants and Ferns. Such lavish colour illustrations, made possible with departmental funding, were not to be readily achieved again until the digital era. (Source: author)

N.S.W. Department of Agriculture, which already had a strong role in promoting science for general public good. Maiden (who remained as Director from 1896-1924) was also responsible for a serious program of extensive botanical research and collecting. He called for a botanical survey of N.S.W. and sent out collecting staff and received specimens from correspondents all over N.S.W., as well as collecting widely himself in N.S.W. and other States. He had wide research interests, particularly in eucalypts, which took him all around the state, and in the history of botany in Australia. He had many contacts through the Linnean and Royal Societies of NSW and nationally through the *Australian and New Zealand Association for the Advancement of Science* (ANZAAS), and he published extensively in local journals, for example, with R.H. Cambage (Maiden and Cambage (1905).

Botanical collecting using access from the Western Railway Line and Bells Line of Road continued into the 20th century, extending onto the sandstone of the Newnes Plateau north of Lithgow where a number of endemic plant species and vegetation communities occur. In 1906 **Henry Deane**, railway engineer and botanist, and a Linnean Society colleague of Maiden, while working on the Wolgan Valley shale railway found and described the now threatened *Boronia deanei* in swamps near Clarence on the Newnes Plateau. Deane published a number of papers on eucalypts with Maiden and was president of the Linnean Society in 1896.

Botanists from the National Herbarium of N.S.W. contributing further to the exploration of the Newnes Plateau area in the early 20th century included Joseph Maiden (eucalypts, history) and **William F. Blakely (**1875-1941) (collecting Fabaceae such as *Pultenaea*, and the endemic *Leptospermum blakelyi*) (Fig. 7). Later, **Ernest Constable** (1903-1986) explored the area after his appointment as botanical collector in 1946. Access was generally along the by-then disused old Wolgan Valley shale railway, or the Old Bells Road. The Great Depression and its aftermath in the 1930s and World War II led to reduced funding for public institutions which limited activity to herbarium specimen-based research.

A later enthusiastic local plant collector was **Keith Ingram (**1912-2002), school teacher and later local resident of Mt Tomah and then Richmond, who amassed a considerable personal herbarium

FIGURE 7 W. F. Blakely, Botanist and Eucalyptologist, botanised on the Newnes Plateau in the 1930s and discovered *Leptospermum blakelyi* near Lithgow. (Source: National Herbarium of NSW).

collection of plant species (37 000 specimens later donated to the National Herbarium of N.S.W.). He collected widely across all states and territories and is honoured by the naming of *Acacia ingramii* and *Bertya ingramii* from the Northern Tablelands and *Zieria ingramii* from near Dubbo in the Central Western Slopes. His interest in rare plants included unsuccessful searches along Bells Line of Road between Bell and Mt Tomah for *Asterolasia buxifolia* (previously only known from an 1835 specimen labelled *Bell's Road Blue Mountains*) (Keith Ingram and P.G. Wilson, pers. comm. 2000). The species was subsequently rediscovered in Hyde Park Reserve at Hartley by R.O. Makinson (Makinson and Benson in prep. 2019).

University of Sydney contributions to botanical research: Mt Wilson and the first ecological studies

At the University of Sydney **Professor Abercrombie Anstruther Lawson** (1870-1927) (Fig. 8), foundation professor of botany from 1913 to 1927 and member of the Linnean Societies of both London and N.S.W., emphasized the importance of field excursions as a teaching technique. He established a teaching herbarium named in honour of botanist John Ray (1627-1705) and provided his own collections as well as specimens collected during various research enterprises (Rayner and Quinnell 2016). Among the holdings there are a number of significant historical collections including about 1500 specimens collected by R.H. Cambage (some of which are likely to have been collected during his time with Woolls), and a set of A.H.S. Lucas' algal collection.

In April 1916, Professor Lawson privately purchased land at Mt Wilson (about 60 acres) from George Valder senior. This aroused his enthusiasm for the diversity of vegetation at Mt Wilson and its outstanding contrasts of geology and vegetation. He formally introduced the newly developing discipline of ecology into the teaching programme and encouraged his staff and the Sydney University Botanical Society (i.e. botany students) to undertake field studies at Mt Wilson. Members of the Botany Department came to Mt Wilson and stayed at *Dennarque* (or *Wildflower Hall* as it was called at that time) and *Campanella*, another guest house, and carried out extensive plant surveys (Mt Wilson and Mt Irvine Historical Society 2006). In the first of three papers Brough et al. (1924) wrote that *the study of Plant Ecology has developed rapidly overseas (in Britain, United States and on the Continent) but little has been carried out so far in N.S.W. despite the innumerable fascinating and important problems awaiting solutions*. A considerable body of material from the surveys was published in three papers in the *Journal and Proceedings of the Linnean Society of N.S.W.* (Brough, McLuckie and Petrie 1924; Petrie 1925; McLuckie and Petrie 1926). Patrick Brough and John McLuckie were lecturers and

FIGURE 8 Professor Abercrombie Lawson, instigator of Sydney University's landmark ecological studies at Mt Wilson, dressed ready for fieldwork. (Source: Sydney University).

Arthur Petrie was a recent graduate whose father had been Linnean Society Macleay Research Fellow. The publications include descriptions of the vegetation on the basalt and sandstone, fire impacts and exotic roadside weeds (Fig. 9). These studies were the first ecological studies to be carried out in N.S.W., the first to look seriously at fire as an ecological issue, and probably the first ecological study of any kind to have been carried out in Australia. Specimens collected by the Mt Wilson researchers held at the John Ray Herbarium (R.Carolin pers comm. 2019), together with Lawson's lantern slides from the Macleay Museum (Rayner and Quinnell 2016) which include a slide of a tree fern *Cyathea australis* that looks to be taken at Mt Wilson, are significant items for the history of ecology in N.S.W.

The John Ray Herbarium also holds collections by its sometime curator and assistant to Lawson, Obed Evans, and by Noel Beadle, who were both major contributors to the first edition of the classic *Flora of the Sydney Region*, (Beadle, Evans and Carolin 1963). This publication made comprehensive botanical field identification accessible for the first time, and has been a major impetus for conservation, particularly in its subsequent revised editions.

Sydney University advances descriptive ecology and botanical education in the 1930s

Lawson died in 1927, but by the early 1930s descriptive ecology was considered a serious university subject. Ecological work begun by him was continued through a series of major studies throughout the state by students, many of whom were women. These studies included the coastal sand dunes of Myall Lakes by Rutherford Robertson in 1934, rainforest and eucalypt forest at Barrington Tops by Lilian Fraser and Joyce Vickery in 1936-37, and the Bulli-Illawarra escarpment vegetation by Consett Davis in 1938.

Eric Ashby at Sydney University 1938-1946

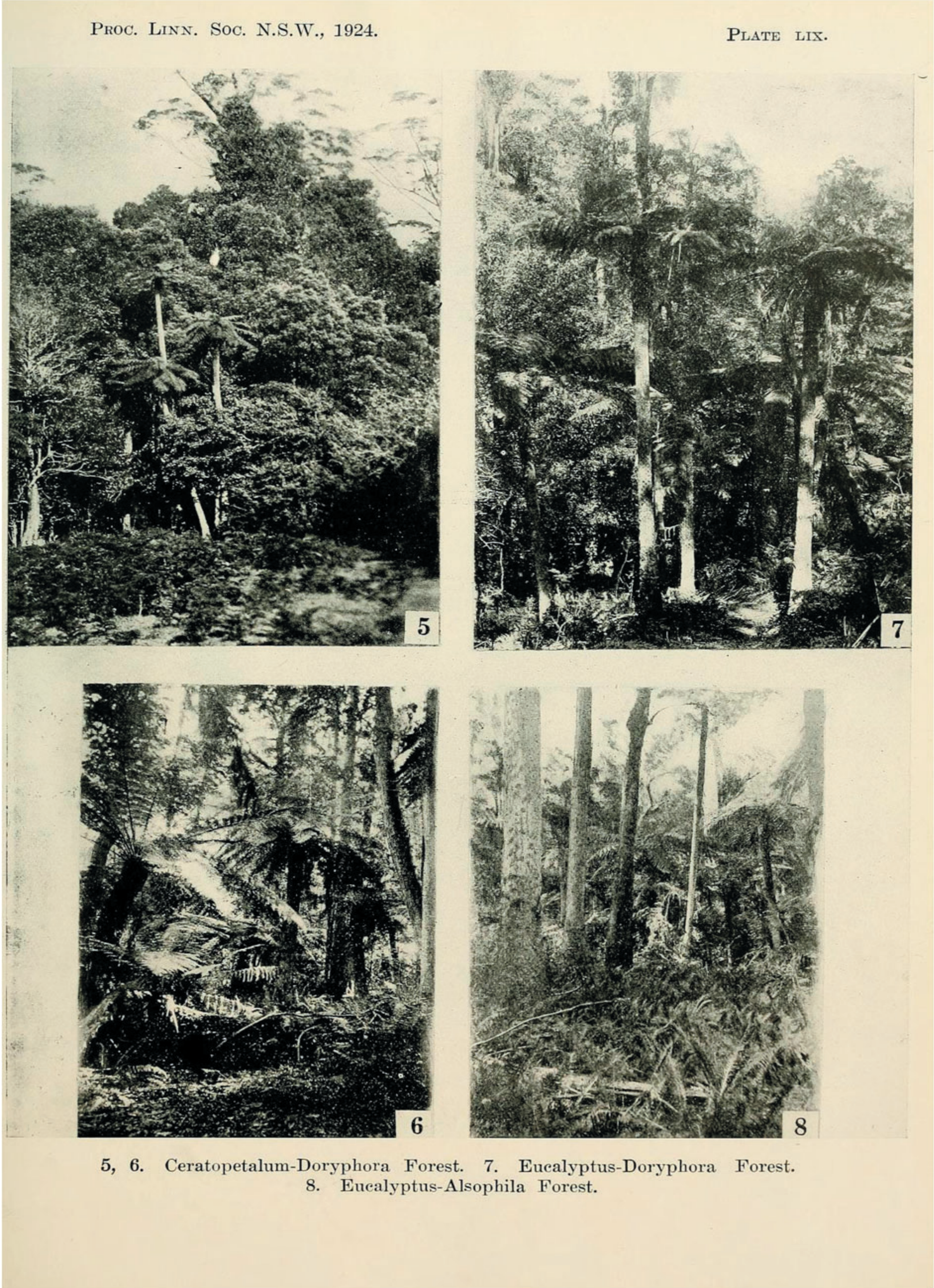
Eric Ashby, later Lord Ashby (1904-1992) and master of Clare College and vice-chancellor of Cambridge University, was appointed professor of botany at Sydney University in 1938 when only 33. Born in Essex and having held lectureships at Imperial College London, Chicago and Bristol, the charismatic Ashby imbued his students with the philosophy of science and rigorous scientific methods. He was enthusiastic about Australian plants and how research could address poor land management practices. He continued Lawson's work and under his influence, Ilma Pidgeon researched sandstone and shale vegetation in the Sydney area from 1937 to 1941 and disturbed plant associations, particularly on mined and overgrazed areas around Broken Hill in western N.S.W. The Mt Wilson researchers Patrick Brough and John McLuckie developed a botany teaching resource known then as '*A key to some of the plants of the Sydney Region*', later expanded and published by Noel Beadle, Obed Evans and Roger Carolin, with substantial assistance from the National Herbarium of N.S.W., as *Handbook of the Vascular Plants of the Sydney District and Blue Mountains* (Beadle, Evans and Carolin 1963). Subsequently, revised editions have become the classic Sydney plant identification handbook *Flora of the Sydney Region* (Beadle et al. 1972 to Pellow et al. 2009).

Ashby supported education at all levels. As noted in his foreword to Gladys Carey's (1941) *Botany by observation - a textbook for Australian schools* Ashby believed the whole purpose of teaching botany at school was defeated if it didn't give children an appreciation and enthusiasm for their own environment. This he considered to be common sense not narrow provincialism (King 2015). John McLuckie went on to write a botany text relevant to Australia and New Zealand (McLuckie and McKee 1954).

Post World War II – baby boomers, public science and the discovery of biodiversity, and that it is threatened

By the mid 20th century research had passed almost completely from the Gentlemen Naturalists to professionals associated with research institutions, though these had limited funding during the previous two decades dominated by the Great Depression and World War II. Linnean Society of N.S.W. publications in 1950 included only two authors who did not have an institutional affiliation as indicated by their addresses (Augee 2010).

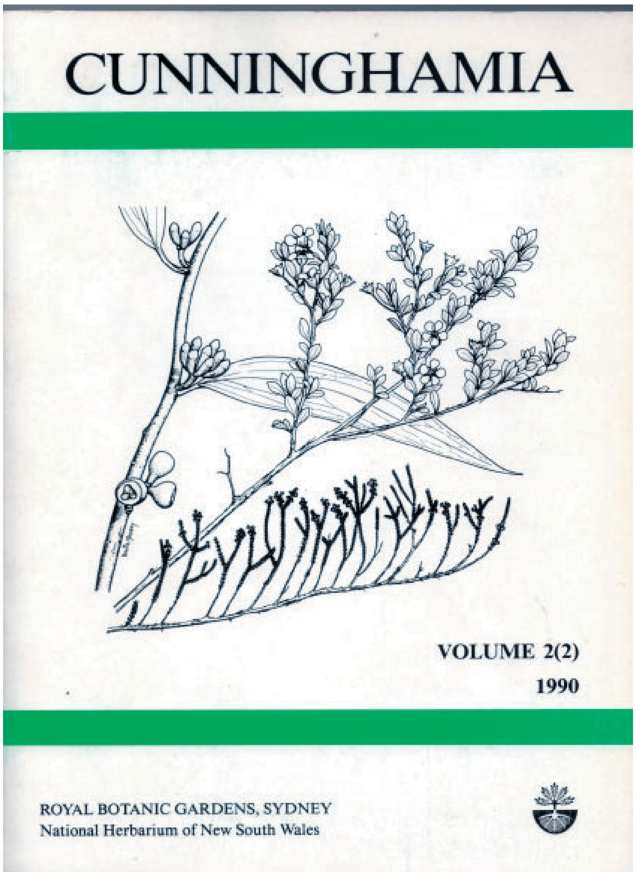
The 1970s brought an increasing interest in the Australian flora by the baby boomer generation (i.e. those born between 1945 and 1960) and increased resources for biological research and publicly funded science. The Australian Biological Resources Study (ABRS) set up by the Whitlam Labor Government provided resources to public institutions across Australia including the National Herbarium of N.S.W. for systematic flora studies, and later for vegetation survey and mapping. Comprehensive identification publications such as the *Flora of Australia* were begun, while the establishment in 1968 of the N.S.W. National Parks and Wildlife Service recognised the need to protect and manage land for nature conservation.



Proc. Linn. Soc. N.S.W., 1924. Plate lix.

5, 6. Ceratopetalum-Doryphora Forest. 7. Eucalyptus-Doryphora Forest.
8. Eucalyptus-Alsophila Forest.

FIGURE 9 Plate from the Sydney University ecological study of Mt Wilson published in 1924 in the Proceedings of the Linnean Society of N.S.W. showing contrasting aspects of the rainforest and eucalypt forest. Though limited by the poor photographic reproduction of the time these are some of the earliest photos to specifically illustrate ecological issues. (Source: Linnean Society of NSW).



CUNNINGHAMIA

VOLUME 2(2)
1990

ROYAL BOTANIC GARDENS, SYDNEY
National Herbarium of New South Wales

FIGURE 10 Journals produced by the National Herbarium of N.S.W. in response to the scientific discoveries of the mid to late 20th century were the *Contributions* (later to become *Telopea*) and *Cunninghamia*: a journal of plant ecology for Eastern Australia. *Cunninghamia* was launched at the 1981 International Botanical Congress in Sydney. The 1990 cover (*Cunninghamia* vol 2 no 2) illustrated three rare plants from the Newnes Plateau– *Eucalyptus gregsoniana* (left), *Leptospermum blakelyi* (centre) and an unusual prostrate form of *Micromyrtus sessilis* (lower). (Source: National Herbarium of NSW).

The Rare or Threatened Australian Plants listing (ROTAP) was established to draw attention to the vulnerability of rare or threatened species (Leigh, Briggs and Hartley 1981), to be followed by the N.S.W. *Threatened Species Conservation Act* in 1995 (now replaced by the current N.S.W. *Biodiversity Conservation Act 2016*).

New and more specialised national biological societies were established, including the Ecological Society of Australia and the Australian Systematic Botany Society, with their own national publishing outlets. These and the journals published by CSIRO led to fewer publications from the old state-based and broader learned societies. The house journals of institutions also increased their publications and readership output, including *Telopea: a journal of plant systematics* and *Cunninghamia: a journal of plant ecology for eastern Australia* from the National Herbarium of N.S.W., and various technical reports and monographs from the Australian Museum (Fig. 10).

With money for trained staff and field work, and four-wheel drive vehicles allowing access to more difficult areas, there was an increase in plant collecting, description and ecology. Interesting plant collection sites from earlier in the century were now revisited and explored further. The Newnes State Forest had been the site of a number of earlier collections by Gregson (unusual mallee eucalypts), Deane (*Boronia deanei* – Fig.11) and Blakely (*Leptospermum* and *Dillwynia* species). Access to the area now known as the Newnes Plateau was along the old Bells Line of Road, and the old Wolgan Valley railway route and various forestry tracks.

FIGURE 11 *Boronia deanei,* first collected by Henry Deane in 1906 near Clarence, was not subsequently seen until 1978, when its rediscovery during vegetation survey work was greeted enthusiastically by Botanic Gardens ecology assistant Helen Bryant. At that time scientific publications were still limited to black and white illustrations. *Boronia deanei* is now endangered as a result of longwall coalmining causing drying out of its restricted swamp habitat, (Source: author).

Collecting trips and research projects were undertaken by a number of botanists from the National Herbarium of N.S.W. including Lawrence Johnson (mallee eucalypts, Proteaceae), Tony Rodd (rainforest and general collecting), Peter Hind (general collecting, rare plants) Peter Weston (*Persoonia* systematics) and Doug Benson (vegetation mapping (Benson and Keith 1990); rare plants and environmental impact assessment).

Peter Hind, for example, spent considerable time collecting on the Newnes Plateau, much of it in his own time. In describing *Prostanthera hindii* (Hind was a joint collector of the type material), Conn (1997) stated that '*the specific epithet acknowledges the considerable contribution that Mr Peter Hind (NSW) has made to our understanding of the flora of Australia, and in particular of the Newnes Plateau of the Wollemi National Park*.' Similarly, Weston and Johnson (1997) named *Persoonia hindii* for Peter Hind '*who first collected this species*.'

The 1970s also brought major environmental threats to the area. Proposals by the N.S.W. Electricity Commission in 1978 to dam the Colo River and construct a power station at Birds Rock on the Newnes Plateau were met with fierce public opposition. One benefit was that newly required environmental impact surveys provided some basic data on the poorly known area. The threatened dam was stopped by the declaration of Wollemi National Park in 1979, but the power station proposal was replaced by the proposed Birds Rock Colliery with associated coal washery and a rail link to the main western railway line (Birds Rock Colliery 1981a,b). Botanical surveys of the proposed site by the Royal Botanic Gardens Sydney highlighted the importance of the Newnes Plateau shrub swamps, some of which were directly impacted by the colliery infrastructure and rail line (D. Benson appendices in Birds Rock Colliery 1981a,b). A public inquiry approved the colliery development but subsequently changing economic conditions prevented its establishment. Coal mining under the Newnes Plateau is now being done by longwall mine extraction from collieries on the margins of the plateau, and is now threatening the swamps through water loss by subsidence impacts (Benson and Baird 2012).

Interest in biodiversity of small, delicate and rare organisms in the late 20th century led to work on bryophytes and fungi, particularly by Macquarie University School of Biological Sciences; e.g. bryophytes of Mt Tomah (Ramsay et al. 1990); bryophytes at Mt Wilson, Mt Banks and Mt Tomah (Downing et al. 2007); fungi at Mt Wilson (Alec Wood and the Sydney Fungal Studies Group). Interest in swamps has led to a number of pollen studies at Mountain Lagoon and Newnes Plateau (e.g. Robbie and Martin 2007), and exploration of fire histories, e.g. at Gooches Crater (Black, Mooney and Attenbrow 2008).

Geomorphology studies by Macquarie University have included one on landform erosion associated with lyrebirds at Calcined Knoll at Bell (Adamson, Selkirk and Mitchell 1983) and studies on the Newnes Plateau, including recognition of Last Glacial maximum sand dunes with implications for past climates (Hesse et al. 2003) and unusual heath/geomorphology relations (Wilkinson and Humphreys 2006). Since 2000 increasing attention has been directed to the geological diversity and importance of the sandstone pagoda country of the Newnes Plateau (Washington and Wray 2011), currently proposed for National Heritage Listing (Washington and Wray 2015).

The Wollemi Pine and World Heritage Listing

The ongoing contribution of enthusiast bushwalkers and their exploration of hitherto inaccessible country resulted in the exciting discovery of the Wollemi Pine *Wollemia nobilis* in 1994. The discovery received wide international attention. *Wollemia* is a genus of coniferous tree in the family Araucariaceae known only through fossil records until the living species *Wollemia nobilis* was discovered in a remote series of narrow, steep-sided sandstone gorges in a wilderness area of Wollemi National Park, north of Bells Line of Road. The discoverer, David Noble, a National Parks field officer with adventurous bushwalking and rock climbing abilities, and good botanical knowledge, quickly recognised the trees as unusual and worthy of further investigation. Generating considerable research interest, the species was described jointly by N.S.W. National Parks and Royal Botanic Gardens botanists and named to honour both its discoverer and the tree's stature (Jones et al. 1995).

The Greater Blue Mountains including Wollemi and Blue Mountains National Parks, was inscribed on the World Heritage list in 2000 for its outstanding biodiversity, particularly in terms of the richness of eucalypt diversity (almost 100 species – Hager and Benson 2010). About 1 million hectares are now protected in the Greater Blue Mountains World Heritage Area. This happened after decades of public pressure (Colley and Gold (2004), but the listing was dependent on the strong scientific case for its success. The extensive body of research publications and biodiversity collection data relating to Bells Line of Road and the Newnes Plateau area (highlighted by the Wollemi Pine in the Wollemi National Park farther north) provided a substantial part of the case for listing the Greater Blue Mountains as a World Heritage Area. The assessment report by botanist Teresa James (1994) included chapters on sclerophyll ecosystems by James and Phillip Kodela, and on rainforests by Gwen Harden.

Unfortunately, much of the Newnes Plateau, a key destination of the *Botanists Way*, was not included in that listing (as it was, and remains, part of Newnes State Forest rather than national park), and significant vegetation (montane swamps and mires, and rare species) remains threatened, particularly by subsidence from longwall coal mining. By 2017 several important listed swamps had been impacted by subsidence, evident in piezometer data and visible in dying vegetation and lack of groundwater, and unlikely to recover (Young 2017). Since the first plans to mine the area in the 1980s a vigorous community-based campaign for protection of the Gardens of Stone Stage 2, covering much of this area has been waged by conservation groups, particularly the Colong Foundation, and the final outcome for the long-term management of the area is still in doubt in 2019. Future decisions on its conservation and management will be an important part of the ongoing Botanists Way story.

DISCUSSION

Evaluation of the *Botanists Way*

Is the botanical history of the area promoted as the *Botanists Way* unique? Did botanical exploration happen similarly along other geographical corridors radiating from Sydney? What about the Western Road (now Great Western Highway) across the Blue Mountains, or the roads to the Illawarra (Princes Highway) or to Goulburn (Hume Highway), or the road to the coast north of Newcastle (Pacific Highway)? At this stage no similar case has been made for any of these areas. Perhaps the geology along the Bells Line of Road was important - the ridge is relatively narrow with few easy deviations except for the basalt-capped mountains. Early botanical visitors were attracted to the rainforest vegetation, the easily accessible shale areas around Kurrajong, and later the basalt caps of Mt Tomah and Mt Wilson with their red soils, rainforests and ferns. These mounts are not as prominent or easily accessible from the Western Road, though similar basalt country does occur in the Southern Highlands (Mittagong to Robertson). These areas were attractive places, in a cool climate, and the wealthy in Sydney set up country retreats with attractive European-style gardens, yet overlooking the rugged Australian sandstone country beyond. As a result the Bells Line of Road may have attracted a higher proportion of botanically interested people, with the time to explore, collect plants seriously and correspond with experts. Because of its relative inaccessibility generally needing four-wheel drive access, the Newnes Plateau with its interesting plant species and the highest altitude sandstone landscape in the Blue Mountains attracted botanical interest later than the Western Road at Katoomba or Blackheath.

The *Botanists Way* route is now mostly through national parks (Blue Mountains and Wollemi) and its natural landscape is relatively little disturbed. It has not been heavily overlaid by development, unlike the Western Road which, though passing through national park, carries the history and impacts of the first crossing of the Blue Mountains (the Bicentenary was celebrated in 2013), the development of the Blue Mountains towns, the building of the railway to the interior, and the subsequent impacts of tourism and recreation. Bells Line of Road has been primarily a narrow transport corridor, but there are likely to be further impacts in the near future. Currently (2019) the proposed Castlereagh Connection motorway corridor route from Castlereagh to Bells Line of Road at Kurrajong potentially threatens significant remnant rainforest vegetation at Grose Vale, and future motorway upgrading along Bells Line of Road is likely to impact World Heritage listed vegetation and impose a substantial barrier on north-south faunal migration and movement. An increase in wildlife road-kills is likely to result from increased traffic in the short term, while widening of the road will reduce genetic connectivity in the longer term unless provision is made for faunal crossings.

The Way forward

As originally promoted by the Blue Mountains Botanic Garden, the *Botanists Way* concept referred to a relatively narrow geographical corridor between Kurrajong and Mt Tomah. However, the rich biodiversity of the surrounding area and its associated botanical history as discussed above justify expanding the concept to include reference to the Newnes Plateau (Glow-worm Tunnel Road), as well as Chifley Road west to Lithgow (although that road was only completed to Lithgow during World War II). At the eastern end botanical connections can be extended to Richmond and Windsor.

The historical reach of the concept should also be expanded. The original focus on the early 19th century botanists should be enlarged to include the late 19th century scientific connections, and the importance of the Linnean Society of N.S.W. publications, as well as 20th century botanical exploration and ecological research, the funding of public-good science, and the impact that this has had on conservation biology research and nature conservation in the present time.

There is a growing demand for 'nature tourism', and biodiversity and landscape research should underpin responses. 'Nature tourism' was important in the late 19th century, it is not something new, even if it was in relative decline for much of the 20th century. The natural landscape elements along the *Botanists Way* that attracted botanical interest over nearly two centuries, and the use of botany to explore and interpret the environment, can be successful from a range of perspectives, not only the plants and sites themselves, but to explain the science of systematic biology and the underlying basis of evolution. Interpretation can also be enriched by highlighting the (still surviving) use of Latin in the modern world, and the often obscure meanings of the Greek and Latin derived plant names, or the persons honoured (e.g. see Table 1). Botanical art and biography are important cultural history elements (e.g. Louisa Atkinson's illustrations). Authenticity accentuated through tangible connections to plants and places can stimulate and enrich educational and visitor experiences. Such demands have led to the recent development of university studies bringing together botanical art and history such as at the University of Newcastle's School of Creative Industries.

All this provides a rich palette of interconnecting material for organisations interested in landscape and biodiversity interpretation, such as the Blue Mountains Botanic Garden, National Parks and Wildlife Service, the Greater Blue Mountains World Heritage Area, the National Trust of Australia, Western Sydney University, Blue Mountains City Council and Hawkesbury City Council. The area provides considerable scope for both botanical scientific research and biographical studies. Note the recent interest in Hassans Walls Reserve, Lithgow, its history (Painter 2017) and its botany (Lollback et al. 2014), the latter a cooperative project with serious enthusiast naturalists, a photographer and a professional plant collector. Botanical exploration continues.

Future Ways for Botanical Research

Though the *Botanists Way* of this story is focused on a limited geographic area, similar scientific activities and trends (the initial colonial botanical exploration, the later 19th century Gentlemen Naturalists and learned societies, leading to the 20th century publicly-supported research institutions and professional conservation management) were also happening interstate, largely paralleled in and around Melbourne, Brisbane, Perth, etc. It is important to recognise that public-good science in largely government-funded institutions, is a relatively recent development that has been particularly successful and influential in the last 50 years (i.e. essentially in the lifetimes of current researchers). Despite recognition of its obvious successes it is not necessarily a permanent feature of our culture and remains vulnerable to the prevailing political climate. The interest in biodiversity, the recognition of threats such as rainforest clearing and urban expansion, and the need for better conservation measures generated public attention at all levels in the 1960s and 70s. Robertson (1974) related higher levels of science teaching in schools to an increased community awareness in science at that time.

However, the subsequent achievement of major conservation aims in the 1980s and 90s (such as cessation of rainforest logging in N.S.W., the formalisation of wilderness areas, and legislation for environmental protection and threatened species) are mainly dependent on public funding for on-going governance and management. Enactment of legislation may have given the public assurances that environmental and conservation issues are now being appropriately dealt with, but this is not necessarily the case. Decreased public attention provides opportunities to reduce funding commitments and weaken protection legislation (indeed we have retreated a long way from the high point of the 1990s). Publicity for big issues such as climate change also draws attention away from local conservation funding needs.

The 21st century is bringing further changes. While the formal professionalism and support for publicly-funded biological science has reduced the need for inputs from amateur naturalists and enthusiasts (i.e. the equivalent of the Gentleman Naturalist), such people (often professionals in related fields) still exist and make important contributions, for example, in the exploration of remote areas (the discovery of new species such as the Wollemi Pine stands out), or by observations on ecology and geographic ranges of small, generally economically unimportant and less studied taxa such as bryophytes, fungi, lichens and invertebrate taxa. Opportunistic research by enthusiasts can draw attention to and kickstart

Table 1 (next page). Plant species and landscape features honouring or discovered by botanists associated with the Botanists Way. All species are found in the Botanist Way area except *Acacia carneorum*.

Plant species	**Name**	**Notes**
Acacia carneorum Maiden	Joseph Carne and Walter Mervyn Carne	Western N.S.W. shrub species honouring both the Carnes. The Latin ending is genitive plural meaning *of the Carnes*
Acacia maidenii F. Muell.	Joseph Henry Maiden	Large wattle of forest environments
Alania endlicheri Kunth	Allan Cunningham	Small, cliff-dwelling lily essentially confined to the higher Blue Mountains
Atkinsonia ligustrina (Cunn. ex F. Muell.) F. Muell.	Caroline Louisa Atkinson	Interesting shrub mistletoe that parasitises the roots of other plants
Blechnum gregsonii (Watts) Tind.	Jesse Gregson	Cool rainforest fern
Boronia deanei Maiden and Betche	Henry Deane	Rare Newnes Plateau swamp shrub found by Deane
Dictymia brownii	Robert Brown	Epiphytic rainforest fern
Eucalyptus baeuerlenii F. Muell.	Wilhelm Baeuerlen	Small tree on cliff ledges, Upper Blue Mountains
Eucalyptus bensonii L.A.S. Johnson and K.D. Hill	Douglas Benson	Rare mallee from northern Wollemi found by Benson
Eucalyptus cunninghamii G. Don	Allan Cunningham	Rare mallee, Mt Banks
Eucalyptus deanei Maiden	Henry Deane	Tall tree on shale caps and in deep sandstone gorges.
Eucalyptus gregsoniana L.A.S. Johnson and Blaxell	Jesse Gregson and Edward Gregson	Rare Newnes Plateau mallee from honouring the Gregsons
Hakea constablei L.A.S Johnson	Ernest Constable	A prickly shrub in the Mt Wilson-Bell area found by Constable
Isopogon fletcheri F.Muell.	Joseph Fletcher	Rare shrub confined to wet cliffs near Blackheath
Kunzea cambagei Maiden and Betche	Richard H Cambage (1859–1928)	Rare Mt Werong shrub recently reported from the Newnes Plateau
Leptospermum blakelyi Joy Thomps.	William Faris Blakely	Rare Newnes Plateau shrub found by Blakely
Persoonia hindii P.H.Weston and L.A.S. Johnson	Peter Hind	Rare Newnes plateau shrub found by Peter Hind
Viola caleyana G. Don	George Caley	Wet sites, Blue Mtns
Wollemia nobilis Hill Jones	David Noble	Very restricted conifer found in 1994 by Noble
Woollsia pungens (Cav.) F. Muell.	William Woolls	Common shrub in heath / open forest; monotypic genus
Landscape connections		
Browns Ridge	Robert Brown	Grose Vale
Carne Creek	Joseph Carne	Newnes Plateau
du Faurs Rocks	Ecleston Du Faur	Mt Wilson
Mount Banks	Sir Joseph Banks	Upper Grose valley
Mount Caley	George Caley	Upper Grose valley

fields of research on taxa not previously considered mainstream by funding bodies. Enthusiasts can also provide much needed public interest and public support, and is currently being seen in the Citizen Science movement. The potential here was recognised by Robertson in 1974 *...I am glad that I have lived long enough to realise that we need people like Clarke, Waterhouse, Lucas, Copland and others. The reason for the paucity of knowledge of biology and geology in district details in this country, compared with such knowledge in Britain, is that such people are so thin on the ground. The ordinary member here, with his notes and publications, has an important role to play in the establishment of this kind of science.*

The cuts to public-good science in the last decade have been associated with the promotion of the virtues of Citizen Science, often to disguise holes in professional staff. Citizen Science has and will continue to have a major role, but scientists and citizens should be equal partners, rather than the citizens being cheap data-collecting options for a dwindling number of professionals.

The formal publication of a scientific paper with its considered ideas and conclusions, based on an acknowledged body of available data, together with formal review by scientific peers, and long-term availability, remains the bedrock of scientific progress in the biological sciences. Issues in knowledge dissemination through the electronic media include substantial charges for publications and the use of citation indices to evaluate researchers (favouring international over local publications). Opportunities to reduce costs may cause publicly-funded institutions to reduce their role in the science publication process (as they have reduced their role in supporting technical libraries), leaving biodiversity researchers (particularly those doing local biodiversity projects) with limited outlets for peer-reviewed formal publication. The last few years has also seen implementation of policies in publicly-funded institutions that increase dependence on short term grant funding, and often involve reductions in permanent long term employment of scientists and loss of institutional memory. Science is a slow and careful process that builds on the progress of past workers, as the history of the Botanists Way shows.

Particularly on local or regional biodiversity and conservation issues, freely accessible scientific publication needs continued support from scientific societies such as the Ecological Society of Australia and the old learned societies as Martin (2015) indicates for the Linnean Society (though often now with reduced and aging memberships). It cannot be assumed that the huge advances in scientific knowledge relating to biodiversity that have been achieved in the last 60 years (i.e. essentially in the lifetimes of current researchers) will necessarily continue.

ACKNOWLEDGEMENTS

Peter Lister, Western Sydney University (formerly Hawkesbury Agricultural College), provided new ideas on the importance of Hawkesbury Agricultural College; Many colleagues have assisted me in fieldwork along the Botanists Way over the years but Peter Hind has always provided outstanding collecting enthusiasm; Paul Adam and several anonymous referees provided careful and insightful comments on the manuscript which were much appreciated. My time and colleagues on the GBMWHA Advisory Committee convinced me that a more extended account of the Botanists Way was needed.

REFERENCES

Adamson, D., Selkirk, P.M. and Mitchell, P. (1983). The Role of Fire and Lyre Birds in the Sandstone Landscape of the Sydney Basin. In *Aspects of Australian Sandstone Landscapes* (Eds. R.W. Young and G.C. Nanson) pp. 81-93. Australian and New Zealand Geomorphology Group Special Publication No. I. 1983.

Andrews, A.E.J. (1984*) The Devil's Wilderness: George Caley's journey to Mount Banks 1804*. Blubber Head Press: Hobart.

Augee, M. L. (2010) From gentlemen naturalists to professional scientists - the changing nature of the Linnean Society in Sydney. Pp56 - 57 in *The Natural History of Sydney*, Daniel Lunney, Pat Hutchings and Dieter Hochuli (Eds). Royal Zoological Society of N.S.W., Mosman, N.S.W., Australia.

Beadle, N.C.W., Evans, O.D.and Carolin, R.C. (1963) *Handbook of the Vascular Plants of the Sydney District and Blue Mountains*. The author, Armidale.

Beadle, N.C.W., Evans, O.D., Carolin, R.C. and Tindale, M.D. (1972*) Flora of the Sydney Region.* Reed, Sydney.

Benson, D. and Baird, I.R.C. (2012). Vegetation, fauna and groundwater interrelations in low nutrient temperate montane peat swamps in the upper Blue Mountains, New South Wales. *Cunninghamia* **12**, 267-307. https://www.rbgsyd.nsw.gov.au/getmedia/e1dd703e-ace9-4e9a-ab02-f32cd1c7636b/cun124ben267.pdf.aspx

Benson, D. and Keith D.A. (1990) The natural vegetation of the Wallerawang 1:100 000 map sheet. *Cunninghamia* **2**, 305-335.

Benson, D. (2012) The Grose Vale flora and the value of documenting botanically interesting sites. *Cunninghamia* **12**, 229–238.

https://www.rbgsyd.nsw.gov.au/getmedia/8ec1ace4-b6f3-498e-a40c-13c1637dbc5f/Cun123ben229.pdf.aspx

Birds Rock Colliery (1981a) *Environmental Impact Statement January 1981*. EIS362 AB018983 pdf.

Birds Rock Colliery (1981b) *Review of Environmental Impact Statement submissions May 1981*. EIS463 AB019122 pdf

Black, M. P., Mooney, S. D. and Attenbrow, V. (2008) Implications of a 14,200 year contiguous fire record for understanding human-climate relationships at Goochs Swamp, New South Wales, Australia. *The Holocene* **18**, 437-447.

Blythe, R. (1979) *The View in Winter: Reflections on Old Age*. Penguin Books: Harmondsworth, England.

Brough, P., McLuckie, J. and Petrie, A.H.K. (1924) An ecological study of the flora of Mount Wilson. I. The vegetation of the basalt. *Proceedings of the Linnean Society of New South.Wales* **49**, 475–498.

Carey, G.(1943) *Botany by observation: a textbook for Australian schools Sydney*: Angus and Robertson.

Carne, J. E. (1908) The geology and mineral resources of the western coalfields. *Memoirs of the Geological Survey of New South Wales* **6**, 64–152.

Carne, W.M. (1910) Note on the occurrence of a limestone–flora at Grose Vale. *Proceedings of the Linnean Society of New South Wales* **35**, 849–858.

Colley, A. and Gold, H. (2004) *Blue Mountains World Heritage*. The Colong Foundation for Wilderness Ltd: Sydney.

Conn, B.J. (1997) Four rare and/or threatened new species of *Prostanthera section Prostanthera* (Labiatae) from New South Wales. *Telopea* **7**, 231-244.

Dept of Environment and Climate Change (N.S.W.) (2008) *Greater Blue Mountains Drive*. DECC.

Downing, A.J., Brown, E.A., Oldfield, R.J., Selkirk, P.M. and Coveny, R. (2007) Bryophytes and their distribution in the Blue Mountains region of New South Wales *Cunninghamia* **10**, 224-254.

Fletcher, J.J. and Musson, C.T. (1918) Certain shoot-bearing tumours of eucalypts and angophoras, and their modifying influence on the growth habit of the plants. *Proceedings of the Linnean Society of New South Wales* **43**, 191-233.

Gilbert, L. (1980) *Excursions from Berrima and a trip to Manaro and Molonglo in the 1870's by Lousia Atkinson*. Mulini Press Canberra.

Gilbert, L. (1985) *William Woolls – A Most Useful Colonist'* Mulini Press, Canberra.

Gilbert, L. (2001) *The little giant: the life and work of Joseph Henry Maiden 1859-1925.* Kardoorair Press, Armidale.

Gregson, E.J. (1952) Eucalypts of Mt Wilson and Mt Irvine; New South Wales. *Victorian Naturalist*, **68**.

Gregson, J. (1902-3) Lichens collected at Mount Wilson (unpub. copy held at Royal Botanic Gardens Sydney Library).

Groves, R.H. (2017) *Foreword to the Third Edition*. In D.A.Keith. ed., *Australian Vegetation*, 3rd edn. Cambridge: Cambridge University Press.

Hager, T. and Benson, D. (2010) The Eucalypts of the Greater Blue Mountains World Heritage Area: distribution, classification and habitats of the species of *Eucalyptus, Angophora* and *Corymbia* (family Myrtaceae) recorded in its eight conservation reserves *Cunninghamia* **10**, 425–444.

Hall, N. (1978) *Botanists of the Eucalypts*. CSIRO Australia.

Hamilton, A.G. (1899) On the flora of Mt Wilson. *Proceedings of the Linnean Society of New South Wales* **24**, 346-372.

Hesse, P.P., Selkirk, P.M., Adamson, D.A,, Gore, D.B., Nobes, D.C., Price, D.M., Schwenninger, J.L., Smith, B.S., Tulau, M. and Hemmings, F.(2003) Late Quaternary aeolian dunes on the presently humid Blue Mountains, Eastern Australia. *Quaternary International* **108**, 13-32.

Heward, R.(1842) Biographical sketch of the late Allan Cunningham, F.L.S., M.R.G.S.. *Journal of Botany* (London) Volume 42.

Ingram, C. K. (1972) Checklist of the flora of Mount Tomah (600 species). Unpub. ms. Royal Botanic Gardens Sydney Library.

James, T.A. (1994) An assessment of the World Heritage Values of the Blue Mountains and surrounding plateaus. Royal Botanic Gardens, Sydney.

Jones, W.G., Hill, K.D. and Allen, J.M. (1995). Wollemia nobilis, a new living Australian genus and species in the Araucariaceae. *Telopea* **6**, 173–176.

King, R.J. (2015). Early Australian botany texts for schools. *Proceedings of the Linnean Society of New South Wales* **137**, 45-55.

Lawson, E. (1995) *The natural art of Louisa Atkinson*. State Library of New South Wales Press: Sydney.

Lee, I. (1925) *Early explorers in Australia*. Methuen, London.

Lister, P. R. ed. (2017). *An Introduction to the Botany of New South Wales 1926-1929: Charles T. Musson*. (P.R. Lister: Richmond).

Lister, P. R. (2017) *Charles Tucker Musson FLS 14th December 1856 – 9th Dec. 1928 Staff member Hawkesbury Agricultural College 1891-1919* pdf.

Lollback, S., Drewe, H., Coveny, R. and Durie, K. (2014) *Native Plants: Hassans Walls Reserve Lithgow*. (The authors: Lithgow).

Mabberley, D.J. (1985) *Jupiter botanicus Robert Brown of the British Museum.* British Museum (Natural History), London.

McLuckie, J. and McKee, H.S. (1954) *Australian and New Zealand Botany*. Horwitz-Grahame: Sydney.

McLuckie, J. and Petrie, A.H.K. (1926) An ecological study of the flora of Mount Wilson. III. The vegetation of the valleys. *Proceedings of the Linnean Society of New South Wales* **51**, 94–113.

McMinn, W.G. (1970) *Allan Cunningham: Botanist and Explorer*. Melbourne University Press: Melbourne).

Maiden, J.H. (1889) *The Useful Native Plants of Australia* (Facsimile edit. 1975 Compendium: Melbourne).

Maiden, J.H. (1909) *Sir Joseph Banks: the 'Father of Australia'* (Govt Printer Sydney).

Maiden, J.H. and Cambage, R.H. (1905) Notes on the eucalypts of the Blue Mountains. *Proceedings of the Linnean Society of New South Wales* **30**, 190-202.

Makinson, R.O. and Benson, D. (in prep 2019) '*Rich in the botanical and picturesque'*: the remnant granite flora of the River Lett, Hartley, N.S.W.: its botanical history and significance.

Martin, H.A (2015) The story of Science House and the history of the Linnean Society of New South Wales. *Proceedings of the Linnean Society of New South Wales* **137**, 57-70.

Mt Wilson and Mt Irvine Historical Society (2006) *Newsletter* No 13 page 11.

Musson, C. T. and Fletcher, J. J. (1927) On a case of natural hybridism in the genus *Grevillea* (N.O. Proteaceae). *Proceedings of the Linnean Society of New South Wales* **52**: 122-132.

O'Brian, P. (1987) *Joseph Banks: a Life*. (Collins Harvill: London).

Orchard, A.E.and Orchard, T.A. (2015) *Allan Cunningham : letters of a botanist/explorer, 1791-1839.* Tony Orchard, Weston Creek, A.C.T.

Painter, K. (2017) *Hassans Walls - prized and pillaged.* www.mountainmistbooks.com.

Pellow, B.J. Henwood, M.J and Carolin, R.C. (2009) *Flora of the Sydney region.* 5th edition, Sydney University Press.

Petrie, A.H.K. (1925) An ecological study of the flora of Mount Wilson. II. The Eucalyptus forests. *Proceedings of the Linnean Society of New South Wales* **50**, 145–166.

Powell, J. and James, T. (1993) *Epacris sparsa* (Epacridaceae) reinstated. *Telopea* **5**, 375-380.

Rayner, A. and Quinnell R. (2016) Coloured by hand. *Muse* No 15 pp 22-23 University of Sydney.

Robbie, A. and Martin, H. A. (2007) The History of the Vegetation from the Last Glacial Maximum at Mountain Lagoon, Blue Mountains, New South Wales. *Proceedings of the Linnean Society of New South Wales* **128**, 57-80.

Robertson, R. N. (1974) Sir William Macleay Memorial Lecture, 1974. A Society of Natural History. I hope they may succeed. The first hundred years. *Proceedings of the Linnean Society of New South Wales* **99**: 69-78.

Thompson, M.M.H. (1986) *William Woolls, a man of Parramatta*. Hale and Iremonger, Sydney.

Trebeck, P.N. (1886) Mount Wilson and its ferns. *Proceedings of the Linnean Society of New South Wales* (2)1, 491-496.

Vallance, T.G., Moore, D.T. and Groves, E.W. (2001) *Nature's Investigator: The Diary of Robert Brown in Australia, 1801-1805*. Australian Biological Resources Study: Canberra.

Washington, H. (2004). Wollemi, and the Colo. Chap. 5 in Colley, A. and Gold, H. (2004) *Blue Mountains World Heritage*. The Colong Foundation for Wilderness Ltd: Sydney.

Washington, H. and Wray, R. (2011) The geoheritage and geomorphology of the sandstone pagodas of the north-western Blue Mountains region (N.S.W.). *Proceedings of the Linnean Society of New South Wales* **132**, 131-143.

Washington, H. and Wray, R. (2015) Recognising new values: the geodiversity and geoheritage of the Greater Blue Mountains. Chapter 1 in *Values for a new generation: Greater Blue Mountains World Heritage Area.* Greater Blue Mountains World Heritage Area Advisory Committee.

Weston, P.H. and Johnson, L.A.S. (1997) *Persoonia hindii* (Proteaceae), a new species from the Newnes Plateau, New South Wales. *Telopea* **7**, 199-203.

Wilkinson, M. and Humphreys, G.S. (2006) Slope aspect, slope length and slope inclination controls of shallow soils vegetated by sclerophyllous heath—links to long-term landscape evolution. *Geomorphology* **76**, 347-362.

Wilson, E. (2004) *Poetry of Place: Royal Botanic Gardens, Sydney*. Botanic Gardens Trust.

Woolls, W. (1867) *A contribution to the flora of Australia* (F White: Sydney).

Woolls, W (1887) A glance at the flora of Mount Wilson. *Proceedings of the Linnean Society of New South Wales* (2)2: 6-12.

Young, A. (2017) *Upland swamps in the Sydney region*. The author, Thirroul, N.S.W.

APPENDIX. A chronological listing of the main events associated with the Botanists Way and some of the associated people, their lifespans, roles and areas of interest.

	Name	Lifespan	Role	Area of interest
Colonial botanists sent by Sir Joseph Banks (1743-1820)				
	George Caley	1770-1829	naturalist collector	Richmond to Mt Banks (1804)
	Robert Brown	1773-1858	botanist	Lower Grose River
	Allan Cunningham	1791-1839	botanist, explorer	Followed Hoddle's survey west to Mt Tomah (1823)
19th Century local botanists				
	William W Woolls	1814-1893	Clergyman, school master, botanist	Richmond to Mt Wilson
	Caroline Louisa Waring Atkinson (later Mrs Calvert)	1834-1872	botanist, botanical artist	Kurrajong
Collectors and correspondents, the scientific societies particularly the Linnean Society of N.S.W.				
	Eccleston Du Faur	1832-1915	Lands Dept officer	Grose Valley, Mt Wilson
	Wilhelm Baeuerlen	1845-1917	collector	Grose Valley (1899)
	Jesse Gregson	1837-1919	correspondent	Mt Wilson
	Henry Deane	1847-1924	railway engineer, botanist	Newnes Plateau
	Joseph James Fletcher	1850-1926	teacher, zoologist, botanical collector	collected at Kurrajong (1886)
	Richard Hind Cambage	1859-1928	mining engineer, botanist	botanical history and collecting
	Charles Tucker Musson	1856-1928	botany lecturer Hawkesbury Agricultural College	education, botany
	Walter Mervyn Carne	1885-1952	botany lecturer, Hawkesbury Agricultural College	Grose Vale limestone vegetation
	Edward Gregson	1882-1955	correspondent	Mt Wilson
Nationally focussed botanical research begins				
	Joseph Henry Maiden	1859-1925	botanist, Director, Sydney Botanic Gardens	Kurrajong to Mt Tomah (1890s)

	William Faris Blakely	1875-1941	Botanist, Sydney Botanic Gardens	Upper Blue Mtns, Newnes Plateau
The first significant plant ecology studies in N.S.W. 1920-1925 and continued botanical research				
	Abercrombie Anstruther Lawson	1870-1927	Foundation Professor of Botany, Sydney University	Mt Wilson
	Patrick Brough	1885-?	botany lecturer, Sydney University	Mt Wilson
	John McLuckie	1895-1956	ecologist, botanist, Sydney University	Mt Wilson
	Arthur H.K. Petrie	1904-1942	science graduate Sydney University, later plant physiologist	Mt Wilson
	Eric Ashby	1904-1992	Professor of Botany, Sydney University1938-46	Ecology, education
Post World War II activity				
	Ernest Constable	1903-1986	collector, Royal Botanic Gardens Sydney	Mount Tomah area (1950 to 1967)
	Lawrence A.S. Johnson	1925-1997	botanist, Director Royal Botanic Gardens Sydney	upper Blue Mtns, Newnes Plateau
The 1970s, conservation and science expands				
	Keith Ingram	1912-2002	teacher, plant collector	Mt Tomah
	Donald F. Blaxell	current	botanist, Royal Botanic Gardens Sydney	upper Blue Mtns
	Peter Valder	current	botanist, Sydney University	gardens, Mt Wilson
	Anthony N. Rodd	current	botanist, Royal Botanic Gardens Sydney	upper Blue Mtns
	Douglas Benson	current	plant ecologist, mapping, swamps Royal Botanic Gardens Sydney	upper Blue Mtns, Newnes Plateau swamps
	Peter Hind	current	collector Royal Botanic Gardens Sydney	Newnes Plateau
	Peter H. Weston	current	botanist, Royal Botanic Gardens Sydney	upper Blue Mtns
	Alison Downing	current	botanist Macquarie uni	Mt Wilson ferns and bryophytes
	Patricia Selkirk	current	botanist Macquarie uni	Mt Wilson ferns and bryophytes

The Wollemi Pine discovery and description 1995				
	David Noble	current	bushwalker, ranger	discovered *Wollemia*
	Wyn Jones	current	scientist, ranger	described *Wollemia*
	Jan Allen	current	Blue Mtns Botanic Garden	described *Wollemia*
	Kenneth D. Hill	1948-2010	taxonomist, Royal Botanic Gardens Sydney	described *Wollemia*
Listing of the Greater Blue Mountains World Heritage Area 2000				
	Teresa James	current	botanist, Royal Botanic Gardens Sydney	World Heritage submission
	Phillip Kodela	current	botanist, Royal Botanic Gardens Sydney	World Heritage submission
	Tim Hager	current	botanist, NPand WS	World Heritage submission

Science Through Time: Understanding the Archive at Rennix Gap Bog, a Sub-alpine Peatland in Kosciuszko National Park, New South Wales, Australia

GEOFFREY HOPE[1], SCOTT D. MOONEY[2], KATHY ALLEN[3], PATRICK BAKER[3], BEN KEANEY[1], JUSTINE KEMP[5], LEN MARTIN[2], STUART PEARSON[4], JANELLE STEVENSON[2] AND XIANGLIN ZHENG[2].

[1]Department of Archaeology and Natural History, College Asia Pacific, Australian National University, Canberra ACT; [2]School of Biological, Earth and Environmental Sciences, University of New South Wales, Kensington, NSW (s.mooney@unsw.edu.au);
[3]Department of Forest and Ecosystem Science, Melbourne School of Land and Environment, at the University of Melbourne.
[4]School of Physical, Environmental and Mathematical Sciences, University of New South Wales, Canberra, ACT; [5]Australian Rivers Institute, Environment, Planning and Architecture, Griffith University, Nathan Qld.

Hope, G., Mooney, S., Allen, K., Baker, P., Keaney, B., Kemp, J., Martin, L., Pearson, S., Stevenson, J. and Zheng, X. (2019). Science through time: understanding the archive at Rennix Gap Bog, a sub-alpine peatland in Kosciuszko National Park, New South Wales, Australia. *Proceedings of the Linnean Society of New South Wales* **141**, 25-47.

Rennix Gap Bog is a sub-alpine topogenic peatland that contains up to 2 m of organic-rich sediments that have built up over the last approximately 12,000 years. This paper summarises the research and teaching activities that have been undertaken at the site, which has included consideration of the sediment stratigraphy, radiometric dating, palynology, charcoal analyses, dendrochronology and recently, the testate amoebae community composition has been documented. Much of this work is unpublished but has relevance for any future research and provides a long-term context for many contemporary environmental issues, including for issues of relevance to the management of fire in this landscape and vegetation more broadly. In the contemporary environment, the surface of the bog is vegetated with a complex mosaic of *Carex* fen, sub-alpine *Sphagnum* shrub bog and *Poa costiniana* tussock grassland. Pollen analysis suggests that this vegetation has been relatively stable for 10,000 years and prior to that the site was surrounded by sparse vegetation, similar to the alpine herb-grass community of contemporary higher altitude ecosystems. Charcoal analyses suggest that fire activity has varied through time but increased significantly in the historic period. Rennix Gap Bog has not only attracted considerable research but has also been an invaluable, accessible, site for field-based teaching and learning.

Manuscript received 18 June 2018, accepted for publication 14 March 2019.

Keywords: fire, history; palaeoecology; peat.

INTRODUCTION

Understanding the role of time in the development or dynamics of plant communities augments contemporary and historical ecological information (e.g. measurements, documents, images) and allows investigation of longer processes such as climate variability, fire, species change and nutrient release. The use of natural archives is particularly relevant in Australia given the very short period of written history and lack of ecological understanding of the dynamics of most species assemblages (Clark 1990). Peatlands or 'mires' are organic deposits where the remains of plants have built up (with other inclusions of palaeoenvironmental significance) to provide a sequence through time which can be readily dated (Whinam and Hope 2005).

The history of peat formation in the subalpine and alpine zones of Kosciuszko National Park (KNP) has been summarized by Hope and Nanson (2015). This built on landmark studies of snow patch and lower altitude peats by Costin (1972) and Martin (1986b; 1999) together with later work, e.g. Marx et al. (2012). In these valley peatlands organic deposits have an average depth of about 80 cm but reach more than 200 cm in places (Hope et al 2012). Radiometric dating, chiefly radiocarbon (^{14}C) dating, indicate peat initiation by about 16,000 years ago at selected sites but in many cases this occurs later. Studies utilising sediments accumulating in the alpine lakes, including at Blue Lake and Club Lake (Raine 1974, Martin 1986a,b) show that the lakes were ice-free by about 15,000 years ago but only became highly organic in the last 10 or 11,000 years. Most of the sites studied to date are from high rainfall alpine sites and less is known of the subalpine environments in the rain shadow to the east of the main range.

One such archive, Rennix Gap Bog, is a subalpine peatland set in grassy woodlands on the eastern edge of KNP. This peatland has been studied for over fifty years and has been a major resource for teaching of university students. This research has resulted in considerable undocumented information regarding the long environmental history of this site. This paper summarises the scientific studies and the range of educational training carried out on the Rennix Gap Bog peatland.

Location and Site Characteristics of Rennix Gap Bog

Rennix Gap Bog has formed in the centre of one the most easterly of the open, grassed valleys on the undulating high plateau of Mt Kosciuszko. The peatland is crossed by the Kosciuszko Road as it climbs to Rennix Gap with the main part of the peatland south of the road at an altitude of 1575 m. The site is centred on 36°22.0'S 148°30.2'E and is situated within a catchment of 210 ha that has a maximum altitude of 1680 m. The valley is relatively steep and wooded along the western margin and is more open and gentle to the east. The area is underlain by Devonian granodiorite with scattered exposed tors. A small stream traverses the bog, incised about 30 cm into the peat, gradually becoming more entrenched as it flows north and then east as a tributary of Sawpit Creek.

The vegetation of highland regions tends to be strongly altitudinally zoned and the south-eastern highlands are no exception (Costin 1954, 1970; Martin 1986a). Williams and Costin (1994) noted that the distribution of vegetation in high mountain regions is primarily related to summer temperatures. In the Snowy Mountains Galloway (1965) placed the treeline at 1880 m, coinciding with the 10°C mean temperature for the warmest month. Above this treeline, a *Poa caespitosa-Celmisia asteliifolia* alliance (Martin 1986a) characterizes the alpine zone. Below this treeline, the sub-alpine zone extends from about 1830 m to about 1500 m asl.

Rennix Gap Bog occurs within this sub-alpine zone. It is an open area, of about 45 ha, surrounded by an inverted treeline of pure *Eucalyptus pauciflora* woodland. Inverted tree lines, like this one, are associated with localised physiography influencing cold air drainage (Moore and Williams 1976) and are colloquially known as 'frost hollows'. The surrounding Snow Gum woodland is near its lower altitudinal boundary at Rennix Gap Bog, with a mixed Mountain Gum (*E. dalrympleana)* – Snow Gum forest occurring about 80 m lower in altitude.

Rennix Gap Bog is vegetated with a mosaic of *Carex* fen and sub-alpine *Sphagnum* shrub bog with areas of *Poa costiniana tussock* grassland (McDougall and Walsh 2007, Hope et al. 2012). In the Kosciuszko highlands climate is influenced at a local scale by altitude, aspect and exposure, and while altitude is the dominant control, wind is an important ecological determinant (Costin 1954). In sheltered conditions at the foot of the slope on the western margin of the Rennix Gap Bog plain there are small areas of 1.5 m high thickets of *Baeckea gunniana* and *Callistemon pityoides* thickets over well-developed *Sphagnum* bog. Relatively low altitude occurrences of *Astelia alpina* and *Chionogentianis muelleriana* are also found on the bog. The western portion of the bog is somewhat sheltered by woodland and slopes but the eastern side is exposed to strong winds. The precipitation, estimated to be 1390 mm p.a., has low seasonality and includes snow-lie of about two months. The valley floor experiences severe winter frosts although the mean annual air temperature is 6.2°C.

Human History

Archaeological information from mainland Australian high altitudes is relatively scarce and most evidence of prehistoric people is relatively short (Kamminga 1995). This relates to the geological setting, which only rarely produces rock shelters (Flood 1980) and has given rise to acidic soils and sediments resulting in generally poor preservation of any material culture (Kamminga, 1995). Flood (1980 p. 1) noted, however, "several stone axes found on the peaks of the Snowy Mountains bear mute testimony to at least occasional visits by Aborigines". The oldest dated record of human occupation is only *ca.* 11,000 calibrated years before present (cal yr BP), from a cave at 1100 m at Yarrangobilly (Aplin et al. 2010). A recent archaeological survey of rockshelters around 1000-1200 m in the ACT obtained records back to 9000 cal yr BP (Theden Ringl 2016a; b).

Figure 1. The location of Rennix Gap Bog in Kosciuszko National Park. The box surrounding Rennix Gap Bog ("Boggy Plain") shows the extent of Figure 2.

Aborigines who spoke the Ngarigo language inhabited most of the Snowy Mountains and the surrounding uplands, to the north and south for a distance of about 200 km and eastwards for about 120 km from Mt Kosciusko, which was on the western boundary of Ngarigo territory (Tindale 1974). In late spring-early summer the Ngarigo were joined by a significant influx of people from surrounding areas (Sullivan 1978; Flood 1980; Kamminga 1995) associated with the collection of the Bogong moth, *Agrotis infusa*, which aestivates in vast numbers in summer amongst the granite outcrops of the high country (Keaney 2016). Larger campsites, located in valleys such as those around Jindabyne (Fig. 1), were used as staging posts or for inter-tribal trading, rites and ceremonies (Flood 1980). Smaller groups are thought to have spread out into the higher country to collect moths (Payten 1949, cited in Flood 1980; Kamminga 1995). Argue (1995) hence described a range of occupation by Aboriginal people in lower altitude valleys and itinerant camps on the higher plateaux.

Within 50 years of the first white settlement the local Aboriginal populations of the Monaro had been devastated by both smallpox epidemics and violence by Europeans (Hancock 1972, Kamminga 1995). Aborigines continued to exploit the resources of the mountains during the first half of the Nineteenth Century, but by the 1870s there were only a few remaining Ngarigo speakers living on farms and settlements in the Southern Tablelands of NSW.

The European history of the Monaro Plains dates from 1823 (Wakefield, 1969) with extensive grazing occurring by 1836 (Renshaw, 1981). Although it is commonly assumed that pastoralists used the Highlands for summer grazing and drought relief from about the mid-1860s, the Rennix Gap Bog peatland, also known as Boggy Plain, was grazed heavily after 1835 as it was one of the first open areas encountered on ascending the mountain.

Grazing of the high country continued without regulation until 1888 when limited control was established with the *Snow Lease Tenure Act* 1888 and *Crown Lands (Amendment Act)* 1889 (Hancock 1972, Good 1982). From 1890, leases were delineated and not long after, Helms (1893) was the first to 'officially' report on the extensive use of fire by pastoralists in the alpine ecosystems. Helms also expressed considerable concern at the practice.

The original Summit track, followed by a road, passed along the eastern side of Rennix Gap Bog with Harveys Camp located adjacent to the peatland. Fence lines mark this road and in places these are now (2018) nearly buried by peat. A hut is shown at the southern end of the plain in a small Crown Reserve gazetted in 1892 (Scott 2011). Rennix Gap is named after William Edward Rennix, an engineer and surveyor, who was in charge of the survey of the Kosciuszko road built between 1906 and 1909. He died of pneumonia in 1909 after being caught in a blizzard at the gap (Stone 2012). An alternative road passed west of the bog, branching from the 1909 main road, which skirted the northern side of the peatland (Fig. 2).

In 1906 the NSW State Government declared 258 km^2 around the Koscuiszko summit as the Snowy Mountains National Chase (Lembit 2002). The Kosciuszko State Park was created in 1944, covering 500 000 ha (Lembit 2002) and this resulted in further restrictions on grazing and the use of fire (Newman 1954). The present road was constructed across the swamp, presumably post-WWII, and "improved" with drainage on the upstream side. Grazing ceased in 1952 but has continued at a low level due to feral stock, deer and more recently horses. Kosciuszko National Park (KNP) was formally gazetted in 1967 and the first management plan was approved in 1974 (Lembit 2002).

Scientific Research and Teaching at Rennix Gap Bog

On the advice of Alec Costin, who had studied the region as part of his monograph *A study of the ecosystems of the Monaro Region of New South Wales* (Costin 1954), Rennix Gap Bog (as "Boggy Plain") was investigated by Tony Martin (University of Sydney) from 1959 onwards. Martin (unpublished, Figure 3) made a comprehensive vegetation map and described the stratigraphy of the sediments on site from on three sediment cores, which were located relatively close to the main road, and 10 radiocarbon (^{14}C) dates. Martin also worked on the fossil pollen of

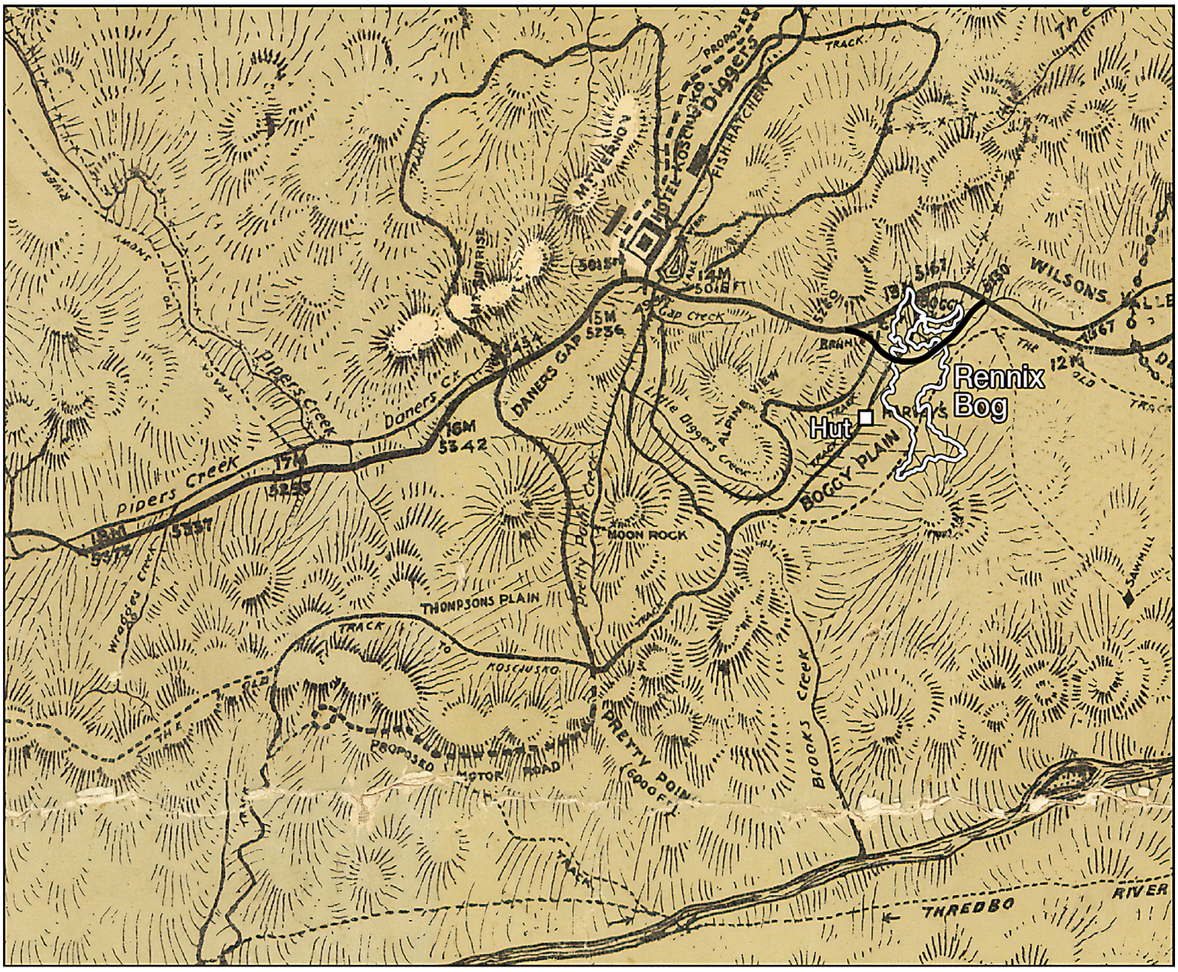


Figure 2. Extract of a Mt Kosciuszko Map from 1909 with the approximate extent of Rennix Gap Bog ("Boggy Plain" on this map) indicated. The black line shows the modern alignment of the road, but the original road skirted the bog to the north.

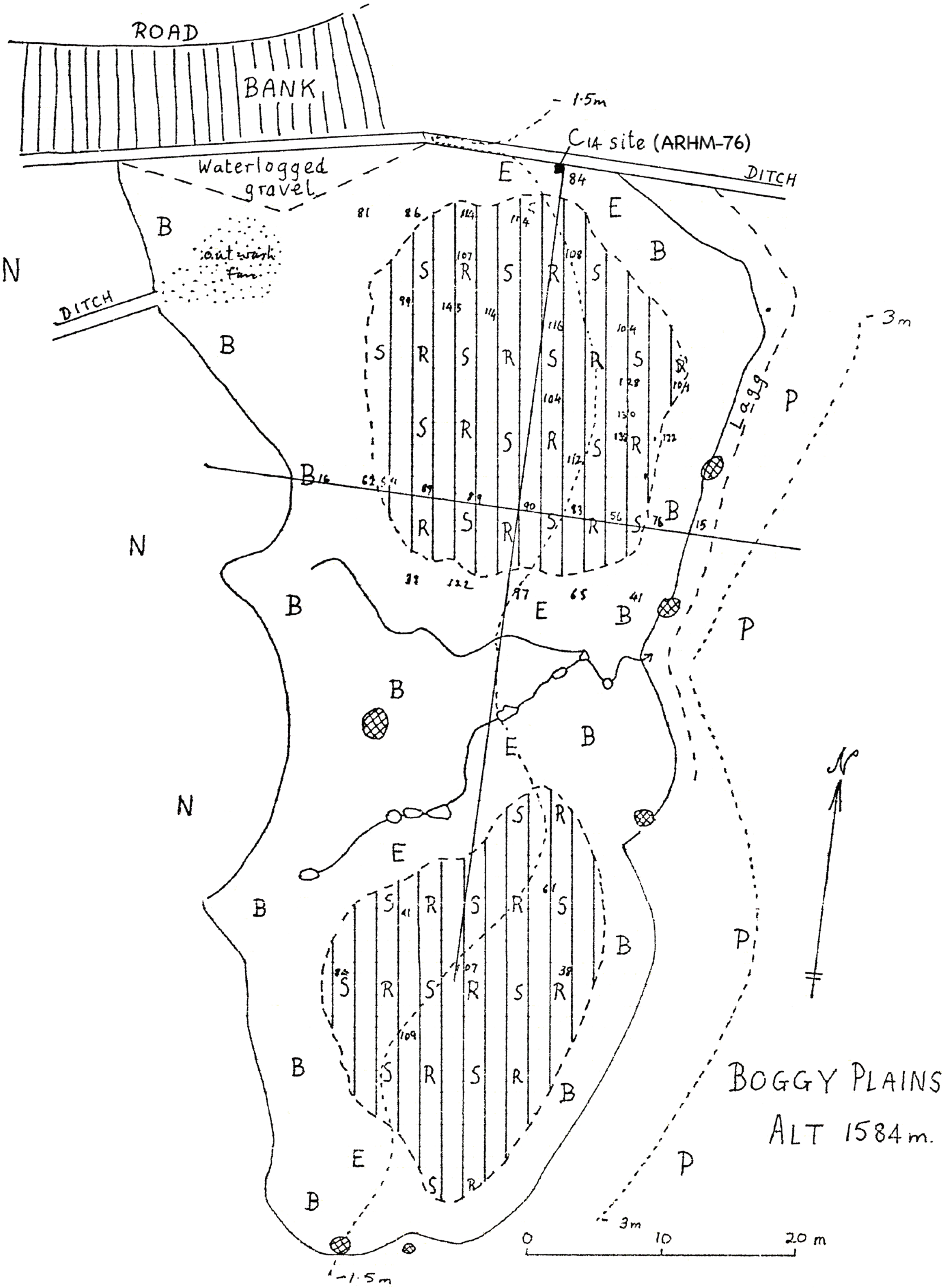


Figure 3. A.R.H. (Tony) Martin's 1959 sketch of a portion of Rennix Gap Bog south of the main road. On this sketch B denotes occurrences of *Baeckea*, *S Sphagnum* and *E Empodisma*..

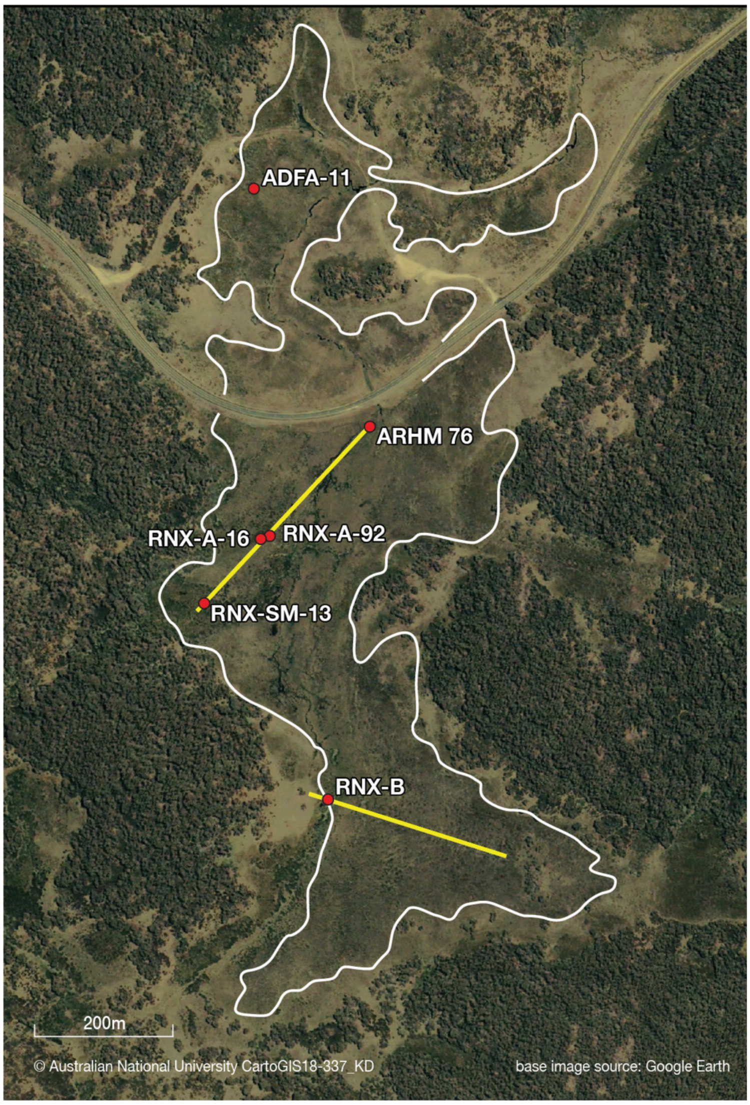


Figure 4. Rennix Gap Bog, showing coring locations and transects mentioned in the text (source: Google Earth Image).

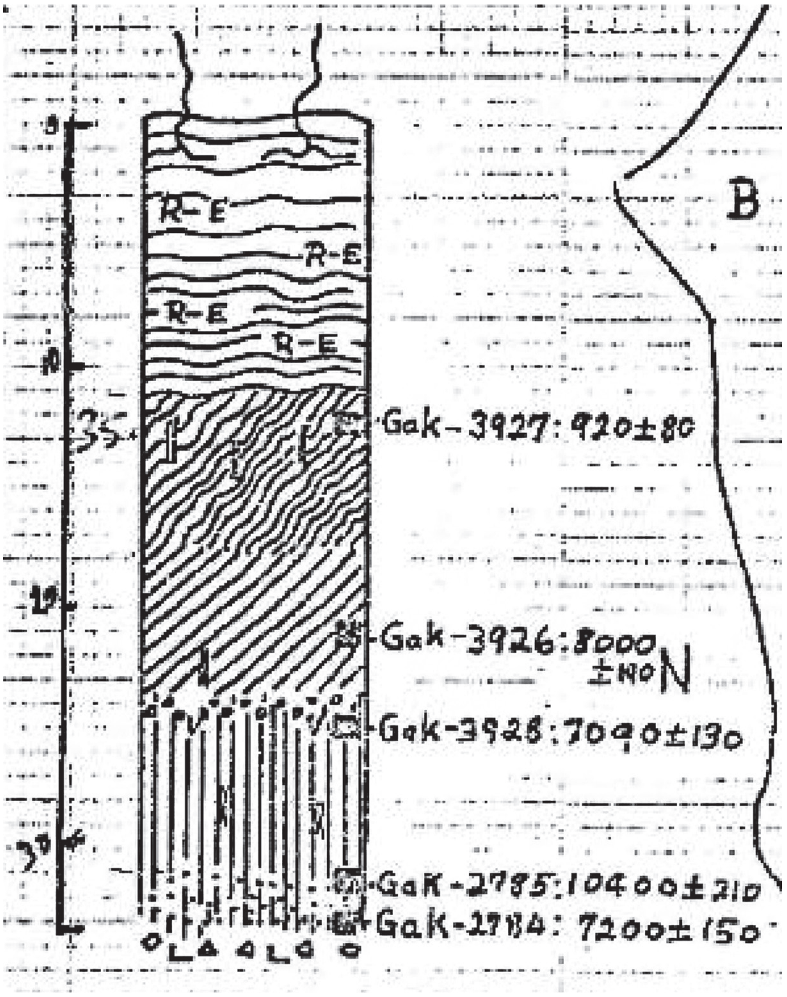
several other Kosciuszko sites (published as Martin 1986b) and on Diggers Creek, a *Sphagnum*-shrub bog at 1720 m, 2.4 km to the southwest of Rennix, which included a brief comparison with Rennix data (Martin 1999).

Rennix Gap is an easily accessible site and has been used extensively for undergraduate teaching. In 1978 Geoff Hope started taking Australian National University (ANU) geography students to the Rennix Gap Bog peatland and returned annually until 1988. During this time, class groups collected information used to describe the stratigraphy across various east-west sections, concentrating on the RNX A and B areas of the swamp, south of the main road, with the most detailed stratigraphic profile across the bog near RNX B (in Figure 4). A single ^{14}C date for the clay-peat interface was completed for the RNX A-80 core which was located about 300m north of RNX B, and a preliminary pollen diagram for the core RNX B-80 was also prepared.

From 1986 similar classes, under the tutelage of Roger McLean, David Gillieson and Stuart Pearson, were undertaken by cadets studying Geography at the Australian Defense Force Academy (ADFA, now UNSW Canberra). This fieldwork, conducted annually until 2015, and sometimes involving more than 100 students, concentrated on the site's geomorphology, landscape ecology and sediment taphonomy using an experiential, hands-on approach. This was originally located close to the Martin cores on the bog, but was subsequently moved, at the request of KNP scientific staff, to the shallower area north of the main road. At about the same time Charles Sturt University (Wagga Wagga) students were also using Rennix Gap for field-based classes, under Ken Page.

In 1993 Justine Kemp undertook research towards her ANU Honours degree under the supervision of Geoff Hope. She studied the late-to-post glacial transition (~20,000-9,000 year sequences) from several sites in the NSW Southern Tablelands and this included Rennix Gap Bog. At Rennix a new sediment core was recovered in the vicinity of the RNX A-80 site to 230 cm depth, revealing an extended clay and sand section overlying weathered granite bedrock below the upper peat. Kemp (1993) completed pollen analysis of the sediments from 90-210 cm, but accelerator mass spectrometry (AMS) ^{14}C dates from the top and bottom of the gravelly sands yielded anomalously young ages. Similarly young ages for mineral sediments underlying peat have been noted in valley bog settings elsewhere in the Australian Alps and may result from contamination by younger organic compounds contained in through-flowing groundwaters (Kemp et al. 2012).

The ADFA and ANU Rennix Gap Bog field activities were followed in upper level classes with microscope-based palynological analyses. At ANU students used samples prepared from the RNX B core and their own samples. In March 2016 ANU



0-32 cm	*Sphagnum* peat with restiad rhizomes
32-44 cm	Black brown humic peat, wood and roots
44-60 cm	Brown sapric peat
60-63 cm	Peat with sand and mica
63-79 cm	Peaty clayey sands
79-85 cm	Peaty sands
Notes: ^{14}C dates were completed at 30-33, 52-54, 62-65, 79-81 and 82.5-85 cm. Additional ^{14}C dates were applied to core 3 (collected *ca.* 1975) at 46-49, 62-65, 75-77, 80-82 and 83-87 cm.	

Figure 5. The stratigraphy of the A.R.H. (Tony) Martin core 2 collected around 1971. In this figure "R – E" indicates Restio-Empodisma rhizomes. The scale on the left hand side is in inches: these have been converted to centimetres in the brief description included below.

undergraduate students (with Janelle Stevenson) re-cored the sediments close to the Kemp site and obtained a 180 cm core (RNX A-16), with the transition from sandy clays to clayey peat at 140-120 cm. ANU undergraduate students quantified charcoal in the core and five samples were ^{14}C dated.

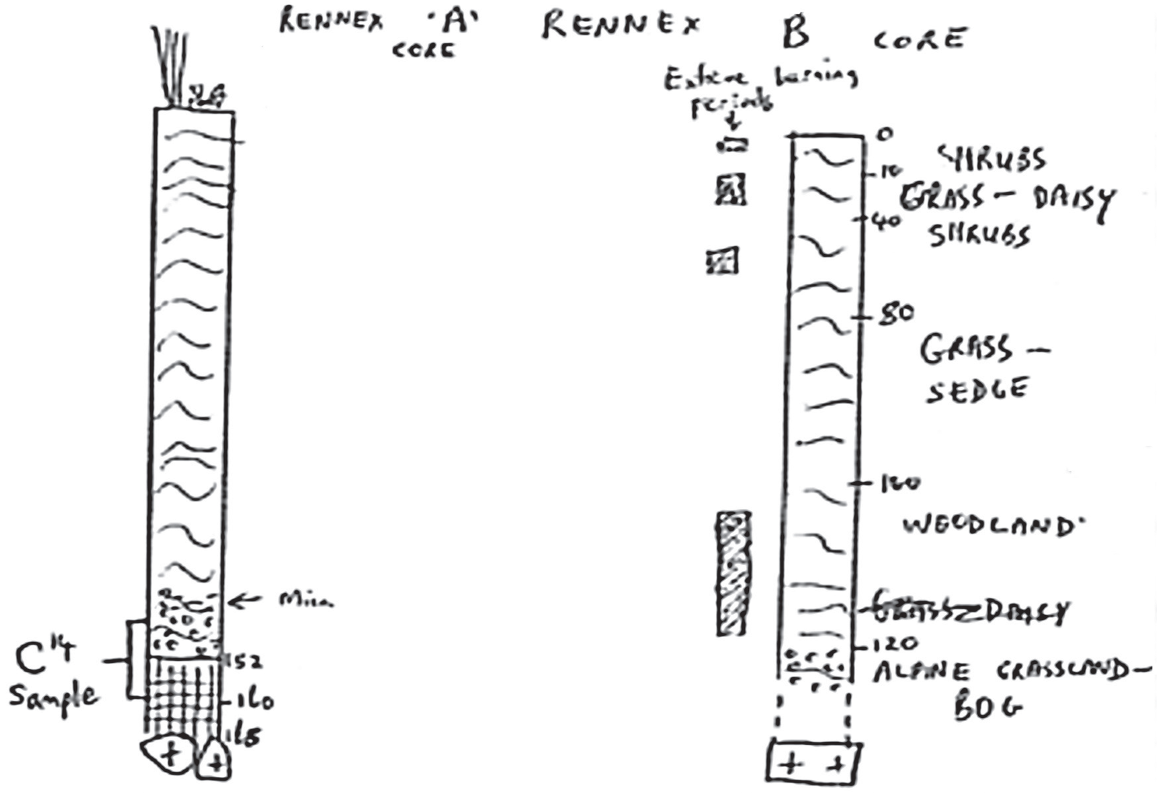
In April of 2013 Scott Mooney (UNSW) began work at Rennix Gap Bog in association with the ARC-funded project *Has 20th Century warming changed southeastern Australia's fire regimes?* (DP12 2012 – 2014). Mooney, Martin and several postgraduate students re-cored the bog on the western margin and obtained a deep peat sequence (to 226 cm). The object of that work was to obtain a detailed fire history from charcoal analysis, and as a part of this Mooney and co-workers radiometrically dated this new core (with 9 lead-210 (^{210}Pb) dates and 6 new AMS ^{14}C dates). As part of this research Patrick Baker and Kathy Allen (University of Melbourne) also undertook dendrochronological research in the Snow Gum woodland surrounding Rennix Gap Bog. This included taking increment cores and quantifying the age of all trees within random quadrats located within a grid with Rennix Gap Bog in the centre.

In 2016 Mooney and UNSW postgraduate student Xianglin Zheng took a series of surface samples across Rennix Gap Bog aimed at quantifying the relationship between environmental parameters (depth-to-water table, moisture content, EC, pH) and the testate amoebae community composition.

RESULTS AND DISCUSSION

Stratigraphy and Dating of the Sediments

Figures 5 to 9 are extracts from field notes and/or lab-based descriptions of the sediments accumulating in Rennix Gap Bog. We have purposely used the original notes of these (where possible), thereby retaining their variegated nature, to reflect the various purposes of the researchers. Figure 10 uses these data to consider



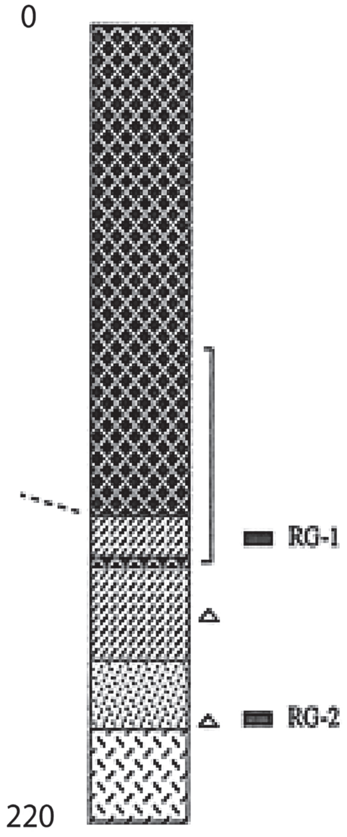
0-135 cm	Black humic peat with root fragments	0-120 cm	Black humic peat with root fragments
135-152 cm	Black humic peat with abundant mica and sand	120-126 cm	Black humic peat with abundant mica and sand
152-168 cm	Grey-brown peaty gravelly sands with abundant mica	126-162 cm	Grey-brown peaty gravelly sands with abundant mica and root fragments
>168 cm	Granite stones		
Notes: One ^{14}C date was analysed from 145 to 160 cm in the Rennix A core. Pollen was analysed to 120 cm.			

Figure 6. A description of the RNX-A-78 and RNX-B core collected 21/3/1978 by Geoff Hope (ANU).

the stratigraphy of the sediments along transects across Rennix Gap Bog.

Table 1 summarises all information about the (radiometric) dating of the Rennix Gap Bog sediments. Examination of the dates shows that there are numerous examples of dating inversions (where a deeper layer provides a younger age than levels above) in individual cores. This is a common problem in shallow peats where roots from younger levels can intrude into older peats and this probably explains inversions in Martin's dates that were based on relatively large slices of bulk peat. The young ages obtained from the sandy clay to peat transition and deeper clay samples in AHRM1976-85, RNX-SM-13-194 and RXA-93-144 and 190 may reflect contamination of sediments with low organic content by traces of younger peats carried down core during sampling or intrusive younger sedge roots. The careful pipetting of charred fragments (RNX-A-16) or identified plant material (RNX-SM-13) from dispersed samples has provided much more reliable age estimates.

The sands and clays underlying small areas of the peatland are the surviving stream deposits that spread across the valley after 15-16,000 years ago, an inference supported by the age of 14,610 ± 375 cal yr BP from the sandy silts at 160 cm in RNX-A-16. This phase of sandy alluviation is also found beneath other



0-90 cm	Dark brown slightly fibrous peat- (not sampled)
90-132 cm	Black humic peat with abundant leaf and root fragments. Water content for this layer exceeds 80% and organic content steadily rises to 50% of the dry weight. Carbonised particles substantially increase after 125cm and peak at 110 cm
132-149 cm	A mixture of grey-brown peaty, gravelly sands with abundant mica and organic debris. Clay minerals include kaolin, gibbsite and poorly-sorted. interlayered clays. Water content steadily increases from 30% at the base to over 50% at the top. Organic content is less than 5% and carbonised particles are insignificant
149-151 cm	This layer consists of brown clayey peats. Water content totals 60% while organic content is 20%. No carbonised particles are recorded
151-178 cm	Grey-brown peaty gravelly sands with abundant mica and root fragments
178-198 cm	Grey gravelly sand with abundant mica
198->220 cm	Weathered granitic saprolite
^{14}C dates: RG-1 144 cm, RG-2 190 cm	

Figure 7. A description of the RNX-A-Kemp core collected in 1993 by Justine Kemp. This core extended to 220 cm and returned pre-Holocene radiocarbon dates (see Table 2): it seemingly was located in a hollow, possibly an old channel, in the underlying sandy plain.

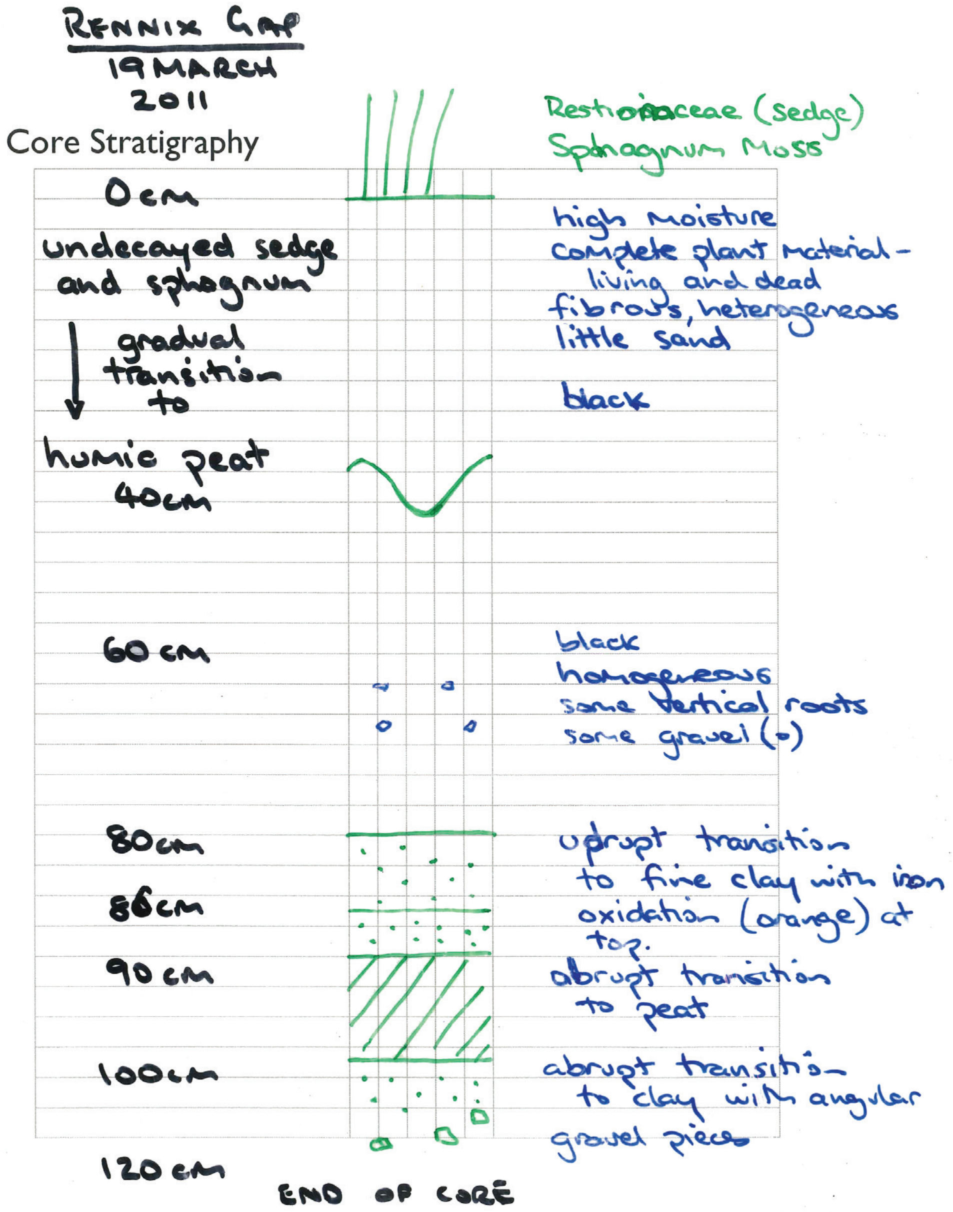
montane and subalpine peatlands in the region (Hope and Nanson 2015) and reflects warming conditions after the maximum cold phase of the last glaciation, identified by Barrows et al. (2002) as 22-19,000 years ago.

The onset of peat formation commenced at Rennix Gap Bog around 12,500 years ago. Dates on bulk peaty sand (RXA-82 and AHRM1960), and macroscopic charcoal particles (RNX-A-16) support this age. Peat probably formed first at the base of the western slopes and along stream lines, gradually spreading onto grasslands on the plain. This result parallels Caledonia Fen in Victoria, at 1280 m, where organic clays abruptly transition to peats at 12,000 ± 485 cal yr BP (Kershaw et al. 2007; 2010). A similar transition occurs at 11,990 ± 485 cal yr BP at Micalong Swamp at 1100m (Kemp and Hope 2014). Increasing moisture and possibly warmth may have controlled this threshold. At Bega Swamp, which is located on the crest of the coastal scarp at 1080 m east of Nimmitabel in NSW, this transition is earlier, at 15,500 ± 350 cal yr BP, perhaps reflecting wetter late Pleistocene conditions there (Donders et al. 2007).

Figure 11 shows a model of the depth-age relationship of the sediments at Rennix Gap Bog, using Bayesian modelling, and a simpler (polynomial) approach, applied to the deepest peat section RNX-SM-13. The depth-age relationship at Rennix Gap Bog (Figure 10) suggests that the net rates of peat accumulation (growth minus decay) are relatively fast in the first few thousand years associated with the early development of the bog, but this rate slows by the mid-Holocene above about 90 cm (representing the last ~8,000 years). The mean resolution of the sediment (near RNX-A) is 42.5 years/cm across the entire profile but the resolution of the recent sediment (e.g. in the Twentieth Century) is approximately 4 years/cm.

Modern Vegetation

The Rennix Gap "bog" is a relatively complex mosaic of *Carex* fen and sub-alpine *Sphagnum*-shrub bog (Hope et al. 2012). The fen component of the site



0-10 cm	Brown living organic material, sedges, pH 4 (5.5)
10-15 cm	Soft fibrous peat, gradual transitions, soft and squidgy
15(20)-30(45) cm	Dark brown humic peat, drier, roots evident, mica crystalline material (evidence of granite derived sediment)
30 (45)-(55) cm	Light grey clay and fine silt, anaerobic, pH 5, sharp transition, (47-56 greens and browns in coarser clay), blue quartz crystals
60 cm	small sharp and angular gravel-sized granite in fine lighter grey clay (green and brown)
70 cm	Light grey grit, soft, dry, yellow stained grey clays
80 cm	White gravel which damaged the corer, pH 5.5

Figure 8. A description of the sediment core ADFA-11 sampled from north of the main road (at 36°21.569'S, 148° 30.244'E) by Stuart Person in 2011.

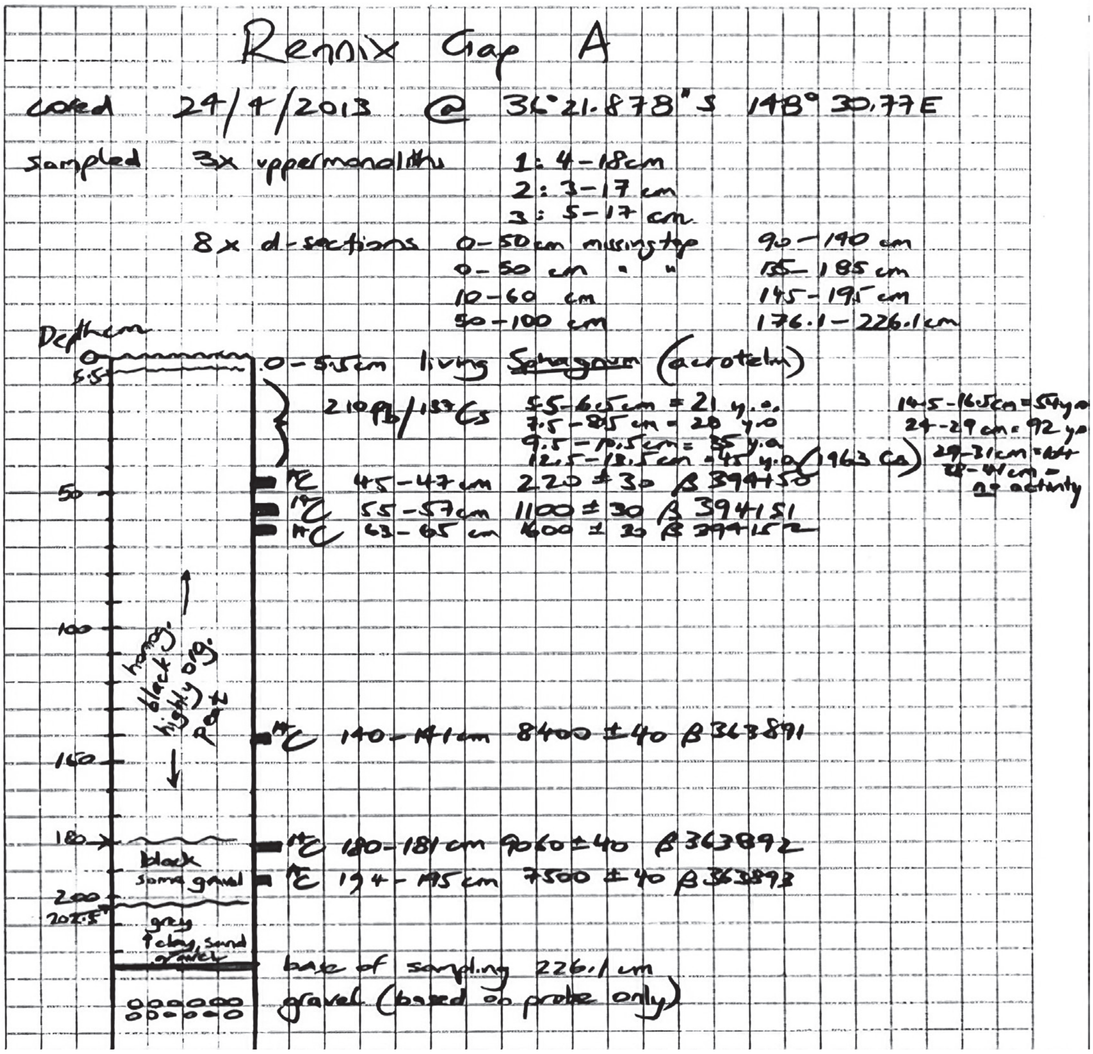


Figure 9. A brief description of the sediment core RNX-SM-13, sampled by a UNSW team in April 2013. This core has been radiometrically dated (see Figure 10) and sampled at a high resolution (0.5 cm contiguous samples from 0 to 60 cm and at 1.0 cm to the base) for the quantification of macroscopic charcoal (>250µm), in Figure 13.

is best described as sedgeland with scattered grasses and herbs in a mat of the sedge *Carex gaudichaudiana*. The sub-alpine shrub bog is variable but marked by shrubs of *Epacris, Richea, Baeckea* and *Callistemon* above *Sphagnum* moss hummocks that are 20-60 cm high. Twig rushes, *Empodisma minus* and *Baloskion australis*, also form dense swards. The shrub-dominated sections of the bog, structurally a heathland (e.g. Specht, 1981), are more common on the western side of the site where shrub height increases to over 1 m. The margins of the peatland are grassy with scattered shrubs and herbs. Many small channels cross the site, and these have aquatic plants such as *Myriophyllum* while *Haloragis micrantha* and *Isolepis fluitans* occupy wet hollows. Table 2 lists the species that we have commonly encountered on Rennix Gap Bog. Part of the peatland was burnt in 2003 but resprouting myrtaceous shrubs and good regeneration by *Epacris* spp has restored shrub cover. *Sphagnum* has recovered more slowly, with old hummocks now often covered by *Empodisma* or grass.

Vegetation History

Kemp worked on a section of basal clays and peat from approximately the RNX-A-site below 90 cm depth that covered the late Pleistocene-early

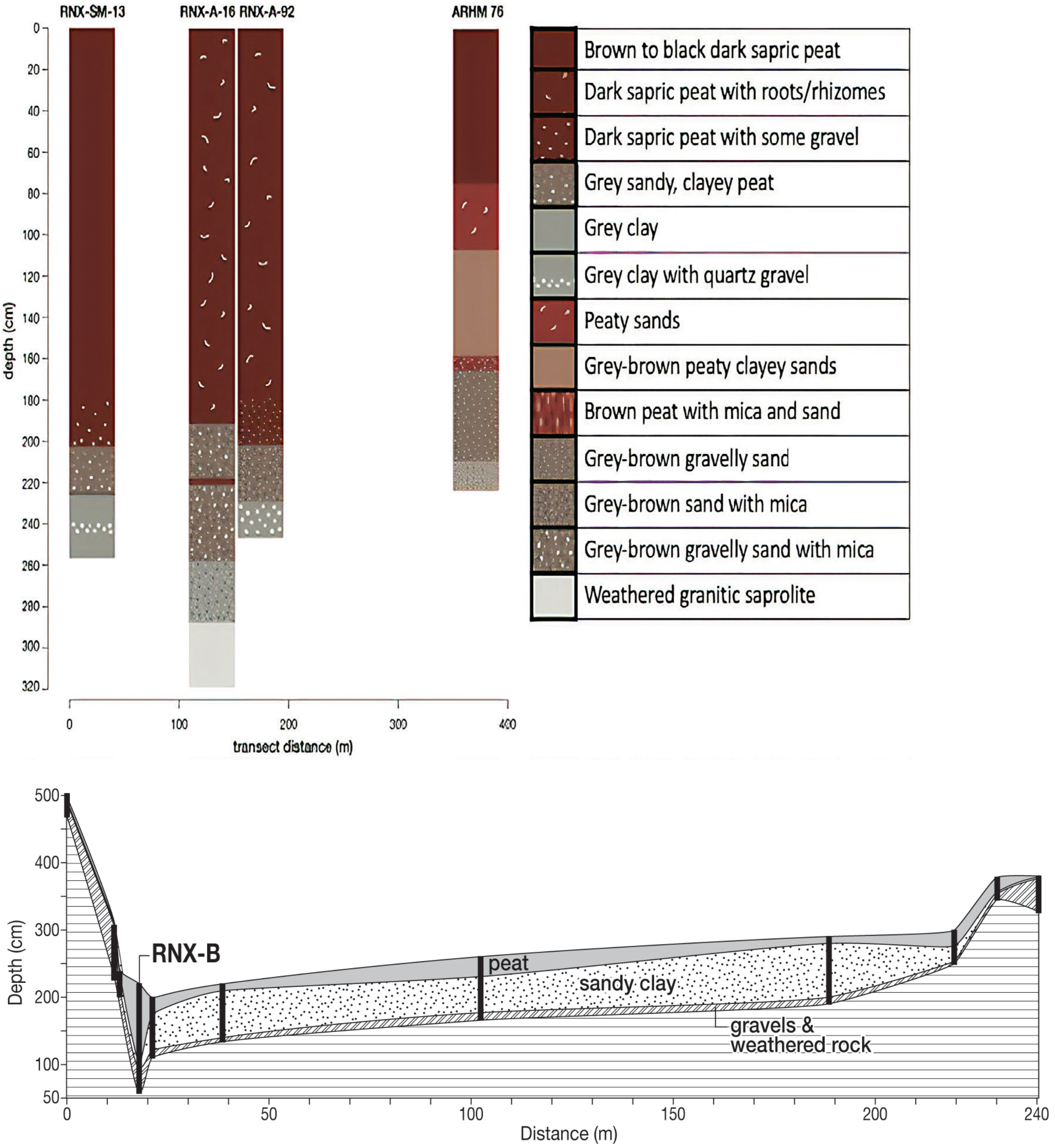


Figure 10. The upper panel (a) summarises the stratigraphy across the northern section of the Rennix Gap Bog and the lower panel (b) is a stylised cross-section showing the stratigraphy of the southern section of the site. The locations of the cross-sections are indicated on Figure 4.

Holocene transition. The dates from RNX-16 provide a consistent chronology, indicating *ca.* 15,400 cal yr BP for the base of the Kemp section at 175 cm. Hope's RNX- B core is undated but has the transition from peaty sands to peat at 120 cm (compared to the same horizon at 132 cm in the Kemp core). RNX-B has been analysed from the surface to 100 cm, providing an overlap that was assessed by comparing the diagrams to allow interpolation of samples. A composite pollen diagram based on the two overlapping sections is summarised in Figure 11. RNX-A-16 and the Martin (ARHM) age-depth relationships are similar above 80 cm giving some support to the hypothesis that the peatland grew consistently in the Holocene. Thus the RNX-16 age model has been applied to the composite pollen record.

The choice of a pollen sum is difficult in these environments (e.g. Martin 1986b; 1999) and this is true for Rennix Gap Bog as the main woody shrubs on the bog (*Baeckea* and epacrids) dominate some

Table 1. Radiometric ages from Rennix Gap Bog.

Core	Depth (cm)	Dating Method	Conventional Radiocarbon (^{14}C) Age (yrs BP)	Calibrated Radiocarbon (^{14}C) Age (yrs BP)	Likely Age* (calendar years)	Lab no.	Material
ARHM1960	79-81	^{14}C	10400 ± 210	12192 ± 359	BC 10185	GAK 2785	sapric peat
	82.5-85	^{14}C	7200 ± 150	8030 ± 149	BC 6035	GAK 2784	sapric peat
ARHM1972	30-33	^{14}C	920 ± 80	837 ± 76	AD 1155	GAK 3927	sapric peat
	52-54	^{14}C	8000 ± 190	8903 ± 495	BC 6885	GAK 3926	sapric peat
	62-65	^{14}C	7090 ± 130	7910 ± 73	BC 5920	GAK 3928	sapric peat
ARHM1976	46-49	^{14}C	2920 ± 100	3086 ± 139	BC 1070	SUA 563	peat
	62-65	^{14}C	4865 ±110	5606 ± 125	BC 3595	SUA 564	peat
	75-77	^{14}C	6120 ±115	7005 ± 148	BC 5000	SUA 565	peat
	80-82	^{14}C	6145 ±115	6970 ± 290	BC 5035	SUA 566	peat
	83-87	^{14}C	4565 ±115	4240 ± 355	BC 3220	SUA 567	peat
RNX-SM-13	5.5-6.5	^{210}Pb		21 ± 4	AD 1992	ANSTO (P294)	peat
	7.5-8.5	^{210}Pb		28 ± 5	AD 1985	ANSTO (P295)	peat
	9.5-10.5	^{210}Pb		35 ± 6	AD 1978	ANSTO (P296)	peat
	12.5-13.5	^{210}Pb		45 ± 8	AD 1968	ANSTO (P297)	peat
	12.5-13.5	^{137}Cs			AD 1963	ANSTO (P297)	peat
	14.5-16.5	^{210}Pb		54 ± 10	AD 1959	ANSTO (P298)	peat
	24-29	^{210}Pb		92 ± 18	AD 1921	ANSTO (P647)	peat
	29-31	^{210}Pb		104 ± 18	AD 1909	ANSTO (P648)	peat
	38-41	^{210}Pb		No activity	older than AD 1900	ANSTO (P649)	peat
	45-47	AMS ^{14}C	190 ± 30	210 ± 75	AD 1730	β394150	plant material
	55-57	AMS ^{14}C	1070 ± 30	941± 38	AD 1020	β394151	plant material
	63-65	AMS ^{14}C	1580 ± 30	1440± 81	AD 540	β394152	plant material
	140-141	AMS ^{14}C	8370 ± 40	9353± 115	BC 7480	β363891	plant material
	180-181	AMS ^{14}C	9060 ± 40	10193± 58	BC 8280	β363892	plant material
	194-195	AMS ^{14}C	7520 ± 40	8287± 93	BC 6410	β363893	plant material
RXA-82 (Hope)	145-160		10,600±120	12430 ± 220	BC 10530	ANU 2177	peaty sand
RXA-93 (Kemp)	144-145	AMS ^{14}C	3640 ± 185		BC 1970	ANSTO 444	NaOH insol residue
	190-191	AMS ^{14}C	9270 ± 155	10500 ± 195	BC 8480	ANSTO 445	NaOH insol residue
RNX16	50-51	AMS ^{14}C	1634 ± 32	1485 ± 80	AD 469	D-AMS 016367	Charcoal >125 µm
	80-81	AMS ^{14}C	4610 ± 34	5250 ± 195	BC 3265	D-AMS 016368	Charcoal >125 µm
	100-101	AMS ^{14}C	8764 ± 41	9720 ± 170	BC 7730	D-AMS 016369	Charcoal >125 µm
	145-146	AMS ^{14}C	10692 ± 36	12630 ± 70	BC 10685	D-AMS 016370	Charcoal >125 µm
	160-161	AMS ^{14}C	12499 ± 49	14610 ± 375	BC 12652	D-AMS 016371	Charcoal >125 µm

* The “Likely Age (calendar years)” is the median probability intercept with the radiocarbon calibration curve using SHCal13.14c (Hogg et al. 2013), rounded to the nearest half-decade

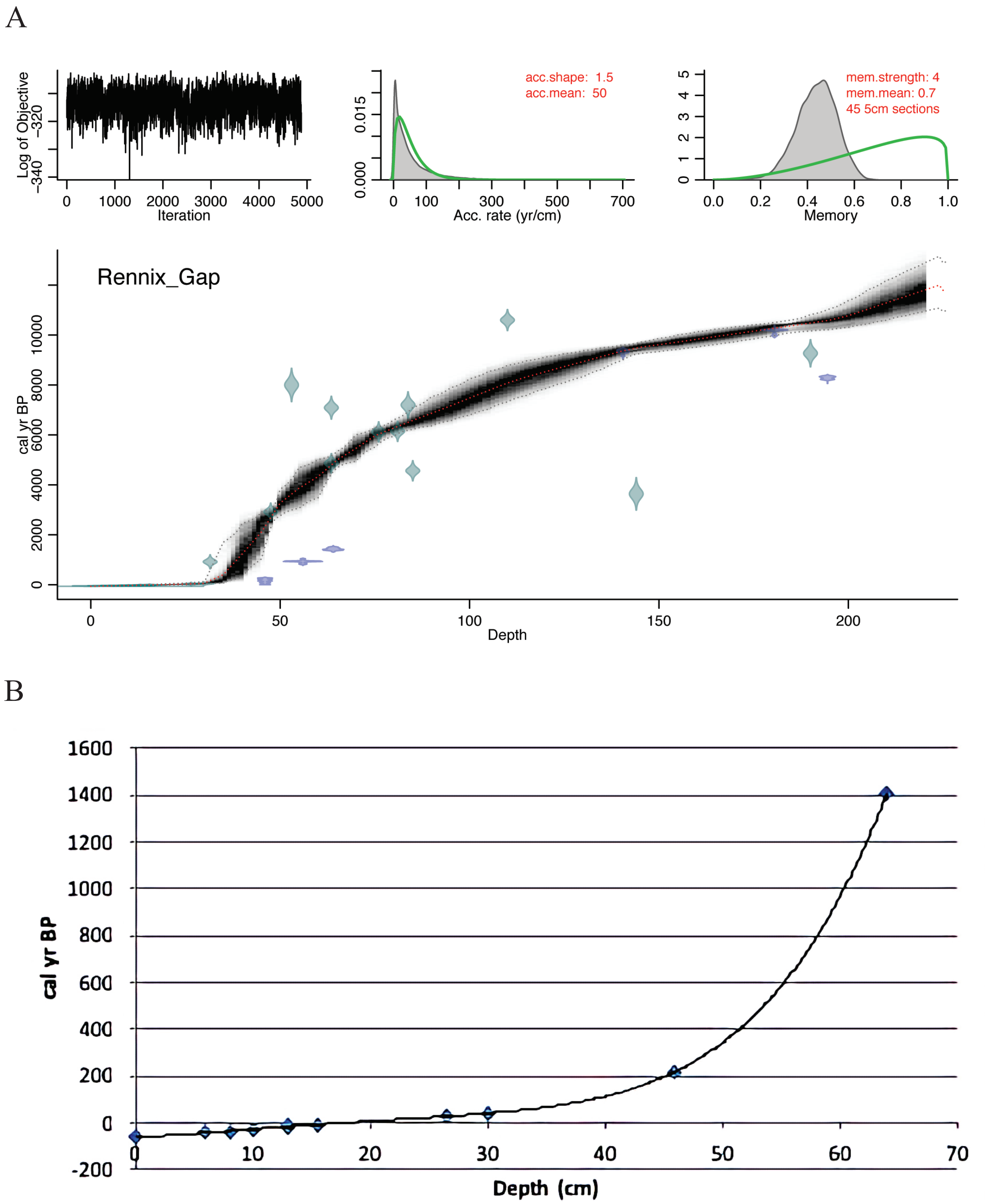


Figure 11. Some depth-age relationships for Rennix Gap Bog. In the top panel (A) all depth-age pairs in Table 2 are used in a BACON age-depth model (Blaauw and Christen, 2011) derived from Bayesian statistics. In this model all dates from across the site are used and hence there is a scatter of results. In the lower panel (B) a (polynomial) age-depth model is developed using only the dates associated with the RNX A locality.

Table 2. A species list generated from field-work at Rennix Gap Bog. The occurrence of these species is delineated to Carex fen, Sphagnum shrub bog or marginal peatland areas. The abundance of the species is described using an ordinal scale: absent -, R= rare or occasional (<5% cover), B= (5-50% cover), C= common (50-75% cover), D= dominant (>75% cover).

Species	**Abundance in Environment**		
	***Carex* fen**	***Sphagnum* shrub bog**	**Marginal peatland areas**
Acaena anserinifolia	-	-	C
Aciphylla simplicifolia	R	-	R
Astelia alpina	R	-	-
Baeckea gunniana	-	D	B
Baloskion australe	D	-	-
Blechnum minus	-	-	B
Brachyscome scapigera	C	R	B
Carex breviculmis	C	-	B
Carex gaudichaudiana	D	-	B
*Centaurium erythraea**	-	-	C
Chionogentias muellerii	-	-	C
Danthonia monticola	-	-	C
Drosera peltata	R	-	-
Empodisma minus	C	D	-
Epacris brevifolia	-	C	-
Epacris paludosa		C	B
Epilobium billardierianum subsp. *hydrophilum*	R	C	B
Galium gaudichaudii	-	-	C
Geranium neglectum	-	-	C
Hakea microcarpa	-	-	C
*Holcus lanatus**	R	-	C
Hydrocotyle laxiflora	R	R	-
Isolepis fluitans	C	-	-
Juncus falcatus	C	-	C
Leptospermum lanigerum	-	-	C
Luzula sp	-	-	B
Myriophyllum pedunculatum	C	-	-
Nertera	R	-	R
Poa costiniana	-	-	D
Poa sieberiana var. *cyanophylla*	-	-	C
Ranunculus	C	C	C
Ranunculus (?Caltha)	R	-	-
Richea continentis	-	C	-
Sphagnum cristatum	-	D	-
Stellaria pungens	-	-	C
Utricularia dichotoma	-	R	-

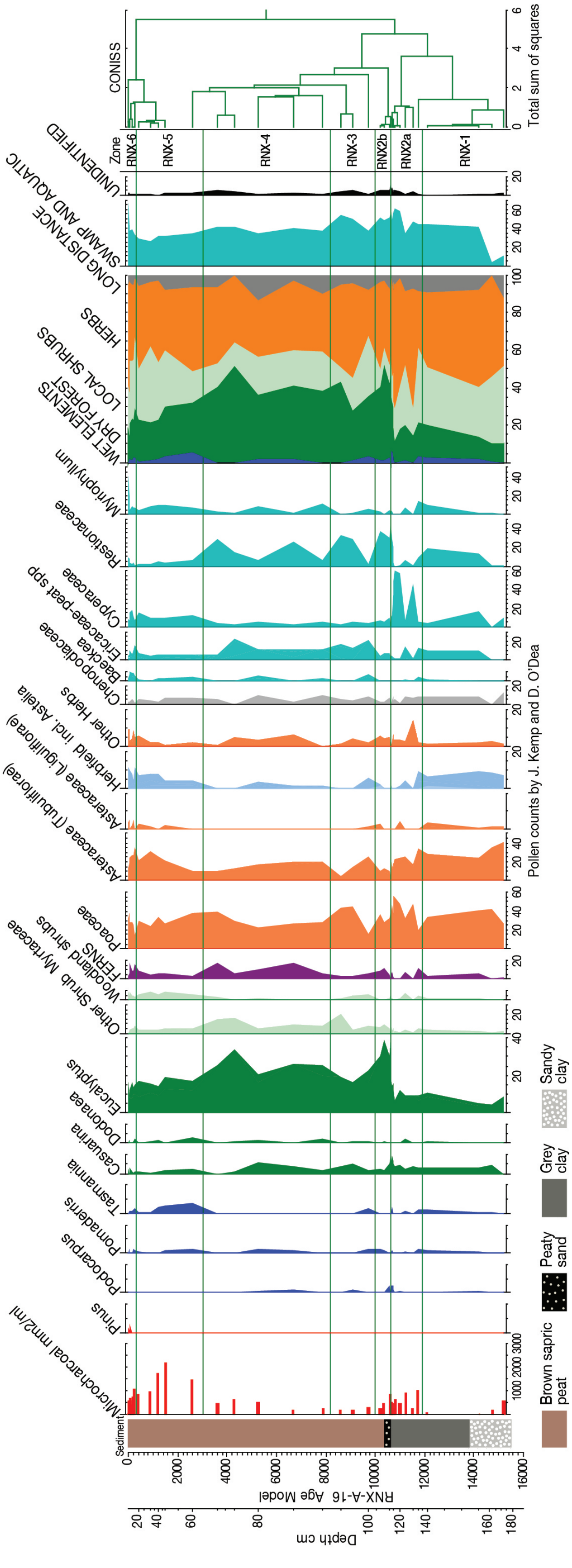


Figure 12. Composite pollen diagram from Rennix B and core RNX-A. The radiocarbon chronology is interpolated from the cores from ARH Martin (Core 2). Justine Kemp completed the palynology.

sediment horizons. These have been excluded from the pollen sum in Figure 12, together with sedges and *Myriophyllum*. Herbs and grass are included in a dryland pollen sum against which individual pollen percentages are calculated.

The basal zone of Figure 12 is dominated by an alpine grassland-herbfield with abundant daisies and sedges. A slow increase in eucalypt representation is evident from 15 to 11,600 years ago and in this basal section the site is a sedge fen. The presence of significant liguliflorous daisy pollen suggests that the herb-rich alpine grasslands supported abundant myrnong (*Microseris* sp. see Gott 2008) even though it was presumably much colder than the present day. These palaeoenvironmental data suggest that Rennix Gap may have resembled the contemporary eastern slopes of Mt Twynham. Fire is rare in this zone. At 11,600 cal yr BP fire increases and grass increases at the expense of herbs and daisies. The bog becomes a sedgeland and the increase of eucalypts stabilizes until around 10,600 cal yr BP.

At this time an abrupt increase of eucalypts in the upper 15 cm of sandy peats and lowest 10 cm of peat marks the arrival of the Snow Gum woodland and a very clear transition of the treeline. Grass, daisies and herbs decline and fire is also less marked. The grassland around the bog records an increase of daisies relative to grass. This situation is stable from 8500 cal yr BP until around 3000 years ago when shrubs and trees decline and herb-rich grasslands expand. These changes might represent either the retreat of the woodland edge (away from the coring location) or the opening out of the woodland canopy. The peatland experiences rising sedge cover at the expense of bog taxa such as Ericaceae and *Empodisma*. Fire may be implicated as charcoal increases in the upper zones.

European influences appear only in the upper 10 cm (of the Figure 12 pollen) with reductions in eucalypt cover and fluctuations in grass and the

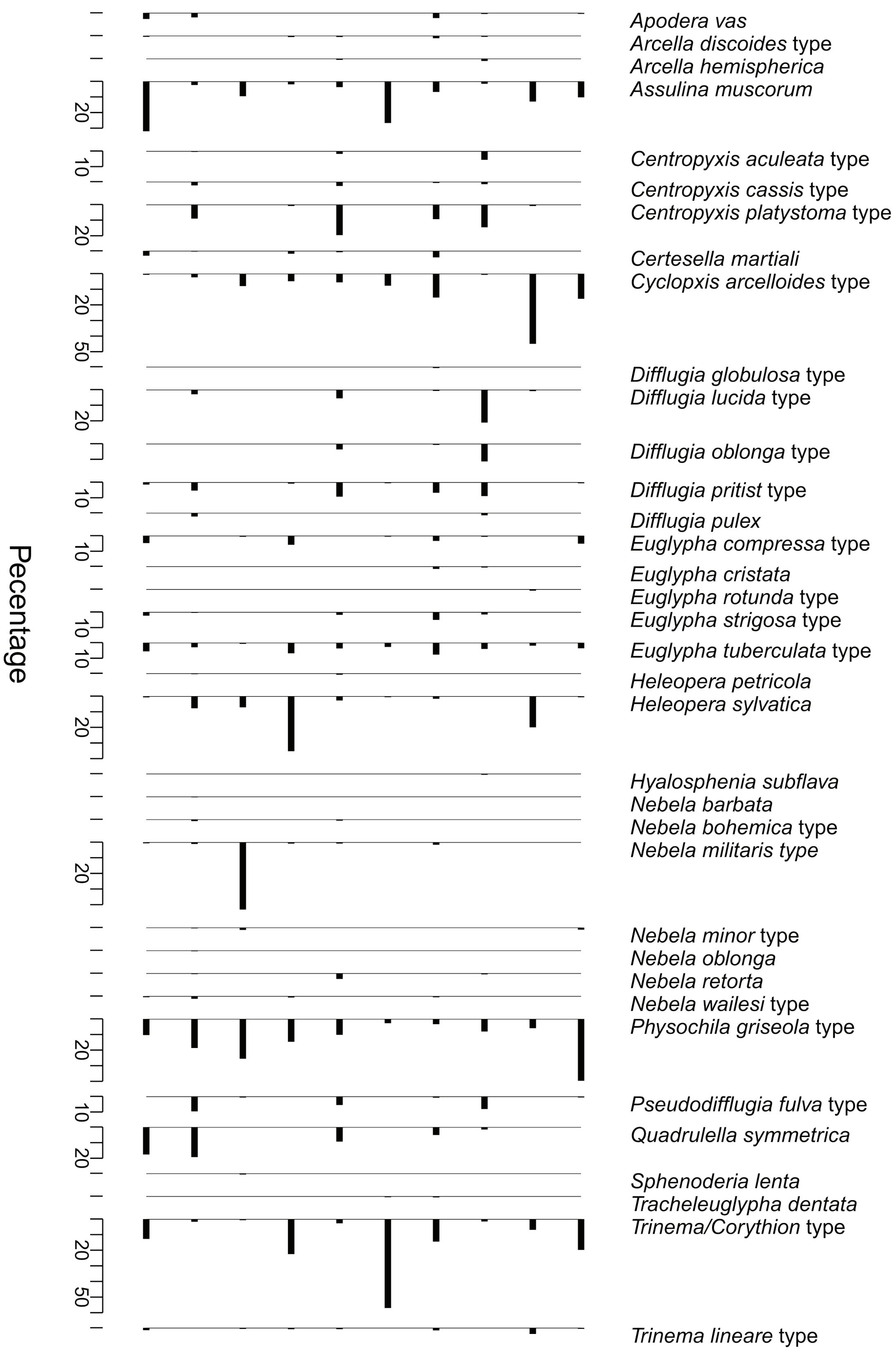
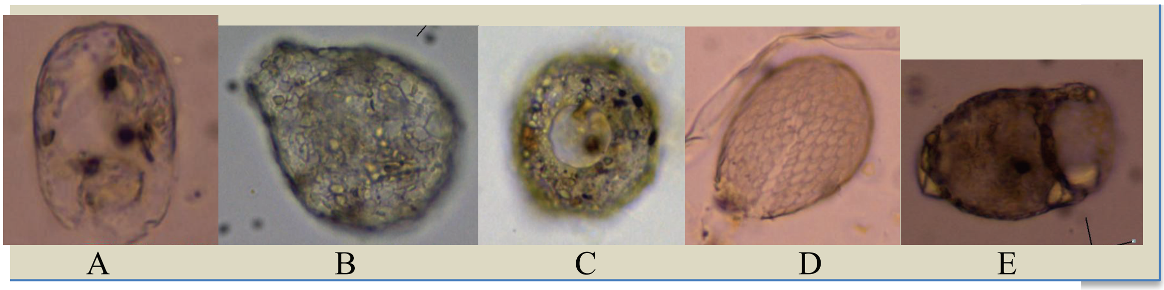


Figure 13. Testate amoebae from Rennix Gap Bog. In this diagram the vertical axis represents the 10 surface samples taken from across Rennix Gap Bog. The images on the following page show some of the common testate amoeba from the site.



Key:
A *Trinema/Corythion* type (length: 48µm)
B *Physochila griseola* type (length 74µm, breadth 59µm)
C *Cyclopyxis arcelloides* type (radius 38µm)
D *Centropyxis playstoma* type (length 61µm, breadth 31µm)
E *Assulina musocurm* (length 44µm)

Figure 13 continued - some of the common testate amoeba from the site. Analysis by Xianglin Zheng (UNSW).

daisies. The fen expands further at the expense of bog, possibly reflecting damage associated with the grazing by cattle.

Testate Amoeba at Rennix Gap

Testate amoebae have been used extensively in the Northern Hemisphere for quantifying depth to water table (DWT) in peat (Mitchell et al. 2008, Amesbury et al. 2016) and hence are one of only a few moisture sensitive proxies. There has been limited research on testate amoebae in Australia, with only two publications on their modern ecology (Meisterfeld and Tan 1998, Bamforth 2015). Figure 13 depicts the testate amoebae sampled across Rennix Gap. From this work the following species have been identified as common on the site: *Trinema/Corythion* type, *Physochila griseola* type, *Cyclopyxis arcelloides* type, *Centropyxis playstoma* type and *Assulina musocurm*.

Fire History: Charcoal and Dendrochronology

Microscopic charcoal was counted by Kemp and O'Dea from the composite record at ca. 10 cm intervals (Fig. 12). Interestingly these small charcoal particles were found in the basal clayey samples examined. While these may reflect long distance transport, they could also suggest that fire was a part of the above-treeline grasslands of the late Pleistocene. They found a distinct increase in charcoal around 3,000 cal yr BP, which coincided with a decline in *Eucalyptus* representation. This is a feature seen in other mires in the region.

The high-resolution macroscopic charcoal records are presented in Figure 14. In comparison to the microscopic charcoal record (Figure 12) no macroscopic charcoal was found in the basal sediments (below 202 cm or 10,875 cal y BP). Tthis may represent the depositional environment (noting that this depth corresponds to the transition to gray, clayey, gravelly sediments in Figure 9) or it might describe that local fire 'turned on' in this environment at about 10,800 years ago as the Snow Gum woodland was established. The late Pleistocene-early Holocene period revealed consistently high fire activity, a feature that is shared with other fire records from eastern Australia (e.g. Black et al. 2008). The mid-Holocene shows a remarkable lack of fire activity, and this then switches back on at about 4,300 cal yr BP. Fire activity in the historic period clearly exceeded that of the centuries that preceded it (Fig 14 C). Fire frequency seems to have peaked in the early historic period (~1840), declined into the early Twentieth Century and but has risen again in the recent past.

Figure 15 shows the dendrochronological record of fire in the woodland surrounding Rennix Gap Bog. The dendro-record revealed that the woodland is mostly relatively young and reflects the regeneration after the 1939 fires. Fire events in the Twentieth Century are often patchy, with some quadrats clearly burnt and other adjacent plots unburnt. The exceptions are the fires of 1954 and 2003, which burnt all of the quadrats analysed.

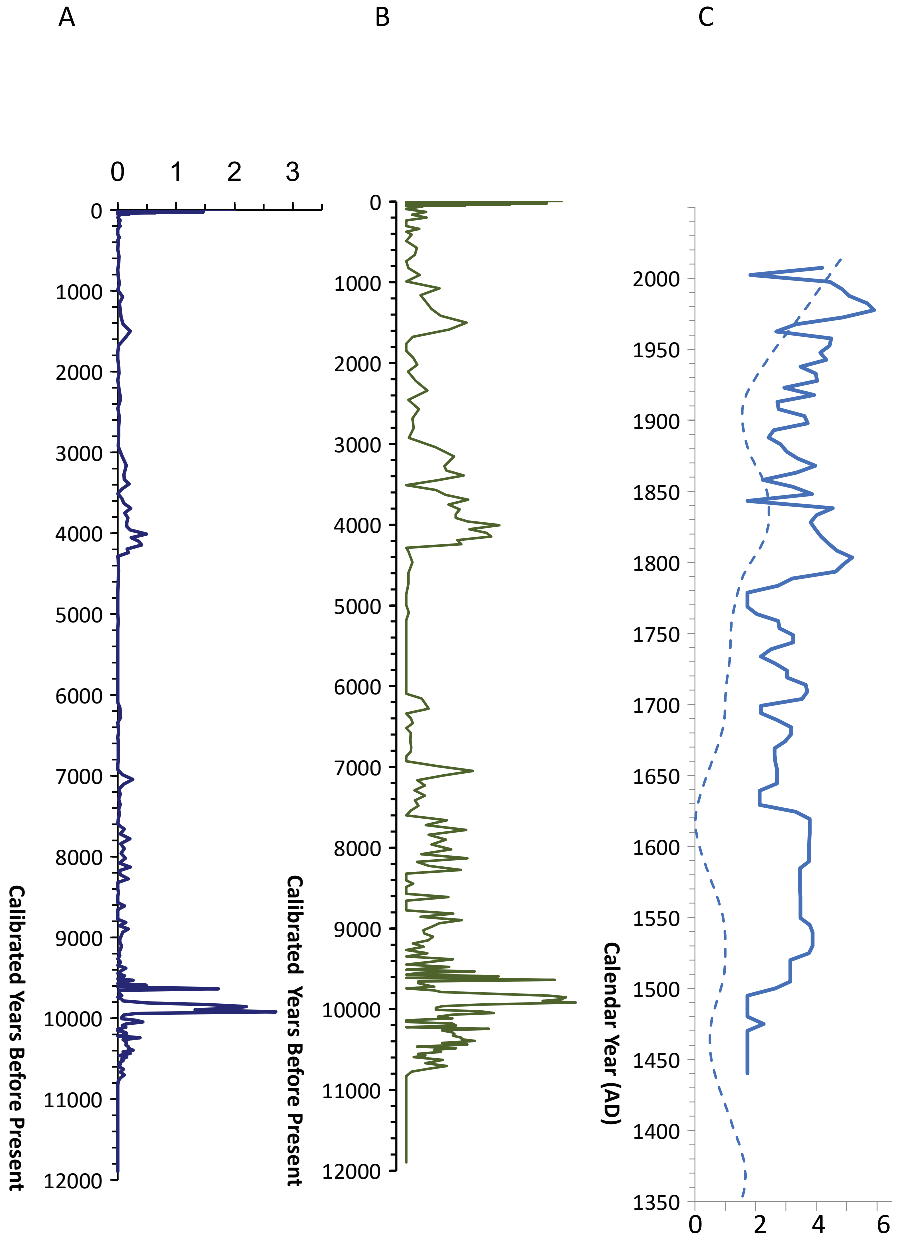


Figure 14. A high-resolution record of macroscopic (>250 µm) charcoal from Rennix Gap Bog, representing fire at a local scale. Panel A shows the accumulation of macroscopic charcoal (CHAR as number of particles/cm2/yr) against the weighted mean age (calibrated years Before Present) inferred from the BACON in Figure 11. Panel B shows the same data, but charcoal data have been transformed to reveal fine details. Panel C shows the recent history of CHAR (solid line) and the inferred fire frequency (dashed line, scale on bottom in fires per 250 years) at Rennix Gap over the last ~500 years, with the vertical axis representing calendar years (AD).

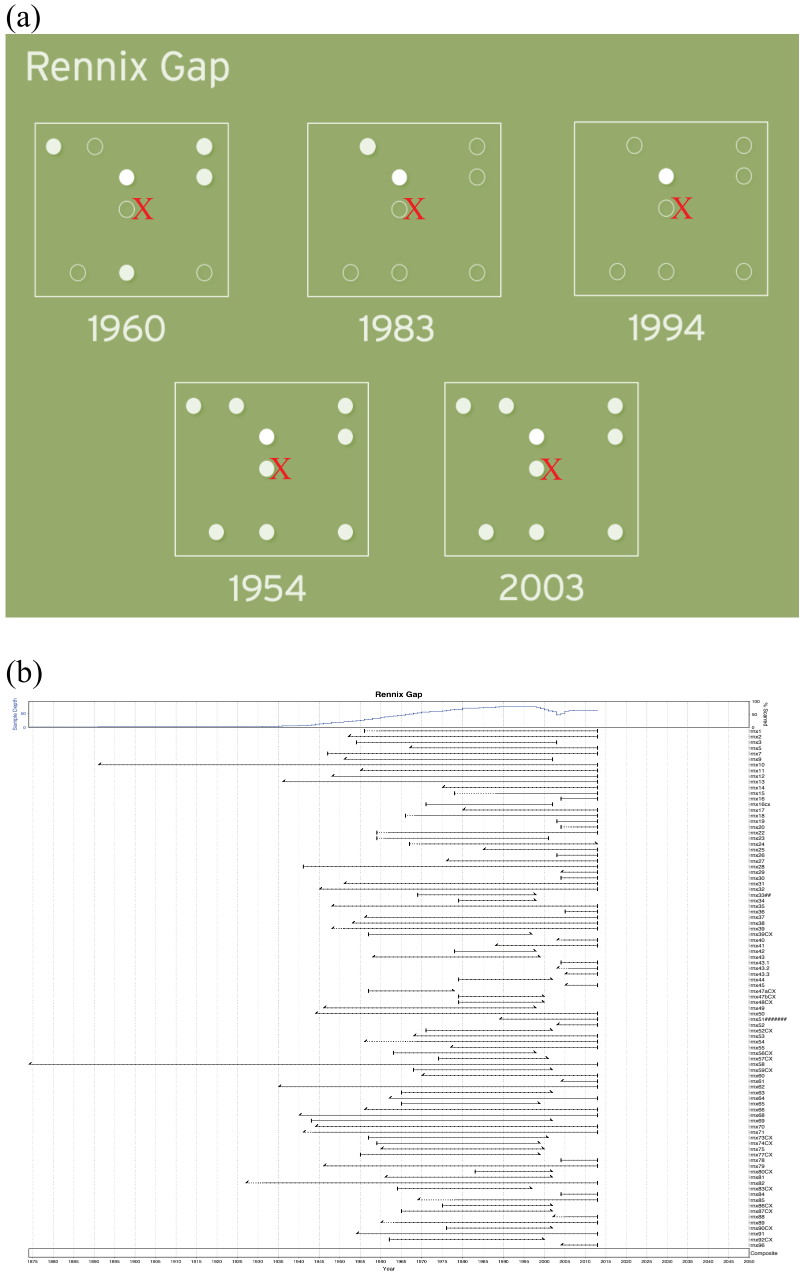


Figure 15. Some of the results from the dendrochronological study in the Snow Gum woodland surrounding Rennix Gap Bog. In the top (a) diagrams Rennix Gap Bog is in the centre (X) and the circles represent quadrats where a complete inventory of the Snow Gum population was undertaken. The open circles represent plots were fire was not recorded and the filled-in circles represent fire in that year. The years in this diagram were chosen to compare the record of fire from sedimentary charcoal with the dendrochronological information: the top row are years with charcoal peaks but little evidence of fire in the Snow Gums and the bottom row are fire years with little charcoal. This mis-match between dendro-perspectives and sedimentary charcoal represents relatively small uncertainty with radiometric dating of the sediments (versus high precision in dendrochronology) and charcoal taphonomy. In (b) the dendrochronological age of the sampled Snow Gum cohort is shown, demonstrating that most trees are relatively young and the oldest is something like 140 years old (in 2015).

Debate concerning the management of fire in Australia's high country and in the forested montane ecosystems and agricultural lands that surround these ecosystems at lower altitudes has a history now exceeding 100 years (e.g. Helms 1893). Debate has particularly raged in the period since the 2003 conflagration, which engulfed the high country and surrounding lands. This work demonstrates that European pastoralists brought significant changes to the fire regime in the Snowy Mountains.

Until recently, the marginal environment and limited food resources (but *cf.* Argue 1995, Gott 2008) of the south-eastern highlands were thought to be responsible for the supposed relatively recent Aboriginal occupation of the highlands (Flood 1980, Flood et al. 1987). It is hence tempting to link the increase in fire activity at about 4000 cal yr BP (Figure 14) to this postulated occupation but evidence of humans at Birrigai at ca. 21,000 yr BP (Flood et al. 1987), at only 730 m altitude but on the northern fringes of the south-eastern highlands in Tidbinbilla Nature Reserve, means that a much longer occupation of the high country must be at least entertained. This conclusion is also justified by archaeological evidence in Tasmania where Aboriginal people were unequivocally occupying alpine-type environments associated with the LGM in Tasmania (Cosgrove et al. 1990, Flood 1995). The new evidence for early Holocene occupation around 1100m mentioned earlier (Theden Ringl 2017a) also supports a long history for human interaction at still higher altitudes. It is hence more likely that fire in the pre-European environment reflects climatic controls with the mid-Holocene changes associated with increasing climatic variability. This also corresponds with ideas by Richard Helms (1893) (and others: Banks 1989, Pyne 1991) who described the high country as free from fire before the advent of the pastoralists' pyromania.

Relatively recent changes in the flora of the Kosciuszko National Park *Sphagnum* peatlands has been considered by Clarke and Martin (1999) and Clarke et al. (2015). They demonstrated some temporal trends over about 50 years but concluded that the mountain mires are relatively resilient, especially to single fire events, but that recovery from grazing is a slower process. This resilience is, however, untested with the likely combined impacts of future climate change, any enhanced fire regime (e.g. frequency, intensity, area burnt) and recovery from past events.

Conclusions: Research and Teaching at Rennix Gap Bog

The Rennix Gap area is important because it provides palaeoenvironmental information for a sub-alpine Snow Gum-dominated vegetation community. It is located at an altitude that it was geographically close to the Kosciuszko ice cap during the Last Glacial Maximum (LGM), which occurred at about 22- 21,000 years ago (Barrows et al. 2002). A late LGM glacial advance at ~19,100 years ago (the Blue Lake Advance) is apparent in the Snowy Mountains (Barrows et al. 2002) and post-glacial warming began after about 17,800 cal. BP (e.g. Menviel et al. 2011). It seems that the modern sub-alpine Snow Gum-dominated environment at Rennix Gap dates to about 10,600 years ago, and that the late glacial period was characterised by a grassland-herbfield community. The Rennix Gap Bog studies also provide a long temporal perspective on fire in this landscape; allowing, for example, a comparison of pre- and post-grazing burning regimes. Comparing the recent sedimentary charcoal records with fire scars on old Snow Gums also provides information on charcoal that is applicable at much broader spatial scales.

Rennix Gap Bog has also been an invaluable teaching resource. Staff working in Rennix Gap Bog never tire from seeing the amazed students' faces as they see evidence of change, from periglacial debris flows to current environments clearly reflected in the changing sediments. Recently it has been a powerful reminder to students that the magnitude and rate of changes anticipated for the next fifty years may exceed those recorded in the core. This field work has thus made incomprehensible periods of time and environmental change through time "real" for students in a way that cannot be replicated in classrooms or virtual reconstructions. An important aspect of this has also been the involvement in ongoing research rather than simple exercises.

This same sense of deep time is one of the rewards that the national parks system can convey to visitors through their educational facilities and outreach. A helpful explanatory notice that has been placed on the "Rennix Walk" track that crosses the northern part of the bog on the old road before turning north currently omits much of the scientific knowledge that is available, as summarised in this paper. There is also scope for a "peatland walk" at Rennix Gap Bog that would introduce the modern and former environments to the interested public.

ACKNOWLEDGEMENTS

Permission to undertake teaching activities did not initially require permits! Subsequent research and activities have occurred under the following Scientific Licenses: Allen SL101321, Hope A1285 (and previous), Keaney S12766, Mooney SL100654, Pearson SL100753. Thanks to staff at NSW Parks and Wildlife Service, Jindabyne for their support over the decades. GH acknowledges the support from NSW OEH for peatland mapping contracts. SM acknowledges the help of Dr Jessica O'Donnell (nee Roe) and Jai Donnelly in the field. Dominique O'Dea (pollen) and Tim Willesdorf (dendro) also contributed to laboratory analyses. The research by SM, PB and KA was funded by the ARC Discovery Grant DP120104322 *Has 20th Century warming changed southeastern Australia's fire regimes?* (2012 – 2014). We are grateful for the encouragement and advice of various 'legends of the high country' including Alec Costin, Tony Martin, Roger Good, Ken Green, Andy Spate, Jennie Whinam and Genevieve Wright. Several iterations of Geography students and many staff at ANU and ADFA/UNSW Canberra are thanked for providing useful stratigraphic information for the peatland.

REFERENCES

Amesbury, M.J., Swindles, G.T., Bobrov, A., Charman, D.J., Holden, J., Lamentowicz, M., Mallon, G., Mazei, Y., Mitchell, E.A.D., Payne, R.J., Roland, T.P., Turner, T.E., Warner, B.G. (2016) Development of a new pan-European testate amoeba transfer function for reconstructing peatland palaeohydrology. *Quaternary Science Reviews* **152**, 132-151.l

Aplin K., Ford F. and Hiscock P. (2010) Early Holocene human occupation and environment of the southeast Australian Alps: new evidence from the Yarrangobilly Plateau, New South Wales. In S. Haberle, J. Stevenson and M. Prebble (eds), Altered Ecologies: Fire, Climate and Human Influence on Terrestrial Landscapes, *Terra Australis* 32. Canberra: ANU E-Press, pp.187–212.

Argue, D. (1995) Aboriginal occupation of the Southern Highlands: Was it really seasonal? *Australian Archaeology* 41, 30-36.

Banks, J.C.G. (1989) A history of forest fire in the Australian Alps. In: R. Good (Ed.) *The Scientific Significance of the Australian Alps*. Australian Alps National Parks Liaison Committee, Canberra, pp. 265-280.

Barrows, T.T., Stone, J.O., Fifield, L.K. and Cresswell, R.G. (2002) The timing of the Last Glacial Maximum in Australia. *Quaternary Science Reviews* **21**: 159-173.

Bamforth, S.S. (2015) Composition of Soil Testate Amoebae Communities: Their Structure and Modifications in the Temperate Rain Forests of New Zealand and Tasmania. *Journal of Eukaryotic Microbiology* **62**, 217-226.

Blaauw, M. and Christen, J.A. (2011) Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis* **6**, 457-474.

Black M.P., Mooney, S.D. and Attenbrow, V. (2008) Implications of a 14,200 year contiguous fire record for understanding human-climate relationships at Goochs Swamp, New South Wales, Australia. *The Holocene* **18**(3), 437-447.

Blay, J. (2015) On Track: Searching out the Bundian Way. New South Publishing, Sydney xv + 328 pp.

Clark, R.L. (1990) Ecological history for environmental management. *Proceedings of the Ecological Society of Australia* **16**, 1-21.

Clarke, P.J. and Martin, A.R.H. (1999) Sphagnum peatlands of Kosciuszko National Park in relation to altitude, time and disturbance. Australian Journal of Botany **47**, 519-536.

Clarke, P.J., Keith, D.A., Vincent, B.E. and Letten, A.D. (2015) Post-grazing and post-fire vegetation dynamics: long-term changes in mountain bogs reveal community resilience. *Journal of Vegetation Science* **26**, 278-290.

Cosgrove, R., Allen, J. and Marshall, B. (1990) Palaeo-ecology and Pleistocene human occupation in south central Tasmania. *Antiquity* **64**, 59e78.

Costin, A. B. (1954) *A study of the ecosystems of the Monaro region of New South Wales*. Soil Conservation Service NSW, Government Printer, Sydney.

Costin, A.B. (1970) Sub-alpine and alpine communities. In: R. M. Moore (Ed) *Australian Grasslands*, ANU Press, Canberra, pp 191-8.

Costin, A.B. (1972) Carbon-14 dates from the Snowy Mountains area, south-eastern Australia, and their interpretation. *Quaternary Research* **2**, 579-590.

Donders, T.H., Haberle, S.G., Hope, G.S., Wagner, F. and Visscher, H. 2007. Transition of the eastern Australian climate system from the post-glacial to the present day ENSO mode. *Quaternary Science Reviews* **26**, 1621-1637.

Flood, J. (1980) *The Moth Hunters: Aboriginal prehistory of the Australian Alps*. Australian Institute of Aboriginal Studies, Canberra.

Flood, J. (1995) *Archaeology of the Dreamtime: The story of prehistoric Australia and its people*. Revised Edition, Angus and Robertson, Sydney.

Flood, J., David, B., Magee, J. and English, B. (1987) Birrigai: a Pleistocene site in the south-eastern highlands. *Archaeology in Oceania* **22**, 9-26.

Galloway, R.W. (1965) Late Quaternary climates in Australia. *Journal of Geology* **73**, 603-618.

Good, R. (1982) The effects of prescribed burning in the sub-alpine area of Kosciusko National Park. MSc Thesis, School of Biological Science, University of New South Wales, Sydney.

Gott, B. (2008) Indigenous use of plants in south-eastern Australia. *Telopea* **12**, 215–226.

Hancock, W. K. (1972) *Discovering Monaro: A study of man's impact on his environment*. Cambridge University Press, Cambridge.

Helms, R. (1893) Report on the grazing leases of the Mt Kosciusko Plateau. *Agriculture Gazette of NSW* **4**: 530-531.

Hogg, A.G., Hua, Q., Blackwell, P.G., Buck, C.E., Guilderson, T.P., Heaton, T.J., Niu, M., Palmer, J.G., Reimer, P.J., Reimer, R.W., Turney, C.S.M. and Zimmerman, S.R.H. (2013) SHCal13 Southern Hemisphere calibration, 0-50,000 Years cal BP. *Radiocarbon* **55**(4): DOI: 10.2458/azu_js_rc.55.16783.

Hope, G. and Nanson, R. (2015) Peatland carbon stores and fluxes in the Snowy Mountains, New South Wales, Australia. *Mires and Peat* **15** (11), 1-23.

Hope, G.S., Nanson, R. and Jones, P. (2012) Peat-forming bogs and fens of the Snowy Mountains of NSW. NSW Office of Environment and Heritage Technical Report. Pp 81.

Kamminga, J. (1995) Prehistory of the Snowy Mountains, Southeastern Australia. In: E. Johnson (Ed) *Ancient Peoples and Landscapes*, Museum of Texas Tech University, pp. 153-171.

Keaney, B. (2016) Bogong Moth aestivation sites as a pioneering archive for understanding the floral, faunal and Indigenous history of the northern Australian alps. Unpublished PhD thesis, Australian National University, Canberra.

Kemp, J. (1993) The end of the Pleistocene in the southern tablelands, southeastern Australia. Unpublished BA thesis, Dept Geography, Australian National University, Canberra.

Kemp, J and Hope, G. (2014) Vegetation and environments since the Last Glacial Maximum in the Southern Tablelands, New South Wales. *Journal of Quaternary Science* **29**(8), 778-788.

Kershaw, A.P., McKenzie G.M., Brown J., Roberts R.G. and van der Kaars S. (2010) Beneath the peat: A refined pollen record from an interstadial at Caledonia Fen, highland eastern Victoria, Australia. *Terra Australis* **32**, 33-48.

Kershaw, A.P.**,** McKenzie, G.M, Porch, N., Roberts, R.G., Brown, J., Heijnis, H., Orr, L.M., Jacobsen, G., Newall, P.R. (2007) A high resolution record of vegetation and climate through the last glacial cycle from Caledonia Fen, south-eastern highlands of Australia. *Journal of Quaternary Science* **22**, 481-500.

Lembit, R. (2002) Kosciuszko – At the crossroads? *National Parks Journal* **46**(4), 5-6.

McDougall, K. L. and Walsh, N. G. (2007) Treeless vegetation of the Australian Alps. *Cunninghamia* **10**(1): 1-57.

Martin, A.R.H. (1986a) Late Glacial and early Holocene vegetation of the alpine zone, Kosciusko National Park. In: *Flora and Fauna of Alpine Australia; ages and origins* (ed: B.A. Barlow), CSIRO Melbourne, pp. 161-170.

Martin, A.R.H. (1986b) Late glacial and Holocene alpine pollen diagrams from Kosciusko National Park, New South Wales, Australia. *Review of Palaeobotany and Palynology* **47**, 367-409.

Martin, A.R.H. (1999) Pollen analysis of Digger's Creek Bog, Kosciuszko National Park: Vegetation history and tree-line change. *Australian J. Botany* **47**, 725-744.

Marx, S.K., Kamber, B.S., McGowan, H.A. and Zawadzki, A. (2010) Atmospheric pollutants in alpine peat bogs record a detailed chronology of industrial and agricultural development on the Australian continent. *Environmental Pollution* **158**, 1615-1628.

Meisterfeld, R. and Tan, L.-W. (1998) First records of Testate Amoebae (Protozoa: Rhizopoda) from Mount Buffalo National Park, Victoria: preliminary notes. *The Victorian Naturalist* **115**, 231-238.

Menviel L, Timmermann A, Timm OE, Mouchet A. (2011) Deconstructing the Last Glacial termination: The role of millennial and orbital-scale forcings. *Quaternary Science Reviews* **30**, 1155–1172.

Mitchell, E.A.D., Charman, D.J. and Warner, B.G. (2008) Testate amoebae analysis in ecological and paleoecological studies of wetlands: past, present and future. *Biodiversity and Conservation* **17**, 2115-2137.

Moore, R.M. and Williams, J.D. (1976) A study of a subalpine woodland-grassland boundary. *Australian Journal of Ecology* **1**, 145-153.

Mulvaney, J. and Kamminga, J. (1999) *Prehistory of Australia*. Allen and Unwin, Sydney.

Newman, J. C. (1954) Burning on sub-alpine pastures. *Journal of the Soil Conservation Service of NSW* **10**, 135-140.

Pyne, S. J. (1991) *Burning Bush: A fire history of Australia*. Henry Holt, New York.

Raine, J. I. (1974) Pollen sedimentation in relation to Quaternary vegetation history of the Snowy Mountains of New South Wales. Unpublished PhD thesis, Australian National University, Canberra.

Renshaw, A. (1981) Kosciusko National Park: our alpine heritage. *National Trust Magazine* **12**, 6-7.

Scott, D. (2011) Tourists on the Summit 1875 – 1914. Betts Camp, the Lakes' Shelters and the Kosciusko Road. Kosciuszko Huts Association.

Specht, R.L. (1981) Major vegetation formations in Australia. In: A. Keast (ed) *Ecological Biogeography of Australia*. Dr Junk, The Hague.

Stone, D. (2012) Walks, Tracks and Trails of New South Wales. CSIRO, Collingwood.

Sullivan, S. (1978) Aborigines of the Uplands of New South Wales. In: *The Aborigines of New South Wales* (Eds: C. Haigh and W. Goldstein), National Parks and Wildlife Service (*Parks and Wildlife* 2(5)), pp 44-49.

Theden Ringl, F. (2016a) Aboriginal presence in the high country: new dates from the Namadgi Ranges in the Australian Capital Territory. *Australian Archaeology* **82**: 25-42. doi.org/10.1080/03122417.2016.1163955

Theden Ringl, F. (2016b) A reassessment of technological change models for the Australian high country. *Archaeology in Oceania* **52**: 81-97. doi:10.1002/arco.5105.

Tindale, N.B. (1974) *Aboriginal Tribes of Australia*. University of California Press, Berkeley.

Wakefield, N.A. (1969) Aspects of exploration and settlement of East Gippsland. *Proceedings of the Royal Society of Victoria* **82**: 7-25.

Whinam J. and Hope G.S. (2005) The peatlands of the Australasian region. In: *Moore – von Sibirien bis Feuerland [Mires - from Siberia to Tierra del Fuego]* (Eds: G.M. Steiner and M. Pfosser), Biologiezentrum der Oberoesterreichischen Landesmuseen Neue Serie 35, Linz, pp 397–434.

Williams, R.J. and Costin, A.B. (1994) Alpine and subalpine vegetation. In: *Australian Vegetation* (Ed: R.H. Groves), Cambridge University Press, Cambridge, pp.467-500.

Rites of Passage: Germination of Vertebrate Dispersed, Regurgitated or Defecated *Phoenix canariensis* Seeds

DIRK HR SPENNEMANN[1] AND MELISSA PIKE[2]

[1]Institute for Land, Water and Society; Charles Sturt University; PO Box 789; Albury NSW 2640 (dspennemann@csu.edu.au) (corresponding author); [2]School of Environmental Sciences, Charles Sturt University; PO Box 789; Albury NSW 2640.

Published on 22 October at https://openjournals.library.sydney.edu.au/index.php/LIN/index

Spennemann, D.H.R. and Pike, M. (2019). Rites of passage: germination of vertebrate dispersed, regurgitated or defecated *Phoenix canariensis* seeds. *Proceedings of the Linnean Society of New South Wales* **141**: 49-58.

Canary Island Date Palms are widely planted as ornamental plants in private and public spaces. As both prolific and long-duration seeders, their drupes provide food for a range of volant and terrestrial vertebrates. This study experimentally examined the germination of vertebrate digested seeds. Whereas seeds in Flying-fox spat did not yield a higher germination rate than undigested controls, seeds that had passed through the gastro-intestinal tract and were deposited in scats, or those that were ingested and regurgitated from the crop, have a significantly better probability of germinating. This establishes Pied Currawongs as effective short-range dispersers and canid frugivores, such as the Red Fox, as major medium- and long-distance vectors of ornamental palms.

Manuscript received 8 March 2019, accepted for publication 9 October 2019.

KEYWORDS**: invasive species, frugivory, palmae, seed dispersal;** *Strepera graculina*, *Vulpes vulpes.*

INTRODUCTION

The seeds of many plants are dispersed via the gastro-intestinal tract of volant and terrestrial vertebrates (Corlett 1998; Corlett 2017; Fedriani and Delibes 2009; Levey, Silva and Galetti 2002; Tsuji, Morimoto and Matsubayashi 2009). Palms are no different in that regard (Zona and Henderson 1989). In addition, studies have shown that some plants benefit from ingestion as mastication and digestive action, as well as immersion in gastric and intestinal fluids, scarifies the seed coat aiding germination (Colon and Campos-Arceiz 2013; Reid and Armesto 2011; Rodriguez-Perez, Riera and Traveset 2005; Traveset 1998).

While a number of volant and terrestrial species are documented as vectors of Canary Island Date Palms (*Phoenix canariensis*) and their congeners (Spennemann 2018f; Zona and Henderson 1989), and thus contribute to the plants' invasiveness, there is a lack of experimental studies that assesses the germination potential of vertebrate dispersed seeds compared with naturally abscised seeds.

A study into the spread of horticulturally-planted Canary Island Date Palms into an agricultural landscape in south-eastern Australia yielded a number of vertebrate dispersed seeds extracted from scats and regurgitates, which allowed for an experimental examination of the issue.

BACKGROUND

Phoenix canariensis

Phoenix canariensis H.Wildpret ex Chabaud (Arecaceae) is a dioecious anemophilous plant that is solely propagated by seed (Barrow 1998), with pollination occurring at distances in excess of 390m (Saro, Robledo-Arnuncio, González-Pérez and Sosa 2014). Canary Island Date Palm readily and reliably sets fruit and seeds freely, annually producing between 5,000 and 30,000 obovoid drupes ('dates') (Djouab, Benamara, Gougam, Amellal and Hidous 2016; Saro et al. 2014), which are a fleshy fruit with a small, single seed and small amount of fibrous pericarp. The drupes range from 15-30mm in length, 12-17mm in thickness and 2–5g in mass (Djouab et al. 2016), of which the seed contributes between 0.9–1.5g. The drupes, which occur in hanging clusters, vary widely in their physical properties (shape, length, diameter, mass, colour) between individual palms. When ripe, they attain a dark orange to red colour.

The Canary Island Date Palm reaches reproductive maturity and first flowers after six to seven years (in some locales between 8 to 10 years)(Borzì 1912), which is the first time that a plant's gender can be determined. In the southern hemisphere *P. canariensis* drupes ripen between March and June (northern hemisphere: November and February), with fruit available to birds until late November (pers. obs.) (Núñez 1997:82). Immediately following ripening, the germination rate of *P. canariensis* is very high (~93%) (Noto and Romano 1987). The seed, which requires temperatures between 25ºC and 35ºC to germinate (Chatty and Tissaoui 1999; Pimenta, da Luz, Pivetta, de Castro and Pizetta 2010) shows its first two-leave shoots at about one year of age (Borzì 1912; Noto and Romano 1987).

Unless affected by disease or pests, the plant can live for 200-300 years (Beech 2017). In its natural distribution, *P. canariensis* is endemic to the Canary Islands (Lipnitz and Kretschmar 1994; Sosa, Naranjo, Márquez, Gil and Saro 2016). It was quickly and widely dispersed during the second half of the ninetieth century as a horticultural feature plant and street tree (Spennemann 2018a; Spennemann 2019b; Zona 2008). Today it is distributed globally in all warm temperate regions (Spennemann 2018b).

As the plants seed freely and their fruits ('drupes') are consumed by a number of vectors, *P. canariensis* has become a weed species that is known to colonise and invade natural areas. In various Australian states. *P. canariensis* it is widely referred to as a 'nuisance plant' (Ku-ring-gai Council 2007:20), 'a garden escape taking up much time to control' (Gye and Thomas 2007), a 'species with huge potential as an invasive weed' (Anonymous 2016) or is even listed 'among the ten worst environmental weeds' (Landcare Echuca 2013). Richardson et al. noted it as a weed plant that "has started to establish along waterways across the regions (NSW, Vic, SA, WA)" (Richardson, Richardson and Shepherd 2006:13f; Richardson, Richardson and Shepherd 2011:19f). In the Australasian setting, *P. canariensis* have been formally regarded as naturalised in New South Wales (Hosking, Conn, Lepschi and Barker 2007), South Australia (Brodie and Reynolds 2012), south-eastern Queensland (Biosecurity Queensland 2018), Victoria (Conn and Walsh 1993), and Western Australia (Lohr and Keighery 2016:32), as well as Norfolk Island (Biosecurity Queensland 2018) and New Zealand (Esler 1987).

Vectors

The primary, long-distance dispersal agent for *P. canariensis* are people, in particular when planting specimens of the palm species as ornamentals (Spennemann 2018a; Spennemann 2018c; Zona 2008). Globally, a range of volant and terrestrial vertebrate vectors are responsible for the dispersal of *P. canariensis* (Spennemann 2019c). Given the size of the seed (8.8–12.2 mm diameter) (Spennemann 2019d), in the Australian context fruit bats (such as *Pteropus poliocephalus*) are possible (Augee and Parry-Jones 1991; Parry-Jones and Augee 1991), but less common dispersers (Spennemann 2018d). The gape size of birds determines their ability to swallow and disperse seeds (Lord 2004; Rey and Gutierrez 1996; Wheelwright 1985). In the Australian context dispersers these are primarily Blackbirds (*Turdus merula*) dispersing to the closest cover (pers. obs.) and Pied Currawong (*Strepera graculina*) predominantly dispersing to the closest perch (Bass 1995). A major consumer of abscised drupes are canids such as the Red Fox (*Vulpes vulpes*), which can transport seeds in their gastro-intestinal tract over greater distances (Debussche and Isenmann 1989; Szuman and Skrzydlewski 1962). The defecation occurs gradually. Field trials suggest that the Red Fox defecates five times in a 24-hour period (Ryszkowski et al. cited after Sequeira 1980). Their behaviour of territorial scent marking results in defecation on or near the same spots, leading to accumulation of scats (Spennemann 2018e) and thus an increased potential for germination.

Germination Studies

A plethora of papers exist that comment on the germination of palm seeds in general (Baskin and Baskin 2014; Broschat and Donselman 1989; Chatty and Tissaoui 1999; Donselman 1982; Gátin 1906; Marcus and Banks 1999; Meerow and Broschat 2017; Mifsud 1996; Pritchard, Wood, Hodges and Vautier 2004; Robinson 2009), as well as on the germination on the congener of *P. canariensis,* the commercially grown date palm *P. dactylifera* (Azad, Rahman and Matin 2011; Singh and Bhargava 2009; Sumianah, Makki and Rumney 1984). Only two studies refer specifically to *P. canariensis* (El-Tarawy, Menesy and Nofal 1989; Pimenta et al. 2010).

There is only a limited number of papers on the germination of vertebrate-ingested palm seed, all relating to seed consumed by coyotes (*Canis latrans*) and racoons (*Procyon lotor*). Studies of the germination

Figure 1. Excreta of the Red Fox (Glenalvon palm nº 7). Sample APV6.

Figure 2. Pellet of undigested material regurgitated by a Pied Currawong (Lieschke palm nº 16). Sample APS24.

of *Washingtonia filifera* seeds ingested by coyotes and racoons provided no or only limited guidance on an appropriate, and replicable methodology (Bullock 1980; Cornett 1985; Cypher and Cypher 1999; Silverstein 2005). Silverstein's (2005) paper is the only study that examined the germination of *Phoenix* spp. seeds after ingestion by vertebrates. He obtained *Phoenix* spp. (and *Washingtonia)* seeds from coyote scats and planted them in a seed starter potting soil in compartmentalized plastic growing trays which were placed in various outdoor and indoor locations. Some of the seeds were pre-treated by washing them for 30 seconds in a 5% bleach solution. Silverstein found that 46.7% of the *Phoenix* seeds (n=60) germinated with a mean of 95 days to germination, whereas *W. filifera* had a germination rate of 75.8% (mean of 71 days) (Silverstein 2005).

MATERIALS AND METHODS

The origin of the samples

The *P, canariensis* seeds used for the experiment were extracted from fox scats (Figure 1), Currawong regurgitates (Figure 2) and flying fox spats collected at the Lutheran Church as well as the property 'Glenalvon' at Alma Park, NSW (Spennemann 2018e). As controls, abscised clean seeds as well as abscised seeds with adhering flesh were collected under palm 15 at 'Glenalvon,' Alma Park. The Alma Park location has been used for a number of studies relating to *P. canariensis.*

Design

The basic methodology used for the experiments reported here followed that of Pimenta et al. (2010). It comprised a regime of 16 hours of simulated daylight and 8 hours of darkness and with environmental temperatures fluctuating between 20°C during the 'night' and 30°C during the 'day.'

The experiment was set up in a climate controlled, window-less laboratory room of 2.6 x 2.8 m. Light was provided by three AquaOne® EcoGlo90 LED lights,

Table 1. Percentage of seeds germinating at Alma Park: Natural soil conditions experiment

Type	Location	2 weeks	3 weeks	4 weeks	5 weeks	n
Currawong	Church	67.52	79.62	80.25	80.25	157
Flying-fox	Glenalvon	50.00	50.00	50.00	50.00	12
Fox	Glenalvon	78.57	88.10	88.10	88.10	84
Abscised seed (2017 season)	Glenalvon	12.00	32.00	48.00	52.00	25
Abscised seed (2018 season)	Glenalvon	38.46	53.85	57.69	57.69	26

each set up centrally above a plastic container. These lights primarily emit at the 430–490 nm spectrum (blue light) and 420–780nm spectrum (white light, peaks at 460nm and 540–620nm). A stable ambient temperature was achieved by the room-specific air-conditioning system, which was manually adjusted twice a day. The temperature was set at the start of the simulated 'day' to 30°C (17:00–9:00) and left cool at the end of the 'day' with the 'night' (9:00–17:00) set at a stable 20ºC. Given the small air space, both the drop and rise of ambient temperature were rapid. Actual room temperatures were logged with a TinyTag Plus 2 TGP-4500 temperature and humidity logger.

The results were analysed in MS Excel and compared with the Chi-squared test with n-1 correction (Campbell 2007; MedCalc Software 2018; Richardson 2011).

Natural soil conditions experiment (A)

To replicate natural germination conditions to the extent possible, the samples were housed in three transparent plastic tubs with lids (34 l, 390 x 790 x 155mm), each filled with 13.33 l of evenly mixed planting substrate comprised of 50% peat moss and 50% Perlite. The surface was levelled and divided into a 3 x 6 grid using wooden skewers. Each cell was populated with nine seeds (3 x 3 pattern). The seeds had been cleaned of adhering material (if any) and measured prior to the experiment (see above). No fungicides were applied in order to simulate natural conditions. The seeds were pressed into substrate, level with the surface, and with their operculum pointing upwards. The surface was then moistened with 1.35 l of standard tap water sprayed with a pressurised mist sprayer evenly across the surface of the tub. The lids were then replaced for the first 48hrs, after which they were removed. This experiment was carried out between 14 June and 27 July 2018. The total number of seeds pertinent to this paper are set out in Table 1.

Soaked seeds experiment (B)

Numerous advice pages on palm seed germination recommend to place seeds between a peatmoss and vermiculite mixture placed in sealed plastic bags or merely between moist paper tissues in sealed plastic bags which are then placed in a warm space (Marcus and Banks 1999; Spanner 2018). The latter method was employed in order to test the germination success of this seasons seeds compared to last season's seeds and to assess the effect of soaking on larger samples. In addition to these primary samples, a number of seeds regurgitated by Currawongs were added.

One half of the samples was pre-treated by soaking the seeds in tap water for 24hrs, while the other half remained untreated. As before, no fungicides were applied in order to simulate natural conditions. The bags were opened after two weeks to assess the rate of germination. All germinated seeds were removed, the bags remoistened and resealed for another week. This process was repeated twice after which the experiment was terminated. The experiment was carried out between 21 June and 20 July 2018. The total number of seeds pertinent to this paper are set out in Table 3.

Recording of germination

In all experiments, the emergence of the cotyledonary petiole (often mistakenly called the radicle) from the operculum was taken as successful germination (Pimenta et al. 2010).

RESULTS

The percentage of animal dispersed seed germination reached its maximum after three weeks, whereas non-ingested seeds continued to germinate in the weeks after that (Table 1; 2). The highest rate of germination was observed for *P. canariensis* seed in fox scats (88.1%) followed by Currawongs (80.3%) and the controls. The germination rate of seeds

Table 2. Percentage of seeds germinating: Soaked seeds experiment

Treatment	Type	Location	2 weeks	3 weeks	4 weeks	5 weeks	n	
not	Currawong	Alma Park Church	72.7	72.7	72.7	./.	66	χ^2= 46.941; *p*< 0.0001
soaked	Abscised seed	Alma Park Glenalvon	16.5	19.3	20.2	./.	109	
	rodent eaten	Alma Park D14	0.0	0.0	0.0	./.	18	
soaked	Currawong	Alma Park Church	71.2	72.7	72.7	./.	66	χ^2= 16.275; *p*= 0.0001
	Abscised seed	Alma Park Glenalvon	38.3	41.1	41.1	./.	107	

Figure 3. *Phoenix canariensis* seed gnawed by a small rodent (D14).

recovered from Flying-fox spats was 50%, while, not surprisingly, none of the rodent-bitten seeds (Figure 3) germinated.

The natural soil conditions experiment found that the observed germination rate for seeds in fox scats and Currawong regurgitates was significantly better than that for and the undigested abscised control seeds (Table 2). There was, however, no statistical difference between the germination rate of seeds in Flying-fox spats and undigested abscised controls (Table 3).

DISCUSSION

While vertebrates are prime dispersers of palm seeds, their effectiveness varies. The comparatively low level of germination success of seeds in Flying-fox spats can be interpreted as the result of a complete lack of scarification. The mastication action of the animal will either tear the pericarp off the seed, leaving striations (Figure 4) or will chew the whole drupe, separating the pericarp from the seed in the oral cavity (Spennemann 2018d). The seed itself is not subjected to any further physical impact, but is pushed to the front of the mouth and ejected with masticated epicarp platelets and squeezed-out endocarp fibres. The observation that the germination rate among Flying-fox dispersed seeds is less than that of the controls could be explained by the fact that the controls lying on the ground had been exposed to some modicum of photo-chemical erosion. As the majority of spit-outs occur at the source tree, Flying-foxes provide very little dispersal benefits.

Even though only a small percentage of volant vectors ingest drupes, birds are by far the most significant in terms of pure quantities of seeds dispersed (in litt.). The size of the seeds that can be dispersed is regulated by the bird's gape size, whereas the overall size of the bird and its crop determines the quantity of seed that can be consumed and thus dispersed. The majority of birds, such as Currawongs, tend to fly to the closest perch to digest their food. There the seeds

Table 3. Differences between the germination rates of vertebrate dispersed seed and controls (naturally abscised seed), Natural soil conditions experiment

				abscised seeds	
	Fox	Currawong	Flying Fox	2017 season	2018 season
Fox	—	*χ2=2.378;* *p=0.1230*	*χ2=10.862;* *p=0.0010*	*χ2=15.445;* *p=0.0001*	*χ2= 11.780;* *p=0.0006*
Currawong	—	—	*χ2=6.351;* *p=0.0117*	*χ2=9.485;* *p=0.0021*	*χ2=6.384;* *p=0.0115*

Figure 4. ***P. canariensis*** **seed chewed by a Flying-fox.**

are regurgitated after less than 20 minutes (Bass 1995). Even though large quantities of seeds accumulate under these perches, their residence time in the bird's gizzard is only very short. Albeit short, the residence time, coupled with the abrading action in the gizzard is sufficient to significantly increase the germination potential compared to naturally abscised seed. Thus the main benefit of Currawongs as vectors rests in the albeit short-distance spatial dispersal of seeds, the quantity of seeds deposited at given locations and the improved germination potential. The net benefit to the palm is less an increase in spatial distribution, but an intensification of its coverage. Dispersal over greater distances occurs only when Currawongs return to their night roosts (Bass 1995).

These findings cannot be extrapolated for smaller birds, such as Blackbirds (*Turdus merula*), Starlings (*Sturnus vulgaris*) and Common Myna (*Sturnus [Acridotheres] tristis), all of* which are known dispersers (Spennemann 2019c), but which have both a smaller gizzard and shorter residence times for ingested fruit.

Canids are major dispersers of fruit including palm drupes (Graae, Pagh and Bruun 2004; Rico-Guzmán, Terrones, Cantó and Bonet 2012; Schmelitschek, French and Parry-Jones 2009; Spennemann and Allen 2000). In most instances the consumption of fruit and subsequent defecation of seed improves a seed's chances or germination success (Traba, Sagrario, Herranz and Clamagirand 2006; Varela and Bucher 2006), even though exceptions are on record (Morales-Paredes, Valdivia and Sade 2015). The findings of this study of enhanced germination capacity conform with the majority of observations.

While vertebrate-dispersed seeds have a greater chance of germination, there are a number of *factors* post-dispersal that affect germination success, namely infestation by insects, predation by rodents and environmental factors. Seeds that successfully germinate while lying on the ground are on occasion lifted above the surface by their emergent radicles (Spennemann, Kent and Cook 2018:9), thus exposing the radicle to consumption by small rodents as well as to desiccation during warm weather events. It is not uncommon to find dry seed with open opercula under palms (pers. obs.). *P. canariensis* seeds under the source palms have a high chance of being predated by rodents (Figure 3), or becoming infested by date stone beetles (*Coccotrypes dactyliperda*) (Spennemann 2019a) which reduces a seed's ability to germinate and successfully develop into a small seedling. Seeds dispersed in canid faeces, however, tend to be avoided by these beetles (Spennemann in press) and thus have a greater chance of establishment. Furthermore, as the germinating seeds are embedded in the matrix of the scats, they are less likely to be raised by the emerging radicle, and thus further protected from predation.

IMPLICATIONS

In the Australian setting, the findings of this study establish the Red Fox as the main long-distance seed vector for Canary Island Date Palm seeds, not only in terms of dispersal distance and dispersal intensity due to repeated defecation at the same location in consequence of territorial scent marking (Gese and Ruff 1997; Macdonald 1979), but also in terms of dispersal success due to the high germination success and low level of post-depositional predation by seed boring beetles. Significantly, Red Foxes are also instrumental in the establishment of Canary Island Date Palms in spaces lacking perch trees, such as in (ungrazed) grassland and scrublands (see example in Spennemann 2018g). Only in areas where the Red Fox is less common, such as in inner urban areas (White, Gubiani, Smallman, Snell and Morton 2006), does dispersal by volant vectors appear to gain greater significance. Among these, Pied Currawong are an effective major vector due to their revisitation of preferred perches.

It would be beneficial to examine the germination potential of Canary Island Date Palm seeds regurgitated by smaller vectors, such as Blackbirds, Starlings and Common Myna. Given the difficulty of identifying and obtaining sufficient quantities of seeds regurgitated by these species, captive feeding experiments may be required.

ACKNOWLEDGMENTS

We are indebted to Robert Cook and Kylie Kent (both Southern Area Technical Support Faculty of Science, Charles Sturt University) for assistance with the germination experiments. Dale Lieschke ('Glenalvon,' Alma Park, NSW) kindly permitted access to the palms on his property.

REFERENCES

Anonymous. (2016). Wednesday walk report 27/4/2016 House Creek in Gerard Moylan and Willows Park. Wodonga: Wodonga urban landcare network.

Augee, M.L., Parry-Jones, K.A. (1991). The diet of flying-foxes in the Sydney and Gosford areas of New South Wales, based on sighting reports 1986–1990. *Australian Zoologist* **27**, 49–54.

Azad, M.S., Rahman, M.T., Matin, M.A. (2011). Seed germination techniques of Phoenix dactylifera: A new experience from Bangladesh. *Frontiers of Agriculture in China* **5**, 241-246.

Barrow, S.C. (1998). A monograph of *Phoenix* L. (Palmae: Coryphoideae). *Kew Bulletin* **53**, 513–575.

Baskin, J.M., Baskin, C.C. (2014). What kind of seed dormancy might palms have? *Seed Science Research* **24**, 17–22.

Bass, D.A. (1995). Contribution of introduced fruits to the winter diet of Pied Currawongs in Armidale, New South Wales. *Corella* **19**, 127-131.

Beech, E. (2017). *Phoenix canariensis*, Palma Canaria. *The IUCN Red List of Threatened Species 2017*.

Biosecurity Queensland. (2018). *Phoenix canariensis* hort. ex Chabaud *Weeds of Australia Biosecurity Queensland Edition*. Brisbane: Biosecurity Queensland, Queensland Government.

Borzì, A. (1912). Sulla coltura del Dattero come Pianta da frutta in Sicilia. *Bollettino dell R. Orto Botanico e Giardino Coloniale di Palermo* **9**, 40-60.

Brodie, C., Reynolds, T. (2012). Review of recent plant naturalisations in South Australia and initial screening for weed risk *Department for Environment and Natural ResourcesTechnical Report 2012/02*. Adelaide: Department for Environment and Natural Resources.

Broschat, T.K., Donselman, H. (1989). Palm seed storage and germination studies. *Principes* **32**, 3–12.

Bullock, S.H. (1980). Dispersal of a desert palm by opportunistic frugivores. *Principes* **24**, 29–32.

Campbell, I. (2007). Chi-squared and Fisher-Irwin tests of two-by-two tables with small sample recommendations. *Statistics in Medicine* **26**, 3661-3675.

Chatty, Y., Tissaoui, T. (Year) of Conference**.** Effect of Temperature on Germination of Ornamental Palm Trees in Tunisia. II International Symposium on Ornamental Palms & other Monocots from the Tropics: ISHS Acta Horticulturae 486, 165–167.

Colon, C.P., Campos-Arceiz, A. (2013). The impact of gut-passage by binturongs (*Arctictis binturong*) on seed germination. *Raffles Bulletin of Zoology* **61**, 417-421.

Conn, B., Walsh, N. (1993). Arecaceae. In: Walsh N and Entwistle T, eds. *Flora of Victoria*. Inkata Press: Melbourne. 165– 167.

Corlett, R.T. (1998). Frugivory and seed dispersal by vertebrates in the Oriental (Indomalayan) Region. *Biological Reviews* **73**, 413–448.

Corlett, R.T. (2017). Frugivory and seed dispersal by vertebrates in tropical and subtropical Asia: An update *Global Ecology and Conservation* **11**, 1–22.

Cornett, J.W. (1985). Germination of *Washingtonia filifera* seeds eaten by coyotes. *Principes* **20**, 19.

Cypher, B.L., Cypher, E.A. (1999). Germination rates of tree seeds ingested by coyotes and raccoons. *The American Midland Naturalist* **142**, 71-76.

Debussche, M., Isenmann, P. (1989). Fleshy fruit characters and the choices of bird and mammal seed dispersers in a Mediterranean region. *Oikos* **56**, 327-338.

Djouab, A., Benamara, S., Gougam, H., Amellal, H., Hidous, K. (2016). Physical and antioxidant properties of two Algerian date fruit species (*Phoenix dactylifera L.* and *Phoenix canariensis L.*). *Emirates Journal of Food and Agriculture* **28**, 601-608.

Donselman, H. (1982). Palm Seed Germination Studies. *Proceedings of the Florida State Horticultural Society* **95**, 256–257.

El-Tarawy, M.A., Menesy, F.A., Nofal, E.M. (1989). Seed germination and seedling growth of Canary Island date palm (Phoenix canariensis Chaub.) as affected by some pregermination treatments. *Journal of Agricultural Research, Tanta University* **13**, 28–37.

Esler, A.E. (1987). The naturalisation of plants in urban Auckland, New Zealand 2. Records of introduction and naturalisation. *New Zealand Journal of Botany* **25**, 523-537.

Fedriani, J.M., Delibes, M. (2009). Functional diversity in fruit-frugivore interactions: a field experiment with Mediterranean mammals. *Ecography* **32**, 983-992.

Gátin, C.-L. (1906). Recherches anatomiques et chimiques sur la germination des palmiers. *Annales des sciences naturelles. Botanique* **3**, 191–314.

Gese, E.M., Ruff, R.L. (1997). Scent-marking by coyotes, *Canis latrans*: the influence of social and ecological factors. *Animal Behaviour* **54**, 1155-1166.

Graae, B.J., Pagh, S., Bruun, H.H. (2004). An experimental evaluation of the Arctic fox (Alopex lagopus) as a seed disperser. *Arctic, Antarctic, and Alpine Research* **36**, 468-473.

Gye, J., Thomas, R. (2007). Paying the price of garden escapes. A snapshot of the work of bush regenerators and the weeds they encounter in Eastern Australia. Sydney South, NSW: Australian Association of Bush Regenerators.

Hosking, J.R., Conn, B.J., Lepschi, B.J., Barker, C.H. (2007). Plant species first recognised as naturalised for New South Wales in 2002 and 2003, with additional comments on species recognised as naturalised in 2000–2001. *Cunninghamia* **10**, 139–166.

Ku-ring-gai Council. (2007). Weed Management Policy7. revised ed. ed. Gordon: Ku-ring-gai Council.

Landcare Echuca. (2013). Environmental Weeds – Problem plants of our district: Landcare Echuca.

Levey, D.J., Silva, W.R., Galetti, M. (2002). *Seed dispersal and frugivory: ecology, evolution and conservation*. CABI International: Wallingford.

Lipnitz, D., Kretschmar, M. (1994). Standortökologische Untersuchungen an *Phoenix canariensis* hort. ex Chabaud (Arecaceae) auf Gran Canaria und Teneriffa (Kanarische Inseln). *Palmarum Hortus Francofortensis: Palmengarten wissenschaftliche Berichte* **4**, 23-63.

Lohr, M.T., Keighery, G.J. (2016). The status and distribution of naturalised alien plants on the islands of the west coast of Western Australia. *Conservation Science of Western Australia* **10**, 1–43.

Lord, J.M. (2004). Frugivore gape size and the evolution of fruit size and shape in southern hemisphere floras. *Austral Ecology* **29**, 430-436.

Macdonald, D.W. (1979). The flexible social system of the golden jackal, *Canis aureus*. *Behavioral Ecology and Sociobiology* **5**, 17-38.

Marcus, J., Banks, K. (1999). A Practical Guide to Germinating Palm Seeds. *Principes* **43**, 56-59.

MedCalc Software. (2018). MEDCALC. Comparison of proportions calculator. Ostend: MedCalc Software.

Meerow, A.W., Broschat, T.K. (2017). Palm Seed Germination. Miami: Environmental Horticulture Department UF/IFAS Extension.

Mifsud, S. (1996). Germinating Palm Seeds. *Chamaerops* **23**.

Morales-Paredes, C., Valdivia, C.E., Sade, S. (2015). La frugivoría por cánidos nativos (Lycalopex spp.) y alóctonos (Canis lupus familiaris) reduce la germinación de semillas de litre (Lithrea caustica) en Chile central. *Bosque (Valdivia)* **36**, 481-486.

Noto, G., Romano, D. (1987). Palms in the Urban Environment in the Southern Latitudes of Italy. In: Thoday PR and Robinson DW, eds. *The Scientific Management of Vegetation in the Urban Environment.*: Acta Horticulturae. 91-97.

Núñez, D.R. (1997). *Frutos secos, oleaginosos, frutales de hueso, almendros y frutales de pepita*. Editum.

Parry-Jones, K.A., Augee, M.L. (1991). Food Selection by Grey-headed Flying Foxes (Pteropus poliocephalus) occupying a Summer Colony Site near Gosford, New South Wales. *Wildlife Research* **18**, 111-124.

Pimenta, R.S., da Luz, P.B., Pivetta, K.F.L., de Castro, A., Pizetta, P.U.C.s. (2010). Efeito da maturação e temperatura na germinação de sementes de *Phoenix canariensis* hort. ex Chabaud - Arecaceae. *Revista Árvore* **34**, 31–38.

Pritchard, H.W., Wood, C.B., Hodges, S., Vautier, H.J. (2004). 100-seed test for desiccation tolerance and germination: a case study on eight tropical palm species. *Seed Science and Technology* **32**, 393-403.

Reid, S., Armesto, J.J. (2011). Avian gut-passage effects on seed germination of shrubland species in Mediterranean central Chile. *Plant Ecology* **212**, 1–10.

Rey, P.J., Gutierrez, J.E. (1996). Pecking of olives by frugivorous birds: a shift in feeding behaviour to overcome gape limitation. *Journal of Avian Biology* **27**, 327-333.

Richardson, F.J., Richardson, R.G., Shepherd, R.C.H. (2006). *Weeds of the south-east : an identification guide for Australia*. R.G. and F.J Richardson: Meredith, Vic.

Richardson, F.J., Richardson, R.G., Shepherd, R.C.H. (2011). *Weeds of the south-east : an identification guide for Australia*. R.G. and F.J Richardson: Meredith, Vic.

Richardson, J.T.E. (2011). The analysis of 2 x 2 contingency tables - Yet again. *Statistics in Medicine* **30**, 890.

Rico-Guzmán, E., Terrones, B., Cantó, J.L., Bonet, A. (2012). Frugivore carnivores: preferences and contribution to seed dispersal of red fox Vulpes vulpes (Linnaeus, 1758) and stone marten Martes foina (Erxleben, 1777) in Carrascal de la Font Roja Natural Park (Alicante, Spain). *Galemys* **24**, 25-33.

Robinson, M.L. (2009). Cooperative Extension SP-02-09: Cultivated Palm Seed Germination. Reno: University of Nevada.

Rodriguez-Perez, J., Riera, N., Traveset, A. (2005). Effect of seed passage through birds and lizards on emergence rate of Mediterranean species: differences between natural and controlled conditions. *Functional Ecology* **19**, 699-706.

Ryszkowski, L., Wagner, C.K., Goszczyński, J., Truszkowski, J. (1971). Operations of predators in a forest and cultivated fields. *Annales Zoologici Fennici* **8**, 160–168.

Saro, I., Robledo-Arnuncio, J.J., González-Pérez, M.A., Sosa, P.A. (2014). Patterns of pollen dispersal in a small population of the Canarian endemic palm (*Phoenix canariensis*). *Heredity* **113**, 215-223.

Schmelitschek, E., French, K., Parry-Jones, K. (2009). Fruit availability and utilisation by grey-headed flying foxes (Pteropodidae: Pteropus poliocephalus) in a human-modified environment on the south coast of New South Wales, Australia. *Wildlife Research* **36**, 592–600.

Sequeira, D.M. (1980). Comparison of the diet of the red fox (Vulpes vulpes L., 1758) in Gelderland (Holland), Denmark and Finnish Lapland. In: Zimen E, ed. *The Red Fox*. Dordrecht: Springer. 35-51.

Silverstein, R.P. (2005). Germination of native and exotic plant seeds dispersed by Coyotes (*Canis Latrans*) in Southern California. *The Southwestern Naturalist* **50**, 472–478.

Singh, R.S., Bhargava, R. (2009). Effect Of Seed Treatments on Germination and Growth Behaviour in Date Palm (Phoenix Species) under hot arid Conditions. *Journal of Tropical Forestry* **25**, 42-48.

Sosa, P.A., Naranjo, A., Márquez, M., Gil, J., Saro, I. (Year) of Conference**.** Mapping of palm trees and palm groves (*Phoenix canariensis*) from the Canary Islands: Distribution and census. EUNOPS XVI. International Meeting of the European Network of Palm Scientists. Las Palmas de Gran Canaria.

Spanner, T.W. (2018). Phoenix canariensis. Canary Island Date Palm. München: Rare Palm Seeds.

Spennemann, D.H.R. (2018a). Canary Islands Palms (*Phoenix canariensis*) in Australia: introduction and early dispersal. *Palms* **62**, 185–201.

Spennemann, D.H.R. (2018b). Geographical distribution of four key ornamental and production palm species *Phoenix canariensis, P. dactylifera, Washingtonia filifera* and *W. robusta*. Albury, NSW: Institute for Land, Water and Society, Charles Sturt University.

Spennemann, D.H.R. (2018c). Nineteenth Century Depictions of the Canary Islands Date Palm (Phoenix Canariensis). A Visual Dataset *Institute for Land, Water and Society Report*. Albury, NSW: Institute for Land, Water and Society, Charles Sturt University.

Spennemann, D.H.R. (2018d). Observations on the consumption and dispersal of *Phoenix canariensis* drupes by the Grey-headed flying fox (*Pteropus polio cephalus*). *European Journal of Ecology* **4**, 41–49.

Spennemann, D.H.R. (2018e). *Phoenix canariensis* seed encountered in scats and ejecta collected at Alma Park. Albury, NSW: Institute for Land, Water and Society, Charles Sturt University.

Spennemann, D.H.R. (2018f). Review of the vertebrate-mediated dispersal of the Date Palm, *Phoenix dactylifera*. *Zoology in the Middle East* **64**, 283-296.

Spennemann, D.H.R. (2018g). *Washingtonia robusta* (Mexican Fan Palm) as a coloniser in an artificial wetland at Albury, New South Wales. *Cunninghamia* **18**, 109-122.

Spennemann, D.H.R. (2019a). Biology, ecology and distribution of the date stone beetle, *Coccotrypes dactyliperda* (Scolytinae, Coleoptera). *Zoology in the Middle East* **65**, 163-182.

Spennemann, D.H.R. (2019b). Canary Islands Palms (*Phoenix canariensis*) as ornamental plants. The first thirty years of the horticultural trade. *Huntia* **17**, 79–102.

Spennemann, D.H.R. (2019c). The connective potential of vertebrate vectors responsible for the dispersal of the Canary Island date palm (*Phoenix canariensis)*. *Flora* **259**, 151468.

Spennemann, D.H.R. (2019d). The contribution of the Canary Island date palm (*Phoenix canariensis*) to the winter diet of frugivores in novel ecosystems. *European Journal of Ecology* **5**, 11–21.

Spennemann, D.H.R. (in press). Infestation of vertebrate defecated palm seeds by *Coccotrypes dactyliperda* (Coleoptera, Curculionidae, Scolytinae) and its implications on the dispersal of palms. *Oriental Insects*, [accepted].

Spennemann, D.H.R., Allen, L.R. (2000). Feral olives (*Olea europaea*) as a future woody weeds in Australia. *Australian Journal of Experimental Agriculture* **40**, 889–901.

Spennemann, D.H.R., Kent, K., Cook, R. (2018). Uninvited guests: Mass Emergence of Scolytinid Beetles in a Seed Germination Experiment and its Management *Institute for Land, Water and Society Report*. Albury, NSW: Institute for Land, Water and Society, Charles Sturt University.

Sumianah, G.M., Makki, Y.M., Rumney, T.G. (1984). Changes in the chemical composition of three cultivars of date seed during germination. *Date Palm Journal* **3**, 395–407.

Szuman, J., Skrzydlewski, A. (1962). Über die Durchgangszeit des Futters durch den Magen-Darm-Kanal beim Blaufuchs. *Archiv für Tierernährung* **12**, 1–4.

Traba, J., Sagrario, A., Herranz, J., Clamagirand, M.C. (2006). Red fox (Vulpes vulpes L.) favour seed dispersal, germination and seedling survival of Mediterranean hackberry (Celtis australis L.) *Acta Oecologica* **30**, 39–45.

Traveset, A. (1998). Effect of seed passage through vertebrate frugivores' guts on germination: a review. *Perspectives in Plant ecology, evolution and systematics* **1**, 151-190.

Tsuji, Y., Morimoto, M., Matsubayashi, K. (2009). Effects of the physical characteristics of seeds on gastrointestinal passage time in captive Japanese macaques. *Journal of Zoology* **280**, 171-176.

Varela, O., Bucher, E.H. (2006). Passage time, viability, and germination of seeds ingested by foxes. *Journal of Arid Environments* **67**, 566-578.

Wheelwright, N.T. (1985). Fruit-size, gape width, and the diets of fruit-eating birds. *Ecology* **66**, 808-818.

White, J.G., Gubiani, R., Smallman, N., Snell, K., Morton, A. (2006). Home range, habitat selection and diet of foxes (Vulpes vulpes) in a semi-urban riparian environment. *Wildlife Research* **33**, 175-180.

Zona, S. (2008). The horticultural history of the Canary Island Date Palm (Phoenix canariensis). *Garden History* **36**, 301–308.

Zona, S., Henderson, A. (1989). A review of animal-mediated seed dispersal of palms. *Selbyana* **11**, 6–21.

Conodonts, Corals and Stromatoporoids from Subsurface Lower Devonian in the Northparkes Porphyry District of Central Western New South Wales and their Regional Stratigraphic Implications

YONG YI ZHEN[1] AND T.J. WELLS[2, 3]

[1]Geological Survey of New South Wales, WB Clarke Geoscience Centre, 947-953 Londonderry Road, Londonderry, NSW 2753, Australia (yong-yi.zhen@planning.nsw.gov.au);
[2]CMOC-Northparkes Mines, PO Box 995, Parkes NSW 2870, Australia; [3]Earth Sciences, University of Tasmania, Box 252-79, Hobart, Tasmania 7001, Australia (tristan.wells@utas.edu.au)

Zhen, Y.Y. and Wells, T.J. (2019). Conodonts, corals and stromatoporoids from subsurface Lower Devonian in the Northparkes porphyry district of central western New South Wales and their regional stratigraphic implications. *Proceedings of the Linnean Society of New South Wales* **141**, 59-80.

Documented in this report is a small fauna recovered from an unnamed stratigraphic unit of bioclastic limestone, black shale and carbonaceous mudstone intersected in a drill hole (NPM-GD871) undertaken by CMOC-Northparkes Mines in the Northparkes porphyry district, located ca 30 km NW of Parkes, central western New South Wales. It includes six conodont species (*Panderodus unicostatus*, *Pandorinellina exigua*, *Pelekysgnathus* sp., *Wurmiella excavata*, *Zieglerodina remscheidensis* and gen. et sp. indet.), one rugose coral (*Microplasma ronense*), three tabulate coral species (*Favosites duni*, *Squameofavosites bryani* and *Thamnopora minor*) and one stromatoporoid species (*Densastroma* sp.). Faunal analysis indicates a maximum age of late Lochkovian and a minimum age of Pragian for this unit, equivalent to the upper part of the Derriwong Group. The fauna is also comparable with those recovered from the Jerula Limestone Member of the Gleninga Formation (upper part of the Yarra Yarra Creek Group) exposed farther west. Conodont data documented here suggest that the base of the Derriwong Group is diachronous across the region, and on the eastern flank of the Tullamore Syncline has a minimum age of the late Pragian rather than early Lochkovian as currently accepted.

Manuscript received 8 August, 2019, accepted for publication 28 October 2019

KEYWORDS: biostratigraphy, conodonts, corals, Early Devonian, geology, New South Wales, Northparkes.

INTRODUCTION

The Northparkes porphyry district, located ca 30 km northwest of the rural centre of Parkes, central western New South Wales, is a region of national metallogenic importance (Fig. 1). The porphyry Cu-Au deposits are related to Ordovician monzonitic intrusive complexes within the region. The study area is within the Pearce Prospect that lies ca 9 km northwest of the current Northparkes (CMOC) mining operations on the northern side of the Bogan River in the northernmost reaches of the Northparkes exploration lease EL5801 (Fig.1). The Pearce Prospect was first delineated by Hooper (1992), then by Arundell et. al. (1997) and Morris et. al. (1999).

The topography of the area is a flat lying gilgai with some overbank deposits from the Bogan River, aeolian transported cover, and float sourced from the low relief hills to the west. The area is currently used for both cropping and grazing, with much of the native vegetation removed. With sparse, shallow drilling and no outcrop, geology until recently has been defined by logging of reverse circulation drilling chips and geophysics and is still comparatively poorly understood. Therefore, any new data will advance the understanding of the geological history, and potentially inform the formation, distribution and preservation of the Cu-Au mineral deposits in this area. We report herein details of Early Devonian conodonts recovered from three limestone samples, and rugose and tabulate

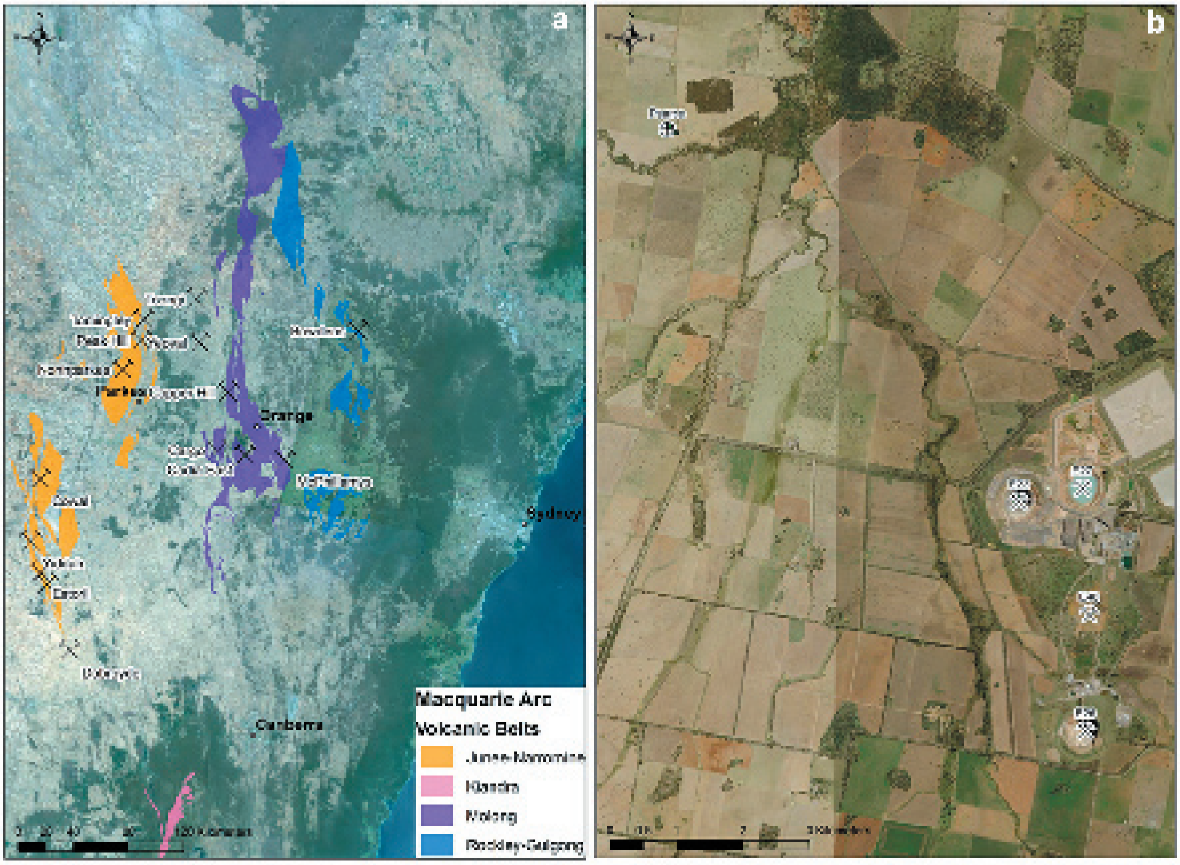


Figure 1. Location maps; a, map showing locations of Northparkes and other major mining sites of the porphyry copper-gold deposits in the Macquarie Volcanic Province of central western New South Wales; b, map showing the locations of the operational mining sites of CMOC-Northparkes Mines and the location of the drill hole NPM-GD871 within the Pearce Prospect (Spatial Services, Department of Finance, Services and Innovation New South Wales, 2019).

corals and stromatoporoids associated with one of the samples from drill hole NPM-GD871. The age of the 35 m of bioclastic limestone, black shale and carbonaceous mudstone in this drill hole, and their unconformable contact with the underlying volcanic rocks, are crucial to the increased understanding of local and regional stratigraphy discussed below.

REGIONAL GEOLOGY

The Macquarie Arc (Fig. 1; Glen et al., 2007; Fergusson, 2014) of eastern Australia comprises four fault-limited belts of mafic to intermediate volcanics, volcanoclastics, and limestones, and calc-alkaline to shoshonitic intrusive rocks. These four belts of the Macquarie Arc occur within Ordovician to early Silurian turbidite sequences that comprise the majority of the Lachlan Fold Belt, which extends from far northern Queensland to eastern Tasmania (Krynen et al., 1990; Gray and Foster, 2004; Crawford et al., 2007b). The Macquarie Arc is interpreted to have formed above an Ordovician to earliest Silurian intra-oceanic supra-subduction zone (Percival and Glen, 2007; Glen et al., 2012), and accreted to the eastern margin of Australia during the Benambran Orogeny (Crawford et al., 2007a). Mechanisms for the development and segmentation of the arc remain contentious (Fergusson and Coney, 1992; Fergusson and Fanning, 2002; Meffre et al., 2007; Cayley, 2011; Moresi et al., 2014; Rawlinson et al., 2014; Fergusson and Henderson, 2015; Pilia et al., 2015).

Large tonnage mineralisation in the Macquarie Arc is associated with silica-saturated alkalic and calc-alkalic porphyries, and related high sulfidation, skarn and carbonate-base-metal epithermal deposits (Cooke et al., 2007; Lickfold et al., 2007). High-grade mineralisation at Northparkes is linked to small volume, oxidised, evolved shoshonitic magmas (~444–435 Ma; Cooke et al., 2007; Lickfold et al., 2007; Pacey et al., 2019).

The Northparkes porphyry district straddles the Forbes Anticline that extends with a north-south axis between the Tullamore Syncline to the west and the Hervey Syncline to the east (Sherwin, 1996, fig. 5). Outcrops of Siluro-Devonian rocks are very rare in this district, and are only observed close to the Ordovician Wombin and Goonumbla Volcanics around the Wombin State Forrest (Krynen et al., 1990). However, the Derriwong and Wallingalair groups of late Silurian to Early Devonian age are exposed to the immediate west of the Northparkes porphyry district, on the eastern flank of the Tullamore Syncline, where the predominantly coarse grained thick-bedded quartzose sandstones and conglomerates of the Wallingalair Group form low ridges. In contrast the Cookeys Plains Formation of the Derriwong Group is dominated by shale, siltstone and fine-grained sandstone with scattered and poorly exposed outcrop. Structure in the area is poorly constrained due to the extent of Quaternary cover and the depth of weathering. The dip of Ordovician rocks in the district is variable but tends to be ca 60ºE while the overlying Devonian rocks near the Pearce Prospect have an approximately 30º dip to the southeast.

Studies of the geology of the Northparkes district have focused on the porphyry mineralisation, the Ordovician Goonumbla Volcanic Complex and the numerous monzonitic intrusive rocks related to the porphry Cu-Au mineralisation (Lickfold et al., 2003, 2007; Simpson et al., 2005; Cooke et al., 2007; Pacey et al., 2019). The Ordovician rocks that are the subject of numerous government and Ph.D. studies are overlain by the comparatively poorly studied Siluro-Devonian sedimentary rocks of the Derriwong Group (Sherwin, 1996; Lyons, 2000).

SAMPLED DRILL CORE SECTION AND MATERIAL

A 2018 drill campaign of CMOC-Northparkes Mines intersected bioclastic limestones, black shale and carbonaceous mudstone in contact with altered volcanic rocks in one of two drill holes at the Pearce prospect (NPM-GD871 at 32°51’38.18629”S, 147°58’54.03845”) (Fig. 1b). Along with aircore and reverse circulation drilling they provide the only information for the subsurface (Fig. 2). For the purpose of this report, stratigraphic logs of the drill holes have been created from the detailed original logging notes (Table 1). No detailed petrographic work has been undertaken to refine the initial classification of the lithologies. Rocks intersected in these drill holes are visually unlike the Ordovician Wombin and Goonumbla volcanics as defined within the Northparkes mining operations, on which the original logging method was based.

Quaternary cover at the Pearce Prospect (Krynen et al., 1990; Sherwin, 1996) (Litho-units 1 and 2) is at least 2–3 m thick. It comprises sub-angular to sub-rounded quartz grains in a generally upward-fining sequence, with evidence of a basal conglomerate at 41 m in GD870 that may represent a palaeochannel (Fig. 2, Table 1). Separating transported cover from the underlying regolith is complex due to the abundance of cracking clays, the reworking of the cover by farming practices and the often deep gilgai. The saprolith profile (Litho-unit 3, Table 1) under the Quaternary cover is interpreted to be a product of weathering of Devonian rocks. The regolith and saprolith profile at the Pearce prospect are substantial, up to 35 m thick and dominated by sedimentary rocks (Litho-unit 3, Fig. 2, Table 1). Based on the abundance of rounded quartz, they might be sourced from the Late Devonian Hervey Group. At the base of complete oxidation (BOCO) in drill hole NPM-GD871 (66.1 m, Fig. 2) there are variably fossiliferous detrital limestones and interbedded siltstones of an unnamed unit. From 66 m to 91 m in NPM-GD871 there are carbonaceous mudstone and shale (Litho-unit 4, conodont samples C3005 and C3006) and detrital limestones (Litho-unit 5, conodont sample C3004) containing crinoid stems, and the stromatoporoids and tabulate corals that are documented in this report. The depositional environment is inferred to be below wave base but proximal to a shallow marine setting: either a lagoon, or a fringing reef in an emergent island arc setting (Table 1).

From 91 to 99m in NPM-GD871 a selective (chlorite-sericite-illite?) altered, moderately sorted, polymict, diorite/andesite clast-dominated breccia with a muddy calcareous matrix is present. An erosional contact is inferred between the fossiliferous beds (Litho-unit 5) and the underlying volcanics (Litho-unit 13), based on the distinct lack of metasomatism in the overlying carbonaceous rocks or in the breccia matrix (Litho-unit 6), despite pervasive alteration in the volcanics. No evidence of submarine emplacement of the volcanics is present suggesting deposition occurred on previously emergent rocks with an auto-brecciated or rubbly carapace. There is no evidence of a fault at this key contact. The nature of the erosional contact is complex, based on the lack of a significant contact in hole GD870. Given that the regional dip of Siluro-Devonian rocks is ca 30º to the SE, the contact should appear at or towards the top of GD870. The lack of fossiliferous rocks or any significant sedimentary strata in GD870 is further

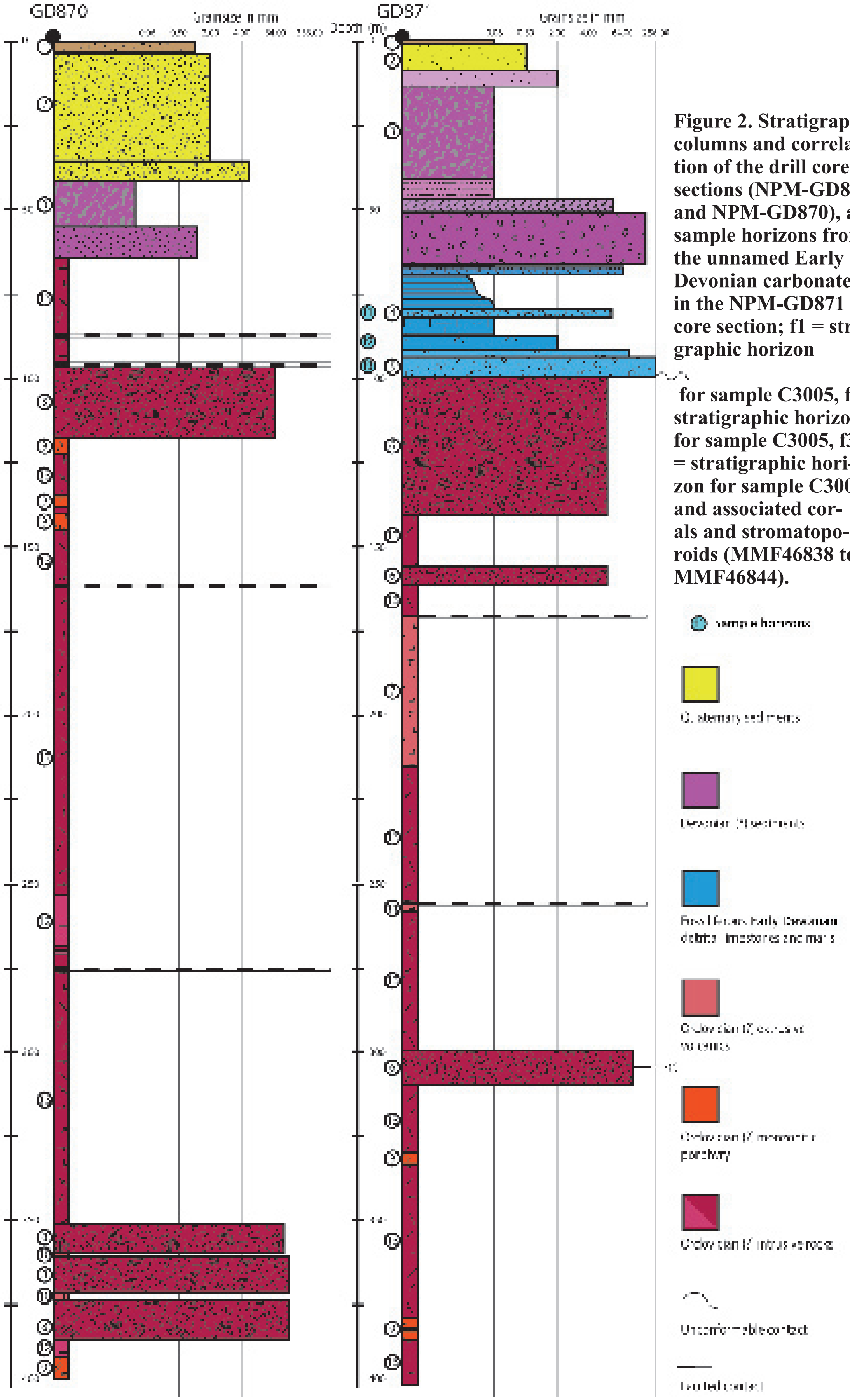


Figure 2. Stratigraphic columns and correlation of the drill core sections (NPM-GD871 and NPM-GD870), and sample horizons from the unnamed Early Devonian carbonate unit in the NPM-GD871 drill core section; f1 = stratigraphic horizon for sample C3005, f2 = stratigraphic horizon for sample C3005, f3 = stratigraphic horizon for sample C3004 and associated corals and stromatoporoids (MMF46838 to MMF46844).

Table 1. Log of the drill core sections and lithostratigraphy

Litho- unit	Apparent thickness	Lithology	Interpretation
1	1-3m (full profile)	Quaternary soils.	Aeolian transported cover and overbank fluvial deposits from the ephemiral Bogan River.
2	8 - 37 m	Well sorted quartz-rich oxidised sandy-clay. Sub-round quartz grains are abundant. Lower 6 m in GD870 is a poorly sorted quartz, lithic fragment rich conglomerate.	Basal conglomerate to an extensive transported Devonian cover sequence.
3	17-38 m	Detextured regolith and saprolith profile, transitions into saprock in last ~2 m of the interval.	Insitu weathered Devonian sediments.
4	27 m	Upward fining bedded carbonaceous black shale with minor fossil content.	Low energy marine facies, product of attrition of an overlying reef into a transitional marine setting well below wave base.
5	8m	Bioclastic limestone unconformablly overlying altered extrusive (?) volcanics.	Either an erosional contact based on clasts of altered volcanics in the matrix, or deposition on the autobrecciated carapace of a lava flow.
6	~2 - 40 m	Pervasive chlorite altered diorite breccia. Bornite at 120 m depth in GD871 is hosted in a epidote-chlorite + hematite alteration altered, silica cemented breccia	Tectonic breccia that has later become a conduit for later intrusive phases.
7	50 m	Crystal crowded plagioclase phyric trachyandesite. Mafics are magnetite, biotite and hornblende, with rare quartz eyes	Extrusive volcanics or a feeder dike related to lavas.
8	8 - 20m	Polymict diorite, trachyandesite, monzonite porphry clast breccia. Monzonite porphyry clasts contain xenoliths of diorite and have chilled margins similar to aplite dykes.	Magmatic breccia, late monzonite porphry is interpreted to be the progenitor to this breccia facies.
9	<3-7m	Plagioclase-hornblende-biotite-titanite phyric monzonite porphyry. Contacts are typically sharp intrusive but are infrequnetly faulted.	Late intrusive phase, hydrous but shows no evidence of significant mineralisation.
10	2 - 3 m	Trachyandesite - basaltic trachyandesite, fine grained to aphanitic groundmass of feldspar, maroon hematite dusting is overprinted by pervasive epidote-chlorite alteration. Mafics occur as radial growths.	extrusive volcanics or a feeder dike related to lavas.

Table 1 continued

Litho- unit	Apparent thickness	Lithology	Interpretation
11	7 m	Cryptic volcanic lava flow or a tuff/fiamme breccia. Aphanitic to very fine grained crystal rich groundmass. Plagiocalse phenocrysts are partially sericitised. Anhydrite filled voids could be vesicles or fiamme.	Petrographic work is required to refine the paragenesis and association of this facies.
12	5 m	Alkali feldspar granite. K-feldspar phenocrysts <20 mm in size have a poikiolitic texture. Variably chloritised mafics include magnetite with biotite, pyroxene and minor hornblende. Lithology is hematite dusted with patchy epidote. Chilled margins at contact between AFG and diorite (13).	Similar to alkali feldspar obsereved in the Northparkes porphry district. Chilled margins at the contact between AFG and diorite provide a paragentic relationship
13	>250 m	Diorite, with a groundmass of interlocking plagioclase. Mafics are pyroxene, amphibole, biotite and blebs of magnetite. Mafics are variably altered to chlorite. Alteration assemblages and intensity vary from unaltered to intense pervasive epidote alteration. Short intervals of albitic and potassic alteration occur near contacts with other intrusive phases 6 and 7.	Cryptic diorite that requires petrographic and geochronolgical refinement as nothing similar is observed in the Northparkes district or regional exploration. Infered to be Ordovician (?).

support for the transitional shallow to deep marine settings.

Based on geochemical similarities, the initial interpretation of the altered volcanics in NPM-GD871 and comparatively unaltered volcanics in GD870 (Lithounits 9-13) are equivalent to the Late Ordovician Wombin Volcanics. Further refinement would require U-Pb dating of zircons or other dateable mineral phases as well as petrographic analysis, which is beyond the scope of the present study. The extensive diorite intrusion logged in GD870 is unusual in the Northparkes district. However, late mafic finger dykes are a common feature in the Northparkes district and are seen cross-cutting the dioritic intrusion in GD870. The unusual monzonitic intrusions and small basaltic trachyandesites (Litho-unit 10) in NPM-GD871 are more typical of the Northparkes intrusive complex of Late Ordovician age, and have a geochemical signature associated with mineralising intrusions at Northparkes. The geochemistry indicates that the bioclastic limestones unconformably overlie mafic to intermediate volcanics similar to the Wombin Volcanics rather than the more felsic Devonian volcanics.

Material studied in this contribution includes a total of 35 identifiable conodont specimens, recovered from three samples (2 specimens in C3004, 25 in C3005 and 9 in C3006) representing the carbonate intervals in the NPM-GD871 drill core section (Fig. 2). Sample C3004 from the detrital limestone (Litho-unit 5) yielded only two conodont specimens but contained abundant macrofossils, which were also examined from 13 thin sections prepared from three levels (MMF46838 and MMF46839 from a depth of 90.8-90.9 m; MMF46840, MMF46841 and MMF46842 from 90.4-90.6 m; MMF46843 and MMF 46844 from 96.0-96.38 m). The conodonts from these three samples have a CAI of 4, indicating a burial temperature of 190 to 300 °C.

METHODS AND REPOSITORY

The larger core sample from depth 90.4 to 96.38 m in NPM-GD871 was selected for preparation of coral and stromatoporoid thin sections, before several pieces with less macrofossil material were selected (C3004) for the acid-leaching process. All the three limestone samples including C3004 (0.45 kg), C3005 (2.3 kg) and C3006 (1.85 kg), were dissolved in 10% acetic acid. The resulting insoluble residues were separated using sodium polytungstate solution. Conodonts illustrated in Figure 3 are SEM photomicrographs captured digitally (numbers with the prefix IY are the file names of the digital images filed with GSNSW image database). In total, 36 conodont specimens are figured and bear the prefix MMMC (MMMC05550 to MMMC05585 inclusive). They are deposited in the microfossil collection, and corals (Figs 4–8) and stromatoporoids (Fig. 9) in the macrofossil collection (MMF46838 to MMF46844), of the Geological Survey of New South Wales, housed at the WB Clarke Geoscience Centre at Londonderry in outer western Sydney. For comparison and to assist regional biostratigraphic correlation, additional conodont specimens from the area to the east of Bogan Gate are illustrated in Figures 10–11.

EARLY DEVONIAN CONODONT FAUNA

Three samples processed have yielded six conodont taxa in the fauna, only five are identifiable, comprising *Panderodus unicostatus* (Branson and Mehl, 1933) (Fig. 3j–m), *Pandorinellina exigua* (Philip, 1966) (Fig. 3h–i), *Pelekysgnathus* sp. (Fig. 3n), *Wurmiella excavata* (Branson and Mehl, 1933) (Fig. c–f), *Zieglerodina remscheidensis* (Ziegler, 1960) (Fig. 3a–b) and gen. et sp. indet. (Fig. 3g). However, the stratigraphical interval bearing corals and stromatoporoids discussed in the following section yielded only a single conodont species, *P. unicostatus,* from sample C3004. Samples C3005 and C3006 produced the identical conodont assemblages, suggesting an Early Devonian (latest Lochkovian to Pragian) age. Among the four specifically identifiable species recovered, *P. unicostatus* has a relatively long stratigraphic range, extending through the entire Silurian into the Lower Devonian, and *W. excavata* has been reported from the lower Silurian to Lower Devonian (Corradini and Corriga, 2010). The Pa element of *Z. remscheidensis* is characterized by having uneven denticulation, a large cusp and a higher distal end of the anterior blade with several larger denticles (Fig. 3a). It has a stratigraphic range restricted to uppermost Silurian (Přídolí) to Middle Devonian (Peavey, 2013).

Pandorinellina exigua differs from other known species of the genus in having a markedly higher anterior third of the blade of the Pa element, which has the posterior-most denticle larger and higher with its posterior edge extending normal to the basal margin. It has been split into two subspecies, *P. exigua exigua* (Philip, 1966) and *P. exigua philipi* (Klapper, 1969), and both are recognized as cosmopolitan with a combined stratigraphic range from latest Lochkovian (the *pesavis* Biozone) to Emsian (the *patulus* Biozone). *Pandorinellina exigua philipi*

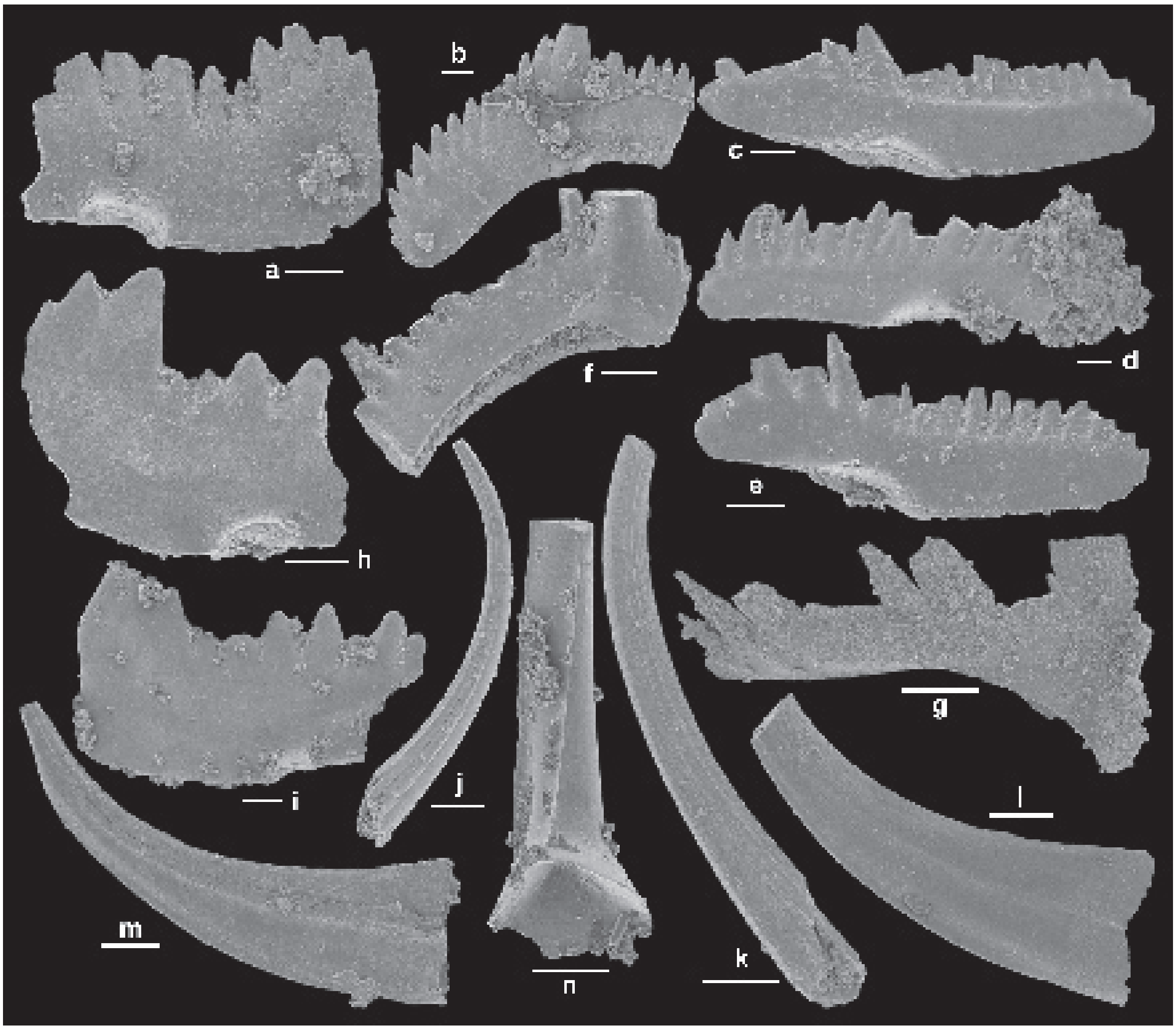


Figure 3. Early Devonian conodonts recovered from three samples (C3004, C3005 and C3006) in the unnamed stratigraphic unit intersected in the NPM-GD871 drill hole; a–b, *Zieglerodina remscheidensis* (Ziegler, 1960) from sample C3005; a, Pa element, MMMC05550, outer-lateral view (IY381-002); b, Pb element; MMMC05551, inner-lateral view (IY381-001); c–g, *Wurmiella excavata* (Branson and Mehl, 1933); c–e, Pa element; c, MMMC05552, sample C3005, outer-lateral view (IY381-004); d, MMMC05553, sample C3006, outer-lateral view (IY381-009); e, MMMC05554, sample C3005, inner-lateral view (IY381-003). f, M element, MMMC05555, sample C3005, posterior view (IY381-005); g, gen. et sp. indet., Sc element, MMMC05556, sample C3006, inner-lateral view (IY381-008); h-i, *Pandorinellina exigua* (Philip, 1966); Pa element; h, MMMC05557, sample C3005, outer-lateral view (IY381-006); i, MMMC05558, sample C3006, inner-lateral view (IY381-007); j-m, *Panderodus unicostatus* (Branson and Mehl, 1933); j–k, sub-symmetrical, graciliform element (qg); j, MMMC05559, sample C3004, outer-lateral view (IY381-012); k, MMMC05560, sample C3005, postero-outer-lateral view (IY381-017); l-m, falciform (pf) element; l, MMMC05561, sample C3005, inner-lateral view (IY381-013); m, MMMC05562, sample C3005, outer-lateral view (IY381-016); n, *Pelekysgnathus* sp., sub-symmetrical element, MMMC05563, sample C3006, posterior view (IY381-010). Scale bars = 100 µm.

can only be distinguished from *P. exigua exigua* by having a more restricted basal cavity. The occurrence of *P. exigua* in the samples from the NPM-GD871 drill core section is crucial for age determination, but the specimens available are difficult to assign at the subspecies level as the basal cavity is only partially preserved in the specimens available. However, their general morphology, particularly the shape, size and number of denticles of the prominent anterior denticle set, and development of the small basal cavity lobes, is closer to that of *P. exigua philipi*.

Pandorinellina exigua philipi is widely distributed and age diagnostic, with a stratigraphic range extending from the upper Lochkovian (*pesavis* Biozone) to upper Emsian (*patulus* Biozone) (Farrell, 2004, fig. 8). In eastern Australia, it has been recorded from the Cavan Bluff (Pragian) and Taemas (Emsian) Limestones (Pedder et al., 1970), Roxburgh Formation (Colquhoun, 1995), Garra Formation (Wilson, 1989; Farrell, 2004), the lower Cunningham Formation (Talent and Mawson, 1999), Trundle Group (Pickett and McClatchie (1991; Mathieson et al., 2016) and an unnamed Lower Devonian stratigraphic unit in the southern Thomson Orogen (Zhen et al., 2017) of New South Wales, from the Buchan Caves Limestone (Mawson et al., 1992) and Waratah Limestone (Bischoff and Argent, 1990) in Victoria, and from the Ukalunda Formation of central Queensland (Mawson and Talent, 2003).

The presence of *Pandorinellina exigua* in the sampled intervals of the NPM-GD871 drill core section indicates a maximum age of latest Lochkovian and a minimum age of Emsian. The two illustrated specimens representing the Pa element of this species (Fig. 3h-i) are both broken, but are morphologically comparable with the types of *P. exigua philipi* from Royal Creek (Pragian *sulcatus* Biozone) in the Yukon territory, Canada (Klapper, 1969), and those of the same age from the Karheen Formation in southeastern Alaska (Savage, 1977), from the Nahkaoling Formation (Pragian) of South China (Lu et al., 2016), and from the Jerula Limestone Member of the Gleninga Formation (Trundle Group) illustrated by Pickett and McClatchie (1991, figs 2B–C, E, F, H) from several localities west of Fifield, and by Mathieson et al. (2016, fig. 31A–F) from a roadside locality (float) some 13 km north of Trundle township in central western New South Wales. The higher anterior third of the blade in the type material of *P. exigua philipi* bears four to seven denticles (Klapper, 1969, pl. 5, figs 1–7), but only four in the material from Alaska (Savage, 1977, pl. 1, figs 33–34). Material assigned to this subspecies from eastern Australia varies from two to four denticles, such as in the samples from Trundle (Mathieson et al., 2016, fig. 31A–F) and those from the Garra Formation (Farrell, 2004) of New South Wales. The specimens from the NPM-GD871 drill core section have two or three denticles on the higher anterior third of the blade (Fig. 3h–i).

CORAL AND STROMATOPOROID ASSEMBLAGE

One rugose coral species, *Microplasma ronense* (Mansuy, 1913), three tabulate coral species, *Favosites duni* Etheridge, 1920, *Squameofavosites bryani* (Jones, 1937) and *Thamnopora minor* Jones, 1941, and a poorly preserved stromatoporoid species were recovered from the same stratigraphic level (Litho-unit 5) in association with conodont sample C3004 (Fig. 2, Table 1). The cystiphyllid rugose coral *M. ronense* is presented in three thin sections (MMF46840a, MMF46840b, MMF46841a; Fig. 4a–d). This species was originally reported from the Emsian or lowermost Eifelian of the Ron region in Vietnam and Laos, south-eastern Asia (Mansuy, 1913; Fontaine, 1961). It has been widely reported in eastern Australia, with a stratigraphic range from the Pragian to Emsian (Zhen 1995; Blake 2010). The specimens have a corallite diameter varying from 5 to 9 mm, thin corallite walls without observable stereozones, and the rare occurrence of short septal spines on the upper surface of dissepiments (Fig. 4a, c, e). They are comparable with those illustrated by Hill (1942) from the Garra Formation exposed near Wellington, central-west New South Wales.

In eastern Australia tabulate coral *Favosites duni* has a stratigraphic range restricted to the Lower Devonian (Etheridge, 1920; Jones, 1941; Hill, 1950; Hill et al., 1967; Jell and Hill, 1970; Blake, 2010). In the current collection, it occurs in five thin sections (MMF46839-a, MMF46841b, MMF46842a, MMF46844a and MMF46844b; Fig. 5a–c), as small hemispherical to irregularly globular or ramose coralla with a diameter of 20–25 mm. Lage corallites typically have 5 to 7 sides and are 1.0–2.2 mm in diameter (mean 1.6 mm), and are surrounded by smaller corallites 0.5 to 0.9 mm in diameter with typically 3 or 4 walls . They are comparable with those recorded from the Lower Devonian (Erebus beds) of eastern-central Queensland (Blake, 2010) in having the same range of corallite sizes, 20 to 22 horizontal tabulae per 10 mm longitudinally, thin corallite walls (0.1–0.15 mm), absence of visible mural pores in longitudinal sections and the rare occurrence of short septal spines. The type material of this species is from the Lower Devonian of Cavan near Yass, southern New South Wales (Etheridge, 1920). It has also been reported from the Douglas Creek Limestone (Emsian) of Queensland (Jones, 1941; Hill et al., 1967; Jell and Hill, 1970) and the Murrindal Limestone (Emsian) of Victoria (Hill, 1950), and shows wide variation in corallite size and density of tabulae. *Favosites forbesi* Milne-Edwards & Haime, 1851 resembles *Favosites duni* in having dimorphic corallites, but with large corallites that are slightly larger in size (2–3 mm) and mural pores that are better developed and commonly seen in longitudinal sections (Hill and Jones 1940; Philip, 1962; Blake, 2010).

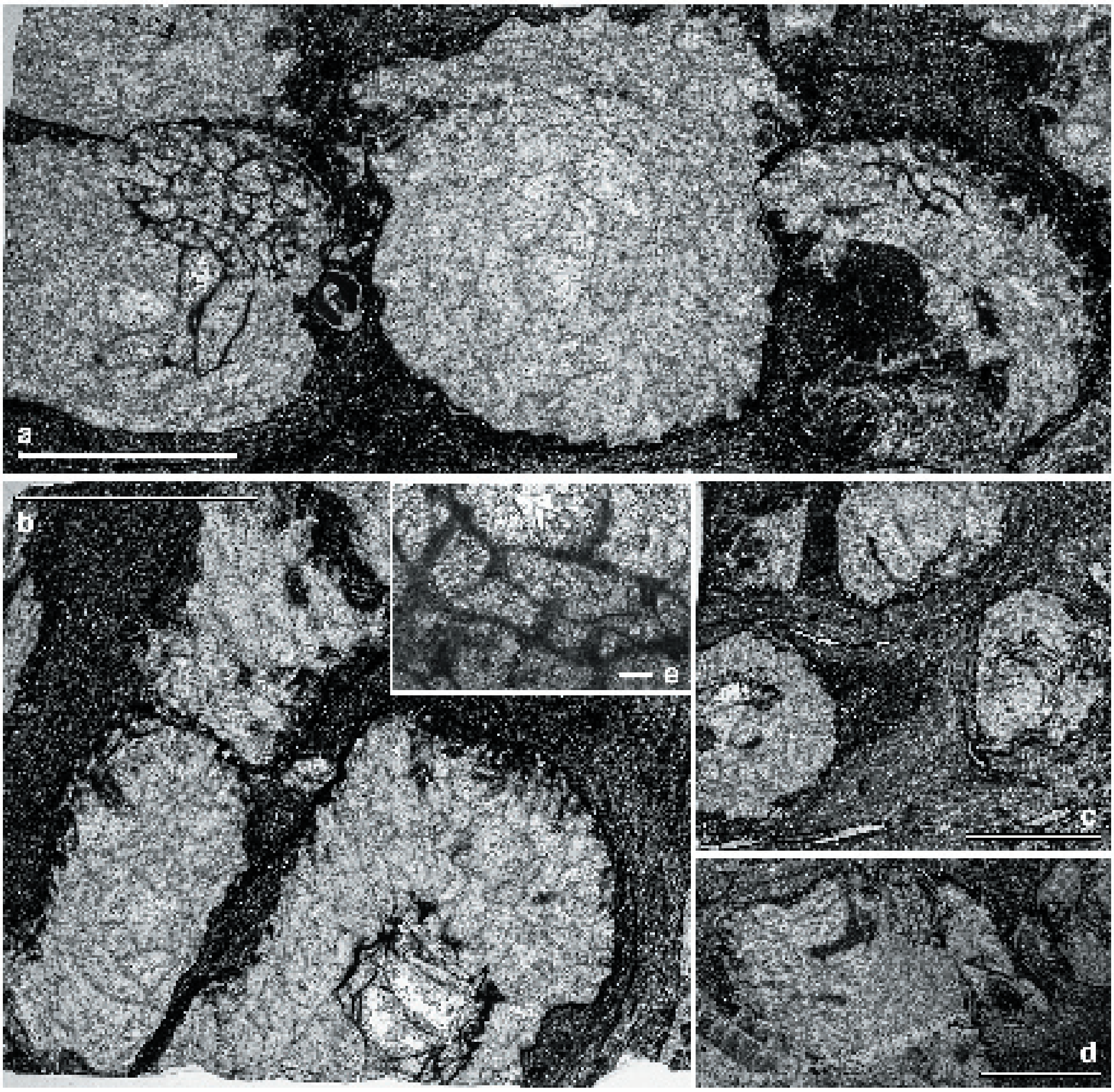


Figure 4. Rugose coral *Microplasma ronense* (Mansuy, 1913) from the unnamed stratigraphic unit (Litho-unit 5) intersected in the NPM-GD871 drill hole; a, MMF46840b-1, TS; b, MMF46840a, LS; c, MMF46841a, TS; d, MMF46841a, TS; scale bars = 5 mm; e, MMF46840b-1, TS, close-up, showing septal spines, scale bar = 0.2 mm.

Tabulate coral *Squameofavosites bryani* has been widely reported from the Lower and Middle Devonian of eastern Australia (Blake, 2010). In the material from drill hole NPM-GD871 (Fig. 2), this species occurs in two thin sections (MMF46838a and MMF46838b; Figs 6–7) prepared from a small foliose corallum. This specimen is identical with the types from the Taemas Limestone (Emsian) at Good Hope, near Yass (Jones, 1937), and those documented from the Cookeys Plains Formation of central western New South Wales (Földvary, 2001) and from the Emsian Craigilee beds and Erebus beds of Queensland (Blake, 2010), in having comparable size of corallites (1–1.5 mm, mean 1.2 mm), moderately thick walls (0.2–0.28 mm in thickness), closely-spaced tabulae (30–36 per 10 mm), mural pore size (0.2–0.27 mm), and abundant occurrence of squamulae that are short and triangular in outline with a thick base, and are paired in neighbouring corallites immediately above mural pores (Fig. 6a–b). However, the mural pores are more abundant and spaced more closely (20–25 per 10 mm) in the current specimen, typically in single or double

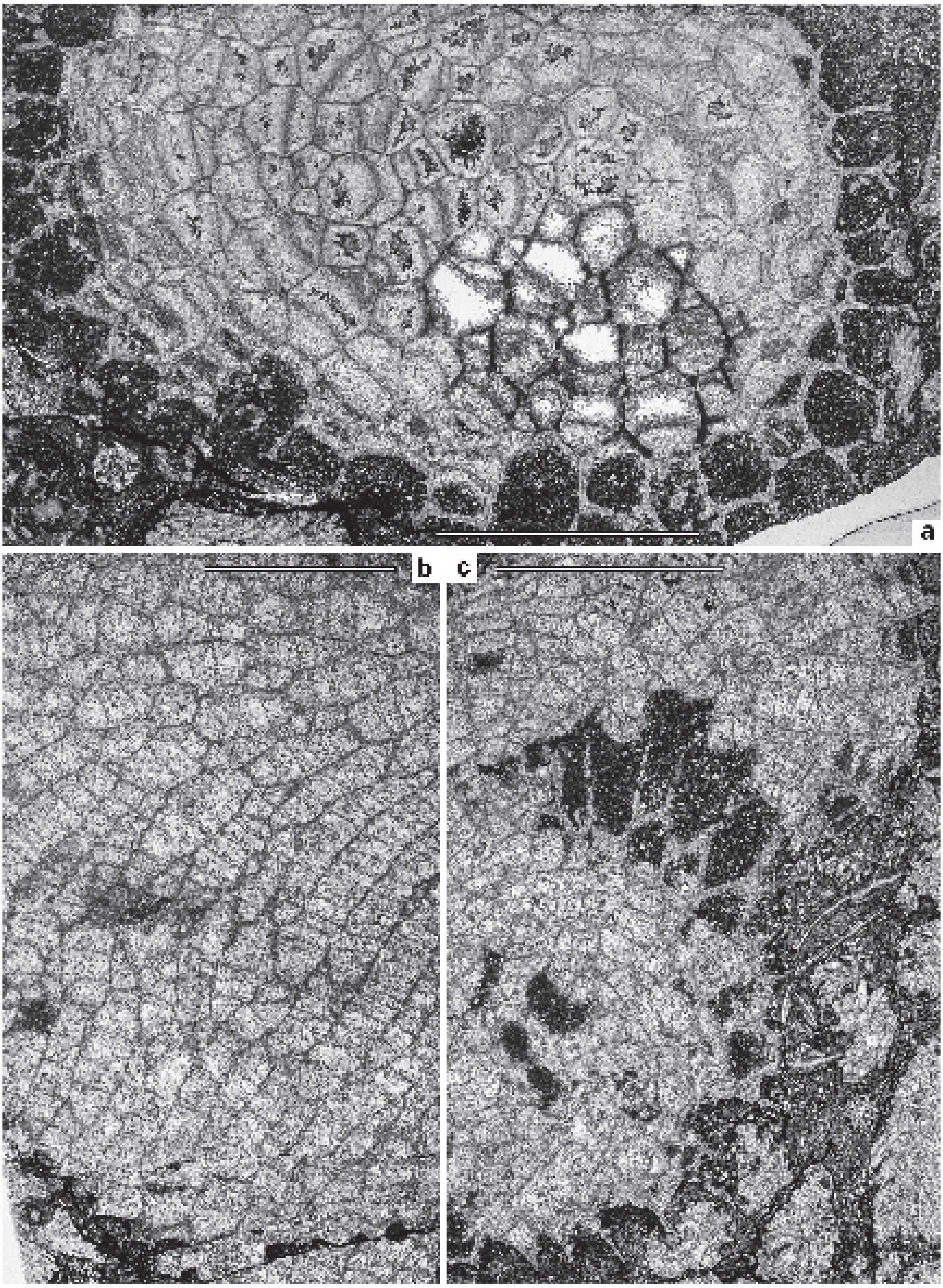


Figure 5. Tabulate coral *Favosites duni* Etheridge, 1920 from the unnamed stratigraphic unit (Litho-unit 5) intersected in the NPM-GD871 drill hole; a, MMF46842a, TS; b, MMF46841b, LS; c, MMF46839-1, TS + LS; scale bars = 5 mm.

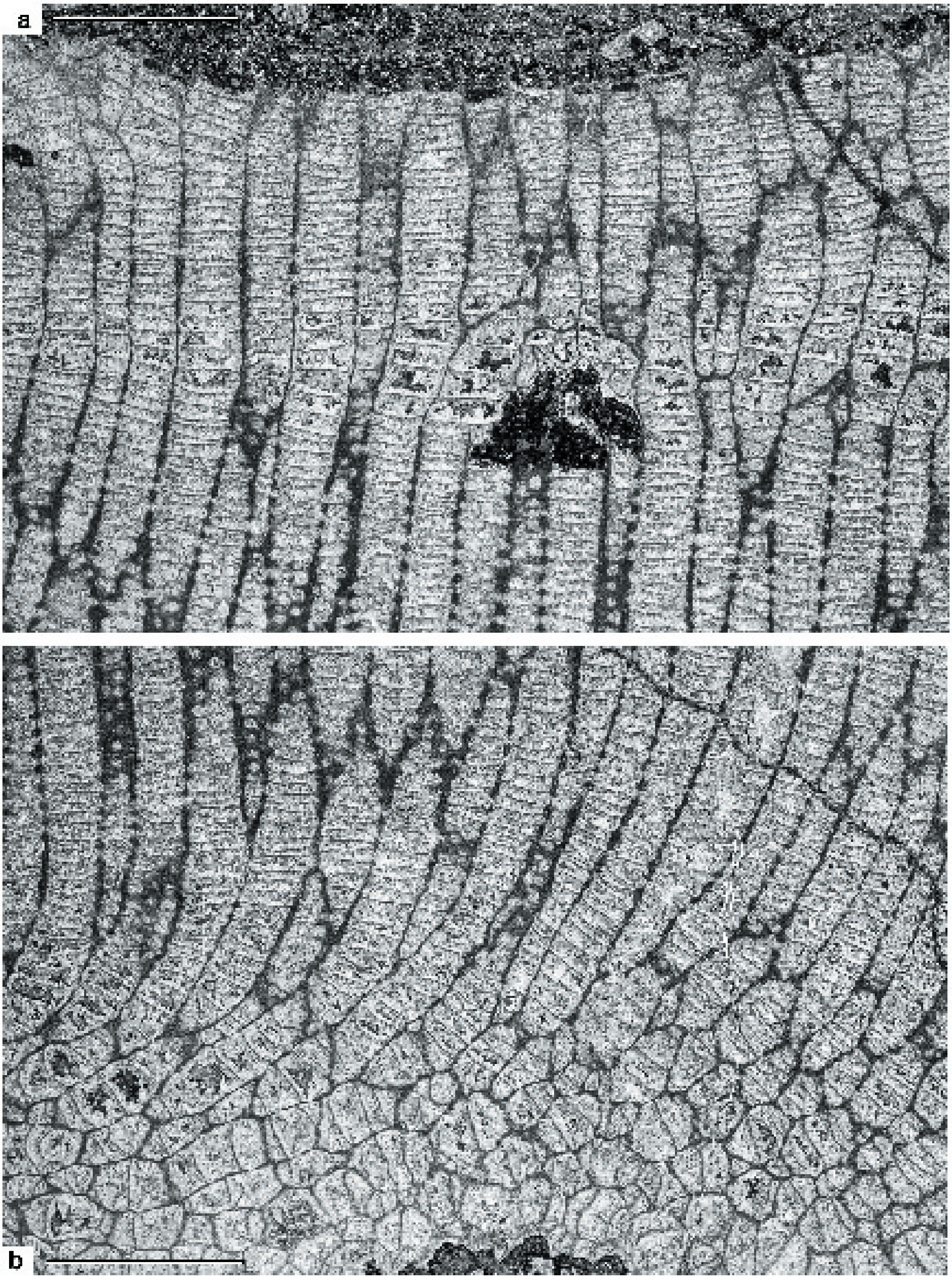


Figure 6. Tabulate coral *Squameofavosites bryani* (Jones, 1937) from the unnamed stratigraphic unit (Litho-unit 5) intersected in the NPM-GD871 drill hole; MMF46838b; a, LS; b, TS + LS; scale bars = 5 mm.

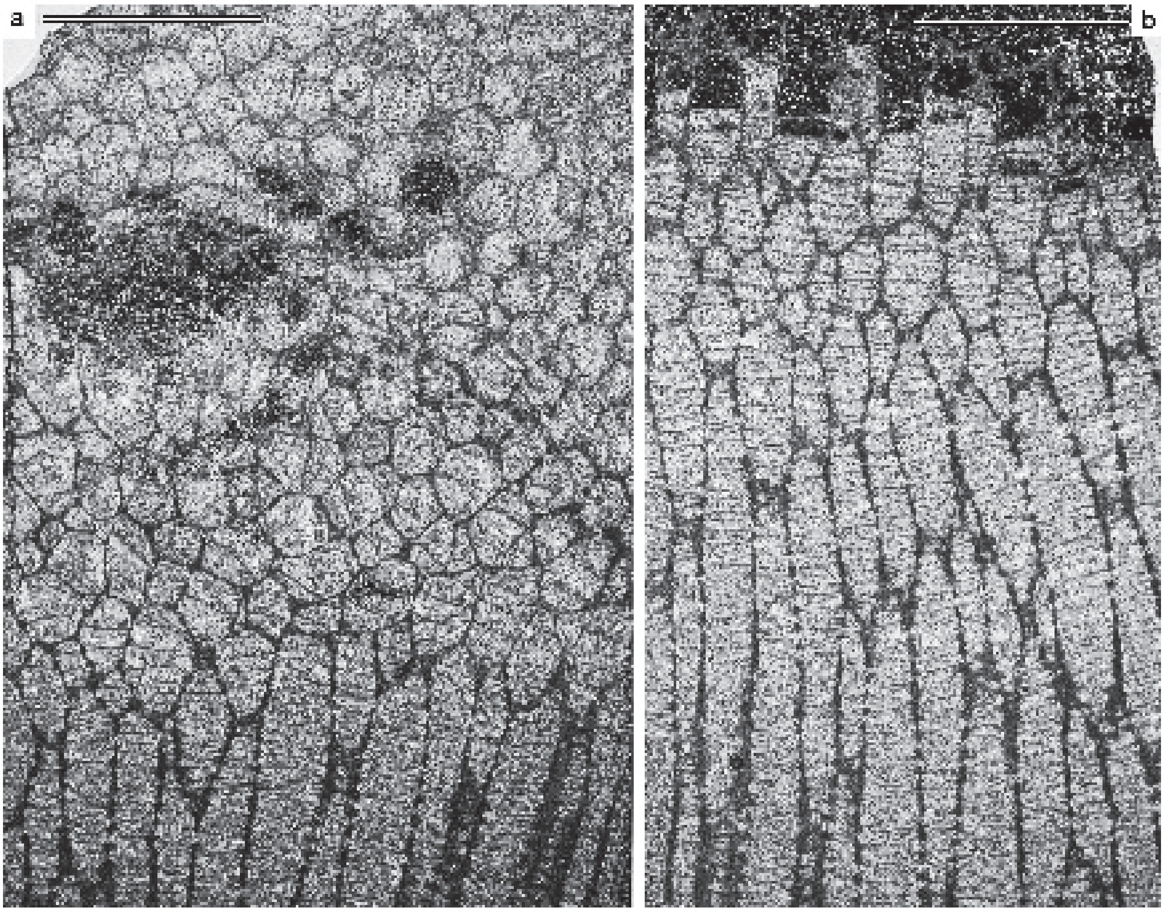


Figure 7. Tabulate coral *Squameofavosites bryani* (Jones, 1937) from the unnamed stratigraphic unit (Litho-unit 5) intersected in the NPM-GD871 drill hole; MMF46838a, a, TS+LS, b, LS, scale bars = 5 mm.

rows (rarely in three rows). In longitudinal sections mural pores are evenly spaced with the neighbouring two rows arranged in alternating horizons (Fig. 6b).

Tabulate coral *Thamnopora minor* (Fig. 8a-d) is the most abundant coral species observed in a nearly six m interval (from 90.8 m to 96.38 m) of the NPM-GD871 drill core section. Coralla are randomly distributed and form several bands of so-called "spaghetti rock" where fragmentary branches are closely packed and in contact (Fig. 8a-b). The coralla are slender (1.8 to 3 mm in diameter) with corallites of 0.2 (axially) to 0.3 mm (distally) in diameter. Rounded corallites with thick walls, well-developed growth lamination and a median suture between corallites (Fig. 8c-d) confirm assignment to *Thamnopora*. Growth form and the general morphology and sizes of coralla and corallites are identical with the syntypes of this species from the Douglas Creek Limestone (Emsian) of Queensland (Jones, 1941; Pickett, 2010). *Thamnopora minor* shows some resemblance to *Thamnopora angulata* Hill, 1950, from the Murrindal Limestone (Emsian) of Victoria, but the Victorian species has slightly larger coralla (4 mm in diameter) and corallites (diameter 0.3 mm axially and 1.5 mm distally). *Thamnopora minor* Dubatolov, 1959 reported from the Middle Devonian of Russia and Vietnam is treated herein as a homonym of *Thamnopora minor* Jones, 1941.

The single stromatoporoid specimen is a small domal skeleton with fine microreticulate structure (Fig. 9a–b). Its microcolliculi are aligned to form a recognizable horizontal structure and suggests that it belongs to a species of *Densastroma*, but poor preservation makes further identification impossible. However, *Densastroma* is only known from the Silurian. In New South Wales, it was previous recorded as *Densastroma pexisum* (Yavorsky, 1929) by Birkhead (1976) from the Mirrabooka Formation (Wenlock to Ludlow) at Cheesemans Creek near Orange. Abundant specimens of this species have

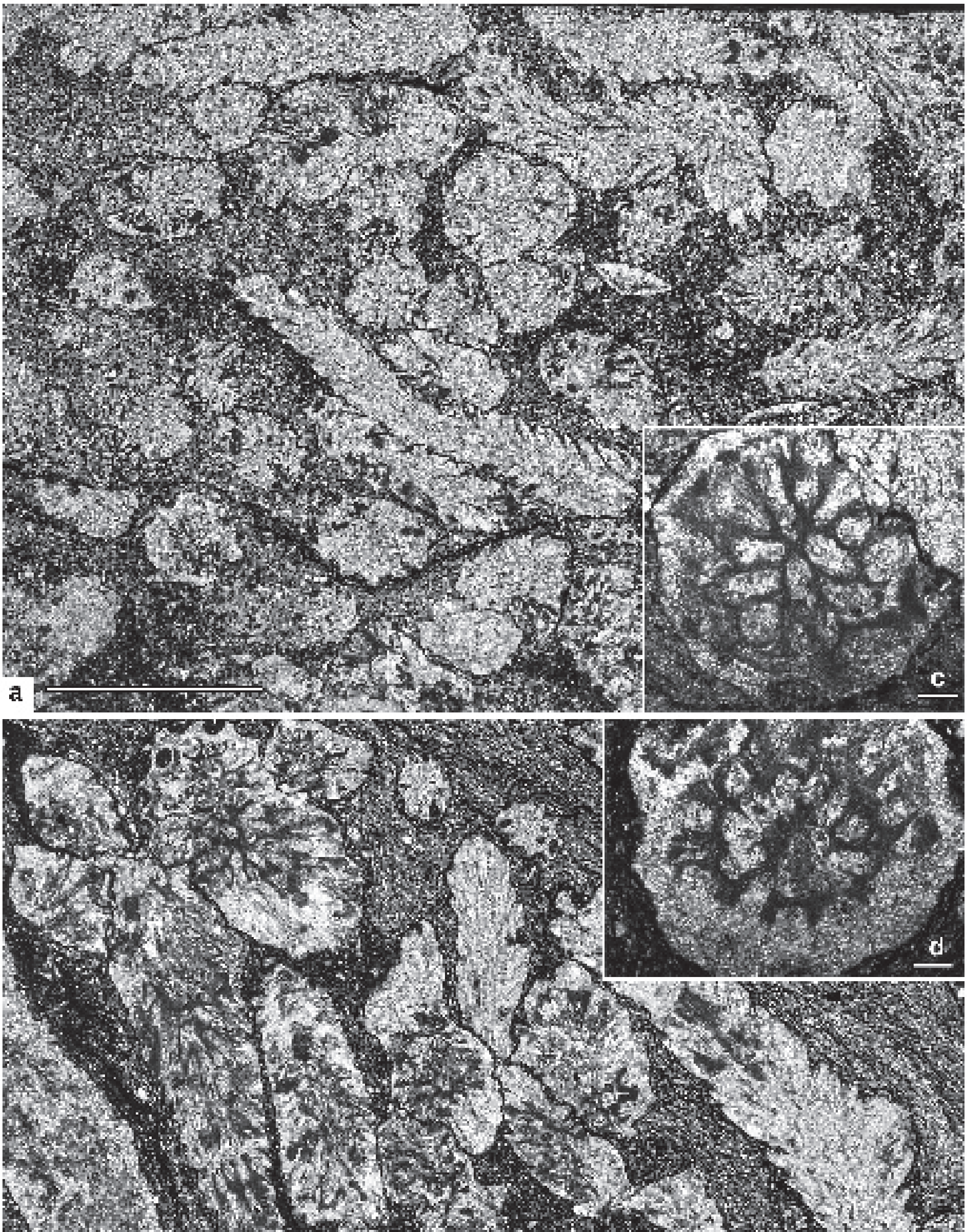


Figure 8. Tabulate coral *Thamnopora minor* Jones, 1941 from the unnamed stratigraphic unit (Litho-unit 5) intersected in the NPM-GD871 drill hole; a, MMF46839-2; b, MMF46840b-2, scale bars = 5 mm; c, MMF46839-2a, TS, d, MMF46840b-2a, TS, close-up, showing growth lamination and median suture between corallites, scale bar = 0.2 mm.

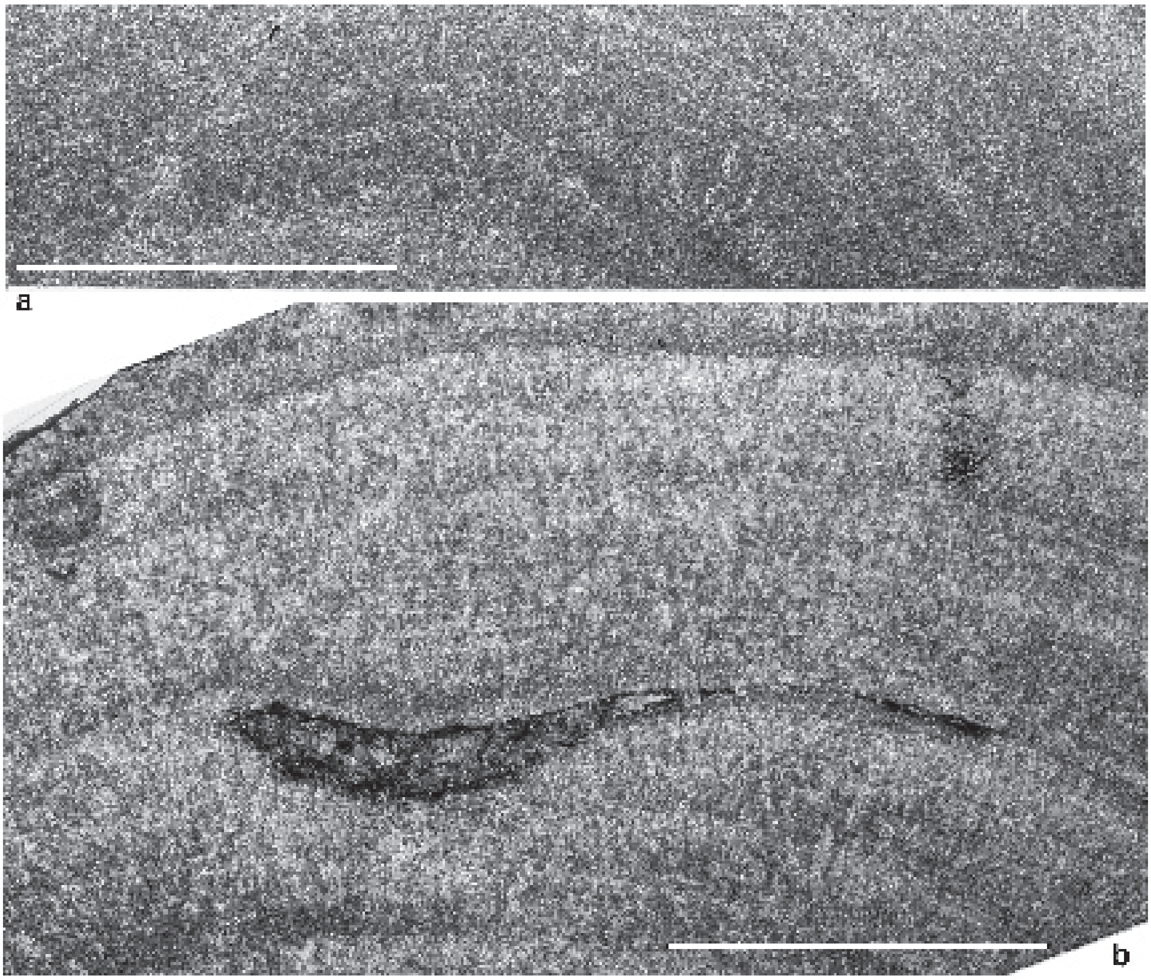


Figure 9. Stromatoporoid *Densastroma* sp. from the unnamed stratigraphic unit (Litho-unit 5) intersected in the NPM-GD871 drill hole; a, MMF46844b, tangential section; b, MMF46844a, vertical section; scale bars = 5 mm.

also been recovered from the Narragal Limestone (Ludlow) of central-west New South Wales (Webby and Zhen, unpublished material). Specimens doubtfully assigned to *Densastroma* were previously reported from the Derriwong Group at Myola Station, 2.5 km southwest of Trundle (Pickett and Ingpen, 1990, table 1) and at a site about 15 km west of Fifield (Pickett and McClatchie, 1991, p. 16).

The late Silurian age suggested by this stromatoporoid specimen contradicts the Early Devonian age derived from the associated conodonts and corals as discussed above. It seems probable that this specimen has been reworked, which is consistent with the detrital nature of the limestone (Litho-unit 5) at the base of the unit, immediately above the unconformity (Fig. 2).

DISCUSSION ON REGIONAL BIOSTRATIGRAPHIC CORRELATION

The Derriwong Group, previously the Derriwong Beds of Raggatt (1936), was defined to include the basal Edols Conglomerate and quartzose sandstone (the Calarie Sandstone), volcanics in the lower part (e.g. Byong Volcanics) and laminated siltstone and fine to medium sandstone, mudstone (or marl) and minor limestone lenses in the upper part (the Cookeys Plains Formation) with an age ranging from the Přídolí (late Silurian) to Pragian (Early Devonian) (Sherwin, 1980, 1996). Sherwin (1980) gave a total estimated thickness of ca 2700 m for the Derriwong Group exposed in the Mineral Hill-Trundle-Peak Hill area, but admitted that the thickness was difficult to measure because of poor and very patchy outcrops in the region. Largely for this same reason, the internal biozonal subdivision and regional correlation of this unit is yet to be established.

The maximum age (Přídolí) of the Derriwong Group was based on studies of conodonts and corals from the area southwest of Trundle (Pickett and Ingpen, 1990) and the area west of Fifield (Pickett and McClatchie, 1991) on the western flank of the Tullamore Syncline, confirmed by the occurrence of conodont species including *Ozarkodina crispa* (Walliser, 1964), *Ozarkodina confluens* (Branson and Mehl, 1933), *Coryssognathus dubius* (Rhodes, 1953) and "*Ozarkodina" eosteinhornensis* (Walliser, 1964). Földvary (2001, 2006) reported a diverse fauna including corals, stromatoporoids, brachiopods and trilobites from the Cookeys Plains Formation exposed in the Bogan Gate-Trundle-Mineral Hill area. The type material of the stromatoporoid species *Plexodictyon conophoroides* (Etheridge, 1921) is from the Cookeys Plains Formation exposed ca 5 km SW of Trundle (Pickett and Ingpen, 1990, p. 11; Földvary, 2001, Locality X). Two topotypes of this species were also illustrated by Földvary (2001, fig. 4.1–4.4). *Plexodictyon* is a distinctive stromatoporoid genus restricted to the Silurian and possibly Upper Ordovician and is widely distributed in Australia, Asia, Europe and North America.

Zhen et al. (2017, fig. 7a–g) reported the presence of the conodont *Caudicriodus woschmidti* (Ziegler, 1960) in several spot samples from the Derriwong Group north of the Mordialloc copper mine, ca 7 Km NNE of Trundle on the western flank of the Tullamore Syncline. *Caudicriodus woschmidti* also occurs in one (C0925, Fig. 10j–k) of the spot samples collected from outcrops mapped as Cookeys Plains Formation exposed ca 10 km NE of Bogan Gate on the eastern flank of the Tullamore Syncline. *Caudicriodus woschmidti* is the nominal species defining the *Caudicriodus woschmidti* conodont Biozone at the base of the Devonian, indicating that the Silurian/Devonian boundary is within the Derriwong Group.

Several samples (C1725 and C0923) from the Cookeys Plains Formation exposed ca 10 km NE of Bogan Gate yielded *Pandorinellina exigua exigua* (Philip, 1966) (Fig. 10a–d), which has a stratigraphic record extending from the latest Pragian (the *pireneae* Biozone) to Emsian (the *serotinus* Biozone) (see Farrell, 2004). Co-occurrence of *P. exigua exigua* and *Ozarkodina selfi* Lane & Ormiston, 1979 (Fig. 10e–i) in some of the samples (e.g. C1725) from outcrops mapped as Cookeys Plains Formation, ca 10 km NE of Bogan Gate, suggest that the minimum age of this unit is late Pragian (the *pireneae* Biozone) rather than early Lochkovian as suggested by previous authors (e.g. Sherwin, 1996; Földvary, 2001). At its type locality in eastern Alaska, *Ozarkodina selfi* has a stratigraphic range restricted to the Pragian (from *sulcatus* to *pireneae* biozones), in the lower part of the Salmontrout Limestone (Lane and Ormiston, 1979). In New South Wales, it was reported from the Mountain Dam Limestone by Mathieson et al., 2016, (referred to as three new subspecies), the White Tank Limestone Member of the Meryula Formation within the Cobar Supergroup (Pickett, 1980), and the Nubrigyn Member of the Cunningham Formation (Talent and Mawson, 1999).

The Wallingalair Group, on the eastern flank of the Tullamore Syncline to the immediate west of the study area (Pearce Prospect; Fig. 1), consists of a lower unit (the Connardoo Sandstone) of medium-coarse grained sandstone and minor conglomeratic sandstone at the base, and an upper unit (the Beugamel Sandstone) of medium-coarse grained quartzose sandstone. The two separated by a flaggy siltstone and fine grained sandstone unit (the Euchabil Gap Formation). Unfortunately, a direct contact relationship between the Derriwong Group and the overlying Wallingalair Group is obscured in the area. The precise age of the Wallingalair Group is still uncertain because of its poor fossil record. Sherwin (1994, p. 30; 1996, p. 64) correlated the base of the Wallingalair Group with that of the Trundle Group, based mainly on the occurrence of a brachiopod species considered to resemble *Howellella jaqueti* (Dun, 1898) from the Coonardoo Sandstone. However, conodonts including *Zieglerodina remscheidensis* (Fig. 11i–l), *Amydrotaxis druceana* (Pickett, 1980) (Fig. 11d–h) and *P. exigua exigua* (Fig. 11a–c) from a limestone sample collected near the base of the Wallingalair Group 4.4 km ESE of Bogan Gate railway station (sample C0785, see Pickett, 1983; likely an allochthonous limestone clast), confirm the minimum age (late Pragian) for the top of the Derriwong Group as discussed above. *Amydrotaxis druceana* (Fig. 11d–h) has a stratigraphic range restricted to the middle Lochkovian (*delta* Biozone) to Pragian (*pireneae* Biozone) (Farrell, 2004, fig. 6). It is widely distributed in New South Wales, recorded from the lower part of the Garra Formation (Druce, 1970; Farrell, 2004), the Boomerang Tank Limestone Member of the Baledmund Formation, the Mountain Dam Limestone, the White Tank Limestone Member of the Meryula Formation and the Rookery Limestone Member of the Meryula Formation within the Cobar Supergroup (Pickett, 1980; Mathieson et al., 2016), and from the lower Cunningham Formation (Talent and Mawson, 1999). It was also reported from the Lilydale Limestone (Wall et al., 1995) and other Pragian limestones (Mawson and Talent, 1994) of Victoria.

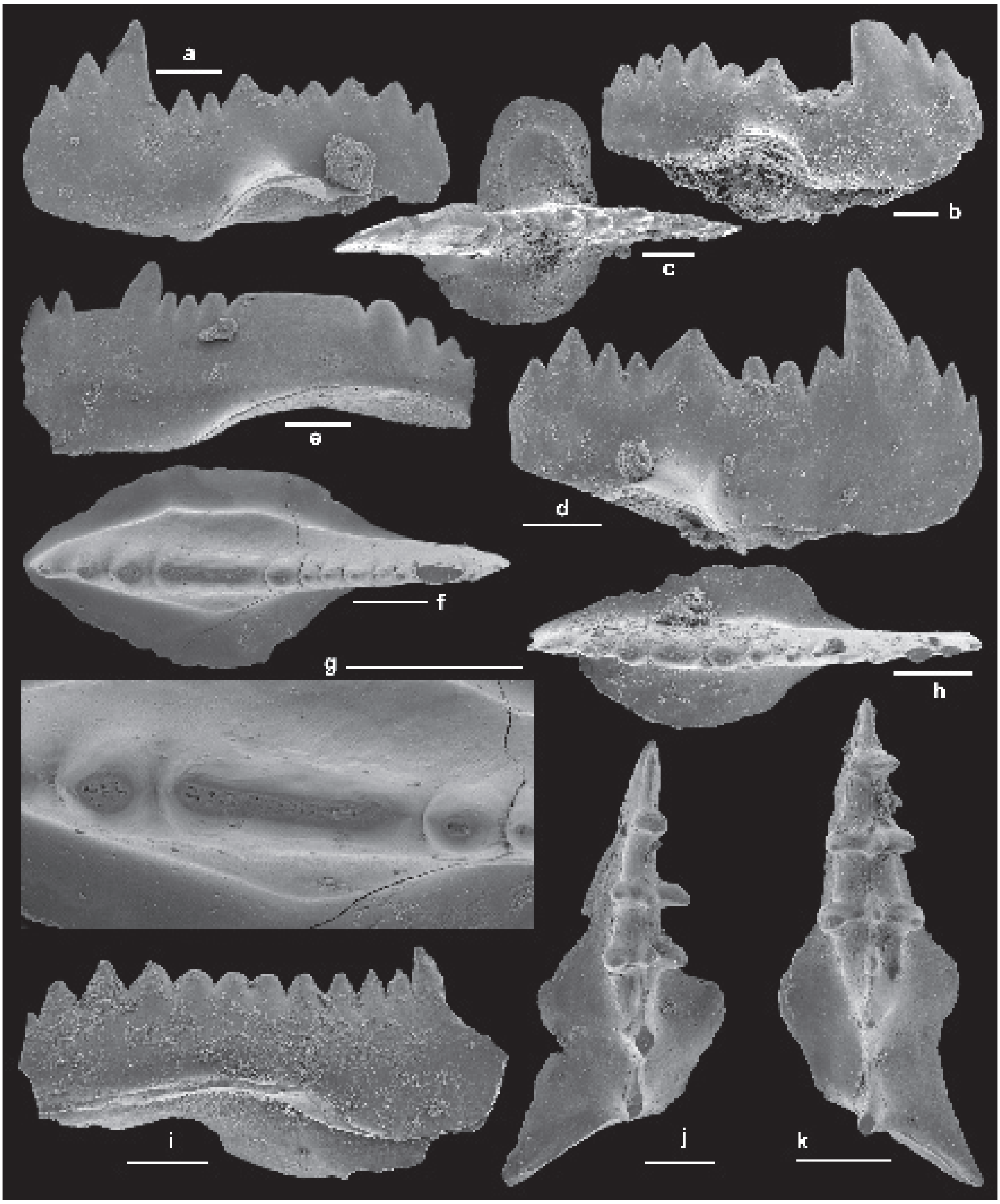


Figure 10. Early Devonian conodonts from the Derriwong Group exposed NE of Bogan Gate; a–d, *Pandorinellina exigua exigua* (Philip, 1966) from sample C1725; Pa element; a, MMMC05564, outer-lateral view (IY385-003); b, MMMC05565, outer-lateral view (IY385-001); c, MMMC05566, apical view (IY385-002); d, MMMC05567, inner-lateral view (IY385-011); e–i, *Ozarkodina selfi* Lane & Ormiston, 1979 from sample C1725; e, MMMC05568, outer-lateral view (IY385-007); f–g, MMMC05569, f, apical view (IY385-005), g, close-up view showing cross section of denticles (IY385-006); h, MMMC05570, apical view (IY385-009); i, MMMC05571, inner-lateral view (IY385-008); j-k, *Caudicriodus woschmidti* (Ziegler, 1960) from sample C0925; j, MMMC05572, apical view (IY385-015); j, MMMC05573, apical view (IY385-016). Scale bars = 100 µm.

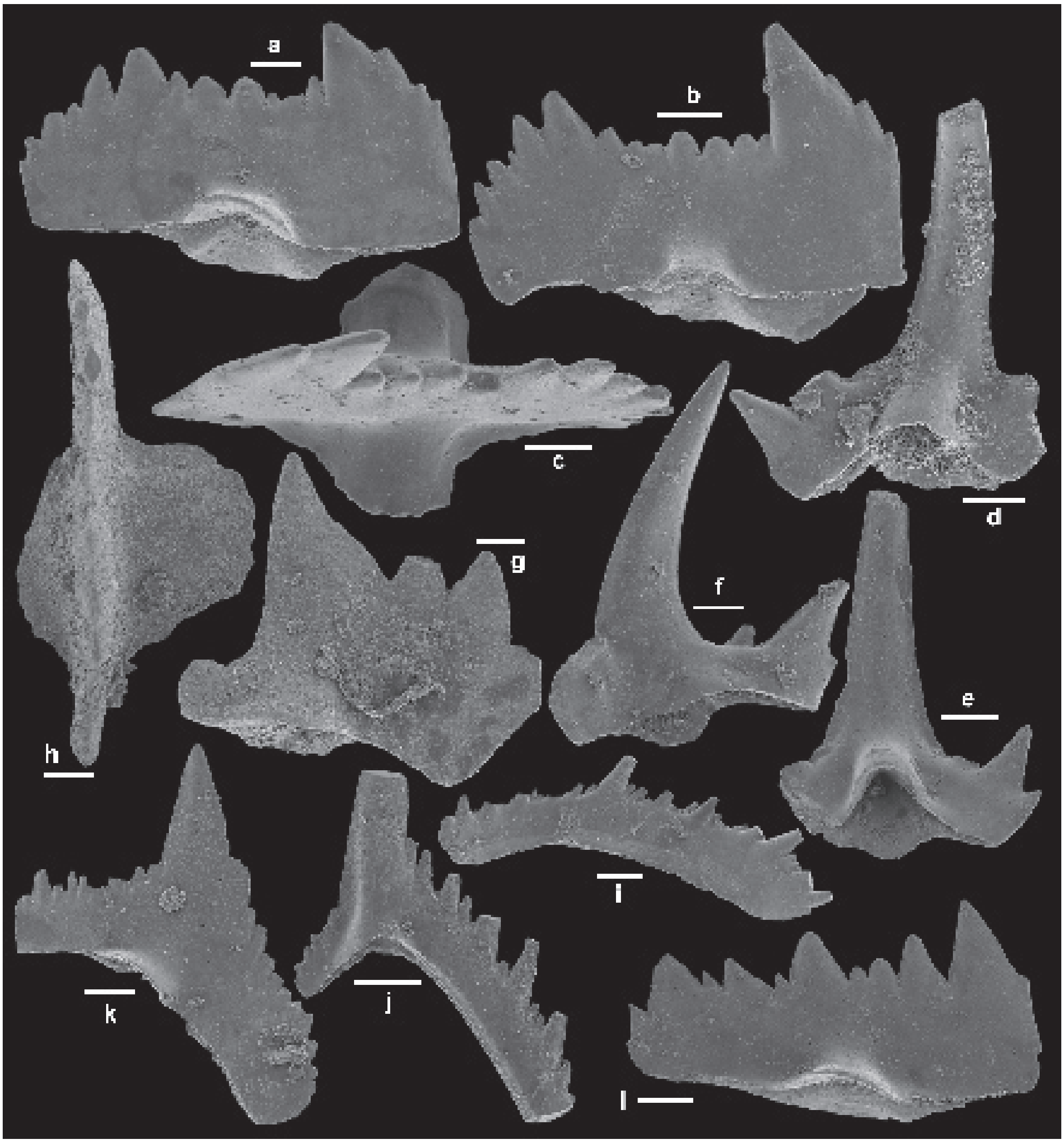


Figure 11. Early Devonian conodonts from a possibly allochthonous limestone clast (sample C0785) near base of the Wallingalair Group exposed 4.4 km ESE of Bogan Gate railway station; a–c, *Pandorinellina exigua exigua* (Philip, 1966), Pa element; a, MMMC05574, outer-lateral view (IY395-005); b, MMMC05575, outer-lateral view (IY395-002); c, MMMC05576, apical view (IY395-001); d–h, *Amydrotaxis druceana* (Pickett, 1980); d–e, Sa element, d, MMMC05577, posterior view (IY395-014); e, MMMC05578, posterior view (IY395-013); f, Sc element, MMMC05579, inner-lateral view (IY395-015); g, Pb element, MMMC05580, inner-lateral view (IY395-012); h, Pa element, MMMC05581, apical view (IY395-016); i–l, *Zieglerodina remscheidensis* (Ziegler, 1960); i, Sc element, MMMC05582, inner-lateral view (IY395-011); j, M element, MMMC05583, posterior view (IY395-010); k, Pb element, MMMC05584, inner-lateral view (IY395-008); l, Pa element, MMMC05585, outer-lateral view (IY395-006). Scale bars = 100 µm.

Therefore, on faunal grounds the unnamed fossiliferous bioclastic limestone with a carbonaceous black mudstone matrix intersected in NPM-GD871 can be correlated with the upper part of the Derriwong Group and the upper part of the Trundle Group (or Yarra Yarra Creek Group) exposed in the area farther west.

Th CAI 4 temperature range is sub-greenschist facies which has important implications for future mineral exploration in the Northparkes district, particularly 'greenrock' alteration vectoring studies (Cooke et al., 2014; Wilkinson et al., 2015). The observed temperature range is consistent with the current tectonic and structural models, which indicate that the Goonumbla Volcanic Complex that hosts the Northparkes porphyries acted as an inert block that portioned strain and remained largely unaffected by deformation (Scheibner and Basden, 1996). The age and maximum temperature indicated by the CAI suggest that the partition of strain around the Northparkes district continued through the Devonian, meaning all epidote samples could be considered to have a hydrothermal origin, making them reliable indicators of mineralising potential in the district (Cooke et al., 2014).

CONCLUSIONS

The unnamed stratigraphic unit with a total apparent thickness of 35 m (Litho-units 4 and 5) intersected in the NPM-GD871 is age correlative with the upper part of the Derriwong Group exposed on the eastern flank of the Tullamore Syncline and with the upper part of the Trundle Group (or Yarra Yarra Creek Group) exposed in the area farther west.

Available conodont data suggest that the Derriwong Group on the eastern flank of the Tullamore Syncline has a minimum age of the late Pragian. Identical conodont faunas from the upper part of the Derriwong Group and from reworked limestone clasts near the base of the overlying Wallingalair Group on the eastern flank of the Tullamore Syncline provide further support for this age determination of the Derriwong Group in the area.

The Wallingalair Group, consisting of predominantly medium-coarse grained sandstone and conglomeratic sandstone at the base, represents a regressive cycle of deposition under marginal marine and fluvial conditions with minor open marine incursions. The faunal relationship documented in this study shows that this sandstone unit is younger than the Trundle or the Yarra Yarra Creek groups exposed in the area farther west, rather than correlative as previously thought.

The contact relationship between the unnamed Early Devonian carbonate unit (Litho-units 4 and 5) and unconformably underlying diorite breccia and Ordovician volcanic rocks intersected in the NPM-GD871 shows that the unconformity defining the base of the Derriwong Group in the region is diachronous. The study area (the Pearce Prospect) within the Northparkes porphyry district was palaeogeographically located on an Ordovician volcanic island, which had likely experienced an extended period of exposure and so was subjected to erosion and weathering during the Silurian and earliest Devonian, and then became submerged during the maximum flooding of the region in the Pragian.

ACKNOWLEDGMENTS

The authors are grateful for the permission and support from CMOC-Northparkes Mines to carry out the collaborative study that enabled publication of this report. Conodont samples were processed by Paul Meszaros at the Palaeontology Lab of the Geological Survey of New South Wales located at Londonderry. Scanning electron microscope photographs of the illustrated conodonts were prepared in the Electron Microscope Unit at Macquarie University. Coral and stromatoporoid thin sections were prepared by Michael Bruce and photographed by David Barnes. Ian Percival is thanked for checking and commenting on an earlier version of the manuscript. Des Strusz and John Pickett are thanked for their careful and constructive reviews of the manuscript. Y.Y. Zhen publishes with permission of the Executive Director, Geological Survey of New South Wales. T.J. Wells acknowledges the support of Northparkes mines and Australian Research Council Linkage Project LP160100483 "Ore deposits and tectonic evolution of the Lachlan Orogen, SE Australia".

REFERENCES

Arundell, M., Morris, L., Collins, G., Robertson, B., Davi, D., Muller, D. and Hannington, M. (1997). 6th annual combined exploration report (ELs 3275, 3276, 3277, 3278, 3279, 3543, 4074, 4075, 4447, 4980 and 4981) 6th April 1996 to 5th April 1997. North Limited Company Report (unpublished).

Birkhead, P.K. (1976). Silurian stromatoporoids from Cheesemans Creek, with a survey of some stromatoporoids from the Hume Limestone Member, Yass, New South Wales. *Records of the Geological Survey of New South Wales* **17**, 87–122.

Bischoff, G.C. and Argent, J.C. (1990). Lower Devonian (late Lochkovian–Pragian) limestone stratigraphy at [*sic*] conodont distribution, Waratah Bay, Victoria. *Courier Forschungsinstitut Senckenberg* **118**, 441–471.

Blake, P.R. (2010). Devonian Corals of the Yarrol Province, eastern central Queensland. *Memoir of* *the Association of Australasian Palaeontologists* **38**, 1–191.

Branson, E.B. and Mehl, M.G. (1933). Conodont studies No. 1: Conodonts from the Harding Sandstone of Colorado; Bainbridge (Silurian) of Missouri; Jefferson City (Lower Ordovician) of Missouri. *University of Missouri Studies* **8** (1), 5–72.

Cayley, R.A. (2011). Exotic crustal block accretion to the eastern Gondwanaland margin in the Late Cambrian–Tasmania, the Selwyn Block, and implications for the Cambrian–Silurian evolution of the Ross, Delamerian, and Lachlan orogens. *Gondwana Research* **19**, 628–649.

Colquhoun, G.P. (1995). Early Devonian conodont faunas from the Capertee High, NE Lachlan Fold Belt, southeastern Australia. *Courier Forschungsinstitut Senckenberg* **182**, 347–369.

Cooke, D., Baker, M., Hollings, P., Sweet, G., Chang, Z., Danyushevsky, L., Gilbert, S., Zhou, T., C. White, N., Gemmell, B. and Inglis, S. (2014). New Advances in Detecting the Distal Geochemical Footprints of Porphyry Systems - Epidote Mineral Chemistry as a Tool for Vectoring and Fertility Assessments. *SEG Special Publication* **18**, 127–152.

Cooke, D.R., Wilson, A.J., House, M.J., Wolfe, R.C., Walshe, J.L., Lickfold, V. and Crawford, A.J. (2007). Alkalic porphyry Au-Cu and associated mineral deposits of the Ordovician to Early Silurian Macquarie Arc, New South Wales. *Australian Journal of Earth Sciences* **54**, 445–463.

Corradini, C. and Corriga, M.G. (2010). Silurian and lowermost Devonian conodonts from the Passo Volaia area (Carnic Alps, Italy). *Bollettino della Società Paleontologica Italiana* **49** (3), 237–253.

Crawford, A.J., Glen, R.A., Cooke, D.R. and Percival, I.G. (2007a). Geological evolution and metallogenesis of the Ordovician Macquarie Arc, Lachlan Orogen, New South Wales: *Australian Journal of Earth Sciences* **54**, 137–141.

Crawford, A.J., Meffre, S., Squire, R.J., Barron, L.M. and Falloon, T.J. (2007b). Middle and Late Ordovician magmatic evolution of the Macquarie Arc, Lachlan Orogen, New South Wales. *Australian Journal of Earth Sciences* **54**, 181–214.

Druce, E.C. (1970). Conodonts from the Garra Formation (Lower Devonian), New South Wales. *Bulletin of the Bureau of Mineral Resources, Geology and Geophysics* **116**, 29–64.

Dubatolov, V.N. (1959). Tabulyaty, geliolitidy i khetetidy silura i devona Kuznetskogo basseyna. (Tabulata, Heliolitida and Chaetetida from the Silurian and Devonian of the Kuznezk basin). *TrudyVsesoyuznyy Neftyanyy Nauchno-issledovatel'skiy Geologorazvedochnyy Institut (VNIGRI)* **139**, 1–472. (in Russian).

Dun, W.S. (1898). Notes on the fauna of the Devonian boulders occurring at the White Cliffs opal-fields. *Records of the Geological Survey of New South Wales* **5** (4), 160–174.

Etheridge, R. Jr (1920). Further additions to the coral fauna of the Devonian and Silurian of New South Wales. *Records of the Geological Survey of New South Wales* **9**, 55–63.

Etheridge, R. Jr (1921). *Clathrodictyon* in the Upper Silurian of the Trundle District, New South Wales. *Records of the Geological Survey of New South Wales* **10**, 7–9.

Farrell, J.R. (2004). Late Přidoli, Lochkovian, and early Pragian conodonts from the Gap area between Larras Lee and Eurimbla, central western NSW, Australia. *Courier Forschungsinstitut Senckenberg* **245**, 107–181.

Fergusson, C.L. (2014). Late Ordovician to mid-Silurian Benambran subduction zones in the Lachlan Orogen, southeastern Australia. *Australian Journal of Earth Sciences* **61**, 587–606.

Fergusson, C.L. and Coney, P.J. (1992). Convergence and intraplate deformation in the Lachlan Fold Belt of southeastern Australia. *Tectonophysics* **214**, 417–439.

Fergusson, C.L. and Fanning, C.M. (2002). Late Ordovician stratigraphy, zircon provenance and tectonics, Lachlan Fold Belt, southeastern Australia. *Australian Journal of Earth Sciences* **49**, 423–436.

Fergusson, C.L. and Henderson, R.A. (2015). Early Palaeozoic continental growth in the Tasmanides of northeast Gondwana and its implications for Rodinia assembly and rifting. *Gondwana Research* **28**, 933–953.

Fontaine, H. (1961). Les Madréporaires paléozoïques du Viêt-Nam, du Laos et du Cambodge. *Archives Géologiques du Viêt-Nam* **5**, 1–276.

Földvary, G.Z. (2001). Siluro-Devonian invertebrate faunas from the Bogan Gate-Trundle-Mineral Hill area of central New South Wales. *Records of the Western Australian Museum* **58** (Supplement), 81–102.

Földvary, G.Z. (2006). *Pseudoplasmopora* (Cnidaria, Tabulata) in the Siluro-Devonian of eastern Australia with comments on its global biogeography. *Proceedings of the Linnean Society of New South Wales* **127**, 175–189.

Glen, R.A., Crawford, A.J. and Cooke, D.R. (2007). Tectonic setting of porphyry Cu-Au mineralisation in the Ordovician-Early Silurian Macquarie Arc, eastern Lachlan Orogen, New South Wales. *Australian Journal of Earth Sciences* **54**, 465–479.

Glen, R.A., Quinn, C.B. and Cooke, D.R. (2012). The Macquarie Arc, Lachlan Orogen, New South Wales; its evolution, tectonic setting and mineral deposits. *Episodes* **35**, 177–186.

Gray, D.R. and Foster, D.A. (2004). Tectonic evolution of the Lachlan Orogen, southeast Australia: historical review, data synthesis and modern perspectives. *Australian Journal of Earth Sciences* **51**, 773–817.

Hill, D. (1942). Middle Palaeozoic rugose corals from the Wellington district, N.S.W. *Journal and Proceedings of the Royal Society of New South Wales* **76**, 182–189.

Hill, D. (1950). Middle Devonian corals from the Buchan district, Victoria. *Proceedings of the Royal Society of Victoria* **62**, 137-164.

Hill, D. and Jones, O.A. (1940). The corals of the Garra Beds, Molong district, New South Wales. *Journal and Proceedings of the Royal Society of New South Wales* **74**, 175–208.

Hill, D., Playford, G. and Woods, J.T. (1967). Devonian fossils of Queensland. Queensland Palaeontographical Society, Brisbane. 32 pp.

Hopper, B. (1992). Report No. PK93/32S, 1st annual report for EL4074 October 1992. Geopeko company report (unpublished).

Jell, J.S. and Hill, D. (1970). Revision of the coral fauna from the Devonian Douglas Creek Limestone, Clermont, central Queensland. *Proceedings of the Royal Society of Queensland* **81**, 93–120.

Jones, O.A. (1937). The Australian massive species of the coral genus *Favosites*. *Records of the Australian Museum* **20**, 79–102.

Jones, O.A. (1941). The Devonian Tabulata of Douglas and Drummond Creeks, Clermont, Queensland. *Proceedings of the Royal Society of Queensland* **53**, 41–60.

Klapper, G. (with a contribution by Ormiston, A.R.) (1969). Lower Devonian conodont sequence, Royal Creek, Yukon Territory, and Devon Island, Canada. *Journal of Paleontology* **43** (1), 1–27.

Krynen, J.P., Sherwin, L. and Clarke, I. (1990). Stratigraphy and structure. In: Clarke, I. and Sherwin, L. (eds), Geological setting of gold and copper deposits in the Parkes area, New South Wales. *Records of the Geological Survey of New South Wales* **23**, 1–76.

Lane, H.R. and Ormiston, A.E. (1979). Siluro-Devonian biostratigraphy of the Salmontrout River area, east-central Alaska. *Geologica et Palaeontologica* **13**, 39–96.

Lickfold, V., Cooke, D.R., Smith, S.G. and Ullrich, T.D. (2003). Endeavour copper-gold porphyry deposits, Northparkes, New South Wales: Intrusive history and fluid evolution. *Economic Geology* **98**, 1607–1636.

Lickfold, V., Cooke, D.R., Crawford, A.J. and Fanning, C.M. (2007). Shoshonitic magmatism and the formation of the Northparkes porphyry Cu-Au deposits, New South Wales: *Australian Journal of Earth Sciences* **54**, 417–444.

Lu, J.F., Qie, W.Q. and Chen, X.Q. (2016). Pragian and lower Emsian (Lower Devonian) conodonts from Liujing, Guangxi, South China. *Alcheringa* **40**, 275–296.

Lyons, P. (2000). Structural Geology, in Lyons, P., Raymond, O. L., and Duggan, M. B., eds., Forbes 1:250,000 Geological Sheet SI55-7 Explanatory Notes AGSO Record 2000/20, Australian Geological Survey Organisation, p. 152–154.

Mansuy, H. (1913). Faunes des calcaires à Productus de l'Indochine. *Mémoires du Service Géologique de l'Indo-chine* **2** (4), 1–133.

Mathieson, D., Mawson, R., Simpson, A.J. and Talent, J.A. (2016). Late Silurian (Ludlow) and Early Devonian (Pragian) conodonts from the Cobar Supergroup, western New South Wales, Australia. *Bulletin of Geosciences* **91** (3), 583–652.

Mawson, R. and Talent, J.A. (1994). Age of an Early Devonian carbonate fan and isolated limestone clasts and megaclasts, east-central Victoria. *Proceedings of the Royal Society of Victoria* **106**, 31–70.

Mawson, R. and Talent, J.A. (2003). Conodont faunas from sequences on or marginal to the Anakie Inlier (central Queensland, Australia) in relation to Devonian transgressions. *Bulletin of Geosciences* **78**, 335–358.

Mawson, R., Talent, J.A., Brock, G.A. and Engelbretsen, M.J. (1992). Conodont data in relation to sequences about the Pragian–Emsian boundary (Early Devonian) in south-eastern Australia. *Proceedings of the Royal Society of Victoria* **104**, 23–56.

Meffre, S., Scott, R.J., Glen, R.A. and Squire, R.J. (2007). Re-evaluation of contact relationships between Ordovician volcanic belts and the quartz-rich turbidites of the Lachlan Orogen. *Australian Journal of Earth Sciences* **54**, 363–383.

Milne-Edwards, H. and Haime, J. (1850–1855). A monograph of the British fossil corals: pp. 1–299, pls 1–72. Palaeontographical Society Monograph (London).

Moresi, L., Betts, P.G., Miller, M.S. and Cayley, R.A. (2014). Dynamics of continental accretion. *Nature* **508** (7495), 245–248.

Morris, L. Arundell, M., Collins, G., Saedbom. S. and Roberston, B. (1999). 7th annual combined exploration report (Els 3275, 3276, 3277, 3278, 3279, 3543, 4074, 4075, 4447, 4980, 4981, 5323) 6th April 1997 to 5th April 1998. North Limited Company Report (unpublished).

Pacey, A., Wilkinson, J.J., Owens, J., Priest, D., Cooke, D.R. and Millar, I.L. (2019). The Anatomy of an Alkalic Porphyry Cu-Au System: Geology and Alteration at Northparkes Mines, New South Wales, Australia. *Economic Geology* **114**, 441–472.

Peavey, F.N.R. (2013). Review, Revision, and Paleobiogeography of Ludlow (Silurian) to Lochkovian (Devonian) Spathognathodontid Conodont Taxa. Ph.D. Thesis (unpublished), Texas Tech University, Lubbock, USA, 121 pp.

Pedder, A.E.H., Jackson, J.H. and Philip, G.M. (1970). Lower Devonian biostratigraphy in the Wee Jasper region of New South Wales. *Journal of Paleontology* **44**, 206–251.

Percival, I.G. and Glen, R.A. (2007). Ordovician to earliest Silurian history of the Macquarie Arc, Lachlan Orogen, New South Wales. *Australian Journal of Earth Sciences* **54**, 143–165.

Philip, G.M. (1962). The palaeontology and stratigraphy of the Siluro-Devonian sediments of the Tyers area, Gippsland, Victoria. *Proceedings of the Royal Society of Victoria* **75**, 123–246.

Philip, G.M. (1966). Lower Devonian conodonts from the Buchan Group, eastern Victoria. *Micropaleontology* **12**, 441–460.

Pickett, J.W. (1980). Conodont assemblages from the Cobar Supergroup (Early Devonian), New South Wales. *Alcheringa* **4**, 67–88.

Pickett, J.W. (1983). Conodont assemblages from Parkes, Bogan Gate and Mineral Hill. Geological Survey of New South Wales, Report GS1982/182 (unpublished).

Pickett, J.W. (2010). Fossil corals of Australia, New Zealand, New Guinea and Antarctica: bibliography and index. *Memoir of the Association of Australasian Palaeontologists* **40**, 1–189.

Pickett, J.W. and Ingpen, I.A. (1990). Ordovician and Silurian strata south of Trundle, New South Wales. *Geological Survey of New South Wales, Quarterly Notes* **78**, 1–14.

Pickett, J.W. and McClatchie, L. (1991). Age and relations of stratigraphic units in the Murda Syncline area. *Geological Survey of New South Wales, Quarterly Notes* **85**, 9–32.

Pilia, S., Rawlinson, N., Direen, N.G., Reading, A.M., Cayley, R., Pryer, L., Arroucau, P. and Duffett, M. (2015). Linking mainland Australia and Tasmania using ambient seismic noise tomography: Implications for the tectonic evolution of the east Gondwana margin. *Gondwana Research* **28**, 1212–1227.

Raggatt, H.G. (1936). Geology and mineral resources of the Condobolin-Trundle district. Geological Survey of New South Wales, Report GS1936/026 (unpublished).

Rawlinson, N., Arroucau, P., Musgrave, R., Cayley, R., Young, M. and Salmon, M. (2014). Complex continental growth along the proto-Pacific margin of East Gondwana. *Geology* **42**, 783–786.

Rhodes, F.H.T. (1953). Some British lower Palaeozoic conodont faunas. *Royal Society of London, Philosophical Transactions Series B* **237**, 261–334.

Savage, N.M. (1977). Lower Devonian conodonts from Karheen Formation, southeastern Alaska. *Canadian Journal of Earth Sciences* **14**, 278–284.

Scheibner, E. and Basden, H. (eds) (1996). Geology of New South Wales - Synthesis. Volume 1 Structural Framework. *Geological Survey of New South Wales, Memoir Geology* **13** (1), 1–295.

Sherwin, L. (1980). Faunal correlation of the Silurian-Devonian units, Mineral Hill–Trundle–Peak Hill area. *Geological Survey of New South Wales, Quarterly Notes* **39**, 1–14.

Sherwin, L. (1994). Palaeozoic stratigraphy of the Narromine 1:250 000 sheet area. *Geological Survey of New South Wales, Quarterly Notes* **39**, 1–35.

Sherwin, L. (1996). Narromine 1:250 000 geological sheet SI/55-3, explanatory notes. Geological Survey of New South Wales, Sydney, viii + 104 pp.

Simpson, C.J., Cas, R.A.F. and Arundell, M.C. (2005). Volcanic evolution of a long-lived Ordovician island-arc province in the Parkes region of the Lachlan fold belt, southeastern Australia. *Australian Journal of Earth Sciences* **52**, 863–886.

Talent, J.A. and Mawson, R. (1999). North-eastern Molong Platform and adjacent Hill End Trough, eastern Australia: mid-Palaeozoic conodont data and implications. *Abhandlungen der Geologischen Bundesanstalt* **54**, 49–105.

Wall, R., Mawson, R., Talent, J.A. and Cooper, B.J. (1995). Late Pragian conodonts from an environmentally hostile context, the Lilydale Limestone of central Victoria. *Courier Forschungsinstut Senckenberg* **182**, 371–387.

Walliser, O.H. (1964). Conodonten des Silurs. *Abhandlungen des Hessischen Landesamtes für Bodenforschung zu Wiesbaden* **41**, 1–106.

Wilkinson, J.J., Chang, Z.S., Cooke, D.R., Baker, M.J., Wilkinson, C.C., Inglis, S., Chen, H.Y. and Gemmell, J.B. (2015). The chlorite proximitor: A new tool for detecting porphyry ore deposits. *Journal of Geochemical Exploration* **152**, 10–26.

Wilson, G.A. (1989). Documentation of conodont assemblages across the Lochkovian–Pragian (Early Devonian) boundary at Wellington, central New South Wales, Australia. *Courier Forschungsinstut Senckenberg* **117**, 117–171.

Yavorsky, V.I. (1929). Siluriiskie Stromatoporoidea. *Izvestiya geologiskogo komiteta* **48**, 77–114. (in Russian).

Zhen, Y.Y. (1995). Late Emsian rugose corals of the Mount Podge area, Burdekin Basin, north Queensland. *Alcheringa* **19**, 193–234.

Zhen, Y.Y., Hegarty, R., Percival, I.G. and Pickett, J.W. (2017). Early Devonian conodonts from the southern Thomson Orogen and northern Lachlan Orogen in north-western New South Wales. *Proceedings of the Linnean Society of New South Wales* **139**, 69–83.

Ziegler, W. (1960). Conodonten aus dem Rheinischen Unterdevon (Gedinnium) des Remscheider Sattels (Rheinisches Schiefergebirge). *Paläontologische Zeitschrift* **34**, 169–201.

Eucalyptus cunninghamii (Myrtaceae) in the Blue Mountains of New South Wales – an Unexpected Connection between Botany and Geology

DAVID COLEBY[1] AND RAE DRUITT[2]

[1]Corresponding Author, Sublime Point Bushcare Group, 11 Willoughby Road, Leura, NSW, 2780, Australia
(davidcoleby@bigpond.com);
[2]Wentworth Falls Lake Bushcare Group, 23 Boronia Road, Wentworth Falls, NSW, 2782 Australia

Published on 12 December 2019 at https://openjournals.library.sydney.edu.au/index.php/LIN/index

Coleby, D. and Druitt, R. (2019). *Eucalyptus cunninghamii* (Myrtaceae) in the Blue Mountains of New South Wales – an unexpected connection between botany and geology. *Proceedings of the Linnean Society of New South Wales* **141**, 81-95.

A three-year field study of the rare *Eucalyptus cunninghamii* Sweet (Myrtaceae), the Cliff Mallee Ash, uncovered a hitherto unrecognised connection between this taxon and its substrate. *E cunninghamii* has long been known to grow on cliff edges around two valleys of the upper Blue Mountains, the Grose and the Jamison, but details of that habitat were unexplored. We show that its preferred habitat in the upper Blue Mountains is on or just downslope of a clay layer, most often the Wentworth Falls Claystone Member (WFC), and that *E cunninghamii* is not found elsewhere (except for an anomalous outlier near Mittagong) because the WFC is not expressed stratigraphically except around the clifflines of the two valleys. This and other environmental features delimit the distribution of *E cunninghamii* to a very precise geospatial range which may cause problems in times of climate change.

Manuscript received 26 August 2019, accepted for publication 28 October 2019.

KEYWORDS: Blue Mountains, botany, claystone, cunninghamii, Eucalyptus, geology, Wentworth Falls.

INTRODUCTION

Eucalyptus cunninghamii (Euclid 2019, Fairley 2004, Fairley and Moore 2000, Brooker and Kleinig 2006, Carolin and Tindale 1994) is one if six mallees in the eight "green ashes" of the Greater Blue Mountains World Heritage Area (Hager and Benson 2010). The others are *E apiculata, E laophila, E dendromorpha, E burgessiana,* and *E stricta.* They form a complicated genetic series, currently under investigation (Rutherford et al. 2016, Rutherford 2017, Rutherford 2019). Our field study complements this genetic research, and attempts to find markers to support known genetic differences within *Eucalyptus cunninghamii*. Along the way we discovered a hitherto unrecognised connection between this taxon and its substrate.

Its status is 2RCA (i.e. rare but probably adequately conserved) under the ROTAP Rare Plants classification of Briggs & Leigh (1996). At November 2019 there were 109 records in the National Herbarium in the Royal Botanic Garden and Domain Trust in Sydney, records which identified 12 occurrences overall, 11 in the upper Blue Mountains and one outlier at Wanganderry Walls near Mittagong (PlantNET 2019, AVH 2019). Our study increased the total number of occurrences of *Eucalyptus cunninghamii* to 38 without an increase in its range. However, because the outlier at Wanganderry Walls is now considered (S. Rutherford, pers. comm. 2019) genetically different, it was not included in our study of the connection between botany and geology. Thus our study examined 37 occurrences in the upper Blue Mountains

METHODS

We visited the 11 known occurrences in the upper Blue Mountains and collected data at each one, including GPS latitude and longitude, altitude, aspect, slope and Area of Occupation (AOO). We assigned a name and two-letter code for each occurrence, and converted latitude and longitude to more easily handled Grid References. Patterns emerging from this initial phase enabled us to find and record 26 more occurrences in the upper Blue Mountains (Table 1). Map references in the upper Blue Mountains are on one of three 1:25,000 Topographic and Orthophoto, Third Edition, GDA Maps: Jamison 8930-2N, Katoomba 8930-1S, and Mt Wilson 8930-1N. Measured map references and measured latitude and longitude were cross-checked using Redfearn's formulae (Geoscience Australia).

We collected samples of leaves and soils from a downhill transect at one site (Kedumba Walls). These samples, together with some from nearby clays and clayrocks, were air-dried for five days and then oven-dried for 72 hours at 80°C. They were packaged as 10g samples in paper envelopes. Analyses were carried out by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICPAES) in Isotope Tracing in Natural Systems (ITNS) at the Australian Nuclear Science and Technology Organisation (ANSTO), Lucas Heights, Sydney. Elements analysed were Al, Ba, Fe, Sr, Ca, Cu, K, Mg, Mn, Na, P, S and Zn. The analyses did not include hydrogen, carbon, oxygen, nitrogen or silicon.

RESULTS AND DISCUSSION

The 37 occurrences of the upper Blue Mountains (Figure 1) fall neatly into two groups, the Jamison Valley Group in the south (21) and the Grose Valley Group in the north (16), separated by at least 8 km of urban development along the spine of the upper Blue Mountains. These two groups are further divided for reasons of biogeographic isolation.

In the Grose Valley there are three upland biogeographic isolations of *Eucalyptus cunninghamii*, Grose North, Pulpit Rock and Grose South. The Grose River Valley, 2 km wide and over 600 m deep between Mount Banks and Mount Hay, is the physical barrier for biological contact between Grose North and Grose South. A second biogeographic barrier, Govetts Creek, isolates Pulpit Rock from all other occurrences of *Eucalyptus cunninghamii* in the Grose Valley (Figure 1 and Tables 1 and 2).

In the Jamison Valley there are two biogeographic isolations of *Eucalyptus cunninghamii*, Jamison West and Jamison South. Their nearest occurrences are separated by 3 km of rugged terrain between Sublime Point (Leura) and Lincolns Rock/Little Switzerland (Kings Tableland), where the Jamison Creek (at 300 m altitude) is over 500 m below the average upland terrain. In this area no occurrences of *E cunninghamii* were found on the cliffs and surrounds at Inspiration Point, Moya Point and Cathedral Point. This separation represents a barrier to biological contact. Occurrences in Jamison West lie on an E–W line between Sublime Point and Giant Stairs (Katoomba), whereas occurrences in Jamison South lie on a N–S line between Undercliff Track and Kedumba Gate (Kings Tableland).

These six populations of *Eucalyptus cunninghamii*, three in the Grose Valley, two in the Jamison Valley and the outlier at Wanganderry Walls, represent biogeographic isolations. Table 2 summarises their average geospatial data. Note that grand averages are weighted for population sizes.

When we examined the data within each population of the upper Blue Mountains we discovered a close correlation between Easting and Altitude (Table 1). This feature is most easily shown graphically (Figures 2a–d). Twenty four of the 37 occurrences lie on trend lines with an east–west slope of just less than one degree.

In Grose North six of the nine occurrences labelled the 940 sub-Group (Figures 1 and 2a) occupy a narrow range of 935–945 m above the other three: one at Walls Cliff 2 (the base of Pierces Pass) is anomalously low at 665 m. In Grose South all seven occurrences lie on a well-defined trend (Figures 1 and 2b). In Jamison West seven of the ten occurrences lie on a smooth E–W trend, but three others (GF, GL1 and SP4) occur at significantly higher altitudes (Figures 1 and 2c). In Jamison South eight occurrences lie on a smooth N–S trend but three others (CR, KR and KG) occur at significantly lower altitudes: these three occurrences intersect with the Bodington Monocline (Holland 1974) which causes a change in slope (Figures 1 and 2d). Of the 37 occurrences in the upper Blue Mountains, twenty-four that lie on trend lines in Figure 2 are shown as blue diamonds; those that do not are shown as 12 red squares or one green triangle.

Because the scales of the abscissas in Figures 2a–d are 100 times that of the ordinate, the true environmental slopes are ~1 degree. Also, to accentuate these very shallow slopes, vertical origins have been highly suppressed. Thus in Figure 2b the west-to-east fall is roughly 115 metres over a distance of 7 km, in Figure 2c the fall is roughly 50 m over 2.3 km, and in Figure 2d the fall is roughly 23 m over 5 km.

We sought, and found, a reason for this regularity between easting and altitude, which indicates a largely planar distribution of *Eucalyptus cunninghamii* if, for the moment, we ignore the 13 off-trend occurrences.

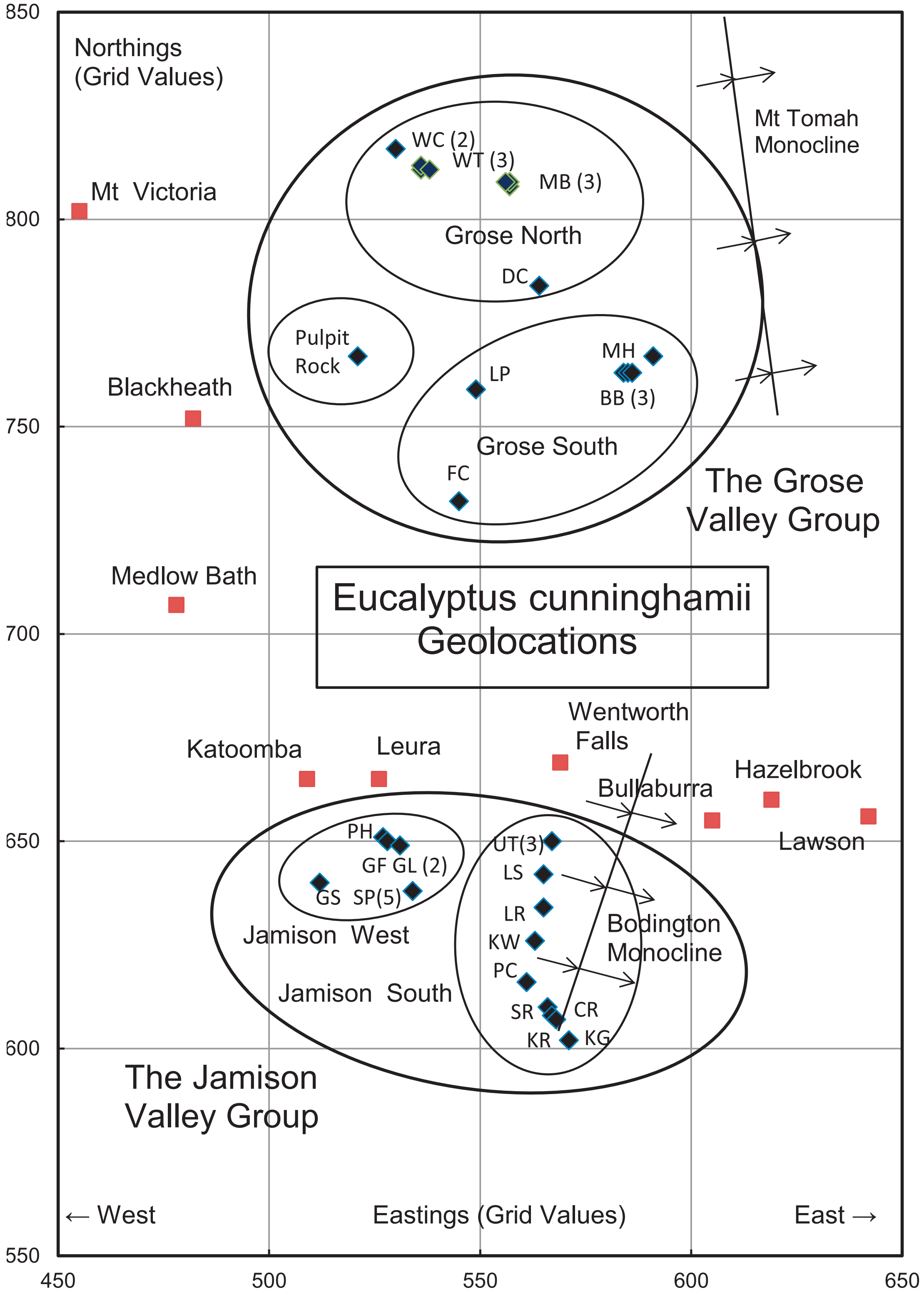


Figure 1. ***Eucalyptus cunninghamii*** **Geolocations, showing 37 occurrences in five populations in the upper Blue Mountains. See Table 1 for details. Eastings and Northings are Grid Values. Red squares are railway stations.**

Table 1. *E cunninghamii*, geospatial attributes, Grose Valley and Jamison Valley.

Occurrence	Code	Map References		Latitude	Longitude	Altitude
(* New occurrences)		Easting	Northing			(m)
E cunninghamii: Geospatial Attributes: Grose North						
Walls Cliff 1	WC1	530	817	-33º 34′ 33″ S	150º 20′ 18″ E	885
*Walls Cliff 2	WC2	529	818	-33º 34′ 31.3″ S	150º 20′ 16.4″ E	665
*Wongarra 1	W1	536	812	-33º 34′ 46.6″ S	150º 20′ 41.2″ E	935
Wongarra 2	W2	536	813	-33º 34′ 48.1″ S	150º 20′ 41.5″ E	945
*Wongarra 3	W3	538	812	-33º 34′ 50.8″ S	150º 20′ 49.2″ E	940
Mount Banks 1	MB1	558	808	-33º 35′ 04″ S	150º 22′ 04″ E	940
*Mount Banks 2	MB2	557	809	-33º 35′ 1.8″ S	150º 22′ 1.7″ E	940
*Mount Banks 3	MB3	556	809	-33º 35′ 1.0″ S	150º 22′ 00″ E	945
*David Crevasse	DC	564	784	-33º 36′ 23.1″ S	150º 22′ 27.6″ E	845
E cunninghamii: Geospatial Attributes: Grose South (inc PR)						
Pulpit Rock	PR	521	767	-33º 37′ 15″ S	150º 19′ 40″ E	925
Fortress Cliff	FC	545	732	-33º 39′ 10″ S	150º 21′ 10″ E	860
*Lockley Pylon	LP	549	759	-33º 37′ 41.4″ S	150º 21′ 27.5″ E	870
*Butterbox West	BW	583	764	-33º 37′ 32.6″ S	150º 23′ 44″ E	809
Butterbox South	BS	584	763	-33º 37′ 29″ S	150º 23′ 44″ E	810
*Butterbox East	BE	585	762	-33º 37′ 33″ S	150º 23′ 40″ E	810
*Mt Hay SW	MH	591	767	-33º 37′ 20.3″ S	150º 24′ 13.0″ E	820
E cunninghamii : Geospatial Attributes: Jamison West						
Giant Stairs	GS	512	640	-33º 44′ 4″ S	150º 18′ 54″ E	925
*Prince Henry C/W	PH	527	651	-33º 43′ 32.3″ S	150º 19′ 34.1″ E	900
*Gordon Falls L/O	GF	528	650	-33º 43′ 35.8″ S	150º 19′ 57″ E	912
*Golf Links 1	GL1	531	649	-33º 43′ 38.2″ S	150º 20′ 8.2″ E	912
*Golf Links 2	GL2	531	649	-33º 43′ 38.9″ S	150º 20′ 7.7″ E	890
Sublime Point 1	SP1	534	638	-33º 44′ 14″ S	150º 20′ 18″ E	875
*Sublime Point 2	SP2	534	639	-33º 44′ 10.2″ S	150º 20′ 17.5″ E	883
*Sublime Point 3	SP3	534	640	-33º 44′ 8.1″ S	150º 20′ 15.8″ E	890
*Sublime Point 4	SP4	534	640	-33º 44′ 8.4″ S	150º 20′ 16.6″ E	910
*Sublime Point 5	SP5	533	648	-33º 43′ 42.8″ S	150º 20′ 13.2″ E	877
E cunninghamii : Geospatial Attributes: Jamison South						
*Undercliff Track 1	UT1	567	650	-33º 43′ 37″ S	150º 22′ 26.7″ E	830
*Undercliff Track 2	UT2	562	650	-33º 43′ 37.1″ S	150º 22′ 8.8″ E	815
Undercliff Track 3	UT3	557	653	-33º 43′ 27.9″ S	150º 21′ 49.0″ E	853
*Podgers Cliff	PC	562	618	-33º 45′ 20.1″ S	150º 22′ 4.3″ E	850
*Kedumba Walls	KW	563	626	-33º 44′ 55.4″ S	150º 22′ 10.5″ E	841
*Lincoln's Rock	LR	565	634	-33º 44′ 30.2″ S	150º 22′ 18″ E	845
Little Switzerland	LS	565	642	-33º 44′ 04″ S	150º 22′ 18″ E	835
*Sunset Rock	SR	566	610	-33º 45′ 47″ S	150º 22′ 19″ E	845
*Colraine Rock	CR	567	608	-33º 45′ 54.2″ S	150º 22′ 22.1″ E	814
Kedumba Road	KR	568	607	-33º 45′ 57″ S	150º 22′ 26″ E	805
Kedumba Gate	KG	571	602	-33º 46′ 14″ S	150º 22′ 38″ E	790

Table 2. Summary of geospatial attributes of all six populations.

E cunninghamii – Geospatial Attributes
Summary of All Six Populations

Occurrence	Altitude (m)	Aspect (degrees)	Slope (degrees)	AOO (m^2)
Grose North	893	226	29	2560
Pulpit Rock	925	250	20	2000
Grose South	830	244	21	1890
Jamison West	897	214	36	1310
Jamison South	829	239	37	1560
Wanganderry Walls	744	250	25	100
Total				9420
Average	853	237	28	

Substrate

All occurrences of *E cunninghamii* in the upper Blue Mountains are associated with clay, either at the outcrop or closely downslope. One prominent clifftop clay layer, the Wentworth Falls Claystone Member (WFC) (Bembrick and Holland 1972) is regionally extensive and constitutes a marker horizon for a change in direction of sediment provenance (Figure 3).

The WFC was laid down in mid-Triassic times (240 mya) in a widespread fluvial-deltaic system of braided streams (Bembrick 2015, Gorjan 2019), essentially flat across the whole terrain, but not necessarily consistent in either thickness or content. Since the uplift of the Blue Mountains (at least 15 mya, and possibly even over 100 mya) the WFC forms a slightly inclined E-W plane with a slope of about 0.9 degree in the upper Blue Mountains. The most prominent and accessible expression of the WFC occurs along the Undercliff Track at Wentworth Falls (Figure 4).

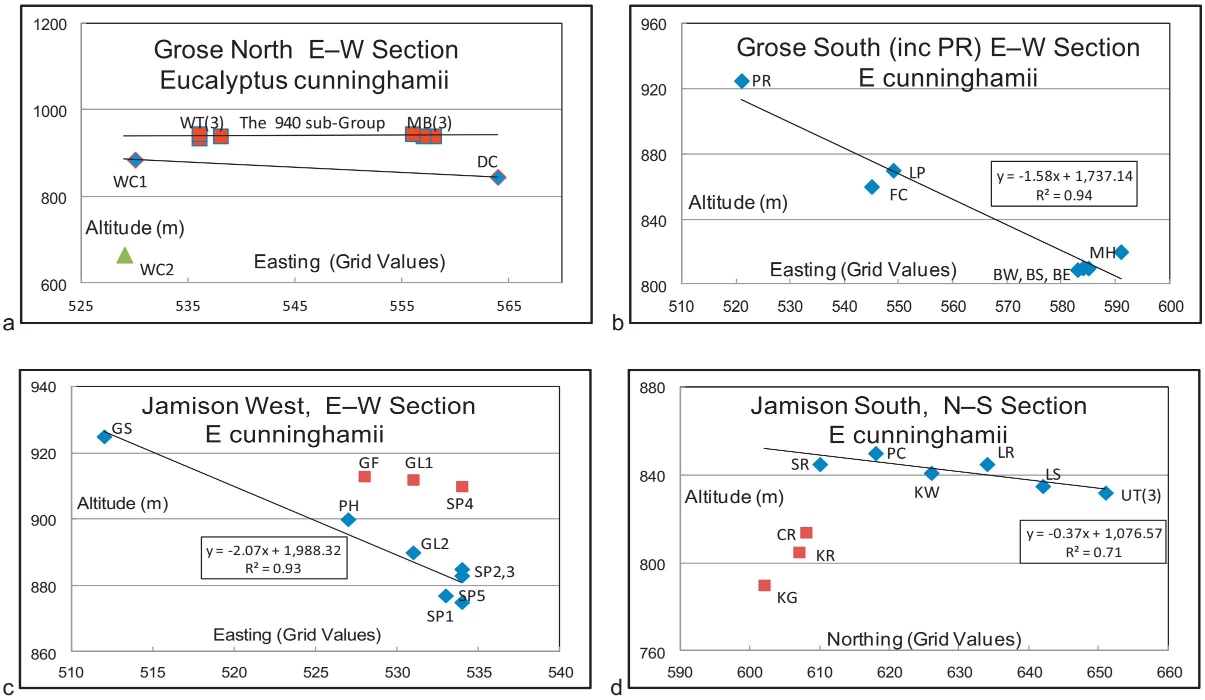


Figure 2. *Eucalyptus cunninghamii* in the upper Blue Mountains, correlations of altitudes with eastings (or northings) for four biogeographic isolations: a) Grose North, b) Grose South (including Pulpit Rock), c) Jamison West, d) Jamison South. Blue diamonds, occurrences on trend; red squares and one green triangle, anomalies (see Text).

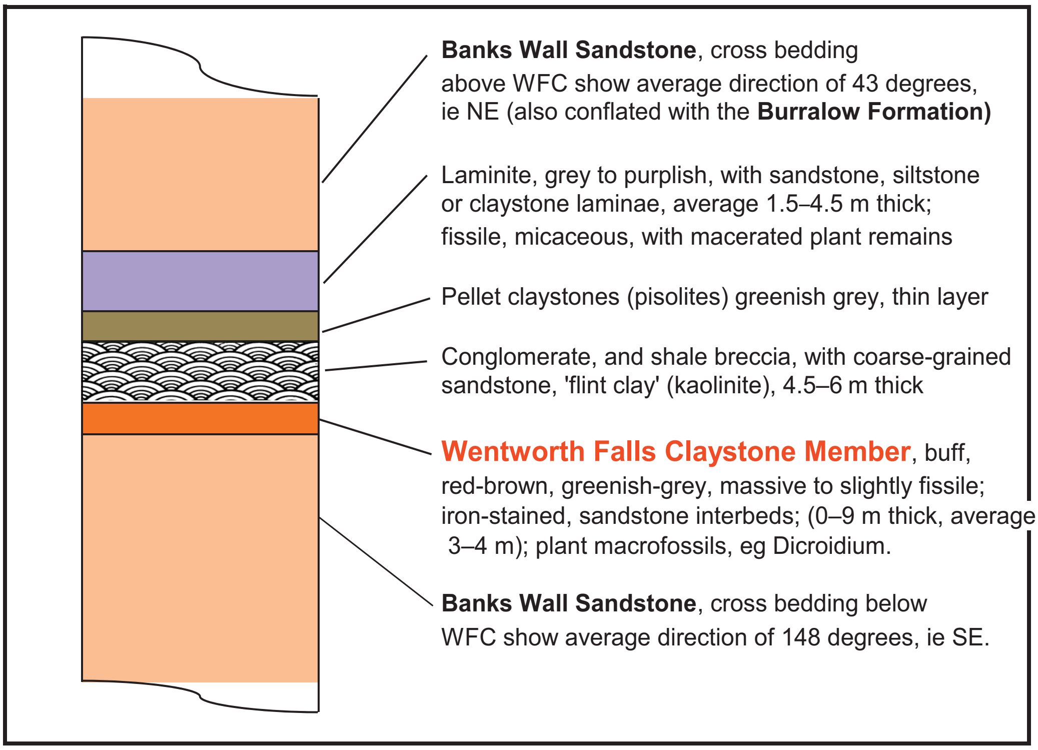


Figure 3. Sketch of the lithologies associated with the Wentworth Falls Claystone Member (WFC), of the Banks Wall Sandstone lying within the Narrabeen Group, based on Bembrick & Holland (1972).

Figure 4. Undercliff Track and WFC at Wentworth Falls.

Table 3. Wentworth Falls Claystone Member (WFC) in the Grose and Jamison valleys.

Wentworth Falls Claystone				
	Code	Northing	Easting	Altitude
		(Grid Values)		(m)
Grose Valley				
GWH Medlow Bath[4]	GWH	692	487	965
N of Neates Glen[1,4]	NNG	733	514	910
Mt Banks Summit	MBS	806	559	840
Mount Hay[2]	MHS	768	590	810
"F" WFKT[4]	"F"	646	577	820
Jamison Valley				
Kure Narrow Neck[4]	KNN	629	481	975
Narrow Neck Quarry[1,3]	NNQ	647	493	953
Sublime Point[1,4]	SP	631	534	875
"F" WFKT[4]	"F"	646	577	820
Sunset Rock	SR	610	566	845

We collected data from a number of journal articles from the 1970s which gave measurements of the location and altitude of the WFC over the Grose and Jamison valleys. These data derive from Bembrick and Holmes[1] (1978), Goldbery[2] (1972), Bembrick and Holland[3] (1972), and Goldbery[4] (1996) manipulated as required from imperial units to metric, and geographic locations from 1:63,360 maps (1935) to GDA94. They are summarised in Table 3.

We then inserted into Figures 2a–d the relevant data for the WFC from Table 3.and graphed the results in Figures 5a–d, where the WFC appears as black circles and black trendlines.

In each graph, slope and intercept of the WFC closely match those of the graphs for *Eucalyptus cunninghamii*. There is a high degree of correlation between these independent sets of data for the five populations in the upper Blue Mountains. The thirteen

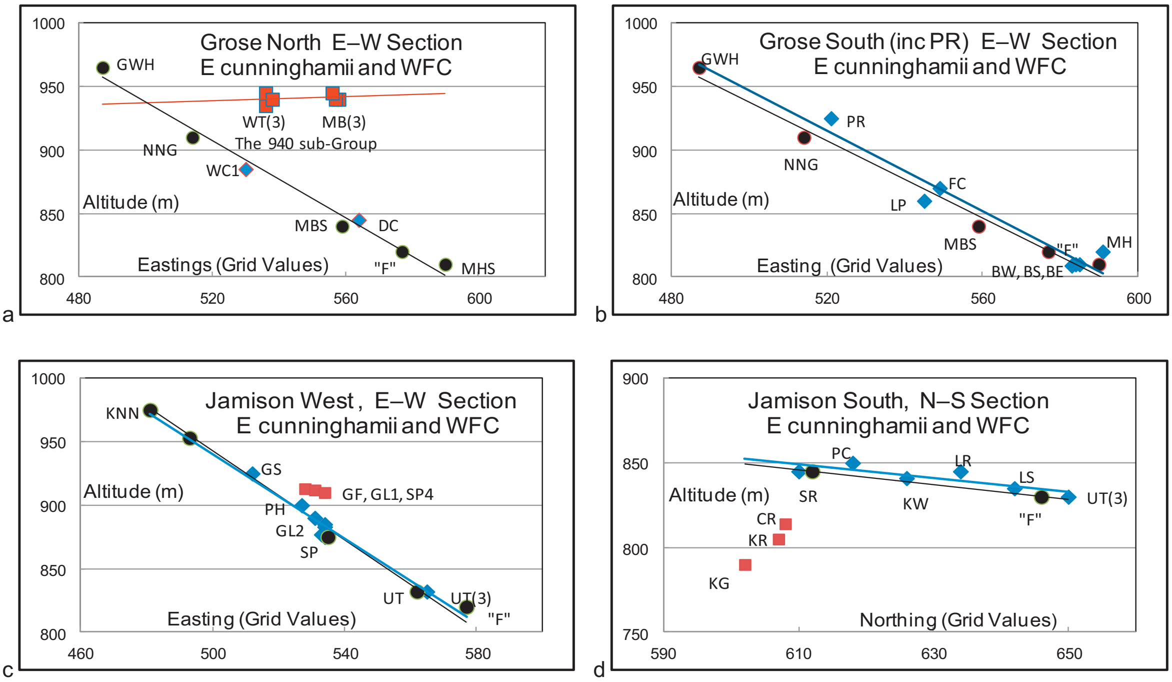


Figure 5. *Eucalyptus cunninghamii* in the upper Blue Mountains, altitudes and eastings (or northings) compared with the Wentworth Falls Claystone Member: a) Grose North, b) Grose South (including Pulpit Rock), c) Jamison West, d) Jamison South. Blue diamonds, occurrences on trend; red squares, anomalies (see text); black circles, WFC.

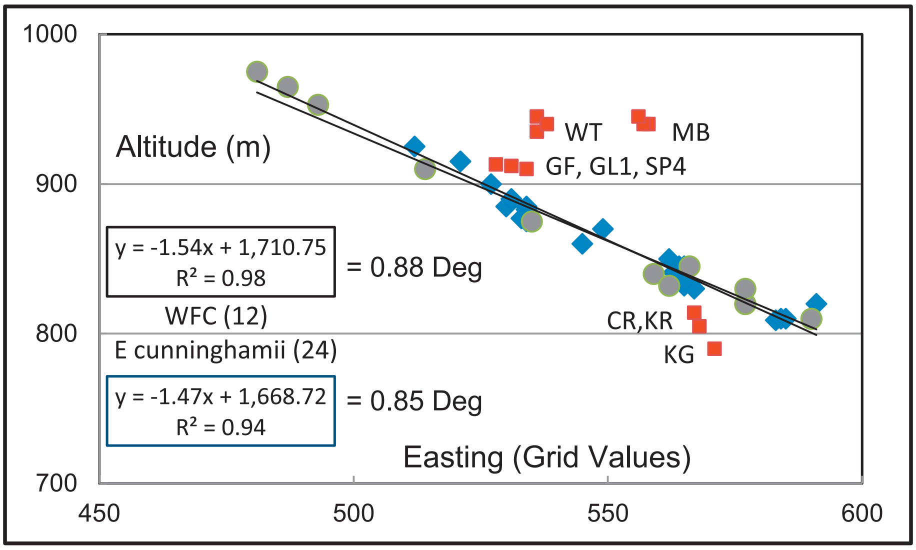


Figure 6. Correspondence of altitudes of 24 occurrences of *E cunninghamii* occurrences with 12 published altitudes of the Wentworth Falls Claystone Member (WFC). *E cunninghamii* data are shown as blue diamonds and blue trendline, WFC data as grey circles and grey trendline. Anomalous altitudes of *E cunninghamii* are shown in red (see text).

occurrences that do not lie on the trend lines depicted in Figures 5a–d are either associated with other claystones or, in the examples at Jamison South, with a change in slope arising from the Bodington Monocline.

As with text notes concerning Figures 2a–d, the origins of Figures 5a–d have been suppressed and the vertical scale is 100 times that of the horizontal. The graph slopes thus accentuate the very shallow real slopes of about 0.9 degree.

We combine the data in Figures 5a-d into one graph (Figure 6) which shows the overall correspondence between the majority (24) of 37 occurrences of *Eucalyptus cunninghamii* and the 12 published occurrences of the Wentworth Falls Claystone Member (WFC).

Anomalous Altitudes

Most, but not all, occurrences of *Eucalyptus cunninghamii* in the upper Blue Mountains are associated with the WFC. The most prominent of the others is the 940 sub-Group (Mount Banks 1, 2 and 3, Wongarra 1, 2 and 3). They occupy a horizontal zone in the north of Grose North at approximately 940 m. They correlate with the upper of two unnamed horizontal claystones (Pickett and Alder, 1997) at Mount Banks (Figure 7). We first measured altitudes in the Marginal Section ABC of Geological Series Sheet 8930-1 Katoomba 1:50,000 (Goldbery, 1996) to establish the altitude of the Mount York Claystone at 729 m at Mount Banks.

There are two unnamed clay layers at MountBanks (Pickett and Alder, 1997). We identified those two layers in one of our photographs of Mount Banks (Figure 7), and measured their altitudes using the known altitudes of the summit (Mt King George,

Figure 7. Claystone Layers at Mount Banks (see text for details).

1062 m) and the Mount York Claystone (729 m). The lower unnamed claystone lies at an altitude of 840 m, the upper clay layer lies at 940 m. The lower clay layer has been interpreted as possibly equivalent to the Wentworth Falls Claystone (Bembrick 2015), and we follow that interpretation here. Mount Banks occurrences (MB 1, 2, 3) of *Eucalyptus cunninghamii* lie on the upper claystone layer (Figure 7). Together with MB1, 2 and 3, the nearby occurrences of *E cunninghamii* at Wongarra 1, 2 and 3, constitute the six occurrences of the "940 sub-Group".

Another occurrence not associated with the WFC (and not shown in Figure 5a) is Walls Cliff 2, where *E cunninghamii* has propagated at 665 m from seed dropping down from Walls Cliff 1 at 885 m.

In Jamison West, because Golf Links 1 lies about 22 m above the trend line, we predicted (and found) Golf Links 2 on the trend line. Similarly, from our discovery of Sublime Point 4, 25 m above the trend line, we predicted (and found) Sublime Point 2 and 3 on the trendline. The occurrence at Gordon Falls, also above the trendline, is on a vertical cliff, and no occurrence on the trendline could be seen or accessed. It is possible that this upper claystone in Jamison West may be a remnant of the Docker Head Claystone (Loughnan et al. 1974, Martyn 2018).

Mount York Claystone

Our investigation of the easting and altitude of clay layers in the upper Blue Mountains also enabled us to graph known eastings and altitudes of both the WFC and the Mount York Claystone (MYC) (Figure 8). The MYC lies halfway up the familiar sandstone cliffs and separates the (lower) Burra-Moko Head Sandstone from the (upper) Banks Wall Sandstone. The MYC is also regionally extensive and planar, with an E–W slope of ~1.5 degrees. Though small, this difference in the slope of the two graphs for MYC and WFC means that the Banks Wall Sandstone that separates them thins down from east to west. At Jamison South on Kings Tableland the separation is over 100 m, but further west, as at the top of the Great Western Highway at Victoria Pass and at the quarry on the Mount York Road, the separation should be almost zero. However, at these locations the WFC has eroded away and no comparison is possible. A recent discussion of the relationship between the geology and the flora of much of the Sydney Basin can be found in Martyn (2018).

All the foregoing discussion refers to the upper Blue Mountains, which traditionally lie west of the Mount Tomah and Bodington monoclines (Figure 1). East of this line the slopes of both the MYC and the

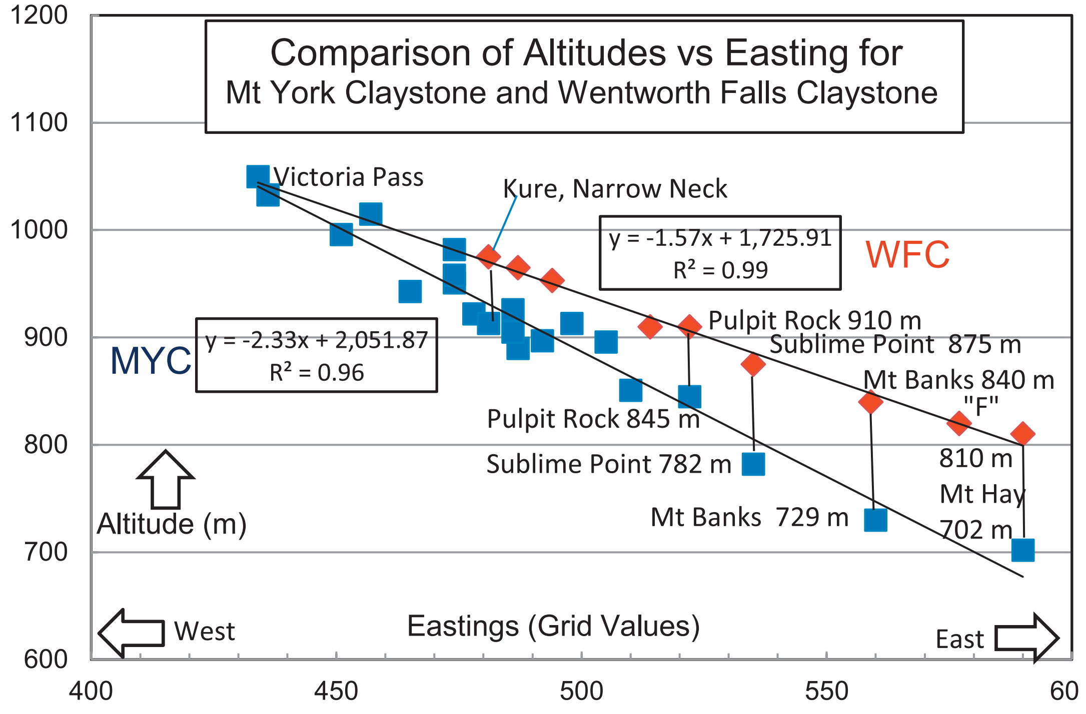


Figure 8. Comparison of altitudes vs easting for the Mount York Claystone and the Wentworth Falls Claystone Member in the upper Blue Mountains.

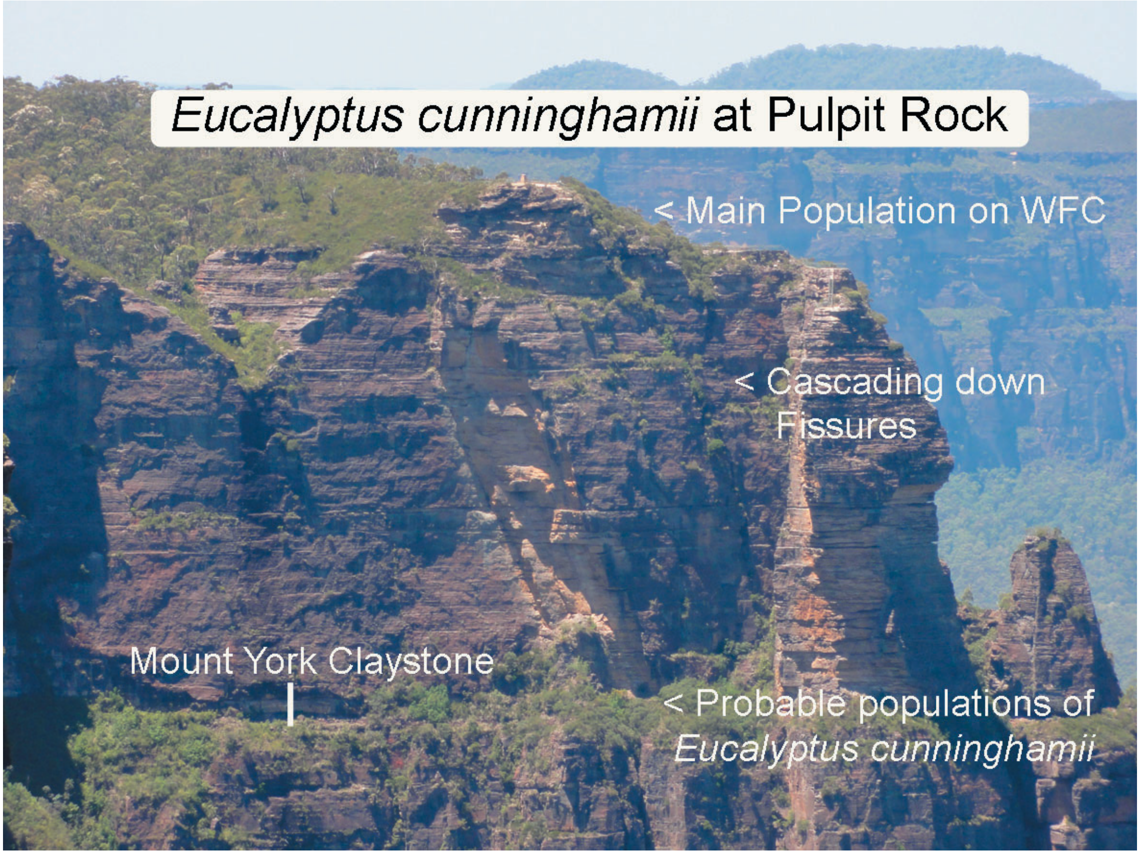


Figure 9. Cascading *Eucalyptus cunninghamii* at Pulpit Rock.

WFC increase to 2–2.5 degrees, with the consequence that neither exhibits a surface outcrop lower down the mountain (Bembrick 1980, Goldbery 1969/1996).

Pulpit Rock demonstrates that *Eucalyptus cunninghamii* cascades down fissures and cracks and inhabits the ledge associated with the Mount York Claystone (Figure 7), some 65 m below the average altitude, 910 m, for Pulpit Rock (Figures 9 and 10). If this interpretation is correct, *Eucalyptus cunninghamii* may be found on other outcrops of the Mount York Claystone, such as at National Pass at Wentworth Falls.

We sought reasons why 24 of our 37 upper Blue Mountains occurrences should show a strong association with the WFC. We chose an occurrence at Kedumba Walls (Jamison South) where it was possible, even on a steep slope (Figure 11), to make a downslope transect to include not only four specimens of *Eucalyptus cunninghamii*, but also the terrain above and below the occurrence (Figure 12). We analysed leaf and soil samples (Table 4).

It appears that the four elements Al, Ba, Fe and Sr are present in soils in far larger quantities than are required for sustained growth of *E cunninghamii*, whereas another eight elements Ca, Cu, K, Mg, Mn, Na, P and S are present in such low proportions as requires concentration in the leaves and other structures of *E cunninghamii* for proper plant development. This results in above-ground storage of vital nutrients (Keith 2004). The remaining element, Zinc, is present in both soils and leaves in about the same concentrations. This analysis does not include hydrogen, carbon, nitrogen or oxygen.

We sought correlations of elemental presence between soils and leaves downslope at Kedumba Walls. There is a positive correlation factor of 0.995 for barium and 0.898 for strontium. Of the remaining elements only sodium (-0.80) was significant. Thus for Ba and Sr at this site their uptake in leaves is proportional to their concentration in soil.

Our expectation that soil analysis at 0 m (above the clay layer) and at 20 m downslope (where there are no *Eucalyptus cunninghamii*) would exhibit differences from the remainder was not realised. The analysis does not therefore pinpoint the reason why the presence of *E cunninghamii* at a particular

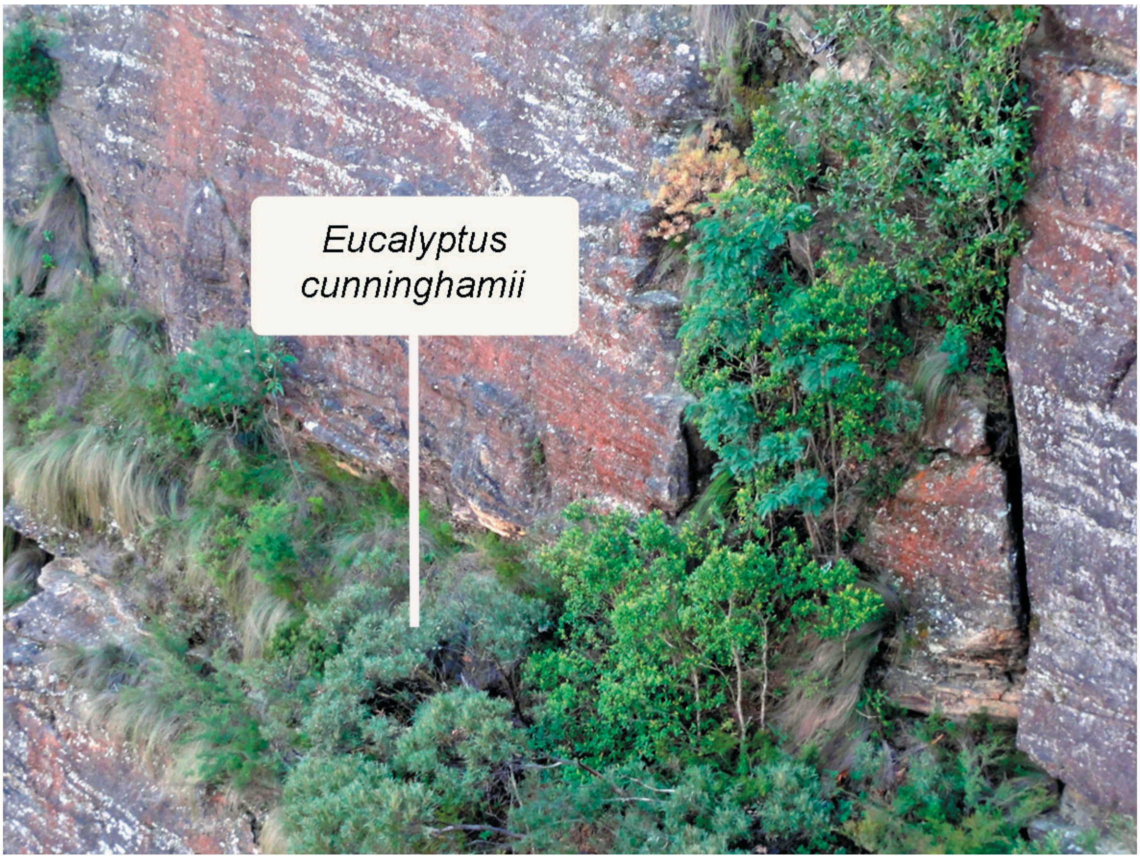


Figure 10. *Eucalyptus cunninghamii* on the MYC.

occurrence should correlate with any particular element in the substrate. The alternative interpretation that the WFC acts as an aquitard, and discharges water at the outcrop to help sustain *E cunninghamii*, was not measured in our study. We lacked resources a) to measure environmental factors such as soil moisture averaged over a year, or b) to determine whether a specific mycorrhizal fungus was present. We also lacked resources to measure similar attributes at other occurrences.

We therefore conducted a similar analysis on leaf and soil samples of *Eucalyptus stricta* from three separate locations in the upper Blue Mountains: Willoughby Road, south Leura; Flat Top carpark on the Mt Hay Road; and the carpark at the northern end of the Mt Hay Road. These three sites are specific for *E stricta* and remote from any other occurrences of *E cunninghamii* (Table 5).

When comparing the data of Tables 4 and 5, the overall pattern is the same in both. Al, Ba, Fe and Sr are all diluted in leaves from their environmental concentrations in soils. Eight other elements, Ca, Cu, K, Mg, Mn, Na, P and S, are all concentrated in the plant above the levels found in their soils. The average 'Dilution percentage' in *Eucalyptus cunninghamii* is 3%, in *E stricta* it is 7%. The average 'Concentration factor' in *E cunninghamii* is 14%, whereas in *E stricta* it is 20%. We found no other significant differences.

Our analyses neglect the probability that elements may not always be biologically available: soluble ferrous iron which oxidises to insoluble ferric iron (Washington and Wray 2011) is an example that produces contorted deposits at some occurrences (Figure 13).

General

Our 37 occurrences do not necessarily represent totality. There may be more *Eucalyptus cunninghamii* in some relatively inaccessible locations, as at Mount Solitary in the Jamison Valley, and along Kedumba Walls (Jamison South) from Rocket Point south to Sunset Rock. In the Grose Valley there are some relatively inaccessible locations between Bell and Mount Banks, and along the SW flanks of Fortress Ridge and Lycon Plateau, where *E cunninghamii* may be discovered.

Figure 11. ***Eucalyptus cunninghamii*** **at Kedumba Walls.**

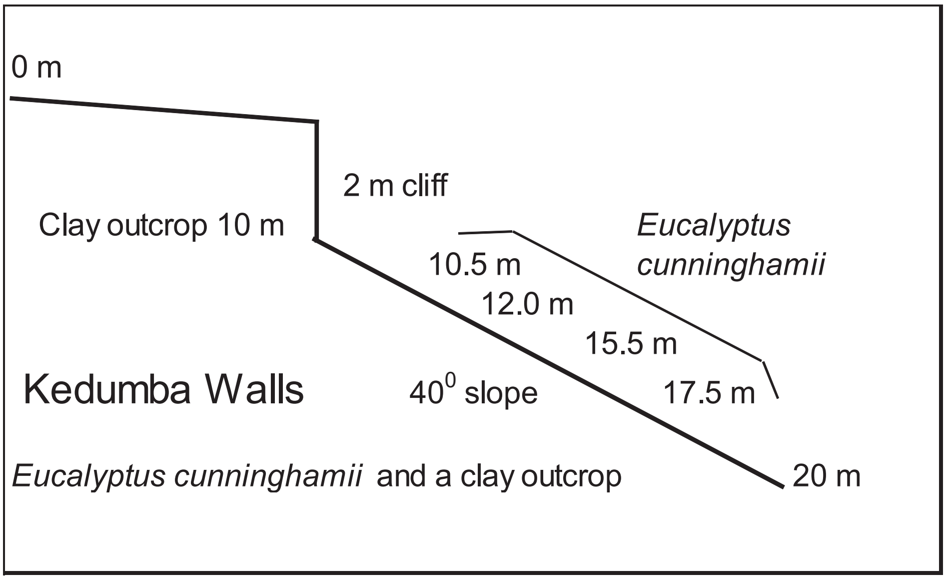


Figure 12. Sketch of terrain at Kedumba Walls.

Table 4. Leaf and soil analyses, Kedumba Walls (see Figure 12)

Elemental analysis at Kedumba Walls (mg/Kg)													
Element / Item	Al (3)	Ba (2)	Ca (2)	Cu (TM)	Fe (TM)	K (1)	Mg (2)	Mn (TM)	Na (1)	P (5)	S (6)	Sr (2)	Zn (TM)
Soil: 0 m	4230	16.5	39	<0.6	6110	454	129	6.1	89	71	119	24	4.8
Soil 10.5 m	3900	15.7	34	<0.7	7200	354	108	16	34	69	107	20.2	5.2
Soil: 12 m	5710	22.5	29	<0.7	6750	596	109	8.1	108	81	101	32.4	3.8
Soil: 15.5 m	9370	84.6	36	<0.7	8600	1030	165	8.1	93	163	101	73	4.4
Soil: 17.5 m	6750	41.3	43	<0.7	6660	703	139	9.1	61	110	89	42.1	4.1
Soil: 20 m	8000	42.1	43	1.1	6340	1020	225	12.5	131	127	196	47.1	7.2
Clay: 10 m	8050	32.1	51	<0.7	12300	818	160	45.8	91	123	116	44.8	6.6
Leaf: 10.5 m	60	0.5	762	3.3	40	4320	1290	260	3130	328	1040	1.5	5.3
Leaf: 12.0 m	44	0.6	946	1.8	30	3520	912	192	2440	375	941	4.4	5.3
Leaf: 15.5 m	53	1.1	1120	2	27	3570	941	265	2670	287	862	6.1	5.1
Leaf: 17.5 m	66	0.7	865	3.5	40	5270	913	163	2530	436	1040	4.3	5.7
Elements which are relatively abundant in soils, but required only in small concentrations in E cunninghamii													
Dilution factor (%)	0.9	1.8			0.5							9.7	
Elements which are relatively scarce in soils, but concentrated in the metabolism of E cunninghamii													
Concentration factor			26	3.8		6.2	7.8	21.3	36.4	3.4	9.8		
This table of analyses does not include Hydrogen, Carbon, Nitrogen and Oxygen													
Correlations (of four leaf samples with four soil samples for each element)	-0.109	0.9954	-0.093		-0.625	-0.26	-0.49	0.4482	-0.801	-0.379	-0.213	0.8978	-0.253

Table 5. Elemental analysis of soils and *Eucalyptus stricta*

Elemental analysis of soils and *Eucalyptus stricta* (mg/Kg)													
Element / Item	Al (3)	Ba (2)	Ca (2)	Cu (TM)	Fe (TM)	K (1)	Mg (2)	Mn (TM)	Na (1)	P (5)	S (6)	Sr (2)	Zn (TM)
Leaves: *Eucalyptus stricta*													
Willoughby Road	88	3.1	3210	2.4	37.4	1650	1200	353	1710	320	851	7	4.6
Flat Top Carpark	45	4.1	4330	6.8	39	3450	1170	292	2370	362	803	11.3	6.5
Mt Hay Carpark	56	4.7	2970	3.4	32	3250	1440	148	2630	509	809	17.9	6.4
Soils: *Eucalyptus stricta*													
Willoughby Road	5740	26.6	79	0.7	10200	358	114	10.1	55.8	109	132	28	5.1
Flat Top Carpark	6270	24.6	167	1	5710	316	122	9.2	34	56	89	16.5	6.7
Mt Hay Carpark	2250	8.4	104	1	1690	206	76.2	4.1	22	45	55	7.8	2.3
Elements which are relatively abundant in soils, but required only in small concentrations in *E stricta*													
Dilution factor %	1.3	20			6.2							1.4	
Elements which are relatively scarce in soils, but concentrated in the metabolism of *E stricta*													
Conc. factor x			30	4.7		9.5	12.2	33.9	60	5.7	8.9		
This table does not include Hydrogen, Carbon, Nitrogen or Oxygen													

Figure 13. Contorted ironstone in claystone.

CONCLUSION

Eucalyptus cunninghamii in the upper Blue Mountains exhibits a marked preference for outcrops of claystone for its habitat. The most prominent of these claystones is the relatively thin, planar and regionally extensive Wentworth Falls Claystone Member (WFC) that outcrops across the upper Blue Mountains of NSW. Geologic accidents of topography and stratigraphy indicate that outcrops of the WFC occur only around the clifftop rims of the Jamison and Grose valleys. *E cunninghamii* in the upper Blue Mountains is therefore constrained to a narrow range of altitudes (approximately 800–920 m), but with occasional deviations to 940 m on other smaller and less extensive claystones. The random outcrops of the Wentworth Falls Claystone Member limit the Extent of Occurrence (EOO) of *E cunninghamii* to less than 200 km^{2,} and its Area of Occupation (AOO) to less than one hectare (Coleby, pers comm., 2019). The implications of climate change for *E cunninghamii* are therefore severe, unless it is capable of adapting. One of the options discussed by Booth (2017), to move, seems improbable, and the third option, to go extinct, is unacceptable.

ACKNOWLEDGEMENTS

It is a pleasure to record a number of people who have made a significant contribution to our study. They include Dr Peter Wilson and Dr Susan Rutherford of the National Herbarium at the Royal Botanic Garden and Domain Trust in Sydney, and the indefatigable Editor of *Cunninghamia*, Doug Benson, all three of whom were the inspiration for our study. Col Bembrick, of Napoleon Reef, accompanied one of us (DC) on several field trips and gave freely of his professional geological expertise. Vera Wong, Senior Project Officer, Saving our Species, and John Good, both of NPWS in Katoomba, provided valuable access to David Crevasse, and found specimens of *E cunninghamii* at the bottom of Pierces Pass. Henri Wong, Analytical Laboratory Manager in Isotope Tracing in Natural Systems (ITNS) used IPCAES to analyse our leaf and soil samples at the Australian Nuclear Science and Technology Organisation (ANSTO), Lucas Heights, Sydney. Dr Brian Marshall of Leura and Dr John Martyn of Turramurra helped to interpret a number of geological attributes.

REFERENCES

Australia's Virtual Herbarium (AVH) (2019), Atlas of Living Australia (ALA) (2019), http://avh.ala.org.au

Bembrick, C, (2015) The Geology of the Blue Mountains, with reference to Cox's Road, http://coxsroaddreaming.org.au/wp-content/uploads/Geol-Blue-Mtns_CSB_edited.pdf

Bembrick, C, (1980). Geology of the Blue Mountains, Western Sydney Basin. In Herbert, C, and Helby, R, (eds), A guide to the Sydney Basin, *Geological Survey of New South Wales,* Bulletin **26**, pp 134-161.*DIGS Publication collection: Catalogue No. 778

Bembrick, C.S., and G.G. Holmes, (1978), Comments on the Geology of the Katoomba 1:50 k Geological Sheet 8930–1, Geological Survey Report GS 1978/296*, Geological Survey of New South Wales, Department of Mines*.

Bembrick, C.S., and W.N. Holland, (1972), Stratigraphy and Structure of the Grose Sandstone in the Blue Mountains, in *Quarterly Notes 7, pp 11-18, Geological Survey of NSW,* 1 April 1972, NSW Department of Mines. *DIGS Report collection: ID = R00040839.

Booth, T.H., (2017), Going nowhere fast: a review of seed dispersal in eucalypts, *Australian Journal of Botany*, **65**, pp 401–410, Turner Review No. 20, ttps://doi.org/10.1071/BT17019

Briggs, J.D. and J.H. Leigh, (1996). Rare or threatened Australian plants, Revised Edition, *CSIRO Publishing, Australia*. ISBN: 9780 6431 05966

Brooker, M.I.H., and D.A. Kleinig, (2006) Field Guide to Eucalypts. Volume 1. South-eastern Australia. 3rd Edition, *Bloomings Books, Melbourne*. ISBN 1 876473 52 5 (Vol 1)

Carolin, R.C., and M.D. Tindale, (1994), Flora of the Sydney Region, *Reed, Sydney*. ISBN 0730 104001

Euclid (2018), http://keyserver.lucidcentral.org:8080/euclid/data/02050e02-0108-490e-89000e0601070d00/media/Html/Eucalyptus_cunninghamii.htm

Fairley, A., (2004), Seldom Seen, Rare Plants of Greater Sydney, *Reed New Holland, Sydney*, ISBN 1 876334 99 1

Fairley, A., and P. Moore, (2000) Native plants of the Sydney District, an identification guide. Second Edition, *Kangaroo Press, Roseville NSW*. ISBN 0 7318 1031 7

Geoscience Australia, (2019) Redfearn's Formulae, http://www.ga.gov.au/geodesy/datums/redfearn_geo_to_grid.jsp and http://www.ga.gov.au/geodesy/datums/redfearn_grid_to_geo.jsp

Goldbery, R., (1972), Geology of the Western Blue Mountains, Bulletin 20, *Geological Survey of New South Wales, Department of Mines, Sydney.*

Goldbery, R., (1996), Australia 1:50,000 Katoomba Geological Series Sheet 8930-1, *Geological Survey of New South Wales, Department of Mineral Resources.*

Gorjan, P., (2019) Geology of the Blue Mountains: A Tourist's Guide, *Yarnspinners Press Collective, PO Box 9, Wentworth Falls NSW 2782.* ISBN 978-0-6481342-2-0.

Holland, W.N., (1974), Origin and development of hanging valleys in the Blue Mountains, New South Wales. PhD Thesis, University of Sydney.

Hager, T. and D. Benson, (2010), Eucalypts of the Greater Blue Mountains World Heritage Area, *Cunninghamia* **11(4):** 2010. ISSN 0727 9620

Loughnan, F.C., R. Goldbery, and W.N. Holland, (1974) Kaolinite clayrocks in the Triassic Banks Wall sandstone of the western Blue Mountains, New South Wales, *Journal of the Geological Society of Australia*, **21:4**, 393-402.

Martyn, J., (2018), Rocks and Trees: A Photographic Journey through the rich and varied geology, scenery and flora of the Sydney Region, *STEP, Sydney*, ISBN 978 0 9578390 4 5

Pickett, J.W., and J.D. Alder, (1997), Layers of time: the Blue Mountains and their Geology, *New South Wales Department of Mineral Resources, Sydney* 34pp. ISBN 0 7313 0274 5

PlantNET (2019), http://plantnet.rbgsyd.nsw.gov.au/search/simple.htm.

Rutherford, S., Wilson, P.G., Rossetto, M., Bonser, S.P., (2016) Phylogenomics of the green ash eucalypts (Myrtaceae) – a tale of reticulate evolution and misidentification. *Australian Systematic Botany* 28: pp. 326–354.

Rutherford, S., (2017) Adaptive variation versus vicariance: what drives speciation in Eucalyptus? PhD thesis, University of New South Wales.

Rutherford, S., (2019) Insights into speciation and species delimitation of closely related eucalypts using an interdisciplinary approach, *Australian Systematic Botany* SB18042 (in press).

Washington, H., and R. Wray, (2011), The Geoheritage and Geomorphology of the Sandstone Pagodas of the Northwestern Blue Mountains Region (NSW), *Proceedings of the Linnean Society of New South Wales* **132**, pp 131-143.

Climate Change Threatens a Fig-Frugivore Mutualism at its Drier, Western Range Margin

K. David Mackay* and C.L. Gross

Ecosystem Management, University of New England, Armidale NSW 2351 Australia
* Author for correspondence: kdavidmackay@gmail.com

Keywords: keystone, *Ficus*, dry rainforest, range shifts, heat-waves, population decline

Mackay, K.D. and Gross, C.L.(2019). Climate change threatens a fig-frugivore mutualism at its drier, western range margin. *Proceedings of the Linnean Society of New South Wales* **141**:S1-S17.

Ficus rubiginosa (the Rusty Fig; Moraceae) provides a keystone food resource for a diverse array of vertebrate frugivores in eastern Australia. These frugivores, in turn, provide vital seed-dispersal services to the fig. The aims of this study were to investigate impacts of population size and climatic variation on avian-frugivore visitation to *F. rubiginosa* at the extreme western, drier margin of the species' range. Eighty-two bird species visited *F. rubiginosa* trees in this three-year study. Twenty-nine species were frugivores or omnivorous frugivore/insectivores. The number of ripe fruit in a tree had the greatest positive influence on frugivore visitation ($p < 0.0001$). Fig-population size influenced the assemblage of frugivore species visiting trees but not the number of frugivores or the rate of frugivore visitation. The number of ripe fruit in a tree was negatively associated with declines in rainfall, to total losses of standing crops through dieback and lack of crop initiation. Predicted long-term declines in rainfall across this region of eastern Australia and increased incidence of drought will lead to reduced crop sizes in *F. rubiginosa* and likely reduce the viability of local populations of this keystone fig. This will threaten the mutualism between *F. rubiginosa* and frugivores across the region.

Manuscript received 30 October 2018, accepted for publication 11 March 2019.

KEYWORDS: climate change, *Ficus,* fragmented habitat, range expansion, small populations

INTRODUCTION

Range shifts and/or local extinctions are increasingly becoming a reality for a wide diversity of organisms (Bergamini et al. 2009, Chen et al. 2009, Lenoir and Svenning 2013, McMenamin et al. 2008, Perry et al. 2005, Przeslawski et al. 2012, Thomas and Lennon 1999, Whitfield et al. 2007). Climate-change-induced temperature rises have been linked to many of these changes (Gottfried et al. 2012, Parmesan and Hanley 2015, Poloczanska et al. 2013). Modelling predicts that birds will come under increasing risk of catastrophic mortality events during heatwaves (McKechnie and Wolf 2010) and that increasing numbers of bird species will be at risk of at least local extinction in the future as a result of climate change. Habitat fragmentation and/or disturbance are also major causes of local avian-population declines or extinctions (Ford 2011a, Ford 2011b, Moran et al. 2009) and can have negative long-term effects on populations of both plants and their avian-frugivore seed-dispersers (Cordeiro and Howe 2001, Cordeiro and Howe 2003, Cosson et al. 1999, Tewksbury et al. 2002). The extent of any impact depends to some extent on the degree of mutual dependence between fruiting trees and avian visitors (Herrera 1984, Jordano 1987, Wheelwright and Orians 1982).

Frugivorous birds are well-known consumers of figs (Shanahan et al. 2001) and their dependency on *Ficus* fruit production at times when other plants are not in fruit is a major reason for the keystone status of fig trees (Lambert and Marshall 1991).

The mechanisms underlying climate-change and habitat-fragmentation effects on plants and their avian visitors, such as the longer-term consequences of habitat disturbance on fundamental ecosystem processes including seed dispersal, are still poorly understood. Frugivore visitation to *Ficus* species has been the subject of many surveys and studies

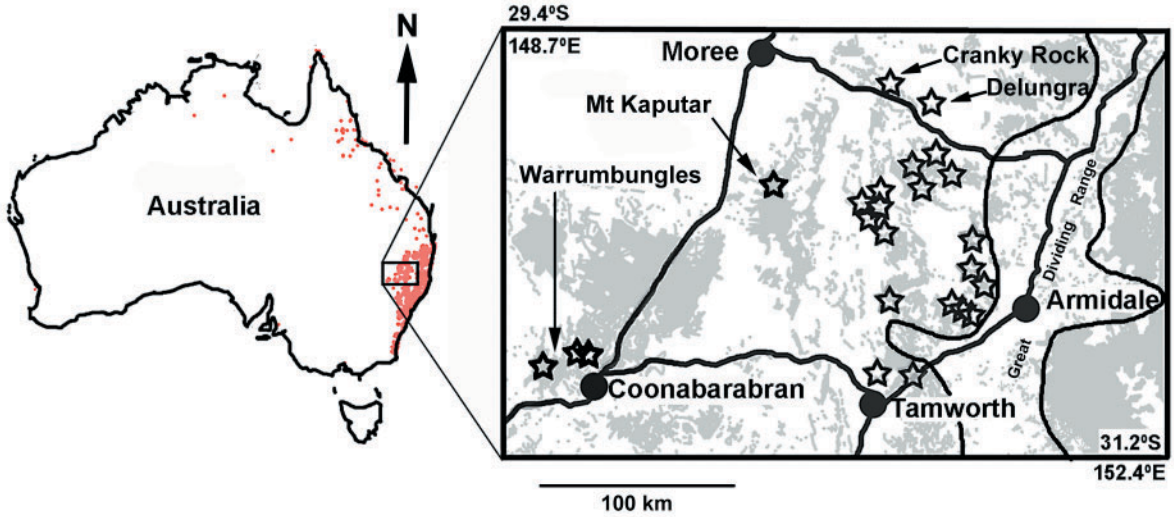


Figure 1. Distribution of *Ficus rubiginosa* in Australia (red dots; includes islands off the Queensland coast), and locations of the 24 study sites (stars) within the 50,000km2 study area in northern New South Wales. Remaining areas of woody vegetation in the region are marked in grey on the map of the study area, based on satellite imagery (Google_Earth 2017).

(Bronstein and Hoffmann 1987, Goodman et al. 1997, Thornton et al. 2001, Lomáscolo et al. 2010, Schleuning et al. 2011). However, little attention has been given to the role fig trees play in supporting populations of avian frugivores in Australia beyond anecdotal observations. No studies of avian visitors to *Ficus rubiginosa* and/or their mutual dependence could be found in the literature. This is despite the keystone (Davic 2003, Paine 1969, Terborgh 1986) status of *Ficus* species, particularly the larger, monoecious species such as *F. rubiginosa* (Shanahan et al. 2001).

Ficus rubiginosa is the only large species of fig tree found commonly on the western, drier side of the Great Dividing Range in Queensland (Qld) and New South Wales (NSW). It is the most productive, fleshy-fruited tree in woodland and dry-rainforest habitats on the western side of the range, with a 2,500 km north-south distribution (Fig. 1). Many small populations of *F. rubiginosa* persist across the study area (Fig. 1), mostly in rocky habitats which are of little or no use for agriculture. Here, *F. rubiginosa* grows predominantly as a lithophyte and less frequently as a hemi-epiphyte (Dixon et al., 2001). It occurs as single isolated trees, in small populations in open, grazed landscapes or in small to large populations in dry-rainforest patches and open woodlands.

The primary aim of this study was to test a hypothesis concerning the provision of a keystone food resource by *F. rubiginosa* for frugivorous birds at *F. rubiginosa*'s western, drier range margin. This hypothesis had three parts: (1) that *Ficus rubiginosa* provides keystone support to populations of avian frugivores at the western, drier edge of the species' range, (2) that climate change is leading to declines in fruit production by *F. rubiginosa* across this region, and (3) that the mutualism between *F. rubiginosa* and avian frugivores is under threat at the species' drier range margin on the western side of the Great Dividing Range in NSW.

MATERIALS AND METHODS

Study area and sites

This study was conducted in the New England Northwest region of New South Wales, between 29.4 and 31.2° south (200 km) and between 148.7 and 152.4° east (350 km) (Fig. 1).

The study area experiences warm to hot summers and cool to mild winters. Average annual rainfall varies from 600 mm to 800 mm west to east (BOM 2017). Altitudes across the study area range between 100 m and 1500 m with *Ficus rubiginosa* populations restricted to altitudes below 1000m (Atlas 2017). This region of eastern Australia has been extensively cleared for agriculture, with over 60% of the woody cover of natural vegetation having been cleared across the study area (Benson et al. 2010). This habitat clearing has left a patchwork of large and small remnants of

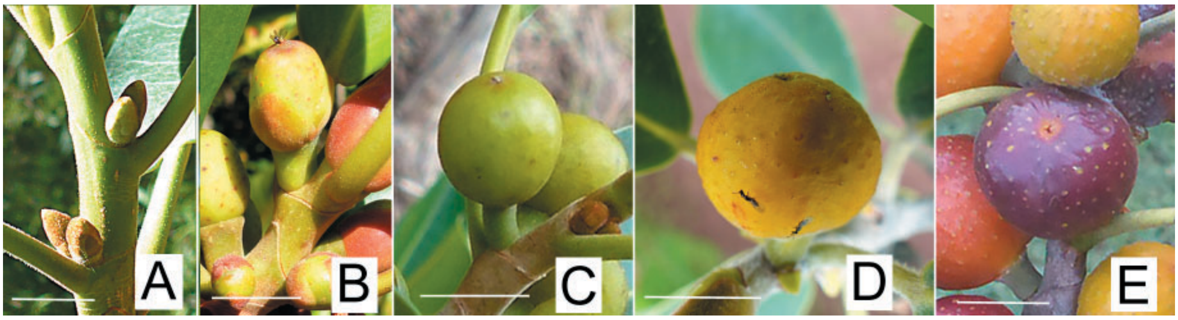


Figure 2. Five recognised stages of syconial development in the genus Ficus: A = bud stage, B = female-flowering stage, C = seed and fig-wasp development stage, D = male-flowering and wasp-emerging stage (pollinating fig wasps and non-pollinating fig wasps), E = ripe stage (Galil and Eisikowitch, 1968). Scale bars = 1 cm.

natural vegetation and single paddock-trees across the landscape. Twenty-four sites were established in the study area in 2014, evenly spread across three habitat-fragment/fig-population size-categories: category 1 = single trees growing within agricultural landscapes or disturbed vegetation (eight sites); category 2 = small populations of between five and fifteen fig trees growing within agricultural landscapes or disturbed vegetation (eight sites); category 3 = over fifty trees growing within contiguous natural vegetation (eight sites); (see Fig. 2 in Mackay et al. 2018 for Google Earth satellite images of examples of the three population sizes). The extreme western, drier range margin of *F. rubiginosa* extends in a north-easterly direction from the Warrumbungles National Park west of Coonabarabran through Mt Kaputar National Park and Cranky Rock near Delungra (Fig. 1). Additional observations were conducted at five sites in mesic habitat within 50 km of the coast between October 2014 and September 2016. These five sites were between Coffs Harbour and Port Macquarie, over 150 km to the east of the inland study sites.

Figure 3. D-stage (yellow, ripening) and E-stage (red, ripe) syconia. D- and E-stage syconia are 9 to 23 mm in diameter in *Ficus rubiginosa*. D and E syconia were almost always on branches simultaneously.

Fruit resources

The fruit of *Ficus rubiginosa*, as in other monoecious *Ficus* species, ripen more-or-less synchronously within crowns but asynchronously among crowns (Janzen 1979). Asynchrony in fruit development among trees results in ripening fruit being available across the breeding population of *F. rubiginosa* throughout the year except during harsh climatic conditions such as drought periods and cold winters (Mackay 2018). However, ripe fruit are not always available within sub-populations (e.g., within study sites), depending on climatic conditions and the number of trees in a site. Trees in which bird observations were recorded were categorised as either vegetative (non-fruiting) or according to recognised developmental stage/s of fruit in the trees ('stages A to E', Galil and Eisikowitch 1968; Fig. 2) and the number of fruit in trees. Ripening fruit turn yellow (stage D). Fruit ripen fully and turn red-brown (stage E) after the wasps have departed. Ripe and ripening fruit are usually on trees simultaneously (Fig. 3) except at early stages of ripening. Mention of the number of ripe fruit on trees in this paper, sometimes described as numbers of 'ripe-and-ripening fruit' on a tree for clarity, refer to the total number of ripening D-stage and ripe E-stage syconia on trees together.

The total numbers of ripe-and-ripening fruit on trees were estimated by counting 1000 fruit and then extrapolating the area covered by that 1,000 fruit to the whole area of the tree when fruit production was observed to be even around the tree. In cases where fruit production was observed to be uneven over the tree (sometimes fruit production was higher on the northern, sunnier sides of trees) then second and/or further counts were made of 1000 fruit and extrapolated across areas of higher/lower fruit production. Fruit numbers were categorised into 5 logarithmic size-classes to minimise any inaccuracies in fruit-count estimates (categories: 1 = 0 to 20 fruit; 2 = 21 to 200 fruit; 3 = 201 to 2,000 fruit; 4 = 2,001 to 20,000 fruit; 5 = 20,001 to 200,000 fruit).

Avian visitors

Five hundred and sixty-two observation periods were conducted at these twenty-four sites over three years, from February 2014 to January 2017. Observations were spread across the three *Ficus*-population categories of single trees, small populations and large populations, and across the twelve months of the year. Observations were spread over all daylight hours. Each observation period was twenty-minutes in duration, considered to be a suitable or minimum survey period to capture bird species diversity and abundance at a tree (Fischer and Lindenmayer 2002a). Observations were conducted using binoculars (Barr and Stroud 'Sahara' 10x42 binoculars) from the cover of a hide and/or a nearby tree within ten to thirty metres of the observed trees. In each twenty-minute observation period all avian visitors to an individual, tagged tree were recorded. For each individual bird its identification, its activity (eating fruit, eating insects or insect products, or 'other' activities) and the length of time spent in the tree over the twenty-minute observation-period was recorded. Each bird was classified as a frugivore, insectivore or other based on individual birds' feeding activities during the observation periods. Species were then categorised based on individual birds' behaviour and categorisations were confirmed using the Birdlife Australia web site (birdlife.org 2017a) and the Handbook of Australian, New Zealand and Antarctic Birds (Higgins et al. 1990-2006). Frugivores also consumed insects (fig wasps) that were contained within ripe/ripening syconia. However, insect consumption was not recorded unless insects or insect products were directly consumed. Consumption of fruit was one aspect of seed dispersal observed in the study. However, not all frugivores are necessarily good seed dispersers (Higgins et al. 1990-2006), and this was noted and mentioned for some species. Seed-dispersal behaviour of frugivores in and after leaving the fig trees was noted and compared/confirmed with published information in the literature about frugivores/seed dispersers. Dependent variables recorded in the 20-minute observation periods were the number of frugivore species, total number of frugivore individuals, and the total time spent in tree by frugivores (summed for all individual frugivores). Fourteen factors that potentially influenced frugivore visitation to fig trees were recorded: latitude, longitude, site, distance from observed tree to nearest non-isolated tree, fig-population size-category, number of trees in the population with ripe or ripening fruit, number of ripe and ripening fruit in the observed tree, date, month, season (3-month seasons of spring, summer, autumn, winter), time of day (Australian Eastern Standard Time), number of insectivore species, total number of insectivores, total time spent in tree by insectivores (summed for all individual insectivores). Fourteen twenty-minute observations were conducted in coastal populations of *F. rubiginosa* to confirm initial assessments made in the field and from the literature (Birdlife Australia 2018, Higgins et al. 1990-2006) that frugivores were present in greater diversity and abundance in mesic coastal regions than inland sites. These observations were compared with inland observations. All observations were conducted during fine, sunny weather.

A seed-germination experiment was conducted on regurgitated seed from the most common frugivore, the Pied Currawong, which was also the second-largest frugivore to visit *F. rubiginosa*. Forty regurgitated pellets, ten from each of four sites, were collected from the ground underneath feeding trees as well as distant from feeding trees and air-dried for later germination trials in glasshouse conditions. Pellets were broken up by hand immediately prior to planting in the glasshouse, and then spread over a soil-vermiculite mix (soil brought in from field sites where the pellets were collected) in plastic containers (standard, 17 x 12 x 3.5 cm take-away food containers, with holes drilled in the bottom for drainage) and placed under sprinklers to test if fig seeds in regurgitated pellets germinated with application of water alone.

Statistical analyses

Conditional Inference Tree analysis, using the Partykit package (Hothorn and Zeileis 2015) in R (R-Core-Team 2017), was used to assess which of the fourteen recorded input variables influenced frugivore and insectivore visitation. Conditional Inference Trees, a recursive partitioning analysis, are especially useful for examining ecological data where input factors may interact hierarchically (De'Ath and Fabricius 2000, Jha and Vandermeer 2010). Conditional Inference Tree analysis is also unbiased, unlike other tree-structured regression models which have a selection bias towards categorical variables with more categories (Hothorn et al. 2006). Factors influencing frugivore visitation to fig trees were assessed at the 0.05 level of significance.

Linear mixed effects models (fixed and random effects) were constructed using methods outlined in Winter (2013) in R (R-Core-Team 2017) to analyse the data for frugivore visitation to trees. The Likelihood Ratio Test (Winter 2013) was used to attain *p*-values: saturated or 'full' models, using all measured factors ('effects'), were compared with alternative, 'reduced' models with each reduced model having a single factor removed, using the 'anova' function to determine Chi-square values, degrees of freedom, *p*-values and Akaike's Information Criterion (AIC) values (Burnham and Anderson 2003). The final fitted models accepted contained those factors which resulted in significant Chi-square values. Frugivore- and insectivore-visitation data were heteroscedastic and were log transformed for homoscedacity. Data for the dependent variable 'total time spent by frugivores in trees' were overdispersed so results from the LMER analyses were confirmed by constructing a General Linear Model in R (Lillis 2017, R-Core-Team 2017) with a quasipoisson model to deal with the overdispersion

Analyses of variance (ANOVA) with multiple range tests were used to further examine the effect of fruit number on frugivore visitation. .

A Chi-square test was used to test the null hypothesis of independence between frugivore visitation and bioregion (coast verses inland).

We conducted a follow-up survey of fruit production and frugivore visitation in the three *F. rubiginosa* populations in the Warrumbungles and a fourth site near Armidale in late September 2018 following a further twenty months of drought. This survey was conducted to test our predictions that fruit production by *F. rubiginosa* and frugivore visitation would both decline further if drought conditions persisted for longer periods than our three year study.

RESULTS

Hypothesis one was that *Ficus rubiginosa* provides support to populations of avian frugivores at the western, drier edge of the species' range.

Eighty-four bird species were recorded visiting *F. rubiginosa* over the three years of this study (Appendix 1). Twenty-nine of these species were frugivores, seven were both frugivore and insectivore and seven other species were neither frugivore nor insectivore, with the remainder being insectivores (Mackay et al. 2018). These trophic descriptions refer only to these birds' recorded behaviours in *F. rubiginosa* during the study. The majority of avian visitors recorded visiting *F. rubiginosa* in coastal populations were frugivores (107 frugivores from 10 species and 18 insectivores from 6 species, n = 14 twenty-minute observation periods). Fewer frugivores visited *F. rubiginosa* trees in drier, inland populations than in mesic, coastal populations ($F_{1,228}$ = 6.02, $p = 0.015$), as well as fewer frugivore species ($F_{1,228}$ = 4.03, $p = 0.046$) and less total time spent by frugivores in *F. rubiginosa* trees ($F_{1,228}$ = 8.90, $p = 0.003$; n= 562 observation periods) per twenty-minute observation period. The majority of avian visitors recorded visiting *F. rubiginosa* in the drier inland region were insectivores (1686 insectivores from 54 species and 1051 frugivores from 27 species, n = 562 observation periods). Whilst there was lower diversity and abundance of frugivores observed in inland sites, *F. rubiginosa* trees remained an important food resource for a high diversity of frugivore species with 27 of the 29 frugivore species recorded in total being recorded in inland populations (Appendix 1). No difference was found in total frugivore numbers among *Ficus* population sizes. *Ficus rubiginosa* provided large numbers of fleshy fruit from early spring through autumn, when other fruit sources were often scarce or lacking within study sites and across the wider region.

Conditional Inference Tree analyses (see plots in Appendix 3) showed (1) that the number of frugivore species recorded in a tree was affected by the number of ripe fruit in the tree, the latitude (more frugivores in the two northern populations when the number of ripe fruit ≤ 20) and, in trees with between 200 and 2,000 ripening fruit, there was a negative relationship found between the number of frugivore species in a tree and the number of insectivores in the tree; (2) that the number of frugivores in a tree was most affected by the number of ripe and ripening fruit in the tree, with a steady increase in the number of frugivores as the number of fruit increased, with latitude affecting the number of frugivores in a tree to a minor degree with more frugivores visiting trees with fewer than 20 fruit at latitudes north of 29.923°S (i.e., the two northern populations in Fig. 1); and (3) that the time spent by frugivores in trees was significantly affected by only one of the input factors, the number of ripe fruit in the tree.

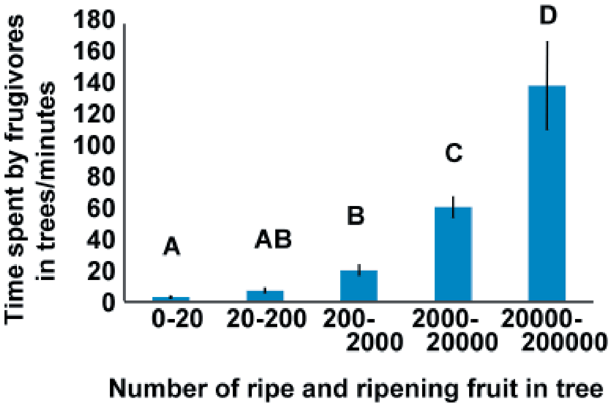


Figure 4. Mean total time (±SE) spent by frugivores in trees (minutes per twenty-minute observation period) against the number of ripe fruit in trees. Fruit numbers were categorised as shown on the x-axis. Letters (A, B, C, D) indicate significantly different means at p < 0.05 level).

Figure 5. Loss of fruit and leaves through dieback of branch tips during drought conditions. Photographed in December 2014.

Linear mixed effect (LME) analyses confirmed that the number of ripe-and-ripening fruit in a tree had a significant positive influence on the time spent by frugivores in trees ($\chi 2$ (1) = 178.79, $p < 0.0001$); see Appendix 2. Further LME analysis showed that season influenced frugivore visitation, to a lesser extent than fruit number, with a peak in summer ($\chi 2$ (1) = 9.05, $p = 0.0026$). Analysis of variance with a multiple range test further clarified the degree to which fruit number influenced the time spent by frugivores in trees (Fig. 4)

Seed germination experiment.

Each of the 40 Pied Currawong pellets collected and tested for fig-seed germination produced *Ficus rubiginosa* germinant seedlings. Between six and eighty-six *F. rubiginosa* seedlings germinated from each pellet.

Hypothesis two was that climate change is leading to declines in fruit production by *F. rubiginosa* in this region.

Initiation of A-stage syconia (buds, Fig. 2) was significantly reduced in response to lower rainfall (Mackay 2018). Pollination success, measured as percent of fruit set (i.e., as percent of A-stage syconia that developed to D stage) and as seed-to-flower ratios within fruit, declined significantly during periods of lower rainfall (by as much as 90%). Fruit production was further impacted by drought conditions which lead to partial to complete loss of crops to dieback (Fig. 5). Fire was observed to reduce fruit production in two ways: (1) by delaying fruit production in burnt trees – trees remained vegetative for a period as they recovered (resprouted) after being burnt; (2) by reducing crop sizes in recovering trees – trees recovering from fire were always smaller than they had been before being burnt, at least for some time, and produced smaller crops than before being burnt (unpublished data).

Observations of fruiting by *F. rubiginosa* and visitation by frugivores in 2018 showed on-going decline in both measures as the drought continued and intensified. Of the 79 *F. rubiginosa* trees across the four populations, 77 were vegetative. Only two trees had crops of fruit, each with fewer than 200 very small, unripe fruit. No avian frugivores were recorded in the four sites in September 2018 except one Pied Currawong, an omnivore, in one of the Warrumbungles sites.

DISCUSSION

Hypothesis three was that the mutualism between *F. rubiginosa* and avian frugivores is under threat at the species' drier range margin on the western side of the Great Dividing Range in New South Wales.

This hypothesis is supported by the observations and experimental results from this research. The threat to this mutualism that we identified was declining rainfall. We showed that fruit production and frugivore visitation were significantly lower in response to lower rainfall, to drought and to fire. Crop sizes declined to zero in many trees and across many populations in response to drought conditions. This decline in fruit production had become almost universally pervasive across all trees and populations at the three western-most sites by September 2018. Yet in the three years of this study from 2014 to 2017 September was in the middle of a peak in the production of ripe fruit from August to October, with a second, minor peak in January-February (Mackay 2018). This spring peak in fruit production and ripening coincided with the return of migratory and nomadic frugivores to the region. The observed decline is likely to continue into the future and possibly gather pace if climate-change predictions of lower rainfall, lower humidity, lower soil moisture and increased severity and frequency of droughts and fires (BOM 2018) are accurate. This would likely lead to a spiral of further decline and local extinctions in populations of *F. rubiginosa* and other, associated species including many of the frugivores we observed feeding in this tree. Consequences of such decline and local extinction would include community changes and ecosystem shifts on the western, drier side of the Great Dividing Range in NSW and Qld.

Similar patterns of decline have been predicted and reported in many woodland and forest habitats and to their avian species around the world (Brooks et al. 1999, Christiansen and Pitter,1997, Hewson et al. 2007, Robinson and Wilcove 1994) including in Australia (Ford 2011a, Woinarski and Catterall 2004). Ford (2011a) lists extinction debt, habitat degradation, nest predation and declines in keystone food resources among the ecological processes contributing to the decline of woodland birds.

Many of the frugivores recorded feeding in *F. rubiginosa* trees in this study, particularly the larger species able to move longer distances among habitat fragments, are opportunists responding to available food resources. Hence large numbers of these birds congregate at fig trees when they are in fruit. Similarly large numbers of frugivores congregate at other plant species such as Native Olives, *Notolaea microcarpa*, when they are in fruit too. One reason for the keystone status of *F. rubiginosa*, though, is the fact it produces fruit at all times of the year and thus sustains populations of frugivores when other plant species are not in fruit. Chanel-billed Cuckoos, specialist consumers of fruit and particularly figs (Moran et al. 2004, Birdlife-Australia 2017), were the second-most-frequent frugivore visitor to *Ficus rubiginosa* across the region with up to 14 of these large birds seen in fig trees at one time. Channel-billed Cuckoos (Fig. 6a) are migratory and were only recorded in the study region between September and February. Larger frugivores typically disperse seeds over longer distances than smaller birds (Ribeiro da Silva et al. 2015) and Channel-billed Cuckoos were the largest frugivore observed in this study. Owing to their parasitic nesting behaviour, Channel-billed Cuckoos are not restricted to foraging near their nests but are able to forage more widely among fig populations on a day-to-day basis, often flying between populations of fig trees at night as well as during the day. On a seasonal basis, Channel-billed Cuckoos fly several thousand kilometres over the whole north-south range of *Ficus rubiginosa* and beyond (to northern Papua New Guinea) each year (Coates 1985). Channel-billed Cuckoos are thus likely to play an important role at the metapopulation scale as ‘mobile links’ among subpopulations (Lundberg and Moberg 2003), maintaining gene flow among them (Staddon et al. 2010) and facilitating range expansion in times of changing climates and habitats. More than half of all Channel-billed Cuckoos observed were in trees carrying more than twenty thousand ripe and ripening fruit. Channel-billed Cuckoos were not seen in areas that didn’t contain fig trees with ripe fruit. Eastern Koels (Fig. 6b) are another frugivorous, parasitic-nesting cuckoo species commonly seen in *F. rubiginosa* (Appendix 1). They appeared to play a similar if lesser role in seed dispersal to Channel-billed Cuckoos. Fig Birds (Fig. 6c) are another migratory frugivore commonly seen feeding in fig trees including *F. rubiginosa.* Some species of avian frugivore recorded in this study were only recorded in coastal, mesic areas. These include the Wompoo Fruit Dove (Fig. 6d). Many pigeons, including the Wompoo Fruit Dove, are regarded as important seed dispersers (Wotton and Kelly 2012). Some other frequent visitors that consumed fruit were deemed to be potentially good seed dispersers based primarily on published literature (Birdlife Australia 2018, Higgins et al. 1990-2006), corroborated by personal observations. However, other frugivores recorded in this study were not considered good seed dispersers. These included Crimson Rosellas (Fig. 6e), which crushed the seed they consumed and usually consumed fruit when green, before seed was mature. Silvereyes (Fig. 6f) and other small frugivores were not considered good seed dispersers as they usually pecked at the fleshy walls of the fig fruit from the outside and left most seed behind.

Pied Currawongs were the most frequent frugivore species observed in this study (Appendix 1; up to 21 individual Pied Currawongs were observed in a tree at a time). Currawongs are large birds (44-51 cm, 285 g (oiseaux-birds.com)) and thus potentially efficient dispersers of *F. rubiginosa* seed (Ribeiro da Silva et al. 2015). Results from the germination trials and observations of currawong feeding behaviour reinforce this likelihood: feeding in fruiting *F. rubiginosa* trees often entailed filling their crops with fruit and then sitting quietly in a nearby tree

Figure 6. Some of the avian frugivores recorded in Ficus rubiginosa during this study and referred to in the text: (a) Channel-billed Cuckoo (photo by KDM); (b) Eastern Koel (photo by KDM); (c) Wompoo Fruit Dove (photo by CLG); (d) Australian Figbird (photo by Camila Silveira de Souza); (e) Crimson Rosella (photo by KDM); (f) Silvereye (photo by CLG).

whilst digesting the figs they had eaten, followed by regurgitation of indigestible plant material including fig seeds before returning to the feeding tree (personal observation). Pied Currawongs are also nest-predators known to prey on smaller woodland birds (Higgins et al. 1990-2006). This may counter their seed-dispersal service to *F. rubiginosa* if the birds they prey on are also seed dispersers. However, as mentioned above, larger birds such as Pied Currawongs are likely to be better seed dispersers than smaller species and the smaller bird species recorded in *F. rubiginosa* were mainly insectivores rather than frugivores (Mackay et al. 2018).

This study shows that *F. rubiginosa* provides a keystone (Paine 1969, Terborgh 1986, Davic 2003) food resource for a large and diverse array of avian-frugivore species. Total numbers of frugivores did not vary among *F. rubiginosa* population sizes. The species diversity observed in fig trees in the three different population-size categories (single trees, small and large populations) is likely a result of complex interactions between community composition, food resources, edge effects and distances to larger habitat patches (Laurance 2008a, Banks-Leite et al. 2011, Doerr et al. 2011). Such conjectures would need more work to elucidate precise links and causes between environmental factors and frugivore diversity but what this work shows conclusively is that fig trees in the Warrumbungles to Mt Kaputar region are providing an important food resource for avian frugivores and do so throughout the year, when other sources of fruit may be scarce.

Ecologists face enormous challenges in predicting the impacts of climate change on natural systems. However, this study shows that *F. rubiginosa* is a key component of remnant patches of dry rainforest that are scattered across our study area (Atlas 2017, Benson et al. 2010). The support provided by *F. rubiginosa* for frugivores in these habitats is likely to contribute to supporting and conserving entire natural communities in this region and beyond, including endangered semi-evergreen vine thickets, a class of dry rainforest. We conclude that the observed decline in fruit production and concomitant decline in frugivore populations are likely to lead to a compounding spiral of decline in other fleshy-fruited plant species in these dry rainforests. Furthermore, we are likely to see contractions and losses of dry-rainforest patches throughout the range of *F. rubiginosa* on the western side of the Great Dividing Range in NSW and Queensland if predictions of declining rainfall prove correct. This work highlights the need to study indirect impacts of climate change on species – via process such as frugivory and seed dispersal for example. It also highlights the potential for different consequences of climate change such as longitudinal range shifts in response to rainfall changes as well as latitudinal shifts in response to temperature change.

ACKNOWLEDGEMENTS

This project was supported by generous funding provided by the Linnean Society of New South Wales (Macleay Fellowship 2014-2017), The University of New England (Internal Research Grant), a Holsworth Wildlife Research Endowment grant, an Australian Flora Foundation grant, and a Local Land Services NSW Northwest Small Community Grant. Access to land was provided by NSW National Parks, and private landholders: J. and B. Beynon, S. and E. Adams, G. and P. Doak, D. Mitchell, P. Morrissey, D. Baker, N. and L. Phillips, V. Mulley, M. Tosh, J. and F. McGowan, and B. Swain. Fieldwork assistance was provided by E. Adams, T. Choi, K. Heaney, E. Mackay, L. Murray, P. Richards, I. Simpson, C. Silveira de Souza and B. Swain.

REFERENCES

Atlas (2017) Atlas of Living Australia. CSIRO. https://spatial.ala.org.au/?q=lsid:http://id.biodiversity.org.au/node/apni/2894530. Accessed September-October 2017.

Benson JS, Richards P, Waller S, Allen CB (2010) New South Wales vegetation classification and assessment: part 3 plant communities of the NSW Brigalow Belt South, Nandewar and west New England Bioregions and update of NSW Western Plains and South-western Slopes plant communities, Version 3 of the NSWVCA database. *Cunninghamia,* **11**, 457-579.

Bergamini A, Ungricht S, Hofmann H (2009) An elevational shift of cryophilous bryophytes in the last century–an effect of climate warming? *Diversity and Distributions,* **15**, 871-879.

Birdlife_Australia (2018) http://birdlife.org.au/all-about-birds/australias-birds/. Accessed 2 October 2018..

Bom (2018) https://www.climatechangeinaustralia.gov.au/en/climate-projections/future-climate/regional-climate-change-explorer/super-clusters/?current=ESCandtooltip=trueandpopup=true. Accessed 2 October 2018.

Brooks TM, Pimm SL, Oyugi JO (1999) Time lag between deforestation and bird extinction in tropical forest fragments. *Conservation Biology,* **13**, 1140-1150.

Chen I-C, Shiu H-J, Benedick S et al. (2009) Elevation increases in moth assemblages over 42 years on a tropical mountain. *Proceedings of the National Academy of Science*s, **106**, 1479-1483.

Christiansen MB, Pitter E (1997) Species loss in a forest bird community near Lagoa Santa in southeastern Brazil. *Biological Conservation,* **80**, 23-32.

Cordeiro NJ, Howe HF (2001) Low recruitment of trees dispersed by animals in African forest fragments. *Conservation Biology,* **15**, 1733-1741.

Cordeiro NJ, Howe HF (2003) Forest fragmentation severs mutualism between seed dispersers and an endemic African tree. *Proceedings of the National Academy of Sciences of the United States of America,* **100**, 14052-14056.

Cosson JF, Pons JM, Masson D (1999) Effects of forest fragmentation on frugivorous and nectarivorous bats in French Guiana. *Journal of Tropical Ecology,* **15**, 515-534.

Davic R (2003) Linking keystone species and functional groups: a new operational definition of the keystone species concept. *Conservation Ecology,* **7**.

Dixon DJ, Jackes BR, Bielig LM (2001) Figuring out the figs: The *Ficus obliqua-Ficus rubiginosa* complex (Moraceae : Urostigma sect. Malvanthera). *Australian Systematic Botany,* **14**, 133-154.

Ford HA (2011a) The causes of decline of birds of eucalypt woodlands: advances in our knowledge over the last 10 years. *Emu,* **111**, 1-9.

Ford HA (2011b) Twinkling lights or turning down the dimmer switch? Are there two patterns of extinction debt in fragmented landscapes? *Pacific Conservation Biology,* **17**, 303-309.

Galil J, Eisikowitch D (1968) Flowering cycles and fruit types of *Ficus sycomorus* in Israel. *New Phytologist,* **67**, 745-758.

Gottfried M, Pauli H, Futschik A et al. (2012) Continent-wide response of mountain vegetation to climate change. *Nature Climate Change,* **2**, 111.

Herrera CM (1984) A study of avian frugivores, bird dispersed plants, and their interaction in Mediterranean scrublands. *Ecological Monographs,* **54**, 1-23.

Hewson CM, Amar A, Lindsell JA, Thewlis RM, Butler S, Smith K, Fuller RJ (2007) Recent changes in bird populations in British broadleaved woodland. *Ibis,* **149**, 14-28.

Higgins PJ et al. (1990-2006) 'Handbook of Australian, New Zealand and Antarctic Birds'*, (*Melbourne, Oxford University Press).

Jordano P (1987) Patterns of mutualistic interactions in pollination and seed dispersal: connectance, dependence asymmetries, and coevolution. *The American Naturalist,* **129**, 657-677.

Lenoir J, Svenning J-C (2013) Latitudinal and elevational range shifts under contemporary climate change. In: *Encyclopedia of biodiversity.* Academic Press.

Mackay K, Gross C, Rossetto M (2018) Small populations of fig trees offer a keystone food resource and conservation benefits for declining insectivorous birds. *Global Ecology and Conservation*, **14**: e00403.

Mckechnie AE, Wolf BO (2010) Climate change increases the likelihood of catastrophic avian mortality events during extreme heat waves. *Biology Letters,* **6**, 253-256.

Mcmenamin SK, Hadly EA, Wright CK (2008) Climatic change and wetland desiccation cause amphibian decline in Yellowstone National Park. *Proceedings of the National Academy of Sciences,* **105**, 16988-16993.

Moran C, Catterall CP, Kanowski J (2009) Reduced dispersal of native plant species as a consequence of the reduced abundance of frugivore species in fragmented rainforest. *Biological Conservation,* **142**, 541-552.

Oiseaux-Birds.Com http://www.oiseaux-birds.com/card-pied-currawong.html Accessed 21 October 2018.

Paine RT (1969) A note on trophic complexity and community stability. *The American Naturalist,* **103**, 91-93.

Parmesan C, Hanley ME (2015) Plants and climate change: Complexities and surprises. *Annals of Botany,* **116**, 849-864.

Perry AL, Low PJ, Ellis JR, Reynolds JD (2005) Climate change and distribution shifts in marine fishes. *Science,* **308**, 1912-1915.

Poloczanska ES, Brown CJ, Sydeman WJ et al. (2013) Global imprint of climate change on marine life. *Nature Climate Change,* **3**, 919.

Przeslawski R, Falkner I, Ashcroft MB, Hutchings P (2012) Using rigorous selection criteria to investigate marine range shifts. *Estuarine, Coastal and Shelf Science,* **113**, 205-212.

Ribeiro Da Silva F, Montoya D, Furtado R, Memmott J, Pizo MA, Rodrigues RR (2015) The restoration of tropical seed dispersal networks. *Restoration Ecology,* **23**, 852-860.

Robinson SK, Wilcove DS (1994) Forest fragmentation in the temperate zone and its effects on migratory songbirds. *Bird Conservation International,* **4**, 233-249.

Shanahan M, So S, Compton SG, Corlett R (2001) Fig-eating by vertebrate frugivores: a global review. *Biological Reviews,* **76**, 529-572.

Terborgh J (1986) Community aspects of frugivory in tropical forests. In: 'Frugivores and seed dispersal'. (eds Estrada A, Fleming TH) (Dordrecht, Dr W. Junk Publishers).

Tewksbury JJ, Levey DJ, Haddad NM et al. (2002) Corridors affect plants, animals, and their interactions in fragmented landscapes. *Proceedings of the National Academy of Sciences of the United States of America,* **99**, 12923-12926.

Thomas CD, Lennon JJ (1999) Birds extend their ranges northwards. *Nature,* **399**, 213.

Wheelwright NT, Orians GH (1982) Seed dispersal by animals: contrasts with pollen dispersal, problems of terminology, and constraints on coevolution. *The American Naturalist,* **119**, 402-413.

Whitfield SM, Bell KE, Philippi T et al. (2007) Amphibian and reptile declines over 35 years at La Selva, Costa Rica. *Proceedings of the National Academy of Sciences,* **104**, 8352-8356.

Woinarski J, Catterall C (2004) Historical changes in the bird fauna at Coomooboolaroo, northeastern Australia, from the early years of pastoral settlement (1873) to 1999. *Biological Conservation,* **116**, 379-401.

Wotton DM, Kelly D (2012) Do larger frugivores move seeds further? Body size, seed dispersal distance, and a case study of a large, sedentary pigeon. *Journal of Biogeography,* **39**, 1973-1983.

APPENDIX 1

Bird species	Family	Observed bird activity			Bird observations within fig population category:			Number observed in study sites
		eating fruit	eating insects	other	Single trees	5-15 trees	>50 trees	
Emu *Dromaius novaehollandiae*	Casuariidae	X				X		1
Common Bronzewing *Phaps chalcoptera*	Columbidae	X				X		5
Crested Pigeon *Ocyphaps lophotes*	Columbidae	X			X			4
Bar-shouldered Dove *Geopelia humeralis*	Columbidae	X				X		2
Wompoo Fruit Dove (coast only) *Ptilinopus magnificus*	Columbidae	X						0
Topknot Pigeon (coast only) *Lopholaimus antarcticus*	Columbidae	X						0
Eastern Koel *Eudynamys orientalis*	Cuculidae	X			X	X	X	25
Channel-billed Cuckoo *Scythrops novaehollandiae*	Cuculidae	X			X	X	X	106
Galah *Eolophus roseicapilla*	Cacatuidae	X			X			2
Crimson Rosella *Platycercus elegans*	Psittaculidae	X			X	X	X	91
Eastern Rosella *Platycercus eximius*	Psittaculidae	X			X	X	X	41
Rainbow Lorikeet *Trichoglossus moluccanus*	Psittaculidae	X			X	X	X	29
Satin Bowerbird *Ptilonorhynchus violaceus*	Ptilonorhynchidae	X				X		1
Spotted Bowerbird *Ptilonorhynchus maculatus*	Ptilonorhynchidae	X			X	X		12
Black-faced Cuckoo-shrike *Coracina novaehollandiae*	Campephagidae	X			X	X	X	47
Australasian Figbird *Sphecotheres vieilloti*	Oriolidae	X			X	X	X	60
Pied Currawong *Strepera graculina*	Artamidae	X			X	X	X	265
Australian Magpie *Gymnorhina tibicen*	Artamidae	X			X	X		12
Little Raven *Corvus mellori*	Corvidae	X			X	X	X	26
Mistletoebird *Dicaeum hirundinaceum*	Dicaeidae	X				X	X	13
Common Starling *Sturnus vulgaris*	Sturnidae	X			X			15
Common Myna *Acridotheres tristis*	Sturnidae	X			X			4
Australian King-Parrot *Alisterus scapularis*	Psittaculidae	X	X			X		2

Noisy Friarbird *Philemon corniculatus*	Meliphagidae	X	X		X	X	X	84
Spiny-cheeked Honeyeater *Acanthagenys rufogularis*	Meliphagidae	X	X		X	X	X	24
Red Wattlebird *Anthochaera carunculata*	Meliphagidae	X	X		X	X	X	93
Olive-backed Oriole *Oriolus sagittatus*	Oriolidae	X	X		X	X	X	33
Spangled Drongo *Dicrurus bracteatus*	Dicruridae	X	X			X		1
Silvereye *Zosterops lateralis*	Zosteropidae	X	X		X	X	X	183
Horsfield's Bronze-Cuckoo *Chalcites basalis*	Cuculidae		X		X			1
Shining Bronze-Cuckoo *Chalcites lucidus*	Cuculidae		X				X	2
Rainbow Bee-eater *Merops ornatus*	Meropidae		X		X			16
Red-winged Parrot *Aprosmictus erythropterus*	Psittaculidae		X			X		12
White-throated Treecreeper *Cormobates leucophaea*	Climacteridae		X		X	X	X	7
Red-browed Treecreeper Cli*macteris erythrops*	Climacteridae		X			X		4
Brown Treecreeper *Climacteris picumnus*	Climacteridae		X			X	X	6
Variegated Fairy-wren *Malurus lamberti*	Maluridae		X			X		1
Superb Fairy-wren *Malurus cyaneus*	Maluridae		X		X	X	X	333
Striped Honeyeater Plec*torhyncha lanceolata*	Meliphagidae		X			X		4
Little Friarbird *Philemon citreogularis*	Meliphagidae		X			X		2
Brown Honeyeater L*ichmera indistincta*	Meliphagidae		X			X		2
White-eared Honeyeater *Nesoptilotis leucotis*	Meliphagidae		X			X	X	17
Blue-faced Honeyeater *EnTomyzon cyanotis*	Meliphagidae		X		X	X		14
Brown-headed Honeyeater *Melithreptus brevirostris*	Meliphagidae		X			X	X	16
White-naped Honeyeater *Melithreptus lunatus*	Meliphagidae		X				X	3
Eastern Spinebill *Acanthorhynchus tenuirostris*	Meliphagidae		X				X	2
Lewin's Honeyeater (coast only) *Meliphaga lewinii*	Meliphagidae		X				X	0
Singing Honeyeater *Gavicalis virescens*	Meliphagidae		X		X	X		68

White-plumed Honeyeater *Ptilotula penicillata*	Meliphagidae		X		X	X	X	142
Yellow-faced Honeyeater *Caligavis chrysops*	Meliphagidae		X		X	X	X	69
Yellow-tufted Honeyeater *Lichenostomus melanops*	Meliphagidae		X			X		1
Noisy Miner *Manorina melanocephala*	Meliphagidae		X		X	X		125
Spotted Pardalote *Pardalotus punctatus*	Pardalotidae		X				X	6
Brown Gerygone *Gerygone mouki*	Acanthizidae		X			X	X	2
White-throated Gerygone *Gerygone olivacea*	Acanthizidae		X		X	X	X	9
Weebill *Smicrornis brevirostris*	Acanthizidae		X			X	X	23
White-browed Scrubwren *Sericornis frontalis*	Acanthizidae		X		X	X	X	67
Yellow-rumped Thornbill *Acanthiza chrysorrhoa*	Acanthizidae		X		X	X	X	108
Yellow Thornbill *Acanthiza nana*	Acanthizidae		X			X		3
Striated Thornbill *Acanthiza lineata*	Acanthizidae		X		X	X	X	183
Buff-rumped Thornbill *Acanthiza reguloides*	Acanthizidae		X		X	X	X	45
Brown Thornbill *Acanthiza pusilla*	Acanthizidae		X			X	X	88
Rufous Whistler *Pachycephala rufiventris*	Pachycephalidae		X		X	X	X	5
Golden Whistler *Pachycephala pectoralis*	Pachycephalidae		X				X	1
Grey Shrike-thrush *Colluricincla harmonica*	Pachycephalidae		X		X	X	X	12
Dusky Woodswallow *Artamus cyanopterus*	Artamidae		X			X		2
Willie Wagtail *Rhipidura leucophrys*	Rhipiduridae		X		X	X	X	71
Grey Fantail *Rhipidura fuliginosa*	Rhipiduridae		X			X	X	36
Satin Flycatcher *Myiagra cyanoleuca*	Monarchidae		X			X		5
Restless Flycatcher *Myiagra inquieta*	Monarchidae		X		X		X	4
Apostlebird *Struthidea cinerea*	Corcoracidae		X		X			14
Rose Robin *Petroica rosea*	Petroicidae		X		X		X	4
Scarlet Robin *Petroica multicolor*	Petroicidae		X		X			6

Jacky Winter *Microeca fascinans*	Petroicidae		X			X	X	3
Eastern Yellow Robin *Eopsaltria australis*	Petroicidae		X			X		12
Fairy Martin *Petrochelidon ariel*	Hirundinidae		X			X		2
Welcome Swallow *Hirundo neoxena*	Hirundinidae		X		X	X		13
Laughing Kookaburra *Dacelo novaeguineae*	Alcedinidae			X		X		2
Yellow-tailed Black-Cockatoo *Zanda funereus*	Cacatuidae			X			X	1
Magpie-lark *Grallina cyanoleuca*	Monarchidae			X	X			14
Grey-crowned Babbler *Pomatostomus temporalis*	Pomatostomidae			X	X	X		24
Pied Butcherbird *Cracticus nigrogularis*	Artamidae			X	X	X	X	13
Red-browed Finch *Neochmia temporalis*	Estrildidae			X			X	4
Double-barred Finch *Taeniopygia bichenovii*	Estrildidae			X		X		15
TOTAL SPECIES		29	55	7	45	65	46	2821
Frugivore species					20	23	15	
Insectivore species					27	43	33	
Other species					4	6	3	

APPENDIX 2

Number of frugivore species in trees ('Numfrugspp'):

A linear model of the number of frugivore species in a tree was fitted with the number of ripe fruit in a tree and the season as variables. This model was significant ($F_{2,559} = 203.5$, $p < 0.0001$). For each change of season from spring to summer there was, on average, a decline in the number of frugivore species of 0.12 ± 0.04 (SE) species. For each increase in the number of ripe fruits (categorized) there was an increase, on average, of 0.56 ±0.03 (SE) frugivore species. The model fitted was: Number of frugivore species = 0.58*number of ripe fruit – 0.12*season; the predicted number of frugivore species at the average number of ripe fruit = 0.75 ± 0.04 (estimated value ± SE).

Number of frugivores in trees ('Numfrugs'):

As the random effects in the LMER analysis were not significant, the analysis was run again as a simple linear model with fixed effects only using the fixed effects that were significant in the LMER analysis. I constructed a linear model of the number of frugivores in a tree (numfrugs) as a function of the number of ripe fruit in the tree (numripefruit) plus the season (season) plus the number of insectivores in the tree (numinsecs) plus the number of insectivore species in the tree (numinsecspp). Thus, the null model was: numfrugs~ numripefruit + season + numinsecs + numinsecspp. This model was significant ($F_{4,557} = 87.39$, $p <$ 0.0001). However, colinearity problems required the removal of one or other of numinsecs and numinsecspp. Indeed, both variables had to be removed because of the non-linear relationship evident between insectivores and frugivores as fruit numbers increased above 20,000. Therefore the final linear model accepted was numfrugs is a function of the number of ripe fruit in a tree plus the season. This model was significant ($F_{2,559} = 167.1$, $p < 0.0001$). For each change of season from spring (1) to winter (4) there was a decrease, on average, of 0.31 ± 0.12 (estimated value ± SE) frugivores. For each increase in the number of ripe fruit in a tree (categorized) there was an increase, on average, of 1.71 ±0.10 (estimated value ± SE) frugivores. The model fitted was: numfrugs = 1.71*numripefruit - 0.31*season; predicted numfrugs at average numripefruit = 1.91 ± 0.13 (estimated value ± SE).

Time spent by frugivores in trees ('Frugmins'):

Linear mixed effects model: Factors that impacted on time spent by frugivores in a tree (frugmins) were the number of ripe fruit (numripefruit) in the tree plus the season (season) plus the random factor 'site'. The number of ripe fruit affected the time spent by frugivores in a tree ($\chi2$ (1) = 369.89, $p < 0.0001$), increasing frugmins by 2.65minutes ± 1.04 (SE) for each increase in numripefruit. Season affected the time spent by frugivores in a tree ($\chi2$ (1) = 7.28, $p = 0.007$), decreasing frugmins by 0.87minutes ± 1.05 (SE) for each change in season from spring to winter.

Beginning with the best model from the LMER analysis I ran the following glm: glm(formula = frugmins ~ numripefruit + season + Site, family = quasipoisson().

Numripefruit had the largest and most significant impact (estimate = 0.94689, $p < 0.0001$). Season was found to be **not** significant in this GLM. Site is still significant but has only a slight impact (estimate= 0.008964, $p = 0.0221$).

A one-way ANOVA conducted on ln(1+x)-transformed data produced a highly significant result: $F_{4,557} = 131.13$, $p < 0.0001$ (Kruskall-Wallis test statistic = 264.45, $p < 0.0001$) (Fig. 4.12). The impact on the time spent by frugivores in trees from an increase in the number of ripe fruit in the tree was approximately 1.7 minutes per fruit category (95% CI = 1.4 to 2.0 minutes, averaged over the 5 categories).

A GLM fitted to time spent by frugivores in a tree with season as the only variable was highly significant ($p < 0.001$). The impact of season on in a tree is approximately 0.3 minutes reduction each season from spring to winter.

APPENDIX 3

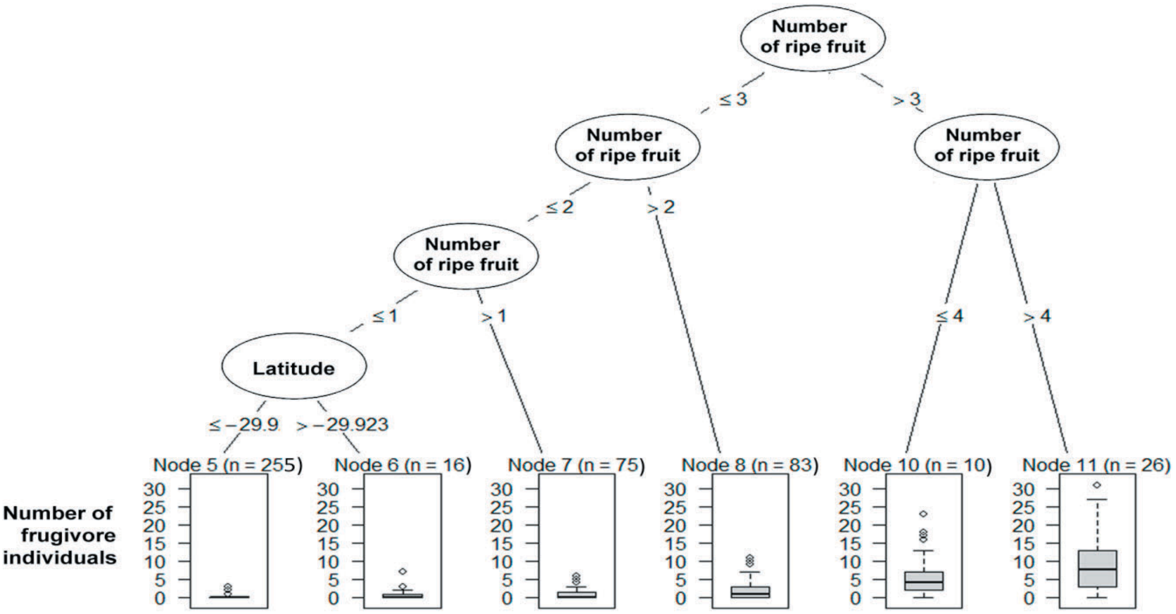


Figure A3.1. Results of Conditional Inference Tree analysis of number of frugivores per 20-minute observation period. The only significant factors were the number of ripe fruit in the tree (with splits at 20 fruit, 200 fruit, 2,000 fruit and 20,000 fruit) and, when there was zero to 20 fruit in a tree, latitude (with a split at 29.9°S i.e., more frugivores in the two northern populations

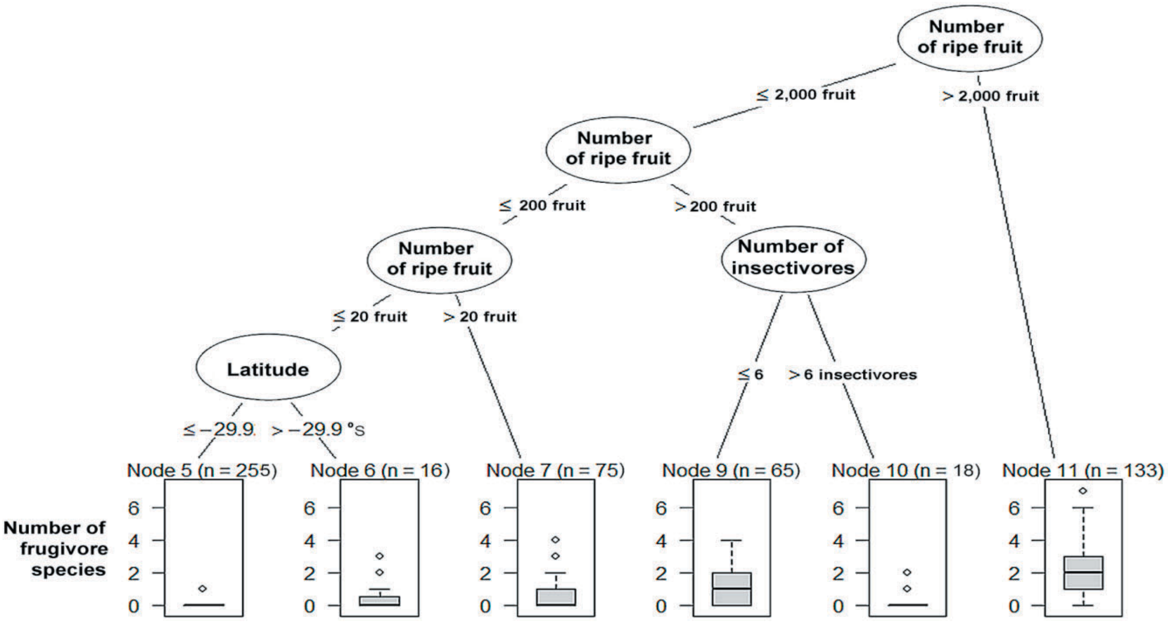


Figure A3.2. Results of Conditional Inference Tree analysis of mean number of frugivore species /minutes per 20-minute observation period. Significant factors were the number of ripe fruit in the tree (with splits at 20 fruit, 200 fruit, and 2,000 fruit) and, when there was zero to 20 fruit in a tree, latitude (with a split at 29.9°S, i.e., below the two northern populations; see map Fig. 4.1) and, when there were 200 to 2,000 fruit in a tree (category 3), the number of insectivores in the tree (fewer frugivores when there were more than 6 insectivores).

The Middle Miocene Flora of the Chalk Mountain Formation, Warrumbungle Volcano Complex, NSW, Australia

HOLMES, W.B.K.[1] AND ANDERSON, H.M.[2]

[1] [wbkholmes@hotmail.com] 46 Kurrajong Street, Dorrigo, NSW 2453, Australia, University of New England, Armidale, NSW 2351

[2] [hmsholmes@googlemail.com], Evolutionary Studies Institute, University of the Witwatersrand, Johannesburg 20150, South Africa

Holmes, W.B.K. and Anderson, H.M. (2019). The Middle Miocene flora of the Chalk Mountain Formation, Warrumbungle Volcano Complex, NSW, Australia. *Proceedings of the Linnean Society of New South Wales* **141**, S19-S32.

A Miocene flora from the Chalk Mountain Formation occurring on a spur of the Warrumbungle Volcano Complex to the north-west of Coonabarabran, near Bugaldie is described. The flora consists of representatives in the families Equisetaceae (*Equisetum* sp. indet.), Isoetaceae and Araucariaceae (*Agathis* sp.). Among the angiosperm families are Cunoniaceae (*Ceratopetalum priscum*), Moraceae, Myrtaceae (*Eucalyptus bugaldiensis*), Urticaceae (*Dendrocnide* sp. A aff. *D. excelsa*). This paper describes the first fossil record of *Dendrocnide* (Urticaceae) leaves from Australia and the second post-Cretaceous record of the genus *Equisetum,* the first from the Miocene. The flora includes rainforest, swamp and sclerophyll plant forms and indicates a warming and drying climate as the Australian plate moved northwards during the Middle Miocene.

Manuscript received 18 February 2019, accepted for publication 22 July 2019.

Key Words: Chalk Mountain, *Equisetum*, *Eucalyptus*, fossil plants, Miocene, Warrumbungle volcano.

INTRODUCTION

The Chalk Mountain Formation occurs on a spur of the Warrumbungle Volcano Complex to the north-west of Coonabarabran, near Bugaldie. It is a caldera deposit of diatomite, tuffs and a band of lignite underlain by basalt dated at 17.2 million years and overlain by basalt dated at 13.7 million years, confirming the Miocene age. The Formation was well-known for the numerous fossils of small Macquarie codfish (Hills 1946) and a fossil owlet-nightjar (Rich and McEvey 1977). The senior author and his family visited Chalk Mountain in the 1970's to collect plant fossils. Papers describing the eucalypt and *Ceratopetalum* collected material were published by Holmes et al. (1983), Holmes and Holmes (1992). The eucalypt paper (Holmes et al. 1983) included a comprehensive palynological study by Dr Helene Martin of the spores and pollen from the Chalk Mountain diatomite and lignite beds that revealed the presence of ferns, gymnosperms and angiosperms and evidence of still extant Australian genera. This paper describes additional rainforest and sclerophyll macrofossil plant material and the second post-Cretaceous record of the genus *Equisetum,* the first record of *Dendrocnide* (Urticaceae) leaves from Australia. The diatomite and lignite beds of the Chalk Mountain Formation are now weathered, overgrown with weeds and natural regrowth. The location is closed to the public and further collecting is unlikely to eventuate.

CHALK MOUNTAIN GEOLOGY

The Chalk Mountain Formation (Grid reference 199148 Gilgandra 1:250 000 Geological Series Sheet SH 55–16) comprises 15–18 metres of lacustrine sediments of siltstone, mudstone, clay, tuff, lignite and mostly of pure diatomite underlain and overlain by volcanic flows (Griffin 1961, Herbert 1968).

The unit is exposed in the now abandoned quarry on Chalk Mountain (Fig. 1) situated on private property approximately 6 kilometres south of the

Figure 1. Chalk Mountain Formation exposure in the abandoned quarry ca 1980.

village of Bugaldie and at the northern margin of the Warrumbungle Volcano complex (White 1994, Kenny 1924). The Formation covers an area of approximately 38 hectares. The rich deposit of pure diatomite was worked from 1919 to 1968 by the Davis Gelatine Co. and produced over 85,000 tonnes to be transported by rail to Sydney for use as an abrasive, filter, insulation material and many other purposes. The Formation is underlain by a thick bed of volcanic basalt, andesite and trachyte and overlain by a basalt flow. K/Ar dating was carried out by Dr A. Ewart of the University of Queensland (Holmes and Holmes, 1992). The underlying basalt was dated at 17.2 mya and the overlying basalt at 13.7 mya, both results at ± 2%, thus confirming the Middle Miocene age.

MATERIAL

The fossil flora is based on collections of past published material housed in the Australian Museum (AMF) and the Geological and Mining Museum (MMF) and from private collections now also registered with the Australian Museum. The fossils are preserved as impressions and no cuticles are available for study. If carbonaceous material is present then it is very friable and breaks into tiny, granular fragments.

SYSTEMATIC PALAEOBOTANY

Order Equisetales
Family Equisetaceae
Genus *Equisetum*
Equisetum sp. indet.
Figs. 2A–E

Material.

AMF 145067.

Description

This taxon is based on an impression of an equisetalean stem fragment. Length preserved 120 mm, base and apex missing; margins almost parallel; average width 6 mm with ca 15 longitudinal striations; impressions of four nodes located from the stem base at 25 mm, 55 mm, 85 mm and 104 mm (Fig. 2A). Branch scars are not well preserved (Figs 2D, C). One node shows five scars each ca 1mm roundish-square (Fig. 2E). No leaf whorls or nodal diaphragms are evident.

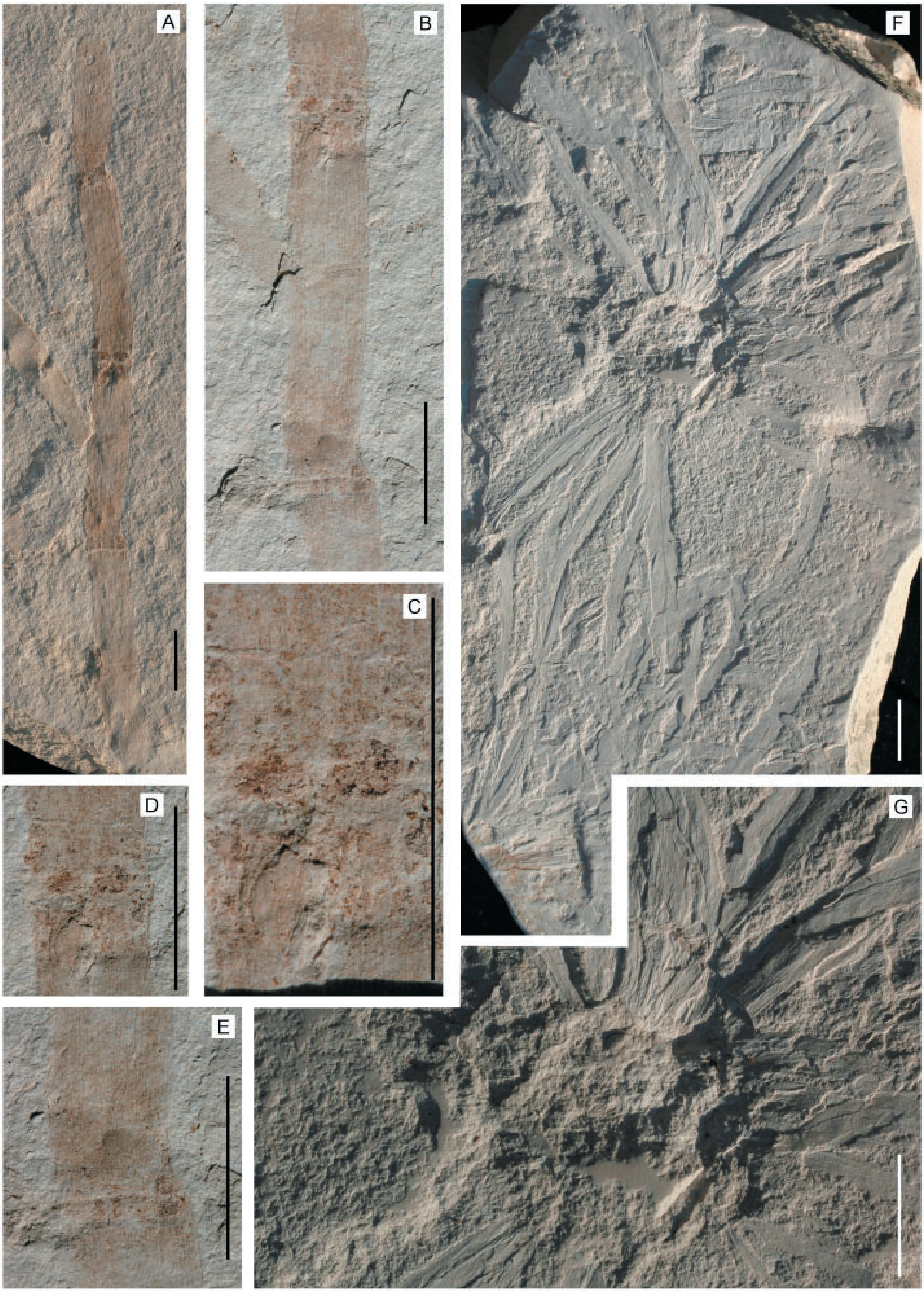


Figure 2. [A–E] *Equisetum* sp. indet. AMF 145067, [F, G] Leaf whorl Isoetaceae, AMF 145068, (scale bar = 10 mm).

Discussion.

Based on the gross form of AMF 145067 (Fig. 2A) this stem with nodal scars (Figs 2B–E) closely resembles the New Zealand Miocene *Equisetum* sp. described by Pole and McLoughlin (2017) but differs by the generally narrower stem with less branch scars at the node. The characters preserved are considered insufficient to warrant the erection of a new specific name. The only other Australian Cenozoic *Equisetum* was described recently by Rozefelds et al. (2019) from Makowata, Queensland. This consists of a short stem (ca 9 x 2.5 mm) with a slightly detached node, to which are attached, in a whorl, numerous leaves (24–30), joined at the base into a sheath and distally free. No nodes are evident on this stem but the large number of leaves clearly sets it apart from the low number of about five leaf or branch scars in the Chalk Mountain fossil. The Makowata fossil is rather unique in showing a whorl of leaves conjoined in a sheath with distal free leaves (not short teeth) similar to some genera occurring in the Triassic of Gondwana such as *Townroviamites* (Holmes 2001, Anderson and Anderson 2018) which have more numerous and much longer leaves.

The sphenophyte family Equisetaceae (which includes the genus *Equisetum* with about 15 extant species commonly known as horsetails) is an ancient group of plants first appearing in the Devonian Period *ca* 300 million years ago (Taylor et al. 2009). By the Carboniferous Period they had evolved into many diverse forms including tree-sized plants. In Gondwana during the Permian Period, sphenophytes formed an understory association with glossopterids that produced some of the World's greatest coal beds (Beeston 1991, McLoughlin 1993). Following the End-Permian extinction event many sphenophyte forms recovered and regained a cosmopolitan distribution (Taylor et al. 2009) and a great diversity in the Triassic of Gondwana (Anderson and Anderson 2018). They are well documented from the Australian and New Zealand Gondwana fossil plant collections (Rigby 1966, Gould 1968, Retallack 1980, Holmes 1982, 2000, 2001). However during Cretaceous time the sphenophytes declined in frequency and diversity throughout the World. *Equisetum,* the only surviving sphenophyte genus has an almost world-wide, natural distribution except for Australia and New Zealand where it was previously considered extinct by the Cenomanian (Cretaceous) with the last records being from the Winton Flora as reported by McLoughlin et al. (2010). However this view has been changed by Pole and McLoughlin (2017) who reported a Miocene (Cenozoic) *Equisetum* from two localities in central Otago, New Zealand and by Rozefelds et al. (2019) who described the first *Equisetum* from the late Eocene or early Oligocene, Makowata, Queensland, Australia. The fossil here described from the Chalk Mountain is significant in that it now extends the range for Australia into the Miocene. The cause of extinction of *Equisetum* from Australia and New Zealand remains obscure but Pole and McLoughlin (2017) suggest it may have been related to substantial environmental changes.

Given the age of the flora it could be argued that this fossil may be more closely compared to some angiosperm genus. However, it is most unlikely that this fossil belongs to *Casuarina* or *Allocasuarina* even though such plants have branchlets with whorls of leaves (tiny teeth) with regular articles (internodes) and bear a superficial resemblance to *Equisetum*. Their branchlets (stems) in all species are about 1 mm in diameter or less, (this fossil stem is 6 mm in diameter) the articles are very short about 10 mm (this fossil internode is from 25 mm up to 104 mm in length). Vegetative Casuarinaceae fossils are well known from the Paleocene of Australia (Scriven & Hill 1995) and the Miocene of New Zealand (Campbell & Holden 1984) and these show the typical tiny stems occurring in branchlets.

Order Lycopodiales
Family Isoetaceae
Leaf whorl, genus and species uncertain

Fig. 2F, G

Material.

AMF. 145068.

Description.

A diatomite block shows three whorls of linear leaves on one surface and on the reverse side a poorly preserved whorl surrounding a stem, possibly a continuation of the stem on the other surface bearing the large leaf whorl. The main leaf whorl shows about 16 linear leaves with parallel margins and faint parallel striations, to >40 mm in length and 4 mm in width surrounding a circular depression of a stem ca 12 mm in circumference. Point of attachment of leaves to the stem is not clearly preserved. The second whorl (lower left of main whorl) is smaller with narrower leaves and the third whorl (close to lower right of main whorl) is partially obscured.

Discussion.

The Chalk Mountain whorl of linear leaves resembles that of *Isoetes beestonii* (Retallack 1997

Fig. 6.3) a lycopod from the earliest Gondwana Triassic of Australia, previously known as *Cylomeia undulata* (White 1981c, 1986 figs 193, 201)

These differ from the Chalk Mountain whorls by the leaves emerging from a common area and the base of the leaves being flared to cordate (Retallack 1997, p. 502, fig. 7A). In the Chalk Mountain specimen the leaves appear to arise from different levels of the stem and in this aspect are more like the Triassic lycopod *Pleuromeia* or *Cyclostrobus* as described by Retallack (1997). Other records of *Isoetes* in Australia are from the Tertiary of Tasmania based on megaspores and leaves described as *I. reticulata* (Hill 1988) and from the Cretaceous of Victoria *I. bulbiformis* (Drinnan and Chambers 1986) is a corm with leaves.

The Chalk Mountain whorl of linear leaves also superficially resemble that of some equisetaleans from the Permian attributed by White (1986, fig. 181) to *Phyllotheca australis*. Similar whorls of linear leaves (*Zonulamites nymboidensis)* were described from the Australian Triassic by Holmes (2000). But the Chalk Mountain whorls of leaves show no evidence of being attached to the stem in a clear whorl or of conjoining at their base to form an encircling sheath around the stem as occurs in *Equisetum*.

Given the age of the flora it could be argued that this fossil may be more closely compared to some angiosperm genus. However, it is most unlikely that this fossil belongs to a plant with a superficial resemblance like *Galium aparine* (Rubiaceae). This has leaves in whorls that at first glance look similar to this Chalk Mountain fossil or like a Permian *Sphenophyllum* (Equisetaceae) but a prominent midrib and reticulate venation clearly set it apart.

The identity of these whorls remains uncertain but appear to be best placed in the Family Isoetaceae and possibly belong in a new genus. These leaf whorls are probably preserved *in situ* due to the stem continuing in 3D through the sediment and the presence of further whorls on the same slab. The extant genus of *Isoetes* (known as Quillworts) with some 192 species in the world (8 species in Australia) grow in or close to water and the leaves arise closely packed together from a central corm.

Order Pinales
Family Araucariaceae
Genus *Agathis*
Agathis sp. aff. *Agathis robusta* (More ex Mueller) Bailey

Figs 3C–E

Material

Based on two specimens, a terminal branch fragment AMF145071 and a single leaf AMF145070.

Description.

AMF145071 is a distal portion of a slender branch ca 25 mm in length as preserved, with four pairs of sub-opposite sessile elliptic leaves to 10 mm wide and 25 mm long, apices acute. Veins numerous, rising at base, fine, closely spaced and running ±ca parallel to the margin.

The second specimen, AMF145070 is a portion of a larger single leaf, with base and apex missing, estimated original length ca 6.5 mm, width 15 mm with fine closely spaced parallel venation.

Discussion.

A number of extant conifers have leaves with parallel veins and in the absence of reproductive structures or cuticles it is difficult to make a firm identification. In the Podocapaceae is *Nageia* with an extant distribution beyond Australia. Araucariaceae is a family restricted to three genera – *Araucaria, Agathis* and *Wollemia* which still grow in Eastern Australia. The first records of this ancient conifer family are from the Triassic Period (Taylor et al. 2009) while their greatest diversity and widest distribution was during the Jurassic Period (White 1981a, b, Anderson et al. 2007 pp 56–59, 135). They are also well known from Tertiary localities in south-eastern Australia (Bigwood and Hill 1985, Hill and Bigwood 1987, Hill et al. 2008).

Based on details of macro leaf form and venation, the Chalk Mountain fossils are placed in *Agathis* with a close affinity to *A. robusta* as illustrated in Harden et al. (2006). In the palynological study of diatomite and lignite from Chalk Mountain undertaken by Helene Martin (in Holmes et al. 1983) *Araucarites australis* Cookson, attributed to *Agathis* and *Araucaria* comprised 18.1% of the pollen in the lignite and 10.7% in the diatomite. *Agathis robusta* is today restricted to populations in rainforests of northern Queensland and south-eastern Queensland. These leaves also show some similarity to the Tertiary fossils of early Oligocene to early Miocene age named *Agathis tasmanica* known from macro and cuticular remains as described by Hill and Bigwood (1987) from Little Rapid River locality in Tasmania.

Genus ?*Agathis*, sp. indet.

Figures 3A, B.

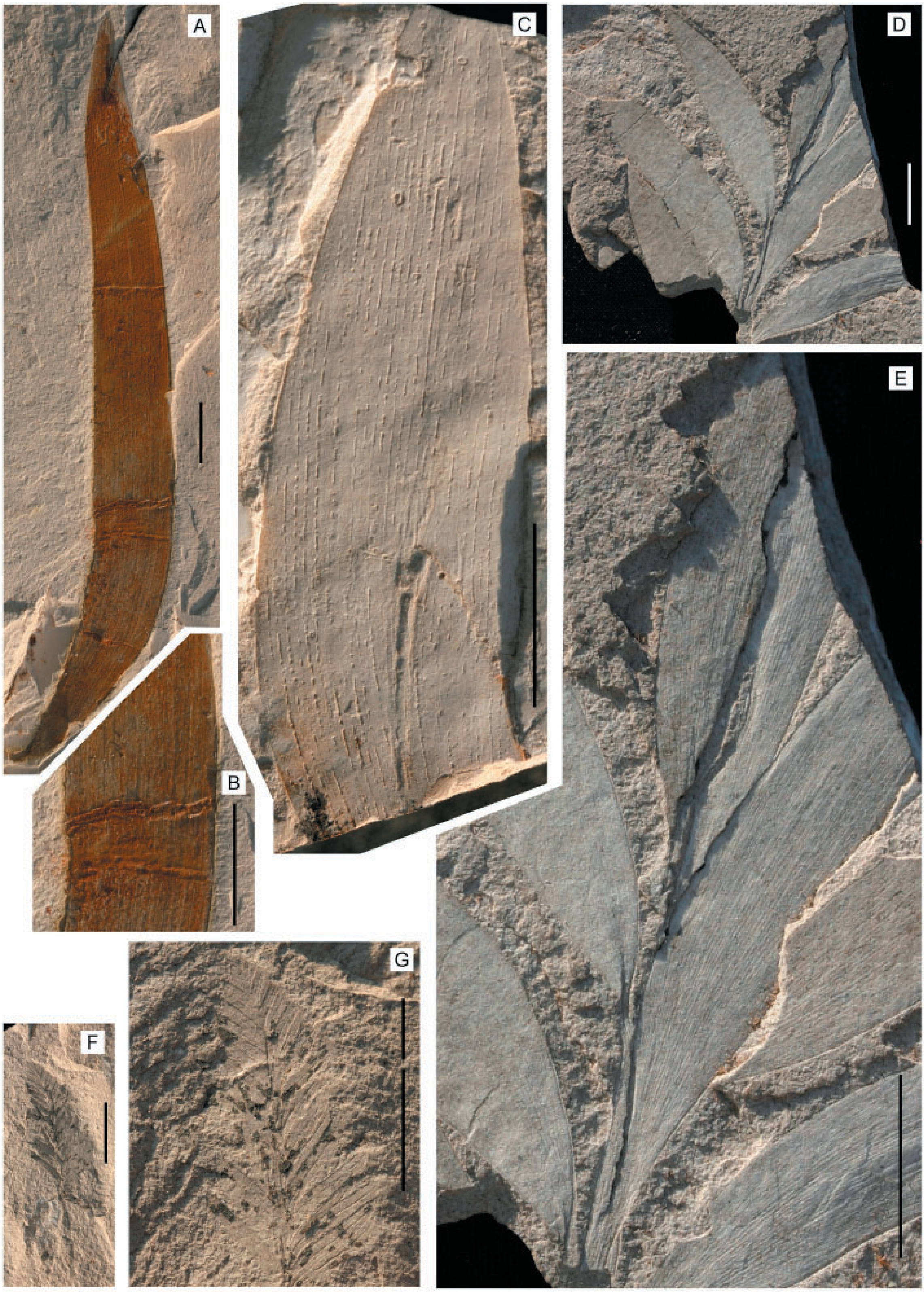


Figure 3. [A, B] ?*Agathis* species indet. AMF 145069; [C–E] *Agathis* sp. aff. *A. robusta*, [C] AMF 145070, [D,E] 145071 [F, G] Foliar conifer-like twig, AMF 145072, (scale bar = 10 mm).

Material

AMF145069.

Description

Leaf elongate elliptic, length 130 mm, central portion with parallel margins 13 mm wide, with ca 20 faint longitudinal ribs or striations; tapering proximally and distally; transverse scars across the stem at 25, 50 and 85 mm from the assumed base.

Discussion

Superficially this specimen resembles an *Equisetum* stem but differs by the proximal and distal tapering and appears more leaf-like. Branch or leaf scars on these apparent nodal scars are not evident. These irregular transverse scars (Fig. 3B) may be insect tunnels or physical damage during preservation. In form and the fine parallel venation this leaf falls within the extreme limits of *Agathis robusta* (Harden et al. 2006) but differs in the greater length from the Chalk Mountain leaves referred to that species above. It can also be compared to the much larger Tertiary leaf described by Bigwood and Hill (1985) as *Araucarioides linearis* which is based on an incomplete leaf, base and tip unknown, 160 mm length (as preserved) and to 15 mm wide. As cuticles are not preserved on the Chalk Mountain fossils no further comparisons can be made with the latter species or others based largely on cuticular differences as described by Hill and Bigwood (1987) and Hill et al. (2008).

This leaf may also be compared with extant Cycadales leaflets (Hill and Osborne 2002) as it has an elongated linear form with fine parallel venation. Most Australian genera *Cycas*, *Lepidozamia*, *Macrozamia* have very long leaflets with a length/width ratio far greater than the Chalk Mountain leaf. However, the leaflets of *Bowenia* come closer being 70–150 mm long and 15–40 mm broad with the margins smooth and occasionally toothed. *B. spectabilis* is unusual for a cycad in bearing bipinnate leaves and its present distribution is restricted to the tropical coastal ranges of north-eastern Queensland. *Macrozamia heteromera* occurs in the Warrumbungle region growing in dry sclerophyll woodlands and the extremely long linear leaflets are usually forked one to three times.

Family and Genus uncertain
Foliar conifer-like twig
Figures 3F, G

Material

AMF145069.

Description

A terminal portion of a foliar twig, 22 mm long as preserved, with ca 24 linear-oblong sessile leaves 1 mm in width and 8 mm long, decreasing distally in length towards the apex. Each leaf with a distinct central vein, secondary veins absent.

Discussion

This foliar twig and leaf form is found in many extant conifer families and we restrict our comparison to two Australian possibilities. It resembles that of *Podocarpus lawrencei,* an extant conifer growing as a tall shrub or tree in Victorian Eminundra rainforest and in heathlands in northern Victoria and southern NSW (Harden et al. 2006). It is also comparable to a larger fossil twig named *P. cupressinoides* from the Eocene of Penrose NSW (White 1986, fig. 365). In gross morphology the twig is also similar in form to some extant angiosperms in the family Epacridaceae.

Angiosperm Families (listed alphabetically)

Family Cunoniaceae
Genus *Ceratopetalum* Sm.
Ceratopetalum priscum Holmes and Holmes, 1992
Fig. 4A

Material

Holotype MMF25501, paratypes AMF 3975, (illustrated in White 1990, p. 197), AMF78245 (c.p. AMF78246), all from Chalk Mountain Formation.

Description

Flower-fruit with five narrow-oblong sepals; apices obtuse, bases not contracted, petals, if present, with a single vein trifurcating distally.

Discussion

The three detached flower-fruits of *Ceratopetalum priscum* from the Chalk Mountain locality are preserved as limonite or colourless impressions (Holmes and Holmes 1992, White 1990, p. 197). They are differentiated from other fossil and extant *Ceratopetalum* species by the sepal bases not being contracted and the petals with a single vein trifurcating distally (Barnes and Hill 1999). In *Ceratopetalum* the sepals of the flower grow larger after fertilisation and remain attached as part of the dehisced fruit.

A more widespread distribution of this extant genus during the Cenozoic is indicated by Holmes and Holmes (1992) who also describe *C. wilkinsonii* from near Emmaville, New South Wales from Late Eocene to Early Oligocene and Barnes and Hill (1999) who listed occurrences placed in *Ceratopetalum* from the

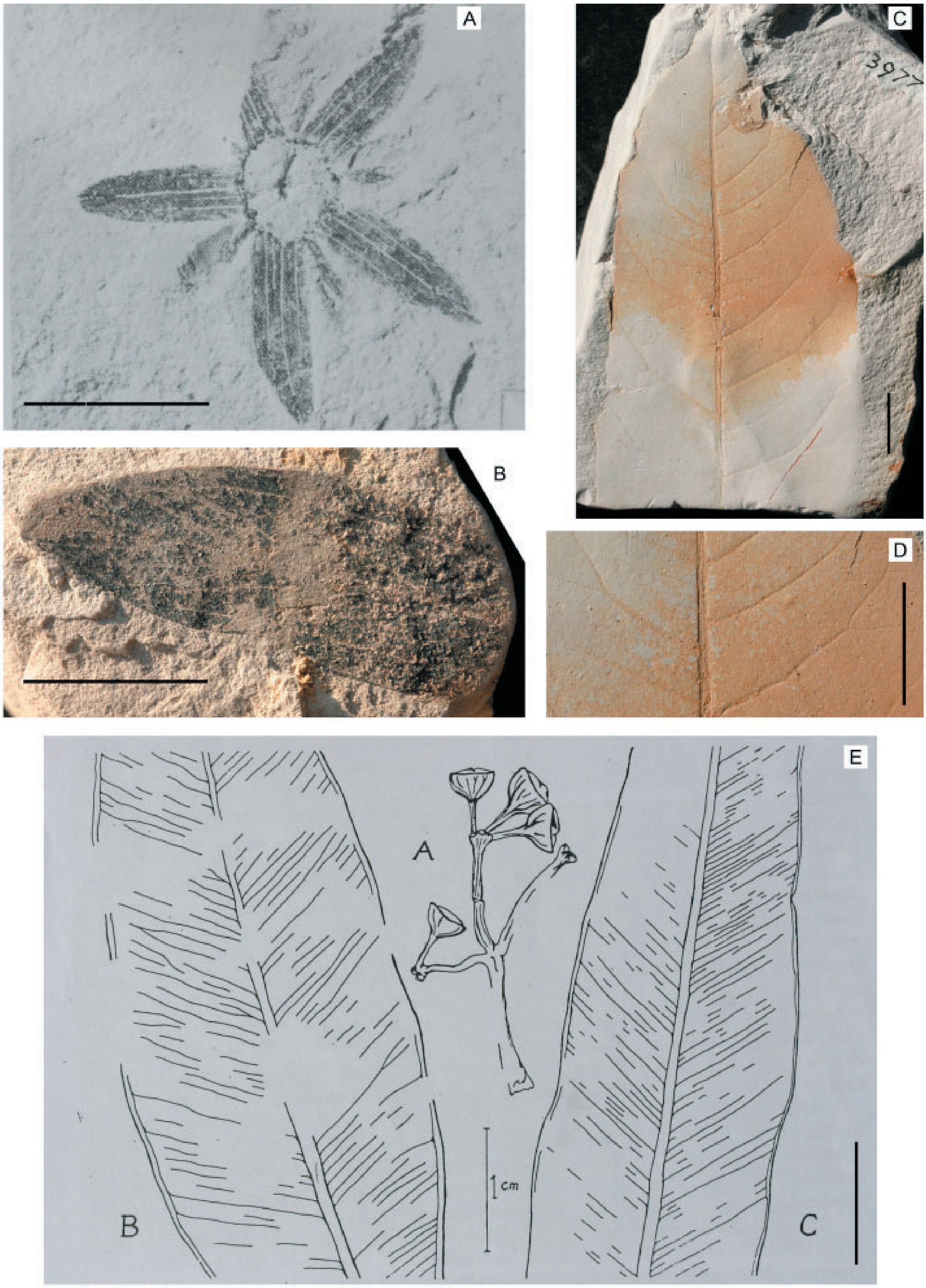


Figure 4. [A] *Ceratopetalum priscum* from Holmes and Holmes (1992, Fig. 1) MMF25501. [B] ?Myrtaceae leaf form [C] AMF 145073. [C, D] ?Moraceae leaf form [D] AMF 145074. [E] from Holmes et al. (1983, Fig.1). [E](A) *Eucalyptus bugaldiensis* AMF61713. [E](B) *Eucalyptus* leaf form A, AMF61721, [E](C) *Eucalyptus* leaf form B, AMF61724, (scale bar = 10 mm).

Middle Eocene Beds of Maslin Bay, South Australia.

The oldest known radially symmetrical five winged fossil fruits with unique characters supporting their inclusion in *Ceratopetalum* are from the Early Eocene of Patagonia, Argentina (Gandolfo and Hermsen 2017). Because the affinities, provenance and age of those fossils is so well established, their new fossil species *C. edgardoromeroi* Gandolfo and Hermsen, is an excellent candidate for use as a calibration point in divergence dating studies of the family Cunoniaceae. It represents the only record of *Ceratopetalum* outside Australasia and further corroborates the biogeographic connection between the Argentina Laguna del Hunco flora and ancient and modern floras of the Australasian region. Jud and Gondalfo (2018) suggest that although Australasia is currently the centre of diversity of the family, the Argentinian findings suggest that west Gondwana had an important role in their diversification. According to Barnes et al. (2001) a Cretaceous origin of Cunoniaceae is possible, and may account for its widespread distribution on Southern Hemisphere landmasses.

Family ?Moraceae
Genus and Species uncertain.
Leaf Form D
Figures 4C, D

Material.
AMF145074.

Description.
Upper portion of a broad ovate leaf 40 mm wide and 85 mm long, as preserved. Apex bluntly pointed. Distinct narrow midvein terminating at apex. Secondary lateral veins irregularly alternate, departing from midrib at ca 60°, decurving across lamina to reach margin at ca 30°, occasionally forking at 2/3 distance to margin.

Discussion
As the leaf base and tertiary venation are not preserved to allow certain identification, this specimen is listed as Leaf Form D. From the features that are present it appears to be of rainforest origin and in particular details of the leaf it resembles some extant native *Ficus* species (Harden et al. 2006). Note that the *Ficus rubiginosa,* Rusty Fig, still grows in the Warrumbungle region (Mackay 2017).

Family Myrtaceae
Genus *Eucalyptus*

Eucalyptus bugaldiensis Holmes and Holmes, 1983
Fig. 4E(A) from Holmes et al.1983

Material.
AMF61713–61720.

Description.
Based on three umbellasters attached at a common point to a stem, each umbellaster is composed of seven or fewer fruit. Fruit hemispherical with the external surface ornamented by 7–10 longitudinal ribs. The rim is flat and exerted valves form a low triangular projection 0.5 mm above the rim.

Discussion.
This material was described in detail by Holmes et al. (1983) and illustrated in colour by White (1990 pp 58, 59). Due to lack of cuticle and attached or closely associated foliage it is difficult to compare these fertile organs with extant *Eucalyptus* species. In gross morphology there is a similarity with the extant Coolabah tree, *Eucalypus microtheca* (subgenus *Symphyomyrtus* section *adnataris*) a widespread species often growing on ground subject to flooding. Christophel (1989) considered the Chalk Mountain leaf and fruit impressions as definitely eucalyptoid as was also noted by Hill et al. (2016).

Eucalyptus sp. Leaf Form A.
Fig.4 E(B) from Holmes et al. 1983

Material.
AMF61721–3

Description.
Leaf lamina lanceolate to narrow falcate, asymmetrical about lamina base; secondary veins ca 1 mm apart, parallel and running at 50° to 60° to the intramarginal vein which runs close and parallel to the leaf margin. Tertiary veins form an irregular network of about 4 rows between the secondary veins.

Discussion.
The venation pattern of Leaf Form A resembles that of various eucalypt species now placed in *Corymbia* and *Angophora* and *Eucalyptus trachyphloia,* a bloodwood growing in the sandy soils of the nearby Pilliga region. See Holmes et al. (1983) for further discussion on the venation pattern and classification.

Eucalyptus sp. Leaf Form B
Fig. 4E(C) from Holmes et al. 1983

Material.

AMF61724–5, MMF15284.

Description.

Leaf lanceolate, slightly falcate, base asymmetrical, secondary veins sub-parallel, spaced irregularly and running a slightly undulate course to the intra-marginal vein.

Discussion.

Eucalyptus Leaf Form B differs from *Eucalyptus* Leaf Form A by the wider spacing and irregular course of the secondary veins. In form and venation Leaf Form B is similar to the leaves of extant *Eucalyptus raveretiana,* Black Ironbark, that grows along inland watercourses, river flats and open woodland (Halford 1997). See Holmes et al. (1983) for further discussion on the venation pattern and for a colour illustration of the attached leaves White (1990 p. 197).

Lange (1980) commented on the absence of eucalypt cuticles from mid-Tertiary floras around the margin of the Australian Plate that were dominated by rainforest. The presence of eucalypt fruit and leaves in the Chalk Mountain flora indicates that the warming and drying of the region was occurring in the Warrumbungle region by the mid Miocene and resulted in the introduction of a sclerophyll flora into a previous rainforest dominated environment.

The earliest *Eucalyptus* fossils were described by Gandolfo et al. (2011) from the Eocene Laguna del Hunco palaeoflora of Patagonia, Argentina and from New Zealand by Pole (1993) indicating the genus may have occurred around the Southern Hemisphere at that time which suggests that the rich extant Australian population of eucalypts may be a relic from an Early Cenozoic time. The cause of extinction of *Eucalyptus* from South America (Hermsen et al. 2012) and New Zealand remains obscure (Hill et al. 2016).

Family ?Myrtaceae
Genus and Species uncertain
Leaf Form C
Figure 4B

Material.

AMF145073.

Description

A small ovate-elliptic leaf, apex rounded-acute: base missing: length as preserved 25 mm, total length probably ca 35 mm, width 10 mm: tri-veined, outer veins running parallel 1mm in from leaf margin. Lateral veins widely spaced, leaving midvein at ca 20° and running almost straight to outer vein.

Discussion.

This small leaf fragment is distinguished by its three veins and the pattern of the lateral veins at an acute angle. The extant rainforest genus *Rhodamnia* has similar three veins from the base but the lateral veins are closely spaced and run at an obtuse angle $>45^{o}$ towards the leaf margin (Floyd 1989, Harden et al. 2006). The three main veins are somewhat similar to those in the much smaller sepals of *Ceratopetallum* (Figure 4A) but the lateral veins differ by being at an acute angle.

Family Urticaceae
Genus *Dendrocnide*
Dendrocnide sp. A aff. *D. excelsa*
Figs 5 A–D

Material.

AMF145075, 145076 and counterpart 145077, 154078.

Description.

Based on the macro features of two closely similar ovate leaves, almost complete but with base missing, to 80 mm wide. Margin slightly undulate, entire to slightly toothed. Midvein to 2 mm in width, decreasing gradually to leaf apex. Secondary veins prominent, leaving midrib as opposite pairs closer to base, sub-opposite to alternate distally as angle of attachment decreases from ca 80° to ca 40° upwards; decurving slightly but close to margin curving upwards to run parallel to leaf margin; rarely forking. Tertiary veins joining secondary veins at right angles 2–3 mm apart. Quaternary veins form an irregular network of very fine lines between the tertiary veins.

Discussion.

The venation pattern of the fossil leaves is identical to that in the mature foliage of extant *Dendrocnide excelsa* (Fig. 5E) and *D. moroides* trees (Floyd 1989, Harden et al. 2006). In Australia these two species have very similar leaves with *D. excelsa* having a cordate base while *D. moroides* is a peltate leaf with the base truncate to cordate. None of the fossil leaves have their base preserved and their identity is thus uncertain. *D. excelsa* is commonly known as the Giant Stinging Tree and has numerous silica spines on the leaf surface. When touched by humans the spines enter the skin causing severe and prolonged pain. The silica spines are not evident on the fossils. The Giant Stinging Tree is a pioneer species in eastern Australian rainforests following openings of the canopy as a result of severe storms. The young trees show vigorous growth with very large juvenile

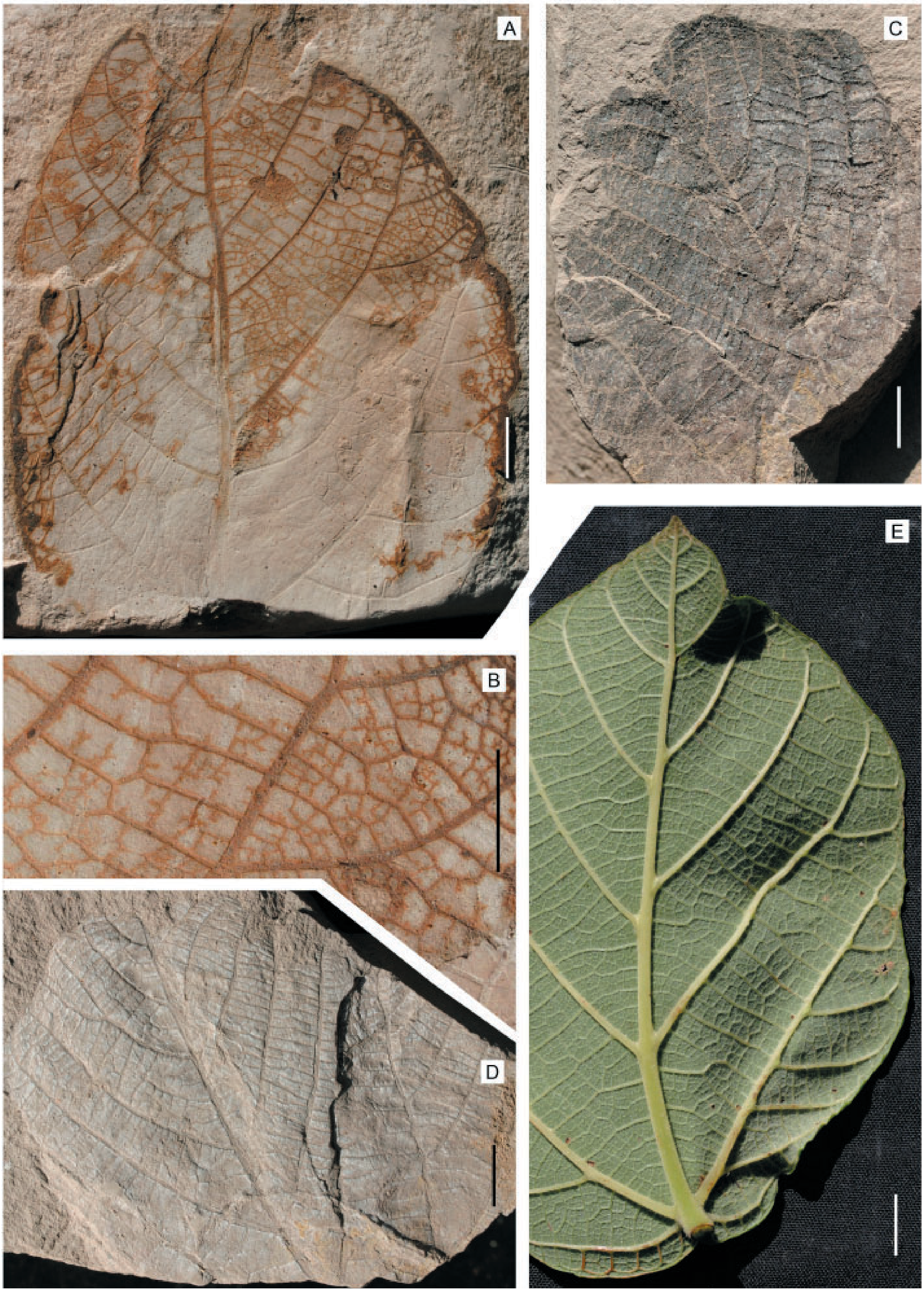


Figure 5. [A–D] *Dendrocnide* sp. A aff. *D. excelsa*. [A, B] AMF 145075. [C] AMF 145076. [D] AMF 145077 (counter part of 145076). [E] *D. excelsa* extant leaf from Dorrigo Rainforest, (scale bar = 10 mm).

leaves that are frequently eaten by insects. On older trees the leaves reduce in size identical to the fossils described above. Extant mature trees may reach 44 m in height and to 6.4 m in diameter at breast height (see www.nationalregisterofbigtrees).

Fossil pollen attributed to the Urticaceae family has been recorded from the Upper Oligocene and Miocene deposits in Australia (Martin 1994). There are no previous macrofossil records of *Dendrocnide* from Australia which makes these leaves from the Chalk Mountains very significant. The world macrofossil record of Urticaceae is scattered and largely based on fossil achenes from the Late Cretaceous of Central Europe (Friis et al. 2010).

An additional fragmentary leaf (AMF154078 not illustrated) shows generally similar venation to the two illustrated specimens but with two unusual secondary veins.

RECONSTRUCTING THE CHALK MOUNTAIN FLORA

In reconstructing a flora based on limited preserved remains, one must accept that the fossil material may have been transported from varying distances and from diverse vegetation types. The macrofossil remains described above and the palynological records of Martin (in Holmes et al. 1983) of swamp, riverside, rainforest and sclerophyll type vegetation preserved in the Chalk Mountain diatomite indicates a variety of sources. Greenwood (1994) noted that fossil leaf accumulations constitute a biased but often detailed record of the parent vegetation. In the Chalk Mountain Formation, except for a thin basal lignite horizon (Fig. 1) the pure diatomite of the lake deposit clearly demonstrates that there were no incoming streams depositing sediments in the caldera (White 1994). The fossil plant material was therefore deposited mainly by gravity or carried from a distance by wind storms. There is some evidence of *in situ* preservation based on the whorls of leaves assigned to the ?Isoetaceae which possibly grew around the lake margin. The occurrence of *Equisetum* also indicates a moist possible swamp environment. The presence of eucalypt material with rainforest remains does not necessarily reflect a common rainforest origin. The eucalypts were probably from a sclerophyll forest adapted for growth on the sandy soils derived from the adjacent and underlying Jurassic Pilliga Sandstone beds and the rainforest species from sheltered and moist gully situations.

The low *Nothofagus* pollen content and the high myrtaceous content including *Eucalyptus* fruit and leaves (Martin in Holmes et al. 1983) indicates that the Warrumbungle region vegetation was responding to a warming and drying climate as the Australian plate moved northwards during the Middle Miocene (Wilford and Brown 1994). This resulted in the introduction of a sclerophyll flora possibly due to an increasing fire frequency that altered the previous rainforest dominated vegetation (Hill et al. 2016, Kershaw et al. 1994).

ACKNOWLEDGEMENTS

The authors wish to thank: the G. Hawker family, previous owners of the Chalk Mountain property for information and allowing access to the diatomite workings many years ago; Mr Neil Percival who donated additional material; Mr Wolfgang and Mrs Nola Bredereck of the Crystal Kingdom in Coonabarabran for early photos of the Chalk Mountain workings; Dr Maria Gandolfo at Dublin EPPC 2019 Conference in Dublin for discussion on her Patagonian fossil floras; the organisers of the 2018 Linnean Society of NSW Symposium on “The Volcanoes of Northwest New South Wales: Exploring Relationships among Geology, Flora, Fauna and Fires” that inspired our further research on the Chalk Mountain fossil flora.

REFERENCES

Anderson, H.M. and Anderson, J.M. (2018). Molteno sphenophytes: late Triassic biodiversity in southern Africa. *Palaeontologia africana* **53** (Special Volume), 1–391, http://wiredspace.wits.ac.za/10539/24672

Anderson, J.M., Anderson, H.M. and Cleal, C.J. (2007). Brief history of the gymnosperms: classification, biodiversity, phytogeography and ecology. *Strelitzia* **20**, 1–280.

Barnes R.W. and Hill R.S. (1999). *Ceratopetalum* fruits from Australian Cainozoic sediments and their significance for petal evolution in the genus. *Australian Systematic Botany* **12**, 635–645.

Barnes, R.W., Hill, R.S. and Bradford, S.C. (2001). The History of Cunoniaceae in Australia from macrofossil evidence. *Australian Journal of Botany* **49**, 301–320.

Beeston, J.W. (1991). Coal facies depositional models. Denison Trough area, Bowen Basin. *Queensland Geology* **2**, 1–34.

Bigwood, A. J. and Hill, R. S. (1985). Tertiary araucarian macrofossils from Tasmania. *Australian Journal of Botany* **33**, 645–656.

Campbell, J.D. and Holden, A.M. (1984). Miocene casuarinacean fossils from Southland and Central Otago, New Zealand. *New Zealand Journal of Botany* **22**, 159–167.

Christophel, D.C. (1989). Evolution of the Australian flora through the Tertiary. *Plant Systematics and Evolution* **162**, 63–78.

Drinnan, A.N. and Chambers, T.C. (1986). Flora of the Lower Cretaceous Koonwarra fossil bed (Korumburra Group), South Gippsland, Victoria. *Memoirs of the Association of Australasian Palaeontologists* **3, 1–77.**

Floyd, A.G. (1989). *Rainforest Trees of Mainland South-eastern Australia*. Forestry Commission of New South Wales. 420 pp.

Friis. E.M., Crane, P.R. and Pedersen, K.R. (2010). *Early Flowers and Angiosperm Evolution.* Cambridge University Press, Cambridge, 585 pp.

Gondalfo, M.A., Hermsen, E.T., Zamaloa, M.C., Nixon, K.C., Gonzalez, C.C., Wilf, P., Cuneo, N.R. and Johnson. K.R. (2011) Oldest known *Eucalyptus* macrofossils are from South America. *PLoS ONE 6(6): e21084. https://doi.org/10.1371/journal.pone.0021084.*

Gandolfo, M.A. and Hermsen, E.T. (2017). *Ceratopetalum* (Cunoniaceae) fruits of Australian affinity from the Early Eocene Laguna del Hunco Flora, Patagonia, Argentina. *Annals of Botany* **119**, 507–516.

Greenwood, D.R. (1994). Palaeobotanical evidence for Tertiary climates. In '*History of the Australian Vegetation: Cretaceous to Recent'* (Ed. Hill, R.S.) pp. 44–59. (University of Adelaide Press, Adelaide, republished 2017).

Griffin, R.J. (1961). The Bugaldie Chalk Mountain diatomaceous earth deposit, New South Wales. *Technical Report Department of Mines, N.S.W.* **7**, 19–36.

Gould, R.E. (1968). Morphology of *Equisetum lacerata* Phillips 1829 and *E. bryanii* sp. nov. from the Mesozoic of South-Eastern Queensland. *Australian Journal of Botany* **16**, 153–176.

Halford, D. (1997). *Eucalyptus raveretiana. Species Management Manual*. Department of Natural Resources, Brisbane.

Harden, G.W., McDonald, W.J.F. and Williams, J.B. (2006*). Rainforest Trees and Shrubs - a Field Guide to their Identification.* Gwen Harden Publishing. 264 pp.

Herbert, C. (1968). Diatomite deposits in the Warrumbungles. *Report Geological Survey, New South Wales* **195** unpublished.

Hermsen, E.J., Gandolfo, M.J.A. and Zamaloa, M.C. (2012). The fossil record of *Eucalyptu*s in Patagonia. *American Journal of Botany* **99**, 1356–1374.

Hill, K. and Osborne, R. (2002). *Cycads of Australia*. Kangaroo Press, Sydney. 116 pp.

Hill, R.S. (1988). Tertiary *Isoetes* from Tasmania. *Alcheringa* **12**, 157–162.

Hill, R.S, and Bigwood, A.J. (1987). Tertiary gymnosperms from Tasmania: Araucariaceae. Alcheringa 11, 325–335.

Hill, R.S., Lewis, T., Carpenter, R.J. and Whang, S.S. (2008). Agathis (Araucariaceae) macrofossils from Cainozoic sediments in south-eastern Australia. Australian Systematic Botany 21, 162–177.

Hill, R.S., Beer, Y.K., Hill, K.E., Macinnes, E., Tarran, M.A. and Wainman, C.C. (2016). Evolution of the eucalypts – an interpretation from the macrofossil record. *Australian Journal of Botany.* **64,** 600–608.

Hills, E.S. (1946). Fossil Murray cod (*Maccullochella macquariensis*) from diatomaceous earths in New South Wales. *Records of the Australian Museum* **21**, 380–382.

Holmes, W.B.K. (1982). The Middle Triassic flora from Benolong, near Dubbo, central-western N.S.W. *Alcheringa* **6,** 1–33.

Holmes, W.B.K. (2000). The Middle Triassic megafossil flora of the Basin Creek Formation, Nymboida Coal Measures, NSW, Australia. Part 1: Bryophyta, Sphenophyta. *Proceedings of the Linnean Society New South Wales* **122,** 42–68.

Holmes, W.B.K. (2001). Equisetalean plant remains from the early to Middle Triassic of New South Wales, Australia. *Records of the Australian Museum* **531**, 9–20.

Holmes, W.B.K., Holmes, F.M. and Martin, H.A. (1983). Fossil *Eucalyptus* remains from the Middle Miocene Chalk Mountain Formation, Warrumbungle Mountains, New South Wales. *Proceedings of the Linnean Society of New South Wales* **106**, 299–310.

Holmes, W.B.K. and Holmes, F.M. (1992). Fossil flowers of *Ceratopetalum* Sm. (Family Cunoniaceae) from the Tertiary of eastern Australia*. Proceedings of the Linnean Society of New South Wales* **113**, 265–270.

Jud, N. and Gandolfo, M.H. (2018). Fossil evidence for the diversification of crown group Cunoniaceae from the early Paleocene (Danian) of Patagonia, Argentina. *10th European Palaeobotany and Palynology Conference, University College Dublin, Poster Abstracts*, Poster number 152, p. 251**.**

Kenny, E.J. (1924). Diatomite, siliceous earths and sands. *New South Wales Department of Mines. Bulletin Number* **15**, 1–18.

Kershaw, A.P., Martin, H.A. and McEwen Mason, J.R.C. (1994). The Neogene: a period of transition. In '*History of the Australian Vegetation: Cretaceous to Recent'* (Ed. Hill, R.S.) pp. 299–327. (University of Adelaide Press, Adelaide, republished 2017).

Lange, R. T. (1980). Evidence of lid-cells and host-specific microfungi in the search for Tertiary *Eucalyptus. Review of Palaeobotany and Palynology* **29**, 29–33.

Mackay, D. (2017). Can the native Rusty Fig*, Ficus rubiginosa,* beat climate change? *Australia Flora Foundation - Final Draft*. 37pp*.*

McLoughlin, S. (1993). Late Permian plants from the Bowen Basin, Queensland, Australia*. Palaeontographica, B*. **222**, 105–149.

McLoughlin, S., Pott, C. and Elliott, D. (2010). The Winton Formation flora (Albian-Cenomanian, Eromanga Basin): implications for vascular plant diversification and decline in the Australian Cretaceous. *Alcheringa* **34**, 303–323.

Martin, H.A. (1994). Australian Tertiary phytogeography: evidence from palynology. In '*History of the Australian Vegetation: Cretaceous to Recent'* (Ed. Hill, R.S.) pp. 104–142. (University of Adelaide Press, Adelaide, republished 2017).

Pole, M.S. (1993). Early Middle Miocene flora of the Manuherikia Group, New Zealand. 7. Myrtaceae including *Eucalyptus. Journal of the Royal Society of New Zealand* **23**, 313–328.

Pole, M. and McLoughlin, S. (2017). The First Cenozoic *Equisetum* from New Zealand. *Geobios* **50**, 259–265.

Retallack, G.J. (1980). Middle Triassic plants and trace fossils from Tank Gully, Canterbury, New Zealand. *Journal of the Royal Society of New Zealand* **10**, 31–63.

Retallack, G.J. (1997). Earliest Triassic origin of *Isoetes* and Quillwort evolutionary radiation. *Journal of Paleontology* **7**, 500–521.

Rich, P.V., and McEvey, A. (1977). A New Owlet Nightjar from the Early to Middle Miocene of Eastern New South Wales. *Memoir National Museum, Victoria* **38**, 247–253.

Rigby, J.F. (1966). Some Gondwana articulates from New South Wales. *Palaeobotanist* **37**, 189–191.

Rozefelds, A.C., Dettmann, M.E., Milroy, A.K., Hammond, H., Clifford, T. and Ekin, M. (2019). The unexpected, recent history of horsetails in Australia. *Australian Systematic Botany* **32**, 255–268.

Scriven L.J. and Hill, R.S. (1995). Macrofossil Casuarina: their identification and the oldest macrofossil record, *Gymnostoma antiquum* sp. nov., from the Late Paleocene of New South Wales, Australia. *Australian Systematic Botany* **8,** 1035–1053.

Taylor, T.M., Taylor, E.L. and Krings, M. (2009). *Paleobotany. The Biology and Evolution of Fossil Plants.* Elsevier, Academic Press. 1230 pp.

White. M.E. (1981a). Fish beds reveal lush fossil forest. *Australian Natural History* **20**, 227–230.

White. M.E. (1981b). Revision of the Talbragar Fish Bed Flora (Jurassic) of New South Wales. *Records of the Australian Museum* **33***,* 695–721.

White, M.E. (1981c). *Cylomeia undulata* (Burges) gen. et sp. nov.; a lycopod of early Triassic, State of New South Wales. *Records of the Australian Museum*. **33**, 723–734.

White, M.E. (1986). *The Greening of Gondwana*. Reed Books, Sydney. 256 pp.

White, M.E. (1990). *The Nature of Hidden Worlds.* Reed Books, Sydney. 256 pp.

White, M.E. (1994). *After the Greening.* Kangaroo Press, Sydney. 288 pp.

Wilford, G.E. and Brown, P.J. (1994). Maps of late Mesozoic-Cenozoic Gondwana break-up: some palaeogeographical implications. In '*History of the Australian Vegetation: Cretaceous to Recent'* (Ed. Hill, R.S.) pp. 5–13. (University of Adelaide Press, Adelaide, republished 2017).

Marooned on an Extinct Volcano: the Conservation Status of Four Endemic Land Snails (Gastropoda: Pulmonata) at Mount Kaputar, New South Wales

MICHAEL J. MURPHY[1], JESSICA K. MURPHY[2], C. JAMES FARIS[3] AND MICHAEL J. MULHOLLAND[4]

[1] NSW National Parks and Wildlife Service, PO Box 952 Moama NSW 2731;
[2] Forsyth Street Wagga Wagga NSW 2650;
[3] NSW National Parks and Wildlife Service, PO Box 72 Narrabri NSW 2390;
[4] NSW National Parks and Wildlife Service, PO Box 848 Narrabri NSW 2390

Murphy, M.J., Murphy, J.K., Faris, C.J. and Mulholland, M.J. (2019). Marooned on an extinct volcano: the conservation status of four endemic land snails (Gastropoda: Pulmonata) at Mount Kaputar, New South Wales. *Proceedings of the Linnean Society of New South Wales* **141**, S33-S44.

Volcanic activity in northern inland New South Wales between 40 and 15 million years ago was followed by general continental-scale drying and coastward contraction of mesic ecosystems between 15 and 2 million years ago. Together, these processes resulted in the creation of high-elevation climatic refuges such as Coolah Tops, Mount Kaputar and the Warrumbungle Range as western outposts of the mesic eastern highlands on the dry western slopes. These areas are important hotspots of land snail species diversity and endemism. A high-elevation and dry rainforest land snail community at Mount Kaputar, recognised as being of outstanding conservation significance, was listed as an endangered ecological community under NSW legislation in 2013. Two species from this community, the Kaputar Pink Slug *Triboniophorus* sp. nov. "Kaputar" and Bronze Rippled Pinwheel Snail *Cralopa kaputarensis*, are currently listed on the *IUCN Red List*, as *endangered* and *data deficient* respectively. This paper provides an updated assessment of the conservation status of the Kaputar Pink Slug, a reassessment of the Bronze Rippled Pinwheel Snail and original assessment of another two endemic Mount Kaputar species (Kaputar Carnivorous Snail *Vitellidelos kaputarensis* and Kaputar Keeled Snail *Thersites* sp. nov. "Kaputar"), concluding that all four species meet the criteria for listing as *endangered* on the *IUCN Red List*.

Manuscript received 15 April 2019, accepted for publication 5 August 2019.

Key words: climate change, conservation assessment, endangered land snails, IUCN Red List, Kaputar Pink Slug, Mount Kaputar.

INTRODUCTION

Wildlife conservation efforts often focus on vertebrate fauna, which represent just 1% of faunal species diversity. Eastern mainland Australia has a rich native land snail fauna estimated at more than 1250 species in 25 families (Stanisic and Ponder 2004; Stanisic et al. 2010; Stanisic et al. 2017). The most species-rich families are the Charopidae, Camaenidae and Helicarionidae. About 90% of species occur in rainforests, where long-term moisture stability and complex microhabitats have supported the evolution and survival of diverse land snail communities, while relatively few species occur in drier eucalypt forests (Stanisic 1994). Rocky habitats providing moisture and shelter are also important, particularly in arid and semi-arid areas (Slatyer et al. 2007; Stanisic et al. 2017). Identifying and protecting hotspots of species diversity and endemism is a high priority for land snail conservation (Ponder 1997; Parkyn and Newell 2013).

Volcanic activity in northern inland New South Wales (NSW) 40 to 15 million years ago (Sutherland 2011) was followed by general continental-scale drying and coastward contraction of mesic ecosystems between 15 and 2 million years ago (Martin 2006). This resulted in the creation of high-elevation climatic refuges such as Coolah Tops, Mount Kaputar and the Warrumbungle Range as western outposts of the mesic eastern highlands on the dry western slopes.

These isolated high-elevation areas are hotspots of land snail species diversity and are notable exceptions to the general pattern in eastern Australia of land snail species diversity decreasing with distance from the coast (Stanisic 1994). Hyman and Stanisic (2005) noted the refugial significance of these sites in land snail evolution. The refuge sites support distinct land snail communities including narrow-range endemic species such as *Austrorhytida warrumbunglensis* (Rhytididae), *Austrochloritis warrumbunglensis* (Camaenidae) and *Ponderconcha warrumbungliana* (Camaenidae) in Warrumbungle National Park (NP) (Shea 1992; Stanisic et al. 2010), and *Austrochloritis liverpoolensis* (Camaenidae), an undescribed *Thersites* species (morpho-species code Camaenidae SN30) and an undescribed rhytidid (Rhytididae SN7) in Coolah Tops NP (Murphy unpublished data). Mount Kaputar NP is the best-studied site to date, supporting a native land snail fauna of 24 species (seven families) including nine endemic species (Murphy and Shea 2015).

A high-elevation and dry rainforest land snail community at Mount Kaputar is considered to be of outstanding conservation significance and was listed as an endangered ecological community under the NSW *Threatened Species Conservation Act 1995* in December 2013 (Murphy and Shea 2015), and subsequently under the NSW *Biodiversity Conservation Act 2016*. Eighteen native land snail species are currently known from this community of which eight are endemic to the community (Murphy and Shea 2015). Two of these endemic species, the Kaputar Pink Slug *Triboniophorus* sp. nov. “Kaputar” (Athoracophoridae) and the Bronze Rippled Pinwheel Snail *Cralopa kaputarensis* (Charopidae) have been previously assessed by the International Union for Conservation of Nature (IUCN), with the former listed as *endangered* (Murphy 2014) and the latter as *data deficient* (Mollusc Specialist Group 1996) on the *IUCN Red List*. The current paper presents an updated version of the Kaputar Pink Slug conservation assessment, a reassessment of the Bronze Rippled Pinwheel Snail and novel assessments for another two endemic species. The four species have overlapping distributions and face similar threats and, to avoid repetition, the four assessments are presented in combination.

STUDY AREA

Mount Kaputar NP (30° 16’ S, 150° 10’ E) (Fig. 1) is about 51340 ha in area and is located near the town of Narrabri in Gamilaraay Aboriginal Country in northern inland NSW, 270 km from the Australian east coast on the western inland slopes of the Great Dividing Range. The majority of the park is in the Nandewar bioregion, extending into the Brigalow Belt South bioregion along parts of the park’s western margin. The park’s landscape comprises the eroded remains of the Nandewar Volcano, a mid-plate alkaline shield volcano dating from the early Miocene (18-19 million years ago) (Sutherland 2011) and now reaching a maximum elevation of 1508 m Australian Height Datum (AHD). The local climate is strongly influenced by elevation, with temperatures differing by up to 12° C between lowland and upland areas and average annual rainfall varying from 800 mm in lowland areas to 1200 mm in upland areas (Hunter and Alexander 2000). The vegetation varies with elevation and topography, including areas of sub-alpine open forest of Snow Gum *Eucalyptus pauciflora*, Ribbon Gum *E. viminalis* and White Gum *E. dalrympleana* (Myrtaceae) above about 1350 m AHD and small patches of dry rainforest with Rusty Fig *Ficus rubiginosa*, Sandpaper Fig *F. coronata* (Moraceae) and Native Olive *Notelaea microcarpa* (Oleaceae) in rocky gullies topographically sheltered from wildfire, at elevations down to less than 500 m AHD (Porteners 1997, 1998; Hunter and Alexander 2000). The endangered land snail community at Mount Kaputar occurs in high elevation areas above 1000 m AHD (an area of about 107 km^2) and in small dry rainforest remnants at lower elevations (estimated to total less than 1 km^2) (Murphy and Shea 2015).

ASSESSMENT METHODS

Species records were collated from systematic field sampling of land snails at 36 sites in Mount Kaputar NP in 2007-2014, a 2.7 km transect survey for slugs in 2011 and data from the collections of the Australian Museum and Queensland Museum (Murphy and Shea 2015), augmented by additional opportunistic field records collected by the four authors over the period 2015-2018 and opportunistic records provided by other local staff. The conservation status of each species was assessed using the *IUCN Red List* criteria (IUCN 2012; IUCN 2017). Estimating population size is difficult for land snails, due to weather-dependent variability in activity. Conservation assessment therefore focussed on criterion B (Geographic Range). In recognition of the incomplete field survey coverage of Mount Kaputar NP (Murphy and Shea 2015), extent of occurrence (EOO) was estimated as a minimum convex polygon enclosing all actual known sites of the species

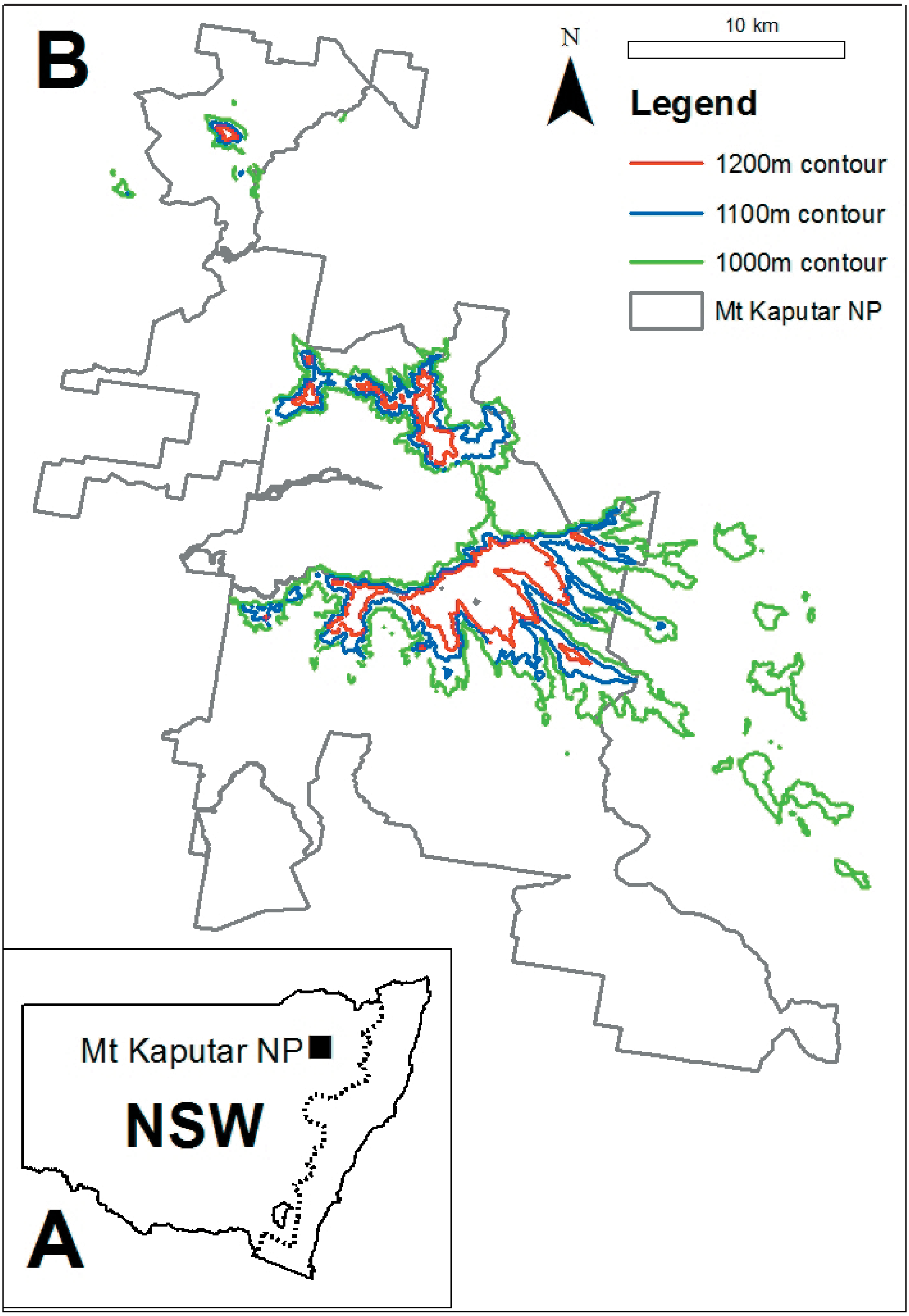


Fig 1. Mount Kaputar NP. Map A, location of the park in northern inland NSW west of the Great Dividing Range (shown by dotted line). Map B, distribution and extent of high elevation areas in the park.

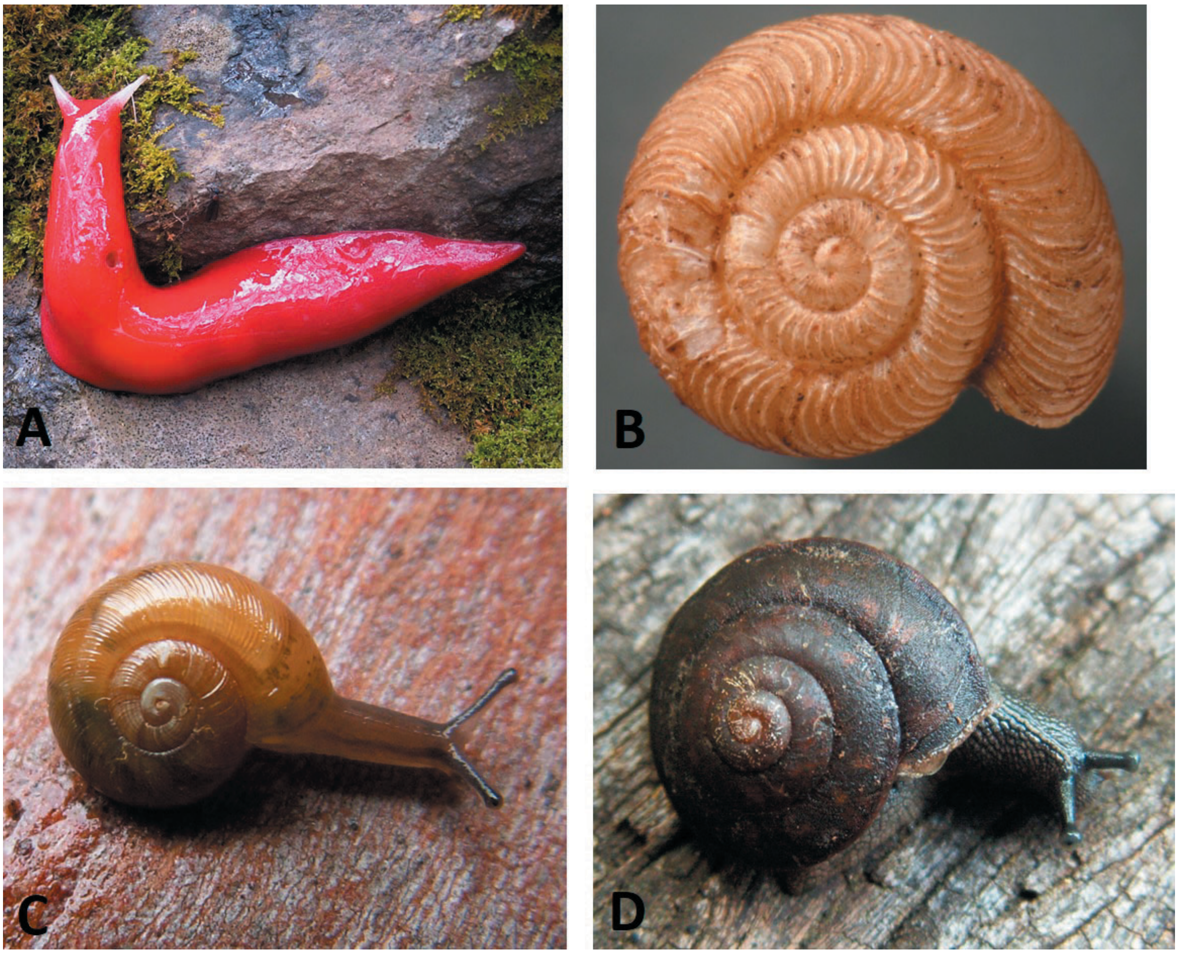


Fig 2. The four subject species. A, Kaputar Pink Slug. Photo: M.J. Murphy. B, Bronze Rippled Pinwheel Snail. Photo: V. Railton. C, Kaputar Carnivorous Snail. Photo: M.J. Murphy. D, Kaputar Keeled Snail. Photo: M.J. Murphy.

together with inferred sites based on habitat mapping. Habitat was mapped by delineating all highland areas at or above the lowest recorded highland occurrence of the species (rounded down to the closest 100 m). Area of occupancy (AOO) was estimated using a 2 x 2 km grid (in GDA94 Zone 56) over a map of Mount Kaputar NP showing known sites and mapped highland habitat areas together with satellite imagery of vegetation cover. Any highland areas on freehold properties adjacent to the park that have been cleared for agriculture were excluded from AOO estimates as being unlikely to be occupied by the species. Grid squares including either known sites or mapped high elevation potential habitat were tallied. The number of locations for each species was assessed, using the IUCN definition of a location as a geographically or ecologically distinct area in which a single threatening event can rapidly affect all individuals of the taxon present (IUCN 2017). The entire Mount Kaputar highland area is threatened by a single event (anthropogenic global warming) and was therefore considered to be one location. Individual lowland dry rainforest sites supporting the species that were disjunct from the highland area were considered to be separate locations.

TAXONOMY, DISTRIBUTION AND ECOLOGY

Kaputar Pink Slug *Triboniophorus* sp. nov. “Kaputar”

The Kaputar Pink Slug (Fig. 2A) is a large bright pink slug with white sole and optic tentacles and is a member of the Gondwanan slug family Athoracophoridae. Members of this family occur in the south-western Pacific including eastern Australia, New Guinea, New Caledonia, Vanuatu, New Zealand and some sub-Antarctic islands (Burton 1980; Smith

Fig 3. Feeding trail of Kaputar Pink Slug. Photo: M.J. Murphy.

1992; Stanisic et al. 2010). A taxonomic review by Gary Barker (pers. comm. in Murphy and Shea 2015) determined the Kaputar Pink Slug to be a distinct undescribed species endemic to Mount Kaputar. Voucher material is available in museum collections (e.g. AMS C.104019, AMS C.107910, AMS C.168560, AMS C.331977, AMS C.403799 (Australian Museum, Sydney) and QM MO32871 (Queensland Museum, Brisbane)). The slug is the only member of the Athoracophoridae found inland of the Great Dividing Range in Australia, with a distance of about 170 km separating the Kaputar Pink Slug from the nearest *Triboniophorus graeffei* populations east of Glen Innes and Armidale on the New England Tableland (Atlas of Living Australia). The previous IUCN assessment of the species (Murphy 2014) was based on a dataset of 40 records. An additional 113 records were collated for this updated assessment, including some from remote Wilderness areas. All records of the Kaputar Pink Slug are from areas above about 1000 m AHD at Mount Kaputar, with the exception of a single record from about 550 m, in streamside rainforest contiguous with the highland area.

The slugs shelter under leaf litter, woody debris and loose rocks during dry conditions. On rainy nights they emerge and crawl over rock outcrops and shrubs and climb tree trunks to heights of 20 m or more, feeding on the biofilm of micro-algae, lichen and fungi growing on the surface of rock faces and eucalypt bark and leaving characteristic feeding trails (Fig. 3). The slugs generally return to shelter in the morning, moving at about 10-20 cm/minute (Murphy and Shea 2015), but under suitably mild and cloudy conditions can continue activity into the afternoon. Predation of the slugs by diurnal birds appears to be rare but includes the Laughing Kookaburra *Dacelo novaeguineae* (Alcedinidae) and Pied Currawong *Strepera graculina* (Artamidae) (Fig. 4).

Apparent abundance of the species is very weather dependent. Sixty-three slugs were counted in 10 minutes along a 200 m walked transect along the edge of a roadside rock cutting on a mild night with light rain in November 2010, and on the following night under dry conditions only two slugs were seen on the same transect (Murphy and Shea 2015). This transect was surveyed again in the mid-afternoon on a rainy day in April 2015 and 103 slugs were counted. In dry weather slugs are inactive and are difficult to find even by hand searching of shelter sites. Feeding trails are a reliable indicator for the species in the absence of active animals.

A pilot study at a site near the Mount Kaputar summit in April 2015 examined the sinuosity of slug feeding trails on eucalypt tree trunks. Although no significant correlation between sinuosity and heights of between 1 and 3 m on tree trunks was found (Spearman's correlation test P > 0.05, rho = 0.066), this brief study demonstrated the feasibility and potential value of using feeding trails as an indirect means of investigating the foraging ecology of the Kaputar Pink Slug. There was a slight positive trend with height (mean sinuosity ratio at 3 m = 1.72 compared to 1.44 at 1 m), possibly suggesting a change in search behaviour from direct movements

Fig 4. Pied Currawong eating a Kaputar Pink Slug. Photo: J. Faris.

to a more area-restricted search (Wallin 1991). The study also determined that the slugs utilised a wide range of tree sizes for grazing, from less than 8 cm to over 60 cm diameter at breast height.

Bronze Rippled Pinwheel Snail *Cralopa kaputarensis* Stanisic, 1990

The Bronze Rippled Pinwheel Snail (Fig. 2B) is a member of the Charopidae, a family with a chiefly Gondwanan distribution including Australasia, southern Africa, sub-Antarctic islands and Central and South America, as well as south-east Asia, Indo-Pacific islands and western North America (Stanisic et al. 2010). Typical of many charopids, it is a small animal with a shell size of about 1.7 mm (Stanisic 1990; Stanisic et al. 2010). The species is endemic to Mount Kaputar, occurring in open forest above about 1200 m and dry rainforest remnants at lower elevation (Murphy and Shea 2015). It lives amongst grass, lichens and leaf litter and under fallen timber and loose rocks (Stanisic 1990; Hyman and Stanisic 2005; Stanisic et al. 2010). The species is thought to be herbivorous, feeding on decaying plant matter and fungi.

Kaputar Carnivorous Snail *Vitellidelos kaputarensis* Shea and Griffiths, 2010

The Kaputar Carnivorous Snail (Fig. 2C) is a member of the Rhytididae, a family of carnivorous snails with a Gondwanan distribution including Australia, New Zealand, New Caledonia, New Guinea and South Africa (Smith 1992; Herbert and Kilburn 2004; Stanisic et al. 2010). It is endemic to Mount Kaputar, with a distribution including open forest above about 1000 m and dry rainforest remnants at lower elevations (Murphy and Shea 2015). It has a dark yellow shell about 7 mm in diameter and lives in leaf litter and under fallen timber (Stanisic et al. 2010) and also under loose rocks (M. Murphy pers. obs.). Prey includes other land snail species.

Kaputar Keeled Snail *Thersites* sp. nov. “Kaputar”

The Kaputar Keeled Snail (Fig. 2D) is a member of the Camaenidae, a family considered a relatively recent arrival in Australia from south-east Asia about 15 million years ago and which has subsequently undergone a major radiation in Australia. It is the most westerly occurring of the *Thersites novaehollandiae*

Table 1. Extent of occurrence (EOO) and area of occupancy (AOO) estimates and number of locations for four Mount Kaputar endemic land snails.

	EOO	AOO	No. locations
Kaputar Pink Slug	545 km^2	280 km^2	2
Bronze Rippled Pinwheel Snail	309 km^2	136 km^2	4
Kaputar Carnivorous Snail	552 km^2	288 km^2	3
Kaputar Keeled Snail	348 km^2	196 km^2	3

species group (J. Stanisic pers. comm. in Murphy and Shea 2015) but is considerably smaller and more strongly keeled. It has a shell size of about 22 mm diameter and the animal is slate-grey in colour with a narrow pale mid-dorsal stripe. In comparison, *Thersites novaehollandiae* (*sensu stricto*) has a shell size of about 43 mm (Stanisic et al. 2010). A distance of about 160 km separates the Kaputar Keeled Snail from the nearest *Thersites novaehollandiae* populations east of Glen Innes and Armidale on the New England Tableland (Atlas of Living Australia). Another undescribed member of this species group is known from Warrabah NP, about 80 km south-east of Mount Kaputar (M. Shea Australian Museum pers. comm.). The Kaputar Keeled Snail has been assigned morpho-species code Camaenidae NE27 pending formal description and voucher material is available in museum collections (e.g. AMS C.79254, AMS C.478666, AMS C.478667, AMS C.481130, AMS C.481132 (Australian Museum) and QM MO32624 and QM MO32876 (Queensland Museum)). The first specimen was collected in 1967 by D.F. McMichael (Australian Museum). This undescribed species is endemic to Mount Kaputar NP, with all records restricted to open forest above about 1100 m and dry rainforest remnants at lower elevations (Murphy and Shea 2015). Animals have been found sheltering by day under loose rocks and fallen timber. *Thersites novaehollandiae* is partly arboreal when active at night, seen on tree trunks up to 6 m above the ground (Murphy 2007), but it is not known whether this behaviour is shared with the Kaputar Keeled Snail. Like other *Thersites* species (Parkyn et al. 2015), the Kaputar Keeled Snail is probably herbivorous, feeding on fungi and decaying plant matter.

CONSERVATION ASSESSMENTS

Extent of occurrence and area of occupation

EOO and AOO estimates for the four species are shown in Table 1 and EOO maps are shown in Figure 5A-D. EOO estimates for all four species are towards the lower end of the 100-5000 km^2 range for the *endangered* category under criterion B1 (IUCN 2017). All AOO estimates are within the 10-500 km^2 range for the *endangered* category under criterion B2 (IUCN 2017). All of the AOO estimates included much unsuitable habitat (low elevation dry eucalypt forest) as a result of the discontinuous distribution of highland areas at Mount Kaputar. A more accurate calculation using GIS mapping estimated the total highland area as approximately 107 km^2 above 1000 m AHD, 48 km^2 above 1100 m AHD and 21 km^2 above 1200 m. The precautionary inclusion of inferred habitat substantially increased EOO and AOO estimates for all four species. AOO estimates in particular are likely to be revised down as more information on where the species do and do not occur becomes available. Estimates for the Kaputar Pink Slug, for example, would be substantially reduced if the currently inferred presence of the taxon in the small disjunct highland areas in the north of Mount Kaputar NP and on freehold properties east of the park was discounted by field survey and the taxon was confirmed to only occur in and around the main highland area.

Number of locations

The number of locations for each species is also given in Table 1. All four species are known from fewer than five locations each and therefore meet criterion B(a) for the category *endangered* (IUCN 2017). The Kaputar Pink Slug is known from the highland area and from one lower elevation dry rainforest site on Oakey Creek. The Bronze Rippled Pinwheel Snail is known from the highland area and from lower elevation dry rainforest at Waa Gorge, Eulah Creek and the base of Mount Yulludunida. Another record of this species described as being from a location east of the Bark Hut camping area (QM49175) could not be reliably assessed as the record coordinates given are instead 500 m west of the camping area. The camping area is within 100 m of the 1200 m high elevation area and this record was therefore included within that location. The Kaputar Carnivorous Snail is known from the highland area and from dry rainforest at Waa Gorge and Sawn Rocks. The Kaputar Keeled

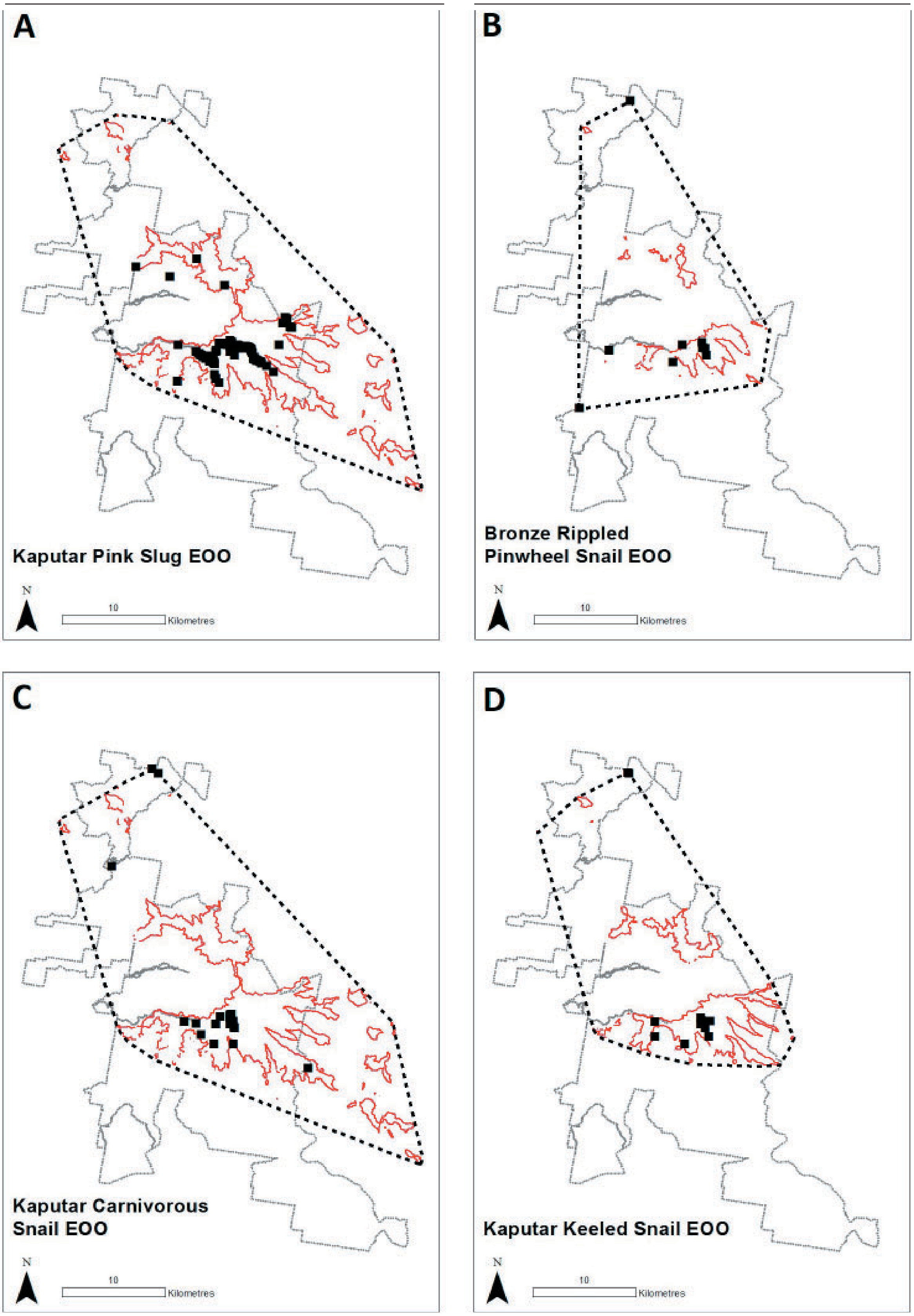


Fig 5. Maps of estimated extent of occurrence (shown as bold dashed line) for the four subject species. A, known sites of Kaputar Pink Slug and highland area over 1000 m. B, known sites of Bronze Rippled Pinwheel Snail and highland area over 1200 m. C, known sites of Kaputar Carnivorous Snail and highland area over 1000 m. D, known sites of Kaputar Keeled Snail and highland area over 1100 m.

Snail is known from the highland area and from dry rainforest at Waa Gorge and Black Mountain Creek.

Threats and continuing decline

A continuing decline is projected for all four species in EOO, AOO and the area, extent and quality of habitat due to a combination of threats, and the four species are therefore considered to meet criterion B(b)(i), (ii) and (iii) (IUCN 2017). Anthropogenic climate change is a major threat to the four species (Murphy and Shea 2015). Elevation-restricted montane ecosystems such as those found at Mount Kaputar are considered particularly susceptible to anthropogenic climate change (Brereton et al. 1995; Hughes 2003; Laurance et al. 2011) and Mount Kaputar is already marginal for sub-alpine ecosystems (NSW National Parks and Wildlife Service 2006). Many land snail species are considered particularly vulnerable to climate change because of poor dispersal ability and restricted distributions (Beltramino et al. 2015; Annagret and Ansart 2017). Land snail species restricted to higher elevation habitats are therefore of particular concern (Pearce and Paustian 2013). The four subject species are already highly restricted in distribution as a result of past climatic drying. Predicted global climate warming is likely to put these species at very high risk of extinction in the near future through further reduction and fragmentation of geographic extent and available habitat. Some land snail species are able to shift their elevation distribution in response to climate warming (Baur and Baur 2013); however, the four subject species already occupy the highest parts of Mount Kaputar, so a contraction from lower elevations must result in a net decrease in habitat area. Mount Kaputar NP has an elevation range of 1200 m and an associated temperature range of about 12°C. A 100 m vertical rise in the environmental envelope for these species at Mount Kaputar would reduce the available high-elevation area by about 55% (for 1000-1100 m) or 56% (for 1100-1200 m) and result in substantial further fragmentation. Based on projected climate impacts in Australia (e.g. Hughes 2003; Suppiah et al. 2007; Green et al. 2008), changes of this scale are considered possible by the latter half of the 21st century, and ongoing uncontrolled climate change could see the complete disappearance of these environmental envelopes.

Additional significant threats to the four subject species include fire and feral pigs (Murphy and Shea 2015). Fire is considered to be a major threat to land snails (Stanisic and Ponder 2004), with post-fire recovery of populations generally relying on survivors in unburnt refuge areas within the burnt area rather than recolonisation from the outside the fire edge (Kiss and Magnon 2003; Santos et al. 2009). Some of Mount Kaputar's sub-alpine vegetation communities have experienced fire frequencies above ecological thresholds and the risk of large intense wildfires extending into previously infrequently burnt wet eucalypt forests and dry rainforest refuges is likely to increase as a result of anthropogenic climate change (Murphy and Shea 2015). An increase in the frequency or intensity of fire events will put increased pressure on the subject species by reducing population recovery time and reducing the effectiveness of fire refugia respectively.

Feral pigs *Sus scrofa* (Suidae) are on ongoing problem in Mount Kaputar NP despite control efforts, damaging land snail habitat by digging over soil and leaf litter, turning logs and rocks and trampling ground vegetation, and are likely to prey directly on larger species such as the Kaputar Pink Slug and Kaputar Keeled Snail. Feral pigs have been found to significantly reduce litter cover and be responsible for both short and long-term reductions in the density of macro-invertebrates in mesic forest habitats (Taylor et al. 2011).

Roads can fragment habitat areas by acting as significant barriers to dispersal by land snails (Baur and Baur 1990). Roads within Mount Kaputar NP are necessary for park management activities including pest control and fire management but may act as barriers to the four subject species. Observation in April 2015 confirmed the risk to Kaputar Pink Slugs from vehicular traffic, with five crushed dead slugs (Fig. 6) found in a 15 m length of the main summit road on a rainy afternoon. Loss of habitat to development has been more substantial outside Mount Kaputar NP. Much of the high-elevation wet eucalypt forest on freehold properties bordering the eastern edge of the park has been cleared for agriculture and it is likely that the majority of off-park habitat for all four species has been lost.

CONSERVATION ACTIONS

The majority of remaining habitat for all four subject species is protected within Mount Kaputar NP, with additional protection through the declaration of much of the park as wilderness under the NSW *Wilderness Act 1987*. The high-elevation and dry rainforest land snail community at Mount Kaputar, including the four subject species and additional narrow-range endemic land snails, is also afforded protection through listing as an *endangered ecological community* under the NSW *Biodiversity*

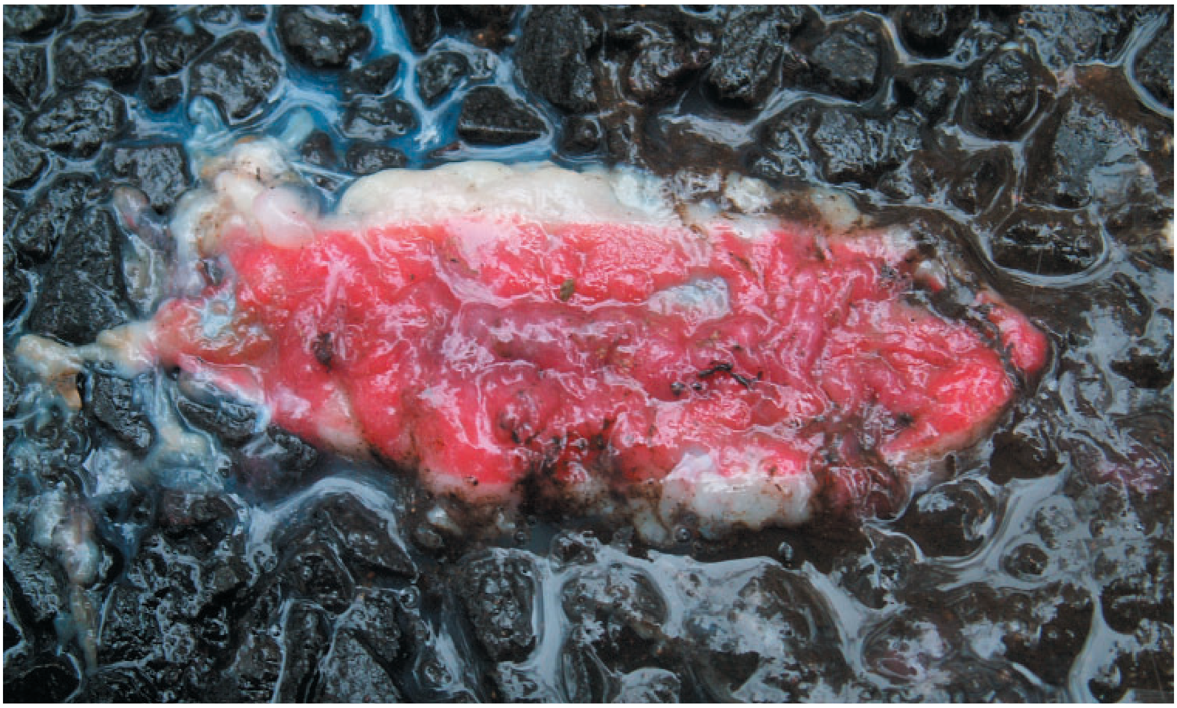


Fig 6. Kaputar Pink Slug killed by motor vehicle. Photo: M.J. Murphy.

Conservation Act 2016, the first endangered land snail community listing in Australia (Murphy and Shea 2015). This listing has raised the public profile of Mount Kaputar's unique land snail community and the threats it faces and has increased the priority for funding and implementation of appropriate threat abatement and recovery actions. The major threat, however, (anthropogenic climate change) requires coordinated action at the global scale (Murphy and Shea 2015).

Key conservation actions required for the four subject species include further field survey to refine the known distributions, and computer modelling to investigate the likely local-scale influence of elevation, aspect and topography on predicted climate changes at Mount Kaputar. The composition of land snail assemblages has strong predictive value for identifying areas of long-term moisture stability which have functioned as refugia during previous periods of climate change (Stanisic 1990, 1994, 1997; Stanisic and Ponder 2004). A dual approach of computer modelling of local-scale climate change impacts and 'following the snails' will optimise the identification of potential future local-scale climatic refugia at Mount Kaputar. Scree slopes and boulder fields are also likely to serve as important climatic refuge areas (Couper and Hoskin 2008; Shoo et al. 2010; Reside et al. 2014; Stanisic et al. 2017) and should be mapped and included in this assessment. Once identified, these climatic refugia should then be a priority for fire management, feral pig control and other local conservation works.

The IUCN criteria can be applied to any taxonomic unit at or below the species level, including forms that are not yet formally described. However, the listing of undescribed species is discouraged by the IUCN unless there is general agreement that the undescribed form is a clearly circumscribed species, that work is underway to formally describe the species, that voucher material is available and that there is a clear conservation benefit in listing the undescribed form (IUCN 2017). The currently undescribed Kaputar Pink Slug met all of these requirements and was listed on the *IUCN Red List* in 2014 (Murphy 2014). The Kaputar Keeled Snail has been recognised as a valid undescribed species by Australian malacological experts and has been assigned a morphospecies code. However, while voucher material is available and listing would contribute to promoting the conservation of the taxon, no formal description of the species is currently underway, a reflection of the very large number of Australian land snails known to be awaiting description and the scarcity of malacologists able to undertake this work. Undescribed species of conservation concern should be a priority for taxonomic workers.

CONCLUSION

On the basis of the above, the Kaputar Pink Slug, Bronze Rippled Pinwheel Snail, Kaputar Carnivorous Snail and Kaputar Keeled Snail are all assessed as *endangered B1ab(i,ii,iii)+2ab(i,ii,iii)* under the IUCN criteria (IUCN 2017). This is consistent with the previous assessment for the Kaputar Pink Slug (Murphy 2014) but would be an elevation from the previous category of *data deficient* for the Bronze Rippled Pinwheel Snail (Mollusc Specialist Group 1996). All four taxa are narrow-range endemics with highly restricted relictual distributions and are threatened by anthropogenic climate change, frequent fire, feral pigs and habitat loss and fragmentation. As noted above, formal taxonomic description is required for two of the species.

The vividly-coloured Kaputar Pink Slug has significant public appeal as an iconic flagship species for recognition of the major global threat to biodiversity posed by anthropogenic climate change. IUCN listing of additional Mount Kaputar land snail species as recommended here would assist in promoting recognition of the significant conservation value of Mount Kaputar and similar volcanic high-elevation climatic refuges for Australia's unique land snail fauna.

ACKNOWLEDGEMENTS

Thanks to Anton Groeneveld and Michael Heinze for providing slug records and Michael Shea for providing Figure 2B.

REFERENCES

Annegret, N. and Ansart, A. (2017). Conservation at a slow pace: terrestrial gastropods facing fast-changing climate. *Conservation Physiology* 5(1), cox007. DOI 10.1093/conphys/cox007

Atlas of Living Australia website at http://www.ala.org.au. Accessed 29 July 2018.

Baur, A. and Baur, B. (1990). Are roads barriers to dispersal in the land snail *Arianta arbustorum*? *Canadian Journal of Zoology* **68**, 613-617.

Baur, A. and Baur, B. (2013). Snails keep the pace: shift in upper elevation limit on mountain slopes as a response to climate warming. *Canadian Journal of Zoology* **91**, 596-599.

Beltramino, A.A., Vogler, R.E., Gutiérrez Gregoric, D.E. and Rumi, A. (2015). Impact of climate change on the distribution of a giant land snail from South America: predicting future trends for setting conservation priorities on native malacofauna. *Climatic Change* **131(4)**, 621-633.

Brereton, R., Bennett, S. and Mansergh, I. (1995). Enhanced greenhouse climate change and its potential effect on selected fauna of south-eastern Australia: a trend analysis. *Biological Conservation* **72(3)**, 339-354. DOI 10.1016/0006-3207(94)00016-J

Burton, D.W. (1980). Anatomical studies on Australian, New Zealand and sub-Antarctic Athoracophoridae (Gastropoda: Pulmonata). *New Zealand Journal of Zoology* **7**, 173-198.

Couper, P.J. and Hoskin, C.J. (2008). Litho-refugia: the importance of rock landscapes for the long-term persistence of Australian rainforest fauna. *Australian Zoologist* **34(4):** 554-560.

Green, K., Stein, J.A. and Driessen, M.M (2008). The projected distributions of *Mastacomys fuscus* and *Rattus lutreolus* in south-eastern Australia under a scenario of climate change: potential for increased competition? *Wildlife Research* **35(2)**, 113-119. DOI 10.1071/WR07055

Herbert, D. and Kilburn, D. (2004). *Field Guide to the Land Snails and Slugs of Eastern South Africa*. Natal Museum, Pietermaritzburg, South Africa.

Hughes, L. (2003). Climate change and Australia: Trends, projections and impacts. *Austral Ecology* **28(4)**, 423-443. DOI 10.1046/j.1442-9993.2003.01300.x

Hunter, J.T. and Alexander, J. (2000). Vegetation and floristics of Mount Kaputar National Park (central and northern portions). Unpublished report to NSW National Parks and Wildlife Service, Narrabri, NSW, Australia.

Hyman, I.T. and Stanisic, J. (2005) New charopid land snails chiefly from limestone in eastern New South Wales. *Memoirs of the Queensland Museum* **50**, 219-302.

International Union for the Conservation of Nature (2012). *IUCN Red List Categories and Criteria Version 3.1 2nd edition.* Available online at: http://www.iucnredlist.org. Accessed 24 February 2019.

International Union for the Conservation of Nature (2017). *Guidelines for Using the IUCN Red List Categories and Criteria* (Version 13). Prepared by the Standards and Petitions Subcommittee. Available online at: http://www.iucnredlist.org/documents/RedListGuidelines.pdf. Accessed 24 February 2019.

Kiss, L. and Magnin, F. (2003) The impact of fire on some Mediterranean land snail communities and patterns of post-fire recolonization. *Journal of Molluscan Studies* **69**, 43-53.

Laurance, W.F., Dell, B., Turton, S.M., Lawes, M.J., Hutley, L.B., McCallum, H., Dale, P., Bird, M., Hardy, G., Prideaux, G., Gawne, B., McMahon, C.R., Yu, R., Hero, J.-M., Schwarzkopf, L., Krockenberger, A., Setterfield, S.A., Douglas, M., Silvester, E., Mahony, M., Vella, K., Saikia, U., Wahren, C.-H., Xu, Z., Smith, B. and Cocklin, C. (2011). The 10 Australian ecosystems most vulnerable to tipping points. *Biological Conservation* **144**, 1472-1480.

Martin, H.A. (2006) Cenozoic climatic change and the development of the arid vegetation in Australia. *Journal of Arid Environments* **66**, 533-563.

Mollusc Specialist Group (1996). *Cralopa kaputarensis*. The IUCN Red List of Threatened Species 1996. DOI 10.2305/IUCN.UK.1996.RLTS.T5469A11175761.en. Downloaded on 27 July 2018.

Murphy, M.J. (2007). The diverse land snail community of Bruxner Park on the north coast of New South Wales, Australia. *The Victorian Naturalist* **124(5)**, 306-309.

Murphy, M. (2014). *Triboniophorus* sp. nov. "Kaputar". *The IUCN Red List of Threatened Species 2014*. DOI 10.2305/IUCN.UK.2014-3.RLTS.T55242781A55243154.en. Downloaded on 24 February 2019.

Murphy, M.J. and Shea, M. (2015). Survey of the land snail fauna (Gastropoda: Pulmonata) of Mount Kaputar National Park in northern inland New South Wales, Australia, including a description of the listing of Australia's first legally recognised endangered land snail community. *Molluscan Research* **35(1)**, 51-64.

NSW National Parks and Wildlife Service (2006). Mount Kaputar National Park Plan of Management. NSW National Parks and Wildlife Service, Sydney, NSW. Available online at https://www.environment.nsw.gov.au. Downloaded on 10 August 2018.

Parkyn, J., Challisthianagara, A., Brooks, L., Specht, A., McMullan-Fisher, S. and Newell, D. (2015). The natural diet of the endangered camaenid land snail *Thersites mitchellae* (Cox, 1864) in northern New South Wales, Australia. *Australian Zoologist* **37:** 343-349.

Parkyn, J. and Newell, D.A. (2013). Australian land snails: a review of ecological research and conservation approaches. *Molluscan Research* **33**, 116-129.

Pearce, T.A. and Paustian, M.E. (2013). Are temperate land snails susceptible to climate change through reduced altitudinal ranges? A Pennsylvania example. *American Malacological Bulletin* **31(2)**, 213-224. DOI 10.4003/006.031.0201.

Ponder, W.F. (1997). Conservation status, threats and habitat requirements of Australian terrestrial and freshwater mollusca. *Memoirs of the Museum of Victoria* **56(2)**, 421-430.

Porteners, M.F. (1997). Vegetation survey of sub-alpine communities in Mount Kaputar National Park. Unpublished report to NSW National Parks and Wildlife Service, Narrabri, NSW, Australia.

Porteners, M.F. (1998). Vegetation survey of Mount Kaputar National Park (southern portion). Unpublished report to NSW National Parks and Wildlife Service, Narrabri, NSW, Australia.

Reside, A.E., Welbergen, J.A., Phillips, B.L., Wardell-Johnson, G.W., Keppel, G., Ferrier, S., Williams, S.E. and Vanderwal, J. (2014). Characteristics of climate change refugia for Australian biodiversity. *Austral Ecology* **39(8):** 887-897.

Santos, X., Bros, V. and Mino, A. (2009). Recolonization of a burned Mediterranean area by terrestrial gastropods. *Biodiversity and Conservation* **18**, 3153. DOI 10.1007/s10531-009-9634-2.

Shea, M. (1992) Some land snails of the Warrumbungles. *Sydney Sheller* **August 1992**, 9.

Shoo, L.P., Storlie, C., Williams, Y.M. and Williams, S.E. (2010). Potential for mountaintop boulder fields to buffer species against extreme heat stress under climate change. International Journal of Biometeorology **54(4)**, 475-478. DOI 10.1007/s00484-009-0286-4.

Slatyer, C., Ponder, W., Rosauer, D. and Davis, L. (2007). Between a rock and a dry place: land snails in arid Australia. In: Dickman, C., Lunney, D. and Burgin, S. (Eds), *Animals of Arid Australia: out on their own?* Transactions of the Royal Zoological Society of New South Wales, Mosman, NSW, pp. 30-41.

Smith, B.J. (1992). *Zoological Catalogue of Australia Vol. 8: Non-Marine Mollusca*. Australian Government Publishing Service, Canberra.

Stanisic, J. (1990). Systematics and biogeography of eastern Australian Charopidae (Mollusca, Pulmonata) from subtropical rainforests. *Memoirs of the Queensland Museum* **30**, 1-241.

Stanisic, J. (1994). The distribution and patterns of species diversity of land snails in eastern Australia. *Memoirs of the Queensland Museum* **36**, 207-214.

Stanisic, J. (1997). An area of exceptional land snail diversity; the Macleay valley, north-eastern New South Wales. *Memoirs of the Museum of Victoria* **56(2)**, 441-448.

Stanisic, J. and Ponder, W.F. (2004). Forest snails in eastern Australia – one aspect of the other 99%. Pp. 127-149 in *Conservation of Australia's Forest Fauna* (2nd edition). Edited by D. Lunney. Royal Zoological Society of NSW, Mosman, NSW.

Stanisic, J., Shea, M., Potter, D. and Griffiths, O. (2010) *Australian Land Snails Volume 1: A Field Guide to Eastern Australian Species*. Bioculture Press, Mauritius.

Stanisic, J., Shea, M., Potter, D. and Griffiths, O. (2017) *Australian Land Snails Volume 2: A Field Guide to Southern, Central and Western Species*. Bioculture Press, Mauritius.

Suppiah, R., Hennessy, K.J., Whetton, P.H., McInnes, K., Macadam, I., Bathols, J., Ricketts, J. and Page, C.M. (2007). Australian climate change projections derived from simulations performed for the IPCC 4th Assessment Report. *Australian Meteorological Magazine* **56**, 131-152.

Sutherland, F.L. (2011). Diversity within geodiversity, underpinning habitats within New South Wales volcanic areas. *Proceedings of the Linnean Society of New South Wales* **132**, 37-54.

Taylor, D.L., Leung, L.K.-P. and Gordon, I.J. (2011). The impact of feral pigs (*Sus scrofa*) on an Australian lowland tropical rainforest. *Wildlife Research* **38**, 437-445.

Wallin, H. (1991). Movement patterns and foraging tactics of a caterpillar hunter inhabiting alfalfa fields. *Functional Ecology* **5**, 740-749.

Biodiversity and Endemism within the Mount Canobolas Volcanic Complex

Richard W. Medd[1] and **Colin C. Bower**[2]

[1]593 Cargo Road, Orange NSW 2800 (dickmedd@yahoo.com.au);
[2]FloraSearch, PO Box 300, Orange NSW 2800 (colbower@bigpond.net.au)

Medd, R.W. and Bower, C.C. (2019). Biodiversity and endemism within the Mount Canobolas volcanic complex. *Proceedings of the Linnean Society of New South Wales* **141**, S45-S83.

Mt Canobolas State Conservation Area (SCA) hosts a small remnant of sub-alpine vegetation consisting of seven recognisable communities with the heathlands on the rock plates appearing to be unique to the SCA. The SCA has a known biota of 884 native species that includes 14 threatened species and at least 10 endemic taxa. Some 200 species are regionally significant, being either rare or at the limits of known geographic range. The vascular flora is particularly species-rich being considerably more diverse than nearby regional reserves and over 12 fold richer than comparable areas of the Kosciusko National Park. One of three endangered ecological communities, the Mt Canobolas *Xanthoparmelia* Lichen Community, is unique to the volcanic province.

While there is some indication the endemic lithophytic lichens, the threatened *Eucalyptus canobolensis* and the heath communities may be substrate specific, there is no strong evidence of a geological association among other flora and fauna. We postulate that the presence of multiple endemic species reflects the geographic isolation which has provided an environment for species evolution by vicariance. Alternatively, Mt Canobolas has acted as a refugium for formerly widespread species that have become extinct elsewhere.

Manuscript received 14 April 2019, accepted for publication 1 October 2019.

KEYWORDS: Central Tablelands, endemic, evolution, inselberg, refugium, sub-alpine, vicariance

INTRODUCTION

Mount Canobolas is an extinct intraplate alkaline volcano (Middlemost 1981; Sutherland 2003; 2011), provincially known as The Mount Canobolas Volcanic Complex (MCVC). Extensive eruptions in probably three main episodes occurred over ± 1 million years in the Middle to Early/Late Miocene, between 13 to 11 mya (Branagan and Packham 2000). Mt Canobolas is the southernmost and youngest central volcano on the Bunya Mountains to Canobolas hotspot track (Sutherland 2003; Davies et al. 2015), also known as the Inland Hotspot Track, which includes the Nandewar Volcanic Suite and Mt Kaputar, and the Warrumbungle Ranges. Each central volcano in this chain formed tall isolated cone-shaped mountains that rose up to 2,500 m above the surrounds with lava spreading up to 80 kilometres from the source. The MCVC initially produced large outpourings of basic lava, of mainly hawaiitic composition, which radiated across the landscape. Subsequent eruptions of felsic domes and copious amounts of pyroclastic material coincided with the extrusion of more mafic trachyte kindred lavas, which comprise the volcanic pile of domical landforms in the central core (Middlemost 1981). The evidence of interlaced lavas and associated ash of various eruptions provides a complex heterogeneous matrix within the central core area, which Middlemost (1981) contends is difficult to unravel because rocks from different events are juxtaposed by volcanic subsidence.

Before the Miocene volcanism the ancient geologies, particularly of the Lachlan Fold Belt which is provincial to the Central West (CW) of NSW, underwent major tectonic events from the Silurian to Early Carboniferous epochs (Foster and Gray 2000). It remains unclear if broad uplift which occurred during these orogenic events gave rise to the eastern highlands or if they are remnants of an even older orogenic mountain range (Branagan and Packham 2000). In any event, there has been significant erosion of both the central volcanoes and adjoining highlands over the last 10 to 25 million years. As a consequence, the volcanic provinces along the chain have decreased in size and altitude, and increased in isolation from each other, with resultant fragmentation into pockets of alpine and sub-alpine areas on high peaks. Mt Canobolas being the youngest and smallest volcano is now the most intact, prominently protruding as a 'landlocked island' up to half a kilometre above the surrounding plateau of the western Central Tablelands (CT). Mt Canobolas ranges in altitude from c. 900 m to 1,397 m at the summit with several peaks, steep valleys and waterfalls (NPWS 2003a). It is surrounded by highlands having variable relief of up to 1,000 m altitude of the extensive CT plateau but dips away to the west into the Central Western Slopes (CWS). The boundary between the CT and CWS is an undulating series of erosional step-down scarps.

Situated on the western boundary of the CT, the MCVC is separated from coastal drainage by the Great Divide (GD), c. 120 km to the east. The western CT can be regarded as a western trending spur of the GD. The so-called Canobolas Divide is a north-west trending range and passes through the centre of the MCVC, forming the watershed dividing the inland drainage of the northern Macquarie-Darling River system from the southern Lachlan River system (Chan 2003). The different constructional landforms that have evolved from the tempestuous geological past have given rise to polymorphic drainage patterns and microclimates around the mountain. The high altitudes dictate a climate of the mountain's own making and the geology provides a geodiversity not found elsewhere in the region (Branagan and Packham 2000). Also, Mt Canobolas supports a significant isolated remnant of vegetation with montane and sub-alpine affinities; the only such area of this ecosystem on the western CT. Much of the high altitude remnant vegetation is contained within the Mt Canobolas State Conservation Area (SCA) covering an area of 1,672 ha (NPWS 2003a) which is situated within the South Eastern Highlands Bioregion in the Interim Biogeographic Regionalisation for Australia (IBRA) sub-region of Orange (NPWS 2003b).

Mt Canobolas shares many characteristics with Mt Kaputar. Both were produced by the same magma source on the Inland Hotspot Track with Mt Kaputar arising some seven million years earlier. Like Mt Canobolas, the summit of Mt Kaputar supports remnant montane and sub-alpine plant communities that are isolated by large distances from other occurrences of these vegetation types on the Northern Tablelands along the GD to the east. The biota of Mt Kaputar includes some 18 species (8 plants and 10 invertebrates, mainly molluscs) considered to be endemic to the mountain (OEH 2018a; Murphy and Shea 2015). Given the similar geology, geographical isolation, high altitudes, and remnant montane and sub-alpine vegetation, it seems plausible that Mt Canobolas may similarly host a range of unique endemic life forms.

However, there has been no comprehensive documentation of the biodiversity of the MCVC, with knowledge of the mountain's biota confined to a limited number of scientific publications and records of opportunistic specimen collections in various institutional and national databases. Accordingly, the biodiversity of Mt Canobolas is poorly known and its scientific significance and conservation value has not been widely appreciated.

The purpose of this paper is to compile for the first time a record of the biodiversity of the Mt Canobolas SCA which covers the core of the MCVC. Emphasis is given to identifying the endemic species and discussing the importance of the area for speciation by vicariance and as a refugium for montane and sub-alpine taxa. The possibility of rare species being linked to a previously more coherent volcanic continuum, allowing the movement of biota along it, is also considered.

MATERIALS AND METHODS

Species lists, arranged by family, of the main components of biodiversity known for the SCA have been compiled mainly from literature sources and the Atlas of Living Australia database (ALA 2018). For plants, recordings were compiled from the Australasian Virtual Herbarium (AVH 2018) as these are based on specimen records held in herbaria, as well as from the literature (Hunter 2002), personal observations by the authors and other recent surveys (M. Porteners pers. comm.). Fungi and invertebrate records from the Biosecurity Collections Unit, NSW Department of Primary Industries at Orange, have been included.

Records of endemics and threatened species were extracted from these data lists. The distribution of each plant and fungal species was examined in the AVH/ALA distribution maps to determine core range limits, with outliers that occur distant to the MCVC noted. Data for vascular plant species occurring in 22 other conservation reserves located within the near CW have also been extracted from BioNet (2018a) to use comparatively. Physiographic data from individual reserve Plans of Management and other sources have also been compiled for each of the reserves. The near CW is defined as within c. 150 km west of the GD Range summit. Most of these reserves are situated within or in close proximity to the CT Botanical Subdivision (Anderson 1961). The western portions of the large Wollemi and Blue Mountain NPs falling within the CT have not been considered.

No published vegetation classification currently exists for the CT west of the Blue Mountains. The only classification available for this area is the online BioNet Vegetation Classification (BVC) (OEH 2018b) which is derived from cluster analysis of data from multiple surveys conducted by government and consultant botanists. The survey data is published and accessible online in the BioNet Vegetation Classification application (OEH 2018b). The output vegetation associations (Plant Community Types [PCT]) are vetted by the Plant Community Type Change Control Panel to ensure its reliability and robustness (OEH 2018b). The BVC supports a state-wide environmental assessment regulatory regime.

For this study, montane and sub-alpine vegetation communities described by Hunter (2002) in the Mt Canobolas SCA were compared with PCTs currently recognised in similar habitats on the Great Dividing Range over 100 km to the east (BioNet 2018b). BioNet (2018b) assigns PCTs to threatened ecological communities (TEC) and the conformity of the relevant PCT on the mountain to each TEC was checked against the community description in the Final Determination (Scientific Committee 2018).

Comments on data accuracy, points of interest about species and threatened communities are provided.

RESULTS AND DISCUSSION

The SCA occupies the core of the MCVC consisting predominately of trachyte kindred rocks and encompasses the high altitude components of the primary ecosystem remnants. Few orders or classes of biota have been systematically surveyed by specialists on Mt Canobolas and much of the data available has not been formally published. Consequently, substantial listings of species have been published only for the bryophytes (Downing et al. 2002) and vascular plants (Hunter 2002). Other non-commissioned surveys of lichens, birds, reptiles, amphibians and mammals have also been undertaken with results recorded only in online databases. The currently known native biota of the SCA consists of 884 species, however systematic surveys have not occurred for many groups so the figure is likely to underestimate the overall numbers. Current knowledge of each major grouping is summarised below. Reference is also made to some of the most important publications for Mt Canobolas relating to taxonomic works describing new species endemic to the mountain.

Vegetation Communities

Hunter (2000; 2002) defined seven vegetation communities within the SCA (Fig. 1). The significance of these is discussed in relation to similar high altitude vegetation types on the GD to the east (Table 1). One Endangered Ecological Community (EEC) and one Critically Endangered Ecological Community (CEEC) are represented.

Community 1. Stringybark–Peppermint Shrubby Open Forests and Woodlands

Covering around 26% of the SCA in areas above 1000 m altitude, this community is characterised by predominantly *Eucalyptus macrorhyncha* and *E. dives,* in association with *E. canobolensis, E. pauciflora, E. dalrympleana* subsp. *dalrympleana, Acacia dealbata, A. melanoxylon* and *Exocarpos cupressiformis.* It has a well-developed shrub layer and ground cover of herbs and grasses. Hunter (2002) states the occurrence within the SCA is significant due to the unusual assortment of associated species, and the community is at its north western geographic limit of occurrence. Hunter's observation that this community, which principally occurs on upper slopes and ridgetops around the peripheral areas of the SCA (Fig. 1), has an unusual assemblage of tree species is pertinent. There are no PCTs in the BioNet Vegetation Classification database (BioNet 2018b) that closely match it. Most recognised PCTs dominated by *E. macrorhyncha* and *E. dives* occur in drier environments than on Mt Canobolas as reflected in their understory shrubs and grasses. The closest PCT in BioNet (2018b) is PCT 730, which does not include *E. canobolensis* as a dominant.

Communities 2 and 4. Outcrop Heaths and Shrublands / Outcrop Low Open Woodlands

These two closely similar communities (Table 1) are found on skeletal soils on rock outcrops. Together they occupy some 6% of the SCA, occurring as small highly disjunct patches throughout (Fig. 1). The main difference between the two is that Community 2 lacks trees. Community 4 may have scattered trees of *E. canobolensis*, *E. bridgesiana* and *A. dealbata.* In both communities the shrubs are scattered and depauperate, although sometimes forming dense thickets, and occur in association with cryptogams, scattered herbs and grasses. These rock outcrops contain the endangered Mt Canobolas *Xanthoparmelia* lichen community.

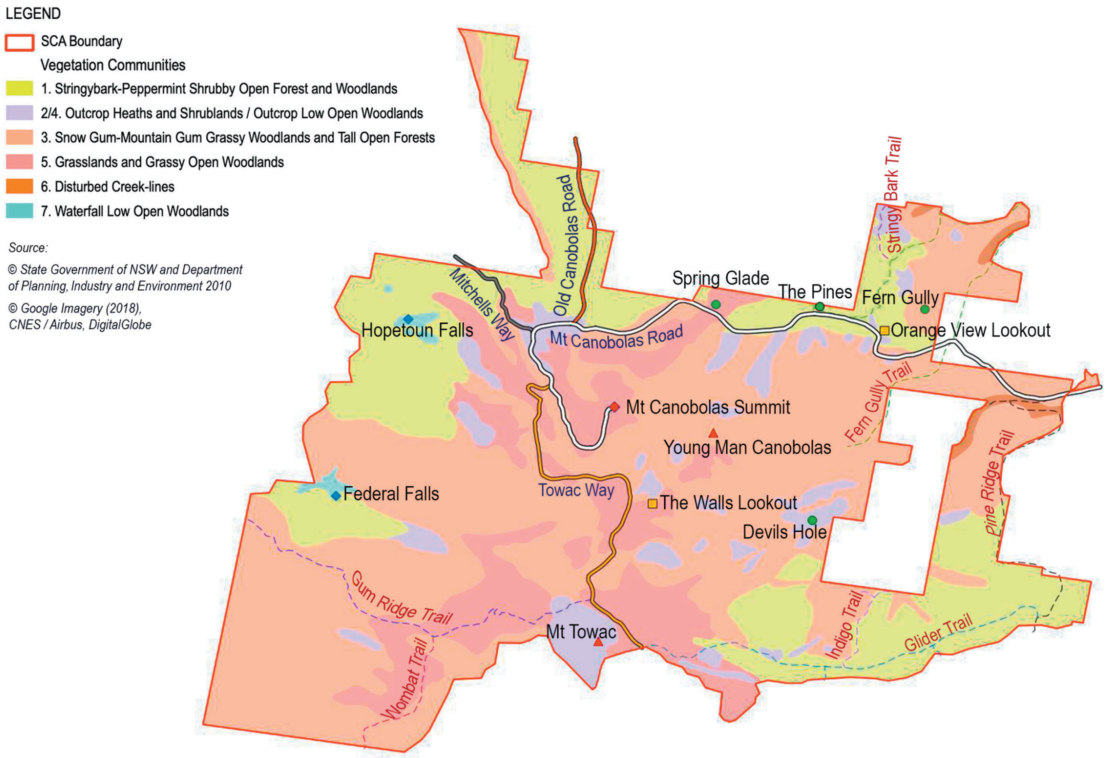


Figure 1. Vegetation communities occurring within the Mt Canobolas State Conservation Area (after Hunter 2002).

Hunter (2002) considers these communities to be restricted to the SCA and unique. No floristically similar heathlands are recognised as PCTs in the BioNet Vegetation Classification (BioNet 2018b).

Community 3. Snow Gum-Mountain Gum Grassy Woodland and Tall Open Forest

This community occupies some 52% of the SCA (Fig. 1) and occurs above 900 m altitude. It is characterised by predominantly *E. pauciflora, E. dalrympleana* subsp. *dalrympleana*, and *E. canobolensis* in association with *E. dives, E. macrorhyncha, E. viminalis* and *A. dealbata*. It has a well-developed layer of low and tall shrubs and a dense ground layer of 80 to 100% cover of climbers and trailers, herbs and grasses. PCT 1197 is closest to community 3 (Table 1).

Community 5. Grasslands and Grassy Open Woodlands

Trees are a minor component of this community which occurs above 1200 m altitude and occupies around 15% of the SCA area (Fig. 1). It is characterised by low densities of *E. pauciflora, E. canobolensis, E. dalrympleana* subsp. *dalrympleana, A. dealbata* and *A. melanoxylon*. The shrub layer is of low stature and sparse or absent whereas the ground layer of twiners, herbs and grasses is well developed. This assemblage is most similar to PCT 1197 in the BioNet Vegetation Classification (BioNet 2018b) (Table 1).

Community 6. Disturbed Creek-lines

Occupying about 1% of its area this community occurs in the north eastern lower reaches of the SCA (Fig. 1). It is characterised by tall open stands of *E. viminalis, E. stellulata, E. pauciflora, E. dalrympleana* subsp. *dalrympleana* and *A. melanoxylon* with a scattered to dense shrub layer, ferns and herbs. This assemblage is most similar to PCT 1191 that is dominated by *E. viminalis, E. pauciflora*, *E. rubida* and *E. stellulata* (BioNet 2018b). Within the SCA, *E. rubida* (Candlebark) is replaced by the threatened *E. canobolensis* (Silver-leaf Candlebark).

Community 7. Waterfall Low Open Woodlands

This community is restricted to locations at Federal and Hopetoun Falls, occupying less than 1% of the SCA (Fig. 1). It is an open shrubland community with occasional stunted trees of *Eucalyptus goniocalyx, E. canobolensis* and *A. melanoxylon*

Table 1. Vegetation Communities in the Mt. Canobolas State Conservation Area.

Hunter (2002)	Dominant Eucalypts and/or shrubs	Nearest PCT[1]	EEC[2]	Comment
1. Stringybark – Peppermint Shrubby Open Forests and Woodlands	*E. macrorhyncha, E. canobolensis, E. dives, E. dalrympleana*	730. Broad-leaved Peppermint - Mountain Gum dry open forest of the Central Tablelands area of the South Eastern Highlands Bioregion	Tableland Basalt Forest in the Sydney Basin and South Eastern Highlands Bioregions	Although PCT 730 is closest to community 1, it is a dry forest type with sparser grass cover than the moist community on Mt Canobolas.
2. Outcrop Heaths and Shrublands	*Mirbelia oxylobioides, Calytrix tetragona, Kunzea parvifolia, Phebalium* sp.	N/A	-	No currently listed PCTs resemble this community.
3. Snow Gum – Mountain Gum Grassy Woodlands and Tall Open Forests	*E. pauciflora, E. dalrympleana*	1197. Snow Gum – Mountain Gum tussock grass-herb forest of the South Eastern Highlands Bioregion	Tableland Basalt Forest in the Sydney Basin and South Eastern Highlands Bioregions	
4. Outcrop Low Open Woodlands	*E. canobolensis, E. bridgesiana / Mirbelia oxylobioides, Calytrix tetragona, Phebalium* sp.	N/A	-	This community occurs on similar sites to community 2, albeit with slightly more soil and scattered tree cover. No currently listed PCTs resemble this community.
5. Grasslands and Grassy Open Woodlands	*E. pauciflora, E. canobolensis, E. dalrympleana*	1197. Snow Gum – Mountain Gum tussock grass-herb forest of the South Eastern Highlands Bioregion	Tableland Basalt Forest in the Sydney Basin and South Eastern Highlands Bioregions	
6. Disturbed Creek-lines	*E. viminalis, E. stellulata, E. pauciflora*	1191. Snow Gum – Candlebark woodland on broad valley flats of the tablelands and slopes, South Eastern Highlands Bioregion	-	This community is similar to the Monaro Tablelands Cool Temperate Grassy Woodland in the South Eastern Highlands Bioregion CEEC[3].
7. Waterfall Low Open Woodlands	Minor *E. goniocalyx*, *E. canobolensis*	N/A	-	A minor community related to communities 2 and 4.

[1] PCT = Plant Community Type (OEH 2018b)

[2] EEC = Endangered Ecological Community listed under the *Biodiversity Conservation Act 2016.*

[3] CEEC = Critically Endangered Ecological Community listed under the *Biodiversity Conservation Act 2016.*

in shallow soils around the falls' margins and often with taller *E. viminalis* near the base of the falls. This community is of very limited extent and it is doubtful that it deserves recognition as an entity distinct from the surrounding vegetation (Table 1).

Communities 1, 3 and 5 conform to the *Tableland Basalt Forest in the Sydney Basin and South Eastern Highlands Bioregions Endangered Ecological Community*. This EEC is generally a tall montane forest dominated by *Eucalyptus dalrympleana* (Mountain Gum) and *E. pauciflora* (Snow Gum) (Scientific Committee 2008). It is known to occur between 600 and 900 m altitude on the eastern parts of the CT. On Mt Canobolas, Tableland Basalt Forests occur extensively as tall open forests in valleys and on ridges in deep volcanic soils above 900 m altitude, hence representing a high altitude variant of the EEC on the western CT.

Community 6 closely resembles the newly recognised *Monaro Tableland Cool Temperate Grassy Woodland in the South Eastern Highlands Bioregion Critically Endangered Ecological Community*, which is predicted by the NSW Office of Environment and Heritage (OEH) to occur in the Orange district (OEH 2019a).

Bryophytes

Bryophytes include mosses, liverworts and hornworts. They are often referred to as 'lower plants' and form an important component of the vegetation but are regularly overlooked in biological surveys.

A rich and diverse mix of 79 species of bryophytes is recorded for Mt Canobolas in 29 families and 51 genera (Table 2), mostly from an initial survey by Downing et al. (2002).

Although no endemic bryophyte species are recorded, the assemblage includes an unusual mix of alpine, arid zone and rainforest species, with 6 species being at their northern range limits and 7 at their westernmost range. Exposed rock platforms with seepage areas on the upper flanks of the mountain are particularly species-rich. The geology of the area is complex and Downing et al. (2002) considered the presence of certain species at particular locations is probably determined by the chemical composition of the substrate rock, although clear patterns could not be discerned. Downing et al. (2002) gave an example of a curious combination of two opposed species growing together: *Encalypta vulgaris*, a calcicole (i.e. a species found only on calcareous substrates) and *Campylopus introflexus*, a calcifuge (i.e. a species never found growing on calcareous substrates). Around the summit some rare alpine species previously known only from Yarrangobilly Caves in the Alps and Kosciuszko National Park occurred together with species from the arid zones to the west. Elsewhere in the SCA in a cool moist and shady gully habitat a thallose epiphytic liverwort occurred; a species usually associated with rainforest gullies of the coast and coastal ranges to the east. Other rare and uncommon mosses, liverworts and hornworts are highlighted in their manuscript. It is unclear if the disjunct and rare species consisting of contiguous arid zone, alpine and rainforest specialists are stranded relics from past climatic ages or whether such species have arrived through superior long-distance dispersal abilities.

Downing et al. (2002) also noted several rare and uncommon species occurred on roadside banks, walking trail margins, fallen logs, on rough basal bark of eucalypts and exposed rocks in the grassy woodlands, which elsewhere in NSW are usually devoid of bryophytes. The bryoflora of the nearby Towac Pinnacle outcrop, to the east of the SCA, was found to include a few species that were either not recorded or uncommon within the SCA, indicating that other species may well occur on the many volcanic outcrops, dykes, domes and plugs comprising the MCVC.

Vascular plants

Vascular plants constitute the largest component of the currently known biota within the SCA. Some 14 fern, 138 monocotyledon and 262 dicotyledon species are present (Table 2). The diversity spans 78 families and 228 genera (Appendix 1). Almost half of the 416 vascular plants are assigned to just 6 superfamilies, namely Asteraceae (47), Cyperaceae (18), Fabaceae (35), Myrtaceae (14), Orchidaceae (40) and Poaceae (47). A number of the species listed by Hunter (2002) cannot be substantiated and so have been excluded from the compilation.

Approximately 60% of the vascular flora species occurring in the SCA can be considered generalists in the sense that they have widespread distribution and display plasticity in being adaptable to a wide range of edaphic, climatic and other environmental variables. As Hunter (2000) observed, these species are generally the most common ones and are found in most of the communities. The remaining flora exhibits varying degrees of specialisation from narrow endemic species to regionally significant species.

Among the plants are at least five endemic species: *Prostanthera gilesii* (Conn and Wilson 2015), *Eucalyptus canobolensis* (Hunter 1998), *Bulbine* sp. (J. Bruhl pers. comm.), *Caladenia* sp. aff. *patersonii* and *Prasophyllum* sp. aff. *odoratum* (D. Jones pers. comm.). Other taxa, including the herb

Table 2. Summary of known biodiversity within the Mt Canobolas State Conservation Area.

Biodiversity	Families	Genera	Native species	Exotic species	Endemic species	Regionally significant species	EEC[1]	TS[2]
Vegetation communities							2	
Bryophytes	29	51	79			13		
Gymnosperms	2	2	1	1				
Ferns and Allies	6	11	14			5		
Monocotyledons	12	61	121	17	3 +	39		
Dicotyledons	58	154	192	70	2 +	76		2
Fungi	28	47	102	1	4	46	1	
Mammals	19	30	29	9		5		5
Birds	35	69	97	2				7
Amphibians	3	4	5					
Reptiles	4	15	20			5		
Fish	1	1	1					
Molluscs	6	10	10	2	?	8		
Insects	81	154	210 +		?			
Velvet worms	1	1	1		1	1		
Flat worms	1	2	2		?	2		
TOTAL	286	612	884 +	102	10 +	200	3	14

[1] Endangered Ecological Communities listed under the *Biodiversity Conservation Act 2016.*

[2] Threatened Species listed under the *Biodiversity Conservation Act 2016* and/or *Commonwealth Environment Protection and Biodiversity Conservation Act 1999*

Craspedia sp. aff. *lamicola* and shrubs in the genera *Asterolasia, Melichrus* and *Phebalium* are likely also to be endemics (I. Telford and J. Bruhl pers. comm.), along with two recently found orchids *Diuris* sp. aff. *chryseopsis* and *Dipodium* sp. aff. *atropurpureum* (Bower 2019).

Two of the endemic plants *P. gilesii* and *E. canobolensis* are listed as threatened (Table 2). The shrub *P. gilesii* (formerly *P*. sp. C) (Giles' Mintbush) is only known from two small colonies and is listed as Critically Endangered under the BC Act 2016 (Scientific Committee 2017). *E. canobolensis* (syn. *E. rubida* subsp. *canobolensis*) (Silver-leaf Candlebark) occurs throughout the SCA and is endemic to the MCVC. Its stronghold is above 1,000 m altitude within the SCA but it occurs sporadically down to ± 900 m altitude on the slopes surrounding the mountain. With a propensity to form hollows, the species provides valuable nesting and roosting habitat as well as copious manna exudate as a food source for arboreal mammals and birds. It is listed as Vulnerable under the BC Act and Endangered under the EPBC Act (Department of the Environment 2008).

The sub-alpine forests and woodlands support 11 eucalypt species as canopy dominants and a broad array of understory shrubs, forbs and grasses, totalling 416 species. Approximately 120 of these can be considered as regionally significant because of their rarity or because they are at their geographical range limits within the CT. By comparison, 475 plant species occur in an area of almost 23,000 ha of montane forests occurring between 1,000 and 1,400 m altitude within Kosciuszko National Park (Doherty et al. 2015). The richness of the flora of the SCA is over 12 fold that of Kosciuszko NP, being almost 260 species per 1,000 ha compared with 20.6

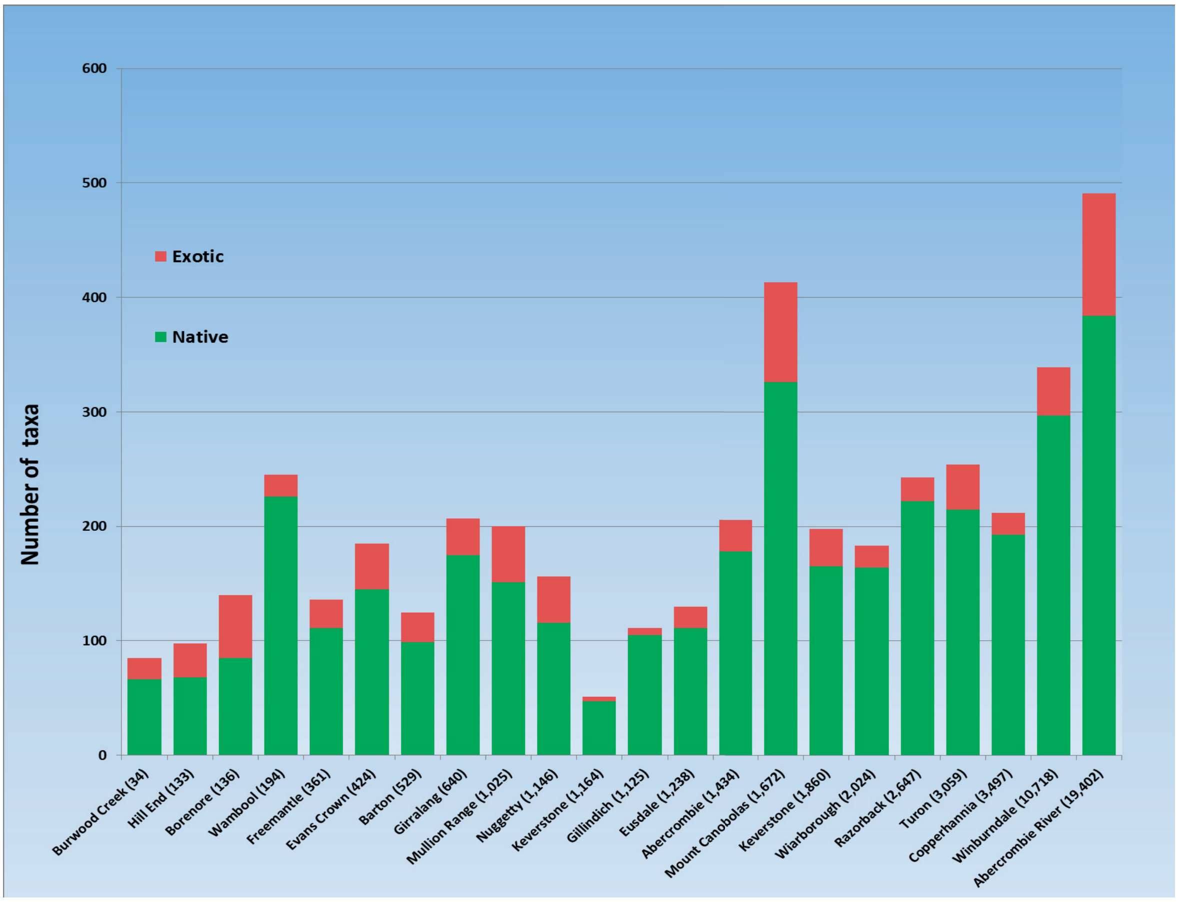


Figure 2. Number of native and exotic vascular plant species recorded for 22 conservation reserves (arranged by increasing area) in the near (eastern) Central West of NSW. Numbers in parentheses following reserve names indicated the area (ha) of each. Data from Bionet (2018a, see Appendix 2).

species per 1,000 ha respectively. Compositionally there are also differences in the floras with the ratio of dicotyledons to monocotyledons being lower in the SCA with 1.6:1 compared with 2.8:1 in Kosciuszko NP. No endemic species occur in the montane forests of Kosciuszko NP and 105 species, which are either disjunct or occurring at their geographic range limits is proportionally much lower than the 120 species for the SCA. In both reserves however, the dicotyledons were similarly dominated by taxa in the Asteraceae, Fabaceae and Myrtaceae and monocotyledons by Cyperaceae, Orchidaceae and Poaceae.

A rich and eclectic suite of 40 terrestrial orchid species occurs within the SCA (Appendix 1). A number of these orchids are unnamed and currently subject to further examination. At least one of these, *Prasophyllum* sp. aff. *odoratum*, recorded after a summer fire in 1982 and again in 2018, is considered to be a fire ephemeral (Bower 2019). Twenty-one orchid species are rare, confined to or at their geographic range limits in the SCA (Appendix 1). The SCA ranks among the most diverse areas for orchids in the near CW along with the Calula Range north of Orange where some 60 species occur (C. Bower pers. obs.), Wambool NR with at least 47 species and Abercrombie Karst Conservation Reserve with 30 or more species (Bionet 2018a). Terrestrial Orchids are intrinsically important as bioindicators of ecosystem health (Swarts and Dixon 2009) so the presence of such a large species diversity is indicative of the stability and resilience of the ecosystems in the SCA.

Most conservation reserves in the near CW are < 2,000 ha in area and have been gazetted since the late 1960s (Appendix 2). The recorded diversity of the vascular flora generally is < 250 species for these reserves (Fig. 2). Mt Canobolas SCA stands out with 416 species, only being surpassed by 491 taxa within Abercrombie Rivers NP, which is almost 12 times larger in area. All of these reserves have been utilised since European settlement, mainly for grazing and or forestry, and in many cases for mining activities. Mt Canobolas had grazing leases in place until about the 1950s before being reserved for conservation and eventually gazetted in 1997. This, together with the SCA's high perimeter to area ratio, rich volcanic soils and being surrounded by cleared and developed silvicultural, agricultural and horticultural lands, has facilitated invasion by exotic species. Twenty-one percent of the vascular flora is exotic, somewhat higher than the mean of 17.2 % for the comparable reserves in the near CW (Appendix 2). In Kosciuszko NP, which also has a history of post-European land use, exotic species contribute 23% of the flora (Doherty et al. 2015) which is higher than for most of the near CW reserves, including the SCA (Appendix 2).

Fungi

No published account of fungi exists for Mt Canobolas, but extensive lichen records (ALA 2018) are known from field work within the SCA, especially by JA Elix of the Australian National University and his colleagues.

Ascomycota fungi records, mainly lichens, show a great diversity among the > 90 species growing on logs, tree trunks, branches, soil and rocky outcrops or platforms in the SCA (Appendix 3). Together with Basidiomycetes, these occur in some 28 families and 47 genera (Table 2). Four lichens, *Gyalideopsis halocarpa*, *Sarcogyne sekikaica* (McCarthy and Elix 2014), *Megalaria montana* (McCarthy and Elix 2016) and *Xanthoparmelia metastrigosa* (Scientific Committee 2001) are endemic to the SCA. One particular assemblage of at least nine species of foliose lichens, including the endemic *X. metastrigosa*, is listed as an Endangered Ecological Community; the only lichen community in Australia with such legal protection. It has been recognised as unique to the SCA, and gazetted as the *Mt Canobolas Xanthoparmelia Lichen Community Endangered Ecological Community* (Scientific Committee 2001).

The assemblage consists of *Cladia fuliginosa, Xanthoparmelia canobolasensis, X. digitiformis, X. metaclystoides, X. metastrigosa, X. multipartita, X. neorimalis* and *X. sulcifera.* It occurs mainly above 1,100 m altitude on rock faces and soils unique to the MCVC. *Xanthoparmelia metastrigosa* is endemic to Mt Canobolas and *X. canobolasensis* is known only from Mt Canobolas and one locality in Tasmania while *X. sulcifera* and *C. fuliginosa* are each known from a limited number of other localities within NSW.

Some 46 species of fungi are regionally significant as they are rare or at their natural geographical range limits. Opportunistic observations of Basidiomycota fungi have resulted in the recording of eight species, which is considered particularly depauperate and dedicated study will undoubtedly identify many additional taxa.

Vertebrates

Knowledge of the vertebrate fauna of the SCA is predominantly from opportunistic records as few systematic surveys have been undertaken and there are no published accounts. The array of 163 vertebrate species in 62 families and 119 genera involves mainly generalist species with no recorded endemics, but does include 12 threatened species (Table 2) that have undergone population decline principally through loss of habitat.

Twenty nine native mammal species have been recorded, five of which are threatened species (Table 3). The mammals include six species of gliders and possums, two species of marsupial mice, four macropods, the *Tachyglossus aculeatus* (Short-beaked Echidna) and *Vombatus ursinus* (Bare-nosed Wombat) (Appendix 4). Most species have widespread distributions, but five have geographic range limits in the SCA. *Miniopterus schreibersii oceanensis* (Eastern Bent-wing Bat), *Petauroides volans* (Greater Glider), *Petaurus australis* (Yellow-bellied Glider) and *Antechinus stuartii* (Brown Antechinus) occur at their western limits whilst *Antechinus agilis* (Agile Antechinus) occurs at its northernmost limit. Presence of the Agile Antechinus has been verified by molecular evidence (A. Kerle pers. comm.) but confirmation of both the Brown Antechinus and Yellow-bellied Glider is required as there have been no recent sightings of either. A camera trap record of *Rattus fuscipes* (Southern Bush Rat) has yet to be verified by live trapping (S. Woodhall pers. comm.). Indicative of the richness of the habitat of the SCA is the diversity of 11 micro bats recorded on the mountain, including three threatened species (Table 3). Nine exotic mammal species also have been recorded, namely Dog, Goat, Horse, House Mouse, Pig, Rabbit, Red Fox, Red Deer and Ship Rat.

Avifauna recorded within the SCA includes 97 native and two exotic species across 35 families and 69 genera (Table 2) from mostly opportunistic observations (Appendix 4). All are widespread species with many being permanent residents; others are migratory. Seven species recorded in the SCA are listed as Vulnerable (Table 3) and are relatively widespread species that have suffered significant population declines since European settlement. Mt Canobolas is important as one place in the highly developed landscape that still provides refuge to these species. Other species use particular niche habitats in the SCA. *Falco peregrinus* (Peregrine Falcon) uses cliff habitats around Federal Falls for nesting and hunting. The mountainous terrain attracts raptors such as *Aquila audax* (Wedge-tail Eagle) which is commonly observed hunting and soaring on thermals as well as,

Table 3. Threatened plant and animal species within the Mt Canobolas State Conservation Area. V = Vulnerable listing, E = Endangered listing and CE = Critically Endangered listing under Threatened Species Acts.

	Family Name	Scientific Name	Common Name	Conservation		Remarks and Reference
				BC Act[1]	EPBC Act[2]	
Plants	Lamiaceae	*Prostanthera gilesii*	Giles' Mintbush	CE		Endemic. Only two small disjunct colonies known; (OEH 2019b)
	Myrtaceae	*Eucalyptus canobolensis*	Silver-leaf Candlebark	V	E	Endemic. Common throughout SCA; (OEH 2019c)
Mammals	Emballonuridae	*Saccolaimus flaviventris*	Yellow-bellied Sheathtail Bat	V		Recorded 2004; (OEH 2017a).
	Miniopteridae	*Miniopterus schreibersii* infrasp. *oceanensis*	Eastern Bent-wing Bat	V		Recorded 2004; (OEH 2019d).
	Petauridae	*Petaurus australis*	Yellow-bellied Glider	V		No recent sighting records; (OEH 2017b).
	Petauridae	*Petauroides volans*	Greater Glider		V	15 records 1997 to 2009; (Department of the Environment 2016).
	Vespertilionidae	*Falsistrellus tasmaniensis*	Eastern False Pipistrelle	V		Recorded 2018; (OEH 2017c).
Birds	Accipitridae	*Hieraaetus morphnoides*	Little Eagle	V		Three records 2002 to 2009; (Scientific Committee 2010a).
	Artamidae	*Artamus cyanopterus cyanopterus*	Dusky Woodswallow	V		Recorded 2001, 2019; (Scientific Committee 2016).
	Neosittidae	*Daphoenositta chrysoptera*	Varied Sittella	V		Two records 1997 to 2014; (Scientific Committee 2010b).
	Petroicidae	*Petroica boodang*	Scarlet Robin	V		Six records 1999 to 2019; (OEH 2017d). 1997-09-27
	Petroicidae	*Petroica phoenicea*	Flame Robin	V		43 records 1997 to 2019; (OEH 2017e).
	Psittacidae	*Neophema pulchella*	Turquoise Parrot	V		Recorded 1978; (OEH 2017f).
	Strigidae	*Ninox strenua*	Powerful Owl	V		Recorded 2019; (OEH 2017g).

[1] Threatened Species listed under the *Biodiversity Conservation Act 2016*.

[2] Threatened Species listed under the *Commonwealth Environment Protection and Biodiversity Conservation Act 1999*.

but less commonly, *Hieraaetus morphnoides* (Little Eagle) and *Falco berigora* (Brown Falcon). Single records of *Acanthiza uropygialis* (Chestnut-Rumped Thornbill), *Acanthagenys rufogularis* (Spiny-cheeked Honeyeater) and *Neophema pulchella* (Turquoise Parrot) are unusual for the area and require further verification. These are likely observations of vagrants, like *Certhionyx variegatus* (Pied Honeyeater) recently sighted in the area, having ventured eastwards during drought conditions.

Currently five widespread amphibians are recorded for the area (Appendix 4). The amphibian record for the SCA is likely to be an under-estimate given that 10 species have been recorded in the Orange district (ALA 2018 and authors' pers. obs.).

Twenty reptilian species have been recorded for the SCA (Appendix 4). These records contain only one snake *Austrelaps ramsayi* (Highland Copperhead), again indicative of the lack of intensive survey. Seven snake species are recorded for inhabited areas near the SCA, along with one turtle. The 19 lizard taxa recorded for the SCA are all widespread common species, however four, along with the Highland Copperhead snake occur at their westernmost range limits (Appendix 4). The lizards are a mixture of highland south-eastern, coastal and western inland species. As with the snakes, the known lizard diversity is likely to be conservative.

One fish species is among the biota recorded near the boundary of the SCA, in Towac/Molong Creek (Appendix 4).

Invertebrates

Over 210 species of invertebrates (Table 2), have been recorded for the SCA (ALA and other database sources, 2018), notwithstanding a lack of systematic survey and published accounts. The insects range across some 14 Orders within 81 families and over 150 genera. A compilation of the invertebrates by Dr Murray Fletcher is available from the authors upon request.

A single rare species *Cephalofovea pavimenta* (Mt Canobolas Velvet Worm) is endemic to Mt Canobolas (Reid et al. 1995) and lives inside rotting logs where it hunts for other small invertebrates. In eastern Australia several Velvet Worms exist as distinct populations that have been isolated from other populations for millions of years (Tait et al. 1990), and may even date back to the breakup of the Gondwana supercontinent. Each is considered rare and vulnerable (New 1995) and hence their presence is a good indicator of environmental quality. Two fluorescent yellow Planarian Worm species occur on the mountain. One is considered an outlying colour variant of *Fletchamia* cf. *sugdeni* isolated from its known distribution in Victoria and Tasmania (L. Winsor pers. comm.). It appears after rain and is commonly observed along walking tracks (S. Woodhall pers. comm.). The other is possibly also a colour variant of *Caenoplana* cf. *sulphurea*, a more widespread species in south eastern Australia and also at its northern range limit in the region (L. Winsor pers. comm.). These species are predatory and normally live in deep leaf litter to avoid desiccation.

A cricket, a flightless darkling beetle, several moths and leafhoppers represent unnamed taxa (M. Fletcher pers. comm.) and two named species, *Monomorium crinitum* and *Johnrehnia canoblaensis* have their type localities as Mt Canobolas. Twelve mollusc species have been observed within the SCA, five of which are endemic to NSW; *Anabellia occidentalis, Brevisentis atratus, B. jacksoniensis, Elsothera brazieri,* and *Galadistes molong* while *Scelidoropa sarahjaneae* is endemic to NSW and NE Victoria. Eight species are rare, regionally significant and also likely indicative of the relictual nature of the mountain.

CONCLUSION

Mount Canobolas is a prominent volcanic inselberg with a distinct relictual montane and sub-alpine flora displaying independently evolving biodiversity that is compositionally distinct from those in all other high altitude areas of the continent. It is an iconic natural remnant area located within the heavily cleared landscapes of Central Western NSW. The physiography of the MCVC, its altitude, geology, soils, isolation from other high altitude areas and influence on the local weather have united to produce a biota specific to the mountain, especially within the SCA. At a landscape level, geodiversity and climate are important drivers of vegetation (Keith 2011). However, there is only tenuous evidence that the MCVC geology has had an influence on the biota. No association could be discerned among the bryoflora whereas there does appear to be some substrate-specific specialisation among the lichens. Likewise the trachyte rock plate heathlands appear to be compositionally different and unique to the MCVC. The endemic *E. canobolensis* also shows a strong affinity to the MCVC footprint, and an *Asterolasia* shrub is suggested as a possible basaltic specialist. The heterogeneity of the core volcanic pile of the MCVC, on which the SCA is centred, may be a factor precluding any strong geological associations. In other respects Mt Canobolas functions as both a refugium for declining species and an evolutionary nursery for new species, driven by its isolation from other high altitude areas along the GD.

This SCA is a scientifically important area containing unique components of genetic variation and irreplaceable biodiversity of high conservation value and is invaluable for biogeographical comparisons. Significantly it hosts at least 10 endemic species and 14 threatened species including 2 plant, 5 mammal and 7 bird species. Mt Canobolas hosts unique sub-alpine rock plate communities with a combination of uncommon cryptogams, including an Endangered lichen community, along with several plant species rarely recorded elsewhere.

The presence of multiple endemic species in diverse groups of flora and fauna in the SCA parallels the findings of high levels of endemism on Mt Kaputar, suggesting that similar evolutionary forces are operating on the two dormant central volcanoes. Both are geographically isolated landlocked islands of high altitude habitats that appear to provide ideal environments for speciation. After the Late Miocene, when the MCVC had ceased activity, the land surface of the eastern highlands would have been much higher with alpine and sub-alpine vegetation considerably more widespread and interconnected than it is today. A long period of erosional activity has lowered the land surfaces resulting in the contraction and fragmentation of sub-alpine habitats which ultimately led to the stranding of remnant communities and populations on Mt Canobolas. The isolation of Mt Canobolas has been in place for long enough to allow the evolution of multiple new life forms, a process known as vicariant speciation, essentially by the splitting of populations into isolated fragments that subsequently evolve independently (e.g. Crisp and Cook 2007; Rix and Harvey 2012). It is postulated that many of the endemic species with close relatives elsewhere have evolved into new species on Mt Canobolas by vicariance where exchange of genetic material has been prevented by geographical and ecological isolation.

Alternatively, Mt Canobolas could have acted as a refugium for formerly widespread species that have become extinct elsewhere (Hope et al. 2004). For these species Mt Canobolas SCA is an important refugium. The Velvet Worm and other relictual species may fit into this category.

The evidence for specialist basalt taxa being responsible for endemism is limited, but nevertheless a possibility. *Asterolasia rupestris* subsp. *rupestris* is restricted to two of the volcanoes on the Inland Hotspot Track. Relict populations of the species are endemic to the volcanic track itself. It is possible this taxon evolved on the track as a basalt specialist and was formerly more widespread when the volcanic chain was more continuous. The *Asterolasia* has now retreated to high altitude refugia on Mt Canobolas and Mt Kaputar. However, the Mt Canobolas and Mt Kaputar populations appear to have been isolated from each other for sufficient time to have differentiated morphologically into distinct taxa (J. Bruhl and I. Telford pers. comm.). *Phebalium* populations restricted to trachyte rock outcrops in the Warrumbungles and the MCVC are possible further substrate specific specialists that are not conspecific.

Two endangered ecological plant communities exist within the SCA. In addition, Hunter (2002) noted the unique composition of the rock outcrop heathland vegetation and its susceptibility to loss owing to the small size and fragmentation of remnants. He also noted the unusual dominance of the endemic *Eucalyptus canobolensis* which confers a unique composition to the SCA's woodland and forest communities, especially Community 1, Stringybark-Peppermint Shrubby Open Forests and Woodlands. As such, the vegetation of the SCA is of considerable conservation significance. The vegetation communities on Mt Canobolas are the result of long-standing ecological and evolutionary processes. Accordingly, the Mt Canobolas SCA provides examples of the ecological responses of vegetation assemblages to isolation, longitudinal displacement and climatic gradients.

A vast and under-explored reservoir of genetic diversity resides in and around the SCA, particularly among the vascular flora (120 taxa) and fungi (46 taxa) that are disjunct, rare or at the limits of their natural geographic ranges. In all 200 species (Table 2), c. 23% of the known native biota, are at their range limit in or in close proximity to the SCA. Whilst the majority of these are among the cryptogams and vascular plants, for most of the invertebrate taxa however, there isn't sufficient information to determine their status in this context. A small number of species, five vascular plants and two fungi are northern species which occur at their southernmost range limits around or on the mountain. A larger number, (24 fungi, 20 vascular plant and 8 bryophytes) are clearly species with their distributional strongholds in southern regions, being at their northernmost range limit on or near the MCVC. Many of these have strong sub-alpine affinities. Others (93 vascular plant, 16 fungi and 5 bryophyte species) are at their westernmost distribution within the CW of NSW and comprise many coastal and Blue Mountains species. Many of these species at the edges of their ranges have become stranded outlying populations that are ecologically and geologically disconnected from occurrences elsewhere. This disconnection has likely set them on a distinct evolutionary pathway over the millennia, potentially leading to speciation.

Range edges are known to be characterized by increased genetic isolation, genetic differentiation, and variability in individual and population performance (Sexton et al. 2009) so are highly important for conservation.

As well as offering abundant opportunities for taxonomic research, examples of ecological, refugium and evolutionary vicariance responses have been identified within the SCA. They provide many fertile avenues for research and education into landlocked island systems, longitudinal displacement and climatic gradients. These same features of the SCA, coupled with the biodiversity, species richness and unusually high representation of irreplaceable species and communities, not only amplify its fundamental scientific value but vindicate the imperative for its nature conservation, in perpetuity.

ACKNOWLEDGEMENTS

We thank Prof. John Elix for reviewing the lichen records (Appendix 3). Thanks also to Dr Jordan Bailey who checked the fungal records and provided additions from the Biosecurity Collections Unit of NSW DPI in Orange (Appendix 3). Alison Downing kindly checked a number of bryophyte records and provided advice on range distributions. Dr Murray Fletcher compiled the species listing and precis for invertebrates and he, Vicki Glover and Rosemary Stapleton checked the bird data listed in Appendix 4. The State Government of NSW Department of Planning, Industry and Environment made available information for the vegetation map (Fig. 1) ably prepared by Suzanne Bower. Constructive suggestions provided by two referees have been incorporated to improve the manuscript.

REFERENCES

ALA (2018). ‘Atlas of Living Australia’. (Atlas of Living Australia: Canberra). Webpage at http://www.ala.org.au. Accessed to Feb 2019.

Anderson, R.H. (1961). Introduction. *Contributions from the NSW National Herbarium*. Nos. **1-18**, 1-15.

AVH (2018). ‘The Australasian Virtual Herbarium’. (The Council of Heads of Australasian Herbaria Inc.: Canberra). Webpage at https://avh.ala.org.au. Accessed to Feb 2019.

BioNet (2018a). ‘BioNet Atlas Search’. (NSW Department of Planning, Industry and Environment: Sydney). Webpage at https://www.environment.nsw.gov.au/atlaspublicapp/UI_Modules/ATLAS_/AtlasSearch.aspx. Accessed April 2018.

BioNet (2018b). ‘BioNet Vegetation Classification’. (NSW Department of Planning, Industry and Environment: Sydney). Webpage at http://www.environment.nsw.gov.au/NSWVCA20PRapp/LoginPR.aspx?ReturnUrl=%2fNSWVCA20PRapp%2fsearch%2fpctsearch.aspx. Accessed April 2018.

Bower, C.C. (2019). ‘Post-fire Survey of Terrestrial Orchids in the Mount Canobolas State Conservation Area. Report to NSW National Parks and Wildlife Service, Bathurst’. (Orange Field Naturalist and Conservation Society: Orange).

Branagan, D.F. and Packham, G.H. (2000). ‘Field Geology of New South Wales 2000’. (NSW Dept. of Mineral Resources: Sydney. Third ed.).

Chan, R.A. (2003). ‘Bathurst and Forbes 1:250 000 map sheets, New South Wales’. (CRC LEME, Geoscience Australia: Canberra).

Conn, B.J. and Wilson, T.C. (2015). Two new species of *Prostanthera* (Lamiaceae) in New South Wales. *Telopea* **18**, 463-474.

Crisp, M.D. and Cook, L.G. (2007). A congruent molecular signature of vicariance across multiple plant lineages. *Molecular Phylogenetics and Evolution* **43**, 1106-1117.

Davies, D.R., Rawlinson, N., Iaffaldano, G. and Campbell, I.H. (2015). Lithospheric controls on magma composition along the Earth’s longest continental hotspot track. *Nature* **525**, 511-514.

Department of the Environment (2008). ‘Approved Conservation Advice for *Eucalyptus canobolensis’*. (Department of the Environment, Water, Heritage and the Arts: Canberra). Webpage at http://www.environment.gov.au/biodiversity/threatened/ species/pubs/64896-conservation-advice.pdf. Accessed April 2019.

Department of the Environment (2016). ‘*Petauroides volans* Greater Glider’. (Department of the Environment, Water, Heritage and the Arts: Canberra). Webpage at https://www.environment.gov.au/cgi-bin/sprat/public/publicspecies.pl?taxon_id=254. Accessed April 2019.

Doherty, M.D., Wright, G. and McDougall, K.L. (2015). The flora of Kosciuszko National Park, New South Wales: Summary and overview. *Cunninghamia* **15,** 13-68.

Downing, A., Oldfield, R. and Fairbairn-Wilson, E. (2002). Mosses, Liverworts and Hornworts of Mount Canobolas, New South Wales. *Cunninghamia* **7,** 527-537.

Foster, D.A. and Gray, D.R. (2000). Evolution and structure of the Lachlan Fold Belt (Orogen) of Eastern Australia. *Annual Review of Earth Planetary Sciences* **28**, 47-80.

Hope, G., Kershaw, P.A., van der Klass, S., Xiangjun, S., Liew, P-M., Heusser, L.E., Takahara, H., McGlone, M., Miyoshi, N. and Moss, P.T. (2004). History of vegetation and habitat change in the Austral-Asian region. *Quaternary International* **118-119**, 103-126.

Hunter, J.T. (1998). *Eucalyptus canobolensis* (Myrtaceae), a new combination for a former subspecies of *Eucalyptus rubida*. *Telopea* **8**, 157-158.

Hunter, J.T. (2000). ‘Vegetation and floristics of Mount Canobolas State Recreation Area. A Report to the NSW National Parks and Wildlife Service’. (J.A. Hunter Pty Ltd: Invergowrie).

Hunter, J.T. (2002). Vegetation and floristics of Mount Canobolas State Recreation Area, Orange, New South Wales. *Cunninghamia* **7**, 501-526.

Keith D.A. (2011). Relationships between geodiversity and vegetation in South-eastern Australia. *Proceedings of the Linnean Society of NSW* **132**, 7–21.

McCarthy, P.M. and Elix, J.A. (2014). Two new lichens from Mt Canobolas, New South Wales. *Telopea* **16**, 119-125.

McCarthy, P.M. and Elix, J.A. (2016). Five new lichen species (Ascomycota) from south-eastern Australia. *Telopea* **19**, 137-151.

Middlemost, E.A.K. (1981). The Canobolas complex, N.S.W., an alkaline shield volcano. *Journal of the Geological Society of Australia* **28,** 33-49.

Murphy, M.J. and Shea, M. (2015). Survey of the land snail fauna (Gastropoda: Pulmonata) of Mount Kaputar National Park in northern inland New South Wales, Australia, including a description of the listing of Australia’s first legally recognised endangered land snail community. *Molluscan Research* **35**, 51-64.

NPWS (2003a). ‘Mount Canobolas State Conservation Area Plan Of Management’. (NSW National Parks and Wildlife Service: Hurstville).

NPWS (2003b). ‘The Bioregions of New South Wales: their biodiversity, conservation and history’. (NSW National Parks and Wildlife Service: Hurstville).

New, T.R. (1995). Onychophora in invertebrate conservation: priorities, practice and prospects. *Zoological Journal of the Linnean Society* **174**, 77–89.

OEH (2017a). ‘Yellow-bellied Sheathtail-bat’. (NSW Department of Planning, Industry and Environment: Sydney). Webpage at https://www.environment.nsw.gov.au/threatenedspeciesapp/profile.aspx?id=10741. Accessed April 2019.

OEH (2017b). ‘Yellow-bellied Glider’. (NSW Department of Planning, Industry and Environment: Sydney). Webpage at https:// www.environment.nsw.gov.au/threatenedspeciesapp/profile.aspx?id=10601. Accessed April 2019.

OEH (2017c). ‘Eastern False Pipistrelle’. (NSW Department of Planning, Industry and Environment: Sydney). Webpage at https://www.environment.nsw.gov.au/threatenedspeciesapp/profile.aspx?id=10331. Accessed April 2019.

OEH (2017d). ‘Scarlet Robin’. (NSW Department of Planning, Industry and Environment: Sydney). Webpage at https:// www.environment.nsw.gov.au/threatenedspeciesapp/profile.aspx?id=20133. Accessed April 2019.

OEH (2017e). ‘Flame Robin’. (NSW Department of Planning, Industry and Environment: Sydney). Webpage at https://www.environment.nsw.gov.au/threatenedspeciesapp/profile.aspx?id=20129. Accessed April 2019.

OEH (2017f). ‘Turquoise Parrot’. (NSW Department of Planning, Industry and Environment: Sydney). Webpage at https://www.environment.nsw.gov.au/threatenedspeciesapp/profile.aspx?id=10555. Accessed April 2019.

OEH (2017g). ‘Powerful Owl’. (NSW Department of Planning, Industry and Environment: Sydney). Webpage at https://www.environment.nsw.gov.au/threatenedspeciesapp/profile.aspx?id=10562. Accessed April 2019.

OEH (2018a). ‘Mount Kaputar National Park Plan of Management’. (NSW Department of Planning, Industry and Environment: Sydney). Webpage at https://www.environment.nsw.gov.au/research-and-publications/publications-search/mount-kaputar-national-park-plan-of-management. Accessed April 2019.

OEH (2018b). ‘BioNet Vegetation Classification’. (NSW Department of Planning, Industry and Environment: Sydney). Webpage at https://www.environment.nsw.gov.au/research/Visclassification.htm. Accessed April 2019.

OEH (2019a). ‘Monaro Tableland Cool Temperate Grassy Woodland in the South Eastern Highlands Bioregion – profile’. (NSW Department of Planning, Industry and Environment: Sydney). Webpage at https://www.environment.nsw.gov.au/threatenedSpeciesApp/profile.aspx?id=20346. Accessed: September 2019.

OEH (2019b). ‘*Prostanthera gilesii*’. (NSW Department of Planning, Industry and Environment: Sydney). Webpage at https://www.environment.nsw.gov.au/threatenedSpeciesApp/profile.aspx?id=20332. Accessed April 2019.

OEH (2019c). ‘Silver-Leaf Candlebark’. (NSW Department of Planning, Industry and Environment: Sydney). Webpage at https://www.environment.nsw.gov.au/threatenedSpeciesApp/profile.aspx?id=10290. Accessed April 2019.

OEH (2019d). ‘Eastern Bentwing-bat’. (NSW Department of Planning, Industry and Environment: Sydney). Webpage at https:// www.environment.nsw.gov.au/threatenedspeciesapp/profile.aspx?id=10534. Accessed April 2019.

Reid, A.L., Tait, N.N., Briscoe, D.A. and Rowell, D.M. (1995). Morphological, cytogenetic and allozymic variation within the genus *Cephalofovea* (Onychophora : Peripatopsidae) with descriptions of three new species. *Journal of the Linnean Society of London, Zoology* **114**, 115–138.

Rix, M.G. and Harvey, M.S. (2012). Phylogeny and historical biogeography of ancient assassin spiders (Araneae: Archaeidae) in the Australian mesic zone: Evidence for Miocene speciation within Tertiary refugia. *Molecular Phylogenetics and Evolution* **62**, 375-396.

Scientific Committee (2001). ‘Mount Canobolas *Xanthoparmelia* lichen community - endangered ecological community listing - final determination’. (NSW Threatened Species Scientific Committee: Sydney). Webpage at https://www.environment.nsw.gov.au/Topics/Animals-and-plants/Threatened-species/NSW-Threatened-Species-Scientific-Committee/Determinations/Final-determinations/2000-2003/Mount-Canobolas-Xanthoparmelia-Lichen-Community-endangered-ecological-community-listing. Accessed April 2019.

Scientific Committee (2008). ‘Tableland Basalt Forest in the Sydney Basin and South Eastern Highlands Bioregions - Determination to make a minor amendment to Part 3 of Schedule 1 of the Threatened Species Conservation Act’. (NSW Threatened Species Scientific Committee: Sydney). Webpage at https://www.environment.nsw.gov.au/determinations/tablelandbasaltforest36a.htm. Accessed April 2019.

Scientific Committee (2010a). ‘Little Eagle, *Hieraaetus morphnoides* (Gould 1841) - vulnerable species listing - final determination’. (NSW Threatened Species Scientific Committee: Sydney). Webpage at https://www.environment.nsw.gov.au/determinations/littleeagleFD.htm. Accessed April 2019.

Scientific Committee (2010b). ‘Varied Sittella, *Daphoenositta chrysoptera* (Latham 1802) - vulnerable species listing - final determination’. (NSW Threatened Species Scientific Committee: Sydney). Webpage at https://www.environment.nsw.gov.au/determinations/variedsittellaFD.htm. Accessed April 2019.

Scientific Committee (2016). ‘Dusky Woodswallow, *Artamus cyanopterus cyanopterus* - Vulnerable species listing - final determination’. (NSW Threatened Species Scientific Committee: Sydney). Webpage at https://www.environment.nsw.gov.au/topics/animals-and-plants/threatened-species/nsw-threatened-species-scientific-committee/determinations/final-determinations/2016/dusky-woodswallow-artamus-cyanopterus-cyanopterus-vulnerable-species-listing. Accessed April 2019.

Scientific Committee (2017). ‘*Prostanthera gilesii*, a shrub - Critically Endangered species listing - final determination’. (NSW Threatened Species Scientific Committee: Sydney). Webpage at https://www.environment.nsw.gov.au/topics/animals-and-plants/threatened-species/nsw-threatened-species-scientific-committee/determinations/final-determinations/2017-2018/prostanthera-gilesii-a-shrub-critically-endangered-species-listing. Accessed April 2019.

Scientific Committee (2018). NSW Threatened Species Scientific Committee. Webpage at https://www.environment.nsw.gov.au/topics/animals-and-plants/threatened-species/nsw-threatened-species-scientific-committee. Accessed April 2019.

Sexton, J.P., McIntyre, P.J., Angert, A.L. and Rice, K.J. (2009). Evolution and ecology of species range limits. *Annual Review of Ecology*, *Evolution, and Systematics* **40**, 415-436.

Sutherland, F.L. (2003). ‘Boomerang’ migratory intraplate Cenozoic volcanism, eastern Australian rift margins and the Indian-Pacific mantle boundary. *Geological Society of Australia Special Publication* **22**, 203-222.

Sutherland, F.L. (2011). Diversity within geodiversity, underpinning habitats in New South Wales volcanic areas. *Proceedings of the Linnean Society of NSW* **132**, 37–54.

Swarts, N.D. and Dixon, K.W. (2009). Terrestrial orchid conservation in the age of extinction. *Annals of Botany* **104**, 543-556.

Tait, N.N., Stutchbury, R.J. and Briscoe, D.A. (1990). Review of the discovery and identification of *Onychophora* in Australia. *Proceedings of the Linnean Society of NSW* **112**, 153–171.

Appendix 1. Vascular plants recorded for Mt Canobolas State Conservation Area (AVH database 2018 and authors' observations) (*Exotic species).

Family	Scientific name	Common name	Regional distribution	Range limit	Remarks
GYMNOSPERMS					
Cupressaceae	*Callitris endlicheri*	Black Cypress Pine	Widespread		Localised, Devils Hole
Pinaceae	**Pinus radiata*	Monterey Pine	Widespread		Wilding, scattered throughout, especially perimeter areas
FERNS AND FERN ALLIES					
Aspleniaceae	*Asplenium flabellifolium*	Necklace Fern	Widespread		Common
	Pleurosorus subglandulosus	Blanket Fern	Widespread		Localised
Blechnaceae	*Blechnum nudum*	Fishbone Water Fern	Widespread	Westernmost	Outlier at Mingham Springs
Dennstaedtiaceae	*Histiopteris incisa*	Bat's Wing Fern	Widespread		Localised, Federal Falls
	Pteridium esculentum	Bracken	Widespread		Common
Dryopteridaceae	*Lastreopsis acuminata*	Creeping Shield Fern	Widespread	Westernmost	Disjunct. Localised, Federal Falls
	Polystichum proliferum	Mother Shield Fern	Widespread	Westernmost	Disjunct. Localised, Fern Gully, The Walls
Ophioglossaceae	*Ophioglossum lusitanicum*	Adders Tongue	Widespread		Occasional
Pteridaceae	*Adiantum aethiopicum*	Common Maidenhair	Widespread		Occasional
	Cheilanthes austrotenuifolia	Rock Fern	Widespread		Common
	Cheilanthes distans	Bristly Cloak Fern	Widespread		Uncommon
	Cheilanthes sieberi subsp. *sieberi*	Poison Rock Fern	Widespread		Common
	Pellaea falcata	Sickle Fern	Widespread	Westernmost	Uncommon
	Pellaea nana	Dwarf Sickle Fern	Widespread	Westernmost	Localised, Federal Falls
MONOCOTYLEDONS					
Antheriaceae	*Arthropodium milleflorum*	Pale Vanilla-lily	Widespread		Common
	Arthropodium minus		Widespread		
	Caesia calliantha	Grass Lily	Widespread	Westernmost	Localised, Orange View Lookout area
	Thysanotus tuberosus	Common Fringe Lily	Widespread		Common
Asphodelaceae	*Bulbine bulbosa*	Native Leek	Widespread		Common
	Bulbine sp. (ms)		Restricted	Endemic	Several rocky locations in SCA
Colchicaceae	*Burchardia umbellata*	Milkmaids	Widespread	Northernmost	Fire ephemeral. Possible outliers at Wellington, Harvey Ranges
	Wurmbea dioica subsp. *dioica*	Early Nancy	Widespread		Occasional
Cyperaceae	*Carex appressa*	Tall Sedge	Widespread		Soaks
	Carex breviculmis		Widespread	Westernmost	Outlier at Warrumbungles
	Carex gaudichaudiana		Widespread	Westernmost	
	Carex incomitata		Widespread	Westernmost	Common

	Carex inversa	Knob Sedge	Widespread		
	Carex longebrachiata		Widespread	Westernmost	Rare
	Cyperus flavidus	Yellow Flat-sedge	Widespread	Westernmost	Outlier at Mullengudgery
	Cyperus sanguinolentus		Widespread		Common, damp areas
	Eleocharis acuta		Widespread		Uncommon, soaks
	Eleocharis atricha		Widespread	Westernmost	Common, damp areas
	Isolepis australiensis		Widespread		
	Isolepis gaudichaudiana	Benambra Club-sedge	Widespread	Westernmost	Outlier at Keewong Creek
	Isolepis hookeriana		Widespread		
	Isolepis subtilissima		Widespread	Westernmost	
	Lipocarpha microcephala	Button Rush	Widespread	Range extn	Rare. Unrecorded for CT
	Lepidosperma gunnii		Widespread	Westernmost	Localised, Devils Hole
	Lepidosperma laterale		Widespread		
	Schoenus apogon	Common Bog-rush	Widespread		Common, soaks
Hypoxidaceae	*Hypoxis hygrometrica* var. *hygrometrica*	Golden Weather-grass	Widespread	Westernmost	Uncommon, soaks
Iridaceae	**Iris germanica*	Tall Bearded Iris	Widespread		
Juncus	*Juncus australis*		Widespread	Westernmost	Outlier at Cowra
	Juncus bufonius	Toad Rush	Widespread		
	Juncus fockei		Widespread	Westernmost	Outlier at Keewong Creek
	Juncus homalocaulis		Widespread		
	Juncus remotiflorus		Widespread		
	Juncus sarophorus		Widespread		
	Juncus subsecundus		Widespread		
	Juncus vaginatus		Widespread		
	Luzula densiflora		Widespread		Occasional
	Luzula flaccida		Widespread		Common
	Luzula modesta		Widespread	Westernmost	
	Luzula ovata		Widespread	Westernmost	
Lomandraceae	*Lomandra confertifolia* subsp. *pallida*	Mat-rush	Widespread	Southernmost	
	Lomandra filiformis subsp. *filiformis*	Wattle Mat-rush	Widespread		Common
	Lomandra filiformis subsp. *flavior*	Wattle Mat-rush	Widespread		New record
	Lomandra longifolia	Spiny-headed Mat-rush	Widespread		
	Lomandra multiflora subsp. *multiflora*	Many-flowered Mat-rush	Widespread		Common

Orchidaceae	*Caladenia carnea*	Pink Fingers	Widespread		Uncommon
	Caladenia congesta	Black Tongue Caladenia	Widespread	Northernmost	Uncommon, Devils Hole. Outlier in Calula Range, possibly also Mudgee
	Caladenia fitzgeraldii	Spider Orchid	Widespread	Westernmost	Rare
	Caladenia fuscata	Dusky Fingers	Widespread		Uncommon
	Caladenia gracilis	Musky Caladenia	Widespread		
	Caladenia phaeoclavia	Brown-clubbed Spider Orchid	Widespread	Westernmost	Common. Outlier at Bowan Park
	Caladenia sp. aff. *patersonii*		Extinct?	Endemic	Rare, possibly extinct. One plant only ever seen
	Calochilus campestris	Copper Beard Orchid	Widespread		Uncommon to rare
	Calochilus robertsonii	Purplish Beard Orchid	Widespread		Uncommon to rare
	Chiloglottis trilabra		Widespread	Westernmost	
	Chiloglottis valida	Large Bird Orchid	Widespread	Northernmost	Common
	Corybas hispidus	Bristly Helmet Orchid	Widespread	Westernmost	Occasional
	Corybas incurvus	Slaty Helmet Orchid	Widespread	Northernmost	Occasional. Outlier at Barrington Tops
	Dipodium punctatum	Hyacinth Orchid	Widespread	Westernmost	Occasional, localised. Outlier in Warrumbungles
	Dipodium sp. aff. *atropurpureum*		Unknown	?Endemic	Occasional to common
	Diuris pardina	Leopard Orchid	Widespread	Northernmost	Common, localised. Outliers to north
	Diuris sp. aff. *chryseopsis*		Restricted	Endemic?	Rare
	Diuris sulphurea	Tiger Orchid	Widespread		Scattered, common
	Eriochilus cucullatus	Parsons Bands	Widespread		Common
	Gastrodia procera	Potato Orchid	Widespread	Westernmost	Disjunct. Rare
	Gastrodia sesamoides	Cinnamon Bells	Widespread	Westernmost	Disjunct. Occasional, scattered
	Genoplesium sagittiferum	A Midge Orchid	Widespread	Westernmost	Disjunct. Common. Conimbla material reclassified *G. systenum*
	Microtis parviflora	Slender Onion Orchid	Widespread		Common
	Microtis unifolia	Common Onion Orchid	Widespread		Abundant
	Prasophyllum brevilabre	Short-lipped Leek Orchid	Widespread	Westernmost	Uncommon. Outlier in Pilliga
	Prasophyllum sp. aff. *odoratum*		Restricted	Endemic	Rare, localised, fire ephemeral
	Pterostylis aestiva	Long-tongue Summer Greenhood	Widespread	Northernmost	Disjunct. Localised, uncommon
	Pterostylis decurva	Summer Greenhood	Widespread	Westernmost	Rare
	Pterostylis falcata	Sickle Greenhood	Extinct?		Not seen in last 50 years, likely locally extinct
	Pterostylis nutans	Nodding Greenhood	Widespread		Uncommon, localised

	Pterostylis rubescens		Widespread		Uncommon
	Pterostylis sp. B		Widespread		Rare
	Pterostylis tenuis		Restricted	Southernmost	Mostly confined to CT. Outlier at Glen Elgin
	Thelymitra brevifolia		Widespread	Northernmost	Outlier at Barrington Tops
	Thelymitra carnea	Tiny Sun Orchid	Widespread		Uncommon
	Thelymitra megcalyptra	Scented Sun Orchid	Widespread		Uncommon
	Thelymitra pauciflora	Slender Sun Orchid	Widespread		Common
	Thelymitra peniculata		Widespread		Occasional
	Thelymitra simulata		Restricted	Westernmost	Disjunct. Rare, localised, Devils Hole
	Thelymitra sp. aff. *ixioides*		Widespread		Common
Phormiaceae	*Dianella caerulea* var. *caerulea*	Blue Flax Lily	Widespread	Westernmost	
	Dianella longifolia var. *longifolia*	Blueberry Lily	Widespread		
	Dianella revoluta var. *revoluta*	Blueberry Lily	Widespread		
	Dianella tasmanica	Tasman Flax-lily	Widespread	Westernmost	
	Stypandra glauca	Nodding Blue Lily	Widespread		Abundant after fire
Poaceae	**Agrostis stolonifera*	Creeping Bent	Widespread		
	**Aira cupaniana*	Silvery Hairgrass	Widespread		
	Anthosachne scabra	Common Wheatgrass	Widespread		Occasional
	Aristida echinata		Widespread	Range extn	
	Austrostipa densiflora		Widespread		Uncommon
	Austrostipa scabra subsp. *falcata*	Speargrass	Widespread		Occasional
	Austrostipa scabra subsp. *scabra*	Speargrass	Widespread		Occasional
	**Briza maxima*	Quaking Grass	Widespread		
	**Briza minor*	Shivery Grass	Widespread		
	**Bromus diandrus*	Great Brome	Widespread		
	**Bromus hordeaceus*	Soft Brome	Widespread		
	**Bromus molliformis*	Soft Brome	Widespread		
	**Bromus sterilis*	Sterile Brome	Widespread		
	Cymbopogon refractus	Barbed Wire Grass	Widespread		Uncommon
	**Dactylis glomerata*	Cocksfoot	Widespread		
	Dichelachne crinita	Longhair Plumegrass	Widespread		Occasional
	Dichelachne inaequiglumis		Widespread		Occasional
	Dichelachne micrantha	Shorthair Plumegrass	Widespread		Occasional
	Dichelachne rara		Widespread		Occasional

	Dichelachne sieberiana		Widespread		Occasional
	Digitaria brownii	Cotton Panic Grass	Widespread		Occasional
	Echinopogon caespitosus	Bushy Hedgehog-grass	Widespread		Occasional
	Echinopogon ovatus	Forest Hedgehog-grass	Widespread		Common
	Eragrostis brownii	Brown's Lovegrass	Widespread		
	Festuca asperula	Graceful Fescue	Widespread		Rarely seen, but proliferated after fire
	**Holcus lanatus*	Yorkshire Fog	Widespread		
	**Hordeum leporinum*	Barley Grass	Widespread		
	Imperata cylindrica	Blady Grass	Widespread	Westernmost	Uncommon
	Microlaena stipoides var. *stipoides*	Weeping Grass	Widespread		Common
	Panicum simile	Two-colour Panic	Widespread		Uncommon
	**Paspalum dilatatum*	Paspalum	Widespread		
	**Poa annua*	Winter Grass	Widespread		
	Poa labillardierei var. *labillardierei*	Tussock	Widespread		Occasional
	Poa sieberiana var. *cyanophylla*		Widespread	Northernmost	Occasional
	Poa sieberiana var. *sieberiana*	Snowgrass	Widespread		Abundant
	Poa tenera	Slender Tussock-grass	Widespread	Northernmost	Occasional. Outliers at Cookamidgera, Cox's Gap, Olinda
	Rytidosperma erianthum	Wallaby Grass	Widespread		Common
	Rytidosperma penicillatum	Slender Wallaby Grass	Widespread	Westernmost	Possible outlier in Weddin Mts
	Rytidosperma pilosum	Smooth-flower Wallaby Grass	Widespread		Occasional
	Rytidosperma racemosum var. *racemosum*		Widespread		Common
	Rytidosperma setaceum	Smallflower Wallaby Grass	Widespread		Occasional
	**Sorghum halepense*	Johnson Grass	Widespread		
	Sporobolus creber	Western Rat-tail Grass	Widespread		Rare
	Themeda triandra	Kangaroo Grass	Widespread		
	Tripogon loliiformis	Fiveminute Grass	Widespread		Localised and uncommon
	** Vulpia bromoides*	Squirrel Tail Fescue	Widespread		
	**Vulpia muralis*		Widespread		
Xanthoraceae	*Xanthorrhoea glauca* subsp. *angustifolia*	A Grass Tree	Widespread		Localised and uncommon
DICOTYLEDONS					
Adoxaceae	**Sambucus nigra*	Elderberry	Widespread		

Ameranthaceae	*Alternanthera* sp. A		Widespread		Uncommon
Apiaceae	*Actinotus gibbonsii*		Widespread		Localised, Devils Hole
	Daucus glochidiatus form F	Native Carrot	Widespread		
	Hydrocotyle algida	Pennywort	Widespread	Northernmost	Possible outlier at Tenterfield
	Hydrocotyle laxiflora	Stinking Pennywort	Widespread		Common
	Hydrocotyle sibthorpioides		Widespread	Westernmost	Occasional
	Lilaeopsis polyantha		Widespread	Westernmost	Disjunct
	Oreomyrrhis eriopoda	Australian Carraway	Widespread	Westernmost	Occasional
Araliaceae	*Astrotricha ledifolia*		Widespread	Northernmost	Occasional. Outliers at Olinda, Tamworth, Tenterfield
	**Hedera helix*	English Ivy	Widespread	Westernmost	
	Polyscias sambucifolia subsp. *decomposita*	Ferny Panax	Widespread	Westernmost	Disjunct. Occasional along Towac Creek
	**Tetrapanax papyrifer*	Rice Paper Plant	Widespread		
Asteraceae	**Bidens pilosa*	Cobblers Pegs	Widespread		
	Brachyscome dissectifolia	Swamp Daisy	Widespread	Southernmost	Disjunct. Devils Hole in soaks
	Brachyscome ptychocarpa	Tiny Daisy	Widespread	Westernmost	Damp areas across SCA. Possible outlier at Trundle
	Brachyscome spathulata		Widespread	Westernmost	Common
	Calotis scabiosifolia var. *integrifolia*	Rough Burr-daisy	Widespread	Northernmost	Occasional. Outliers at Taree and Manara
	Cassinia aculeata subsp. *aculeata*	Common Cassinia	Widespread	Northernmost	Common. Outliers at Mt Airly and Point Lookout
	Cassinia laevis	Cough Bush	Widespread		Occasional
	Cassinia longifolia	Shining Cassinia	Widespread	Northernmost	Common. Range extends sporadically to Kandos/Rylstone with rare outliers. Northern records possibly *C. straminea.*
	Cassinia sifton	Sifton Bush	Widespread		Common
	**Centaurea calcitrapa*	Star Thistle	Widespread		
	**Chondrilla juncea*	Skeleton Weed	Widespread		
	Chrysocephalum apiculatum	Common Everlasting	Widespread		
	Chrysocephalum semipapposum	Clustered Everlasting	Widespread		
	**Cirsium vulgare*	Spear Thistle	Widespread		
	**Conyza bonariensis*	Flaxleaf Fleabane	Widespread		
	**Conyza sumatrensis*	Tall Fleabane	Widespread		
	Coronidium scorpioides	Button Everlasting	Widespread	Westernmost	Occasional
	Craspedia sp. aff. *lamicola*	Billy-buttons	?Restricted	?Endemic	Mostly above 1000 m
	**Crepis capillaris*	Smooth Hawksbeard	Widespread		

	Cymbonotus lawsonianus	Bears-ear	Widespread		Occasional
	Cymbonotus preissianus	Austral Bear's Ear	Widespread	Northernmost	Outliers in Mullion Range, Barrington Tops and Yetman
	Euchiton involucratus	Star Cudweed	Widespread		
	Euchiton japonicus	Creeping Cudweed	Widespread	Westernmost	Outlier in Mandagery SF
	Euchiton sphaericus		Widespread		
	**Hypochaeris radicata*	Catsear, Flatweed	Widespread		
	**Lactuca serriola*	Prickly Lettuce	Widespread		
	Lagenophora stipitata	Blue Bottle-daisy	Widespread	Westernmost	Occasional
	**Madia sativa*	Tarweed, Pitchweed	Widespread		
	Microseris lanceolata	Yam Daisy	Widespread		Occasional
	Olearia chrysophylla		Widespread	Westernmost	Disjunct. Uncommon, upper slopes
	Olearia erubescens		Widespread	Northernmost	Rare, Devils Hole. Outliers to north
	Olearia megalophylla	Large-leaf Daisy Bush	Widespread	Westernmost	Disjunct. Rare, possible misidentification
	Olearia phlogopappa subsp. *continentalis*	Dusty Daisy-bush	Widespread	Westernmost	Disjunct. Localised, common, Devils Hole
	Senecio bathurstianus		Widespread		Common
	Senecio diaschides		Widespread	Westernmost	Occasional
	Senecio hispidulus	Hill Fireweed	Widespread	Westernmost	Outliers at Condobolin, Lake Cargelligo
	Senecio linearifolius var. *macrodontus*	Fireweed Groundsel	Widespread	Westernmost	Uncommon
	Senecio minimus		Widespread	Westernmost	Uncommon
	Senecio pinnatifolius var. *pinnatifolius*	Variable Groundsel	Widespread		
	Senecio prenanthoides		Widespread	Westernmost	Occasional
	Senecio quadridentatus	Cotton Fireweed	Widespread		Common
	Sigesbeckia australiensis		Widespread		Occasional
	Sigesbeckia orientalis subsp. *orientalis*	Indian Weed	Widespread		Occasional
	**Silybum marianum*	Variegated Thistle	Widespread		
	Solenogyne dominii		Widespread		Uncommon
	**Sonchus oleraceus*	Common Sowthistle	Widespread		
	**Taraxacum officinale*	Dandelion	Widespread		
	Vittadinia cuneata var. *cuneata*	Fuzzweed	Widespread		
Boraginaceae	**Amsinckia calycina*		Widespread		
	**Amsinckia intermedia*	Common Fiddleneck	Widespread		
	**Anchusa arvensis*	Wild Bugloss	Widespread		
	Cynoglossum australe		Widespread		Common

	**Echium vulgare*	Vipers Bugloss	Widespread		
	Hackelia suaveolens		Widespread		
	Myosotis australis	Australian Forget-me-not	Widespread		Occasional
	**Myosotis discolor*	Forget-me-not	Widespread		
Brassicaceae	*Cardamine gunnii*		Widespread	Westernmost	
	Cardamine paucijuga		Widespread		
	**Hirschfeldia incana*	Buchan Weed	Widespread		
Callitrichaceae	**Callitriche stagnalis*	Common Starwort	Widespread		
Campanulaceae	*Isotoma fluviatilis* subsp. *fluviatilis*	Swamp Isotome	Widespread	Westernmost	Uncommon, soaks
	Lobelia gibbosa	Tall Lobelia	Widespread		Occasional, fire ephemeral
	Lobelia pedunculata	Matted Pratia	Widespread	Westernmost	Uncommon, soaks
	Wahlenbergia communis	Tufted Bluebell	Widespread		Uncommon
	Wahlenbergia luteola		Widespread		Occasional
	Wahlenbergia multicaulis	Tadgell's Bluebell	Widespread		Occasional
	Wahlenbergia planiflora subsp. *longipila*	Flat Bluebell	Widespread	Southernmost	Disjunct
	Wahlenbergia stricta subsp. *stricta*	Tall Bluebell	Widespread		Occasional
	Wahlenbergia victoriensis		Unknown	Northernmost	Uncommon, moist gully
Caprifoliaceae	**Lonicera japonica*	Japanese Honeysuckle	Widespread		
Caryophyllaceae	**Cerastium balearicum*	Lesser Mouse-ear Chickweed	Widespread		
	**Cerastium glomeratum*	Mouse-ear Chickweed	Widespread		
	**Petrorhagia nanteuilii*		Widespread		
	Scleranthus sp. Fitzs Hill	Knawel	Widespread	Southernmost	Common
	**Silene coronaria*	Rose Campion	Widespread		
	Stellaria angustifolia	Swamp Starwort	Widespread		Uncommon, damp areas
	Stellaria flaccida		Widespread	Westernmost	
	Stellaria pungens	Prickly Starwort	Widespread	Westernmost	Abundant. Outlier in Hervey Ranges
Centrolepidaceae	*Centrolepis strigosa* subsp. *strigosa*		Widespread		Rare, in soaks
Chenopodiaceae	*Dysphania pumilio*	Small Crumbweed	Widespread		Common
Clusiaceae	*Hypericum gramineum*	Small St. John's Wort	Widespread		Occasional
	Hypericum japonicum		Widespread	Westernmost	Damp areas
	**Hypericum perforatum*	St. John’s Wort	Widespread		
Convolvulaceae	*Convolvulus angustissimus*	Blushing Bindweed	Widespread		Occasional

	Dichondra repens	Kidney Weed	Widespread		Common
Crassulaceae	*Crassula sieberiana* subsp. *sieberiana*	Australian Stonecrop	Widespread		Occasional
Dilleniaceae	*Hibbertia calycina*	Lesser Guinea Flower	Widespread		Uncommon
	Hibbertia obtusifolia	Hoary Guinea Flower	Widespread		Common
	Hibbertia riparia	Erect Guinea Flower	Widespread		Occasional
Droseraceae	*Drosera auriculata*		Widespread		
	Drosera peltata	Sundew	Widespread		
Epacridaceae	*Acrotriche serrulata*	Honeypots	Widespread	Westernmost	Outlier at Yenda
	Leucopogon attenuatus	Beard-heath	Widespread		Occasional
	Leucopogon ericoides	Pink Beard-heath	Widespread		Occasional
	Leucopogon fraseri		Widespread	Westernmost	Uncommon. Outlier in Goobang NP
	Leucopogon virgatus		Widespread		Occasional
	Melichrus Mt Canobolas	Urn-heath	?Restricted	?Endemic	Uncommon, scattered
	Monotoca scoparia	Broom-heath	Widespread		Occasional, scattered
Fabaceae	*Acacia brownii*	Heath Wattle	Widespread		
	Acacia buxifolia subsp. *buxifolia*	Box-Leaf Wattle	Widespread		
	Acacia dealbata subsp. *dealbata*	Silver Wattle	Widespread		Abundant
	Acacia gunnii	Ploughshare Wattle	Widespread		Occasional
	Acacia lanigera var. *lanigera*	Woolly Wattle	Widespread		
	Acacia melanoxylon	Blackwood	Widespread	Westernmost	Common. Possible outlier near Dubbo
	Acacia ulicifolia	Prickly Moses	Widespread		
	Acacia verniciflua	Varnish Wattle	Widespread		
	Bossiaea buxifolia		Widespread		Common
	**Cytisus scoparius* subsp. *scoparius*	Scotch Broom	Widespread		
	Daviesia latifolia	Hop Bitter-pea	Widespread		Occasional
	Daviesia leptophylla		Widespread		Occasional
	Desmodium gunnii	Slender Tick-trefoil	Widespread	Westernmost	
	Desmodium varians	Slender Tick-trefoil	Widespread		
	Dillwynia phylicoides		Widespread		
	**Genista monspessulana*	Montpellier Broom	Widespread		
	Glycine clandestina		Widespread		Common
	Glycine tabacina		Widespread		Occasional
	Hardenbergia violacea	Purple Coral Pea	Widespread		
	Hovea heterophylla		Widespread	Westernmost	Outliers at Bowen Park, Bumberry
	Indigofera adesmiifolia	Tick Indigo	Widespread		Occasional
	Indigofera australis	Australian Indigo	Widespread		Common

	Lotus australis	Australian Trefoil	Widespread		Uncommon
	**Medicago polymorpha*	Burr Medic	Widespread		
	Mirbelia oxylobioides	Mountain Mirbelia	Widespread	Northernmost	Disjunct. A southern species, outliers north of Lees Pinch and at Mt Kaputar, Pilliga
	Pultenaea polifolia	Dusky Bush-pea	Widespread	Westernmost	Uncommon. Outlier in Goobang NP
	Pultenaea setulosa	Stony Bush-pea	Widespread		
	Pultenaea spinosa	Spiny Bush-pea	Widespread		Occasional
	Pultenaea subternata		Widespread	Westernmost	Scattered on slopes to west
	**Trifolium arvense*	Haresfoot Clover	Widespread		
	**Trifolium campestre*	Hop Clover	Widespread		
	**Trifolium dubium*	Yellow Suckling Clover	Widespread		
	**Trifolium repens*	White Clover	Widespread		
	**Ulex europaeus*	Gorse	Widespread		
	**Vicia villosa* subsp. *villosa*	Russian Vetch	Widespread		
Gentianaceae	**Centaurium erythraea*	Common Centaury	Widespread		
	**Centaurium tenuiflorum*		Widespread		
Geraniaceae	*Geranium homeanum*		Widespread	Westernmost	
	**Geranium molle* subsp. *molle*	Cranesbill Geranium	Widespread		
	Geranium potentilloides var. *potentilloides*		Widespread	Westernmost	
	Geranium solanderi var. *solanderi*	Native Geranium	Widespread		Common
	Pelargonium australe	Native Storksbill	Widespread		Prolific fire ephemeral
Goodeniaceae	*Goodenia hederacea* subsp. *hederacea*	Forest Goodenia	Widespread		
Haloragaceae	*Gonocarpus elatus*		Widespread		Occasional
	Gonocarpus tetragynus	Raspwort	Widespread		Common
	Haloragis heterophylla	Rough Raspwort	Widespread		
	Haloragis serra		Widespread		Occasional
Lamiaceae	*Ajuga australis*	Austral Bugle	Widespread		
	**Marrubium vulgare*	White Horehound	Widespread		
	Mentha satureioides	Native Pennyroyal	Widespread		Uncommon
	**Mentha spicata*	Spearmint	Widespread		Towac Creek
	Prostanthera gilesii		Restricted	Endemic	Critically endangered
	**Prunella vulgaris*	Self-heal	Widespread		
	Scutellaria humilis	Dwarf Skullcap	Widespread		Occasional
Lauraceae	*Cassytha pubescens*		Widespread		
Loranthaceae	*Amyema miquelii*		Widespread		

	Amyema pendula subsp. *pendula*		Widespread		
Malaceae	**Cotoneaster glaucophyllus*	Glaucous Cotoneaster	Widespread		
	**Crataegus monogyna*	Hawthorn	Widespread		
Myrtaceae	*Calytrix tetragona*	Common Fringe-myrtle	Widespread		Common
	Eucalyptus blakelyi	Blakely's Red Gum	Widespread		Uncommon
	Eucalyptus bridgesiana	Apple Box	Widespread		Occasional
	Eucalyptus canobolensis	Silver-leaf Candlebark	Restricted	Endemic	Abundant. Localised Mt Canobolas volcanics
	Eucalyptus dalrympleana subsp. *dalrympleana*	Mountain Gum	Widespread	Westernmost	Abundant. Disjunct
	Eucalyptus dives	Broad-leaved Peppermint	Widespread	Westernmost	Abundant
	Eucalyptus goniocalyx	Bundy	Widespread		Occasional
	Eucalyptus macrorhyncha	Red Stringybark	Widespread		Abundant
	Eucalyptus pauciflora	Snow Gum	Widespread	Westernmost	Abundant
	Eucalyptus polyanthemos subsp. *polyanthemos*	Red Box	Widespread		Uncommon
	Eucalyptus stellulata	Black Sally	Widespread	Westernmost	Uncommon
	Eucalyptus viminalis	Ribbon Gum	Widespread	Westernmost	Occasional
	Kunzea parvifolia	Violet Kunzea	Widespread		Common
	Leptospermum myrtifolium	Myrtle Tea-tree	Widespread	Westernmost	Possible outlier West Wyalong
Nyctaginaceae	*Boerhavia dominii*	Tarvine	Widespread		
Onagraceae	*Epilobium billardiereanum* subsp. *cinereum*	A Willow-herb	Widespread		
Orobanchaceae	**Orobanche minor*		Widespread		
Oxalidaceae	*Oxalis chnoodes*		Widespread	Westernmost	
	Oxalis exilis		Widespread	Westernmost	Scattered on slopes to west
	Oxalis perennans		Widespread		Common
Phyllanthaceae	*Phyllanthus occidentalis*		Widespread		Occasional
	Poranthera microphylla		Widespread		
Pittosporaceae	*Billardiera scandens*	Hairy Apple Berry	Widespread	Westernmost	Uncommon
	Rhytidosporum procumbens		Widespread		
Plantaginaceae	*Gratiola peruviana*	Australian Brooklime	Widespread	Westernmost	
	**Plantago lanceolata*	Lamb's Tongues	Widespread		
	Plantago varia		Widespread		Common
	**Veronica anagallis-aquatica*	Blue Water Speedwell	Widespread		
	**Veronica arvensis*	Wall Speedwell	Widespread		
	Veronica calycina	Hairy Speedwell	Widespread	Westernmost	Outlier in Warrumbungles

	Veronica derwentiana subsp. *derwentiana*		Widespread	Westernmost	
	Veronica derwentiana subsp. *subglauca*		Widespread	Westernmost	Specimen in RBG needs verification
	Veronica gracilis	Slender Speedwell	Widespread	Westernmost	Possible outlier near Barmedman
Polemoniaceae	**Navarretia squarrosa*	Californian Stinkweed	Widespread		
Polygonaceae	**Acetosella vulgaris*	Sorrel	Widespread		
	Rumex brownii	Swamp Dock	Widespread		Occasional
Portulacaceae	*Neopaxia australasica*		Widespread	Westernmost	Soaks
	Montia fontana subsp. *chondrosperma*		Widespread	Northernmost	A southern species
Primulaceae	**Lysimachia arvensis*	Scarlet Pimpernel	Widespread		
Proteaceae	*Hakea decurrens* subsp. *decurrens*		Widespread		Uncommon
	Persoonia rigida		Widespread		
Ranunculaceae	*Ranunculus amphitrichus*	Small River Buttercup	Widespread	Northernmost	A southern species. Outliers at Moonan Brook, Uralla, Walcha
	Ranunculus inundatus	River Buttercup	Widespread	Westernmost	
	Ranunculus lappaceus	Common Buttercup	Widespread		Common
	Ranunculus pumilio var. *politus*	Ferny Buttercup	Widespread	Easternmost	Outlier Richmond
	Ranunculus pumilio var. *pumilio*	Ferny Buttercup	Widespread		
Rhamnaceae	*Cryptandra amara* var. *amara*	Bitter Cryptandra	Widespread		
	Pomaderris aspera	Hazel Pomaderris	Widespread	Westernmost	Disjunct. Rare
Rosaceae	*Acaena novae-zelandiae*	Bidgee-widgee	Widespread	Westernmost	Common
	Acaena ovina	Sheep’s Burr	Widespread		
	Aphanes australiana		Widespread		
	**Prunus laurocerasus*	Cherry Laurel	Widespread		
	**Rosa rubiginosa*	Sweet Briar	Widespread		
	**Rubus anglocandicans*	Blackberry	Widespread		
	Rubus parvifolius	Native Raspberry	Widespread		
	**Rubus ulmifolius*	Blackberry	Widespread		
	**Sanguisorba minor*	Salad Burnet	Widespread		
Rubiaceae	*Asperula conferta*	Common Woodruff	Widespread		Common
	Asperula scoparia	Prickly Woodruff	Widespread	Westernmost	
	Coprosma quadrifida	Prickly Currant Bush	Widespread	Westernmost	Disjunct. Rare
	**Galium aparine*	Cleavers	Widespread		
	**Galium divaricatum*	Slender Bedstraw	Widespread		
	Galium gaudichaudii	Rough Bedstraw	Widespread		

	Galium leptogonium		Widespread		
	**Galium murale*	Small Bedstraw	Widespread		
	Opercularia aspera	Coarse Stinkweed	Widespread		Occasional
	Opercularia hispida	Hairy Stinkweed	Widespread		Occasional
	Pomax umbellata	Skullcaps	Widespread		Common
Rutaceae	*Asterolasia rupestris* subsp. *rupestris*		Restricted	?Endemic	Localised to one area, rare
	Phebalium squamulosum complex	Scaly Phebalium	Restricted	?Endemic	Localised in disparate colonies
Salicaceae	**Salix* x *fragilis* nothovar. *fragilis*	Crack Willow	Widespread		
Santalaceae	*Exocarpos cupressiformis*	Native Cherry	Widespread		Common
	Exocarpos strictus	Dwarf Cherry	Widespread		
Sapindaceae	*Dodonaea boroniifolia*	Fern-leaf Hop-bush	Widespread		Common
	Dodonaea viscosa subsp. *angustissima*	Narrow-leaved Hopbush	Widespread		Common
Scrophulariaceae	**Verbascum thapsus* subsp. *thapsus*	Great Mullein	Widespread		
	**Verbascum virgatum*	Twiggy Mullein	Widespread		
Solanaceae	**Datura stramonium*	Common Thornapple	Widespread		
	**Solanum chenopodioides*	Whitetip Nightshade	Widespread		
	**Solanum nigrum*	Black-berry Nightshade	Widespread		
	**Solanum triflorum*	Three-flowered Nightshade	Widespread		
Stackhousiaceae	*Stackhousia monogyna*	Creamy Candles	Widespread		Occasional
Stylidiaceae	*Stylidium graminifolium*	Grass Trigger-plant	Widespread		Occasional
Thymelaeaceae	*Pimelea curviflora* var. *gracilis*	Rice Flower	Widespread	Westernmost	Occasional
	Pimelea latifolia subsp. *hirsuta*	Rice Flower	Widespread	Westernmost	Disjunct
	Pimelea ligustrina subsp. *ligustrina*	Tall Rice Flower	Widespread	Westernmost	Disjunct
	Pimelea linifolia subsp. *caesia*	Slender Rice-flower	Widespread	Westernmost	Disjunct
Urticaceae	*Urtica incisa*	Stinging Nettle	Widespread		Occasional
Valerianaceae	**Centranthus ruber* subsp. *ruber*	Red Valerian	Widespread		
Verbenaceae	**Verbena bonariensis*	Purpletop	Widespread		
Violaceae	*Viola betonicifolia*	Native Violet	Widespread		Common
	Viola hederacea	Ivy-leaved Violet	Widespread	Westernmost	Occasional

Appendix 2. Summary of conservation reserves in the near (eastern) Central West indicating year gazetted, area, along with native and exotic vascular plant species recorded in Bionet (2018a).

Conservation Reserve	Year Gazetted	Area (ha)	Total Flora (No Species)	Native Flora (No Species)	Exotic Flora (No Species)	Exotic species (%)
Abercrombie KCR	1997	1,434	206	178	28	13.6
Abercrombie River NP	1995	19,402	491	384	107	21.8
Barton NR	1972	529	125	99	26	20.8
Borenore KCR	1997	136	140	85	55	39.2
Burwood Creek NR	?	34	85	66	19	22.3
Copperhannia NR	1972	3,497	212	193	19	8.9
Eusdale NR	2006	1,238	130	111	19	14.6
Evans Crown NR	1975	424	185	145	40	21.6
Freemantle NR	1973	361	136	111	25	18.4
Gillindich NR	2010	1,225	111	105	6	5.4
Girralang NR	1999	640	207	175	32	15.4
Hill End HS	1967	133	98	68	30	30.6
Keverstone SCA	2011	1,164	51	47	4	7.8
Keverstone NP	1979 to 2011	1,860	198	165	33	16.7
Mount Canobolas SCA	1997	1,672	425	337	88	20.7
Mullion Range SCA	1999	1,025	200	151	49	24.5
Nuggetty SCA	2010	1,146	156	116	40	25.6
Razorback NR	1988	2,647	243	222	21	8.6
Turon NP	2002	3,059	254	215	39	15.4
Wambool NR	1987	194	245	226	19	7.8
Wiarborough NR	2010	2,024	183	164	19	10.4
Winburndale NR	1967	10,718	339	297	42	12.4
Mean			200	166	34	17.4

Appendix 3. Fungi recorded for Mt Canobolas SCA (ALA and other database sources 2018) (*exotic species).

Family	Scientific name	Regional distribution	Range limit	Remarks
Phylum *Ascomycota*				
Acarosporaceae	*Acarospora citrina*	Widespread		Volcanic rock. Northern slopes below summit
	Acarospora fuscata	Restricted	Northernmost	Volcanic rock around summit; restricted to SE mainland
	Acarospora nodulosa	Widespread	Easternmost	An inland species
	Sarcogyne sekikaica	Restricted	Endemic	Volcanic rock around summit
Candelariaceae	*Candelariella* cf. *coralliza*	Widespread		Volcanic rock around summit
Cladoniaceae	*Cladia aggregata*	Widespread		On soil between boulders, summit
	Cladia corallaizon	Widespread		On soil, NE forest slopes
	Cladia fuliginosa	Restricted	Northernmost	Scattered small loose colonies, NE forest slopes and grasslands; restricted to SE Australia
	Cladia muelleri	Widespread		On soil, NE forest slopes
	Cladonia chlorophaea	Widespread		On soil, W face of mountain
	Cladonia corniculata	Widespread	Westernmost	On damp soils and crevices among rocks, W face of mountain
	Cladonia fimbriata	Widespread	Westernmost	On soil, slopes and rocky outcrops with stunted trees
	Cladonia glebosa	Widespread		On charred wood, W face of mountain
	Cladonia sarmentosa	Widespread	Westernmost	On shaded, moist earth bank, W face of mountain
	Cladonia sulcata var. *striata*	Widespread	Westernmost	On soil, NE forest slopes
Collemataceae	*Collema leucocarpum*	Widespread		On mossy volcanic rocks and on *Acacia melanoxylon*, W face of mountain
	Lathagrium durietzii	Widespread		On soil and rock, stunted forest on rocky outcrops, W face of mountain
Gomphillaceae	*Gyalideopsis halocarpa*	Restricted	Endemic	Near summit, exposed heath
Lecanoraceae	*Lecanora bicincta*	Restricted	Northernmost	Volcanic rocks around summit and grassy frost pockets in sub-alpine Snow Gum woodland; restricted to Alpine areas
	Lecanora farinacea	Widespread	Westernmost	Weathered volcanic rocks around summit, woodland
	Lecanora galactiniza	Widespread		Volcanic rocks and scree around summit, woodland
	Lecanora oreinoides	Widespread		Weathered trachyte rocks, heathlands on W face of mountain
	Lecanora pseudistera	Widespread		Volcanic rocks around summit and grassy frost pockets in sub-alpine Snow Gum woodland
	Lecanora rupicola	Widespread	Northernmost	Rocky outcrops

	Lecidella stigmatea	Widespread		Volcanic rocks around summit
	Ramboldia petraeoides	Widespread		Volcanic rocks around summit and dead tree trunks
	Ramboldia sanguinolenta	Widespread	Southernmost	Weathered rocks, woodlands on NW slopes of mountain; outlier recorded near Nimmitabel
	Scoliciosporum umbrinum	Restricted	Northernmost	Volcanic rocks around summit; only mainland record, elsewhere Kangaroo Island and Tasmania
Lecideaceae	*Lecidea atrobrunnea*	Restricted	Northernmost	Volcanic rocks, summit grassy Snow Gum woodland; rare with few records for Vic. alps and WA
	Lecidea capensis	Widespread		Weathered rocks, heath and woodlands, W face of mountain
	Lecidea ochroleuca	Widespread		On rocks, NE forest slopes
Lobariaceae	*Pseudocyphellaria neglecta*	Widespread	Westernmost	Shaded rocks amongst mosses, NE forest slopes
Megalariaceae	*Megalaria montana*	Restricted	Endemic	
Megasporaceae	*Aspicilia contorta*	Widespread	Easternmost	Summit and rock ledge, W slopes of mountain
Mycosphaerellaceae	*Cercospora* sp.	Unknown		Isolated from *Hardenbergia violaceae*
	Mycosphaerella sp.	Unknown		Isolated from *Stypandra glauca*
Pannariaceae	*Fuscopannaria subimmixta*	Widespread		Soil over rocks, Federal Falls
	Psoroma hypnorum	Widespread	Northernmost	Mossy rocks, W face of mountain
Parmeliaceae	*Austroparmelina labrosa*	Widespread	Westernmost	On tree trunks and branches of shrubs, summit and W slopes
	Austroparmelina pruinata	Widespread		On tree trunks and branches of shrubs, summit and W slopes
	Austroparmelina pseudorelicina	Widespread		On tree trunks and branches of shrubs, summit and W slopes
	Flavoparmelia haysomii	Widespread	Westernmost	On volcanic rocks, W face of mountain
	Hypogymnia billardierei	Widespread		On *Leptospermum* twigs
	Hypogymnia pulverata	Widespread	Westernmost	On dead wood, rocky heath and woodlands, W face of mountain
	Hypogymnia subphysodes var. *subphysodes*	Widespread	Westernmost	On dead wood, woodlands, W face of mountain
	Notoparmelia signifera	Widespread		On volcanic rocks, W face of mountain
	Parmotrema reticulatum	Widespread		On volcanic rocks, W face of mountain
	Punctelia borreri	Widespread	Westernmost	On volcanic rocks, W face of mountain
	Usnea inermis	Widespread		On dead *Acacia* branch and bark, rocks in woodland
	Xanthoparmelia atrocapnodes	Widespread		Weathered rock, summit and woodlands on W slopes
	Xanthoparmelia canobolasensis	Restricted	Northernmost	On rocks, woodland NE slopes; only mainland record, elsewhere one location in Tasmania

	Xanthoparmelia congesta	Widespread		Weathered rock, summit and woodlands on W slopes
	Xanthoparmelia dichotoma	Widespread	Northernmost	On soil, NE woodlands; outliers at Tenterfield and Mt Cordeaux Qld.
	Xanthoparmelia digitiformis	Widespread		Shaded rock face, summit areas, Snow Gum woodland
	Xanthoparmelia elixii	Widespread		Exposed rocky outcrops and stunted forests
	Xanthoparmelia flavescentireagens	Widespread		Weathered rock, The Walls, summit areas and woodlands on W slopes
	Xanthoparmelia furcata	Widespread		Rock outcrops, The Walls
	Xanthoparmelia loxodella	Widespread		Volcanic rocks summit and grassy frost pockets in sub-alpine Snow Gum woodland, W slopes
	Xanthoparmelia metaclystoides	Widespread		Weathered rock, NW slopes
	Xanthoparmelia metamorphosa	Widespread		On soil and pebbles, The Walls woodland
	Xanthoparmelia metastrigosa	Restricted	Endemic	Weathered rock and soil, summit and woodlands NE slopes
	Xanthoparmelia mexicana	Widespread		Dead tree trunk among rock outcrops
	Xanthoparmelia multipartita	Restricted	Northernmost	Recorded as a component of Mt Canobolas *Xanthoparmelia* Endangered Ecological Community
	Xanthoparmelia neorimalis	Widespread		Recorded as a component of Mt Canobolas *Xanthoparmelia* Endangered Ecological Community
	Xanthoparmelia oleosa	Widespread		Weathered rocks, summit woodlands
	Xanthoparmelia parviloba	Widespread		
	Xanthoparmelia pulla	Widespread		On rock, summit woodlands
	Xanthoparmelia scabrosa	Widespread		Rock outcrop N slope from summit, Snow Gum woodland
	Xanthoparmelia semiviridis	Widespread		On soil, summit woodlands
	Xanthoparmelia substrigosa	Widespread		On soil and pebbles, The Walls woodland
	Xanthoparmelia sulcifera	Restricted	Westernmost	On soil and pebbles, grasslands around summit; restricted to SE mainland
	Xanthoparmelia willisii	Widespread	Southernmost	On soil, grasslands around summit; outliers in Tasmania
Pertusariaceae	*Pertusaria lophocarpa*	Widespread	Westernmost	Weathered rock, summit area woodlands
Physciaceae	*Buellia aethalia*	Widespread		Summit area
	Buellia canobolasensis	Restricted	Northernmost	Known only from the summit area and another mountain top in the ACT
	Buellia homophylia	Widespread		Volcanic rock, summit area woodlands
	Buellia maficola	Widespread		Type specimen from summit area
	Buellia ocellata	Restricted	Northernmost	Volcanic rock, summit area woodlands; restricted to SE Australia
	Physcia adscendens	Widespread	Northernmost	Shaded rocks, but usually on wood; outliers at Guyra and Lamington NP

	Physcia austrocaesia	Widespread	Northernmost	Dead twigs, woodlands W face; outlier on rock at Stanthorpe
	Physcia jackii	Widespread		On dead *Acacia*, summit and W slopes
	Physcia poncinsii	Widespread	Westernmost	Volcanic rock, summit area woodlands
Porpidiaceae	*Paraporpidia leptocarpa*	Widespread		Amongst rock outcrops in stunted woodlands
Pyronemataceae	*Pyronema omphalodes*	Widespread		
Rhizocarpaceae	*Rhizocarpon distinctum*	Restricted	Northernmost	Weathered rock, heathlands on W face; restricted to SE Australia
	Rhizocarpon geminatum	Restricted	Northernmost	Weathered rock, heathlands on W face; restricted to SE Australia
	Rhizocarpon geographicum	Widespread		On rock, summit and woodlands on W slopes
	Rhizocarpon reductum	Widespread		On rock, summit and woodlands on W slopes
Stereocaulaceae	*Stereocaulon corticatulum*	Widespread	Northernmost	On rock amongst other lichens; outliers at Barrington Tops and Point Lookout
Teloschistaceae	*Caloplaca crenulatella*	Widespread	Rare in NSW	Summit, on scree NW slopes
	Caloplaca rexfilsonii	Widespread		Rock outcrops around summit
	Caloplaca rubelliana	Widespread		Rock outcrops around summit
Thelotremataceae	*Diploschistes scruposus*	Widespread		Volcanic rocks around summit and grassy frost pockets in sub-alpine Snow Gum woodland
	Diploschistes sticticus	Widespread		On rock, summit and woodlands on W slopes
	Ingvariella bispora	Restricted	Northernmost	On rock, summit and heath on W slopes; restricted to SE Australia
Trapeliaceae	*Placopsis perrugosa*	Widespread	Northernmost	Shaded rock, woodlands W face; outliers at Barrington Tops and Ingham Qld
	Rimularia insularis	Restricted	Northernmost	On rock, open woodland; restricted to SE mainland
Phylum *Basidiomycota*				
Phragmidiaceae	**Phragmidium violaceum*	Widespread	Northernmost	Isolated from blackberry
Pileolariaceae	*Uromycladium robinsonii*	Unknown	Northernmost	Isolated from *Acacia melanoxylon.* Only known record for NSW; also recorded for ACT, Vic. and NZ
Pucciniaceae	*Puccinia lagenophorae*	Widespread		Isolated from *Senecio quadridentatus.*
Raveneliaceae	*Bibulocystis pulcherrima* var. *monticola*	Unknown		Isolated from a *Daviesia* sp.
Russulaceae	*Cystangium seminudum*	Widespread	Westernmost	Grassy woodland, Orange View
	Cystangium sessile	Widespread	Westernmost	Grassy woodland, Orange View
	Cystangium shultziae	Widespread	Northernmost	Grassy woodland, Orange View
Ustilaginaceae	*Ustilago comburens*	Widespread	Northernmost	Only known record for NSW; also recorded for ACT, Vic., WA and NZ

Appendix 4. Vertebrates recorded for Mt Canobolas State Conservation Area (ALA and other database sources 2018) (*exotic species).

Order	Family	Scientific name	Common name	Regional distribution	Range limit
ACTINOPTERYGII					
Salmoniformes	Galaxiidae	*Galaxias olidus*	Inland or Mountain Galaxia	Widespread	
AMPHIBIA					
Anura	Hylidae	*Litoria verreauxii*	Whistling Tree Frog	Widespread	
	Limnodynastidae	*Limnodynastes dumerilii dumerilii*	Eastern Banjo Frog	Widespread	
	Myobatrachidae	*Crinia parinsignifera*	Eastern Sign-bearing Froglet	Widespread	
		Crinia signifera	Common Froglet	Widespread	
		Uperoleia laevigata	Smooth Toadlet	Widespread	
AVES					
Anseriformes	Anatidae	*Anas gracilis*	Grey Teal	Widespread	
		Anas superciliosa	Pacific Black Duck	Widespread	
		Aythya australis	White-eyed Duck, Hardhead	Widespread	
		Chenonetta jubata	Australian Wood Duck	Widespread	
Caprimulgiformes	Podargidae	*Podargus strigoides*	Tawny Frogmouth	Widespread	
Ciconiiformes	Ardeidae	*Egretta novaehollandiae*	White-faced Heron	Widespread	
	Threskiornithidae	*Threskiornis spinicollis*	Straw-necked Ibis	Widespread	
Columbiformes	Columbidae	*Phaps chalcoptera*	Common Bronzewing	Widespread	
Coraciiformes	Coraciidae	*Eurystomus orientalis*	Dollarbird	Widespread	
	Halcyonidae	*Dacelo novaeguineae*	Laughing Kookaburra	Widespread	
		Todiramphus sanctus	Sacred Kingfisher	Widespread	
Cuculiformes	Cuculidae	*Cacomantis flabelliformis*	Fan-tailed Cuckoo	Widespread	
		Cacomantis pallidus	Pallid Cuckoo	Widespread	
		Chalcites osculans	Black-eared Cuckoo	Widespread	
		Chrysococcyx basalis	Horsfield's Bronze-cuckoo	Widespread	
		Chrysococcyx lucidus	Shining Bronze-cuckoo	Widespread	
		Eudynamys orientalis	Common Koel, Pacific Koel	Widespread	
Falconiformes	Accipitridae	*Accipiter cirrocephalus*	Collared Sparrowhawk	Widespread	
		Accipiter fasciatus	Brown Goshawk	Widespread	

		Aquila audax	Wedge-tailed Eagle	Widespread	
		Hieraaetus morphnoides	Little Eagle	Widespread	
	Falconidae	*Falco berigora*	Brown Falcon	Widespread	
		Falco cenchroides	Nankeen Kestrel	Widespread	
		Falco peregrinus	Peregrine Falcon	Widespread	
Gruiformes	Rallidae	*Fulica atra*	Eurasian Coot	Widespread	
		Gallinula tenebrosa tenebrosa	Dusky Moorhen	Widespread	
Passeriformes	Acanthizidae	*Acanthiza chrysorrhoa*	Yellow-rumped Thornbill	Widespread	
		Acanthiza lineata	Striated Thornbill	Widespread	
		Acanthiza nana	Yellow Thornbill	Widespread	
		Acanthiza pusilla	Brown Thornbill	Widespread	
		Acanthiza reguloides	Buff-rumped Thornbill	Widespread	
		Acanthiza uropygialis	Chestnut-rumped Thornbill	Widespread	
		Gerygone fusca	Western Gerygone	Widespread	
		Gerygone olivacea	White-throated Gerygone	Widespread	
		Sericornis frontalis	White-browed Scrubwren	Widespread	
		Smicrornis brevirostris	Weebill	Widespread	
	Artamidae	*Artamus cyanopterus*	Dusky Woodswallow	Widespread	
		Artamus superciliosus	White-browed Woodswallow	Widespread	
		Cracticus nigrogularis	Pied Butcherbird	Widespread	
		Cracticus tibicen	Australian Magpie	Widespread	
		Cracticus torquatus	Grey Butcherbird	Widespread	
		Strepera graculina	Pied Currawong	Widespread	
		Strepera versicolor	Grey Currawong	Widespread	
	Campephagidae	*Coracina novaehollandiae*	Black-faced Cuckoo-Shrike	Widespread	
	Climacteridae	*Climacteris erythrops*	Red-browed Treecreeper	Widespread	
		Cormobates leucophaea	White-throated Treecreeper	Widespread	
	Corcoracidae	*Corcorax melanorhamphos*	White-winged Chough	Widespread	
	Corvidae	*Corvus coronoides coronoides*	Australian Raven	Widespread	
		Corvus mellori	Little Raven	Widespread	

	Dicaeidae	*Dicaeum hirundinaceum*	Mistletoebird	Widespread	
	Dicruridae	*Grallina cyanoleuca*	Magpie-lark	Widespread	
		Myiagra cyanoleuca	Satin Flycatcher	Widespread	
		Myiagra inquieta	Restless Flycatcher	Widespread	
		Myiagra rubecula	Leaden Flycatcher	Widespread	
		Rhipidura albiscapa alisteri	Grey Fantail	Widespread	
		Rhipidura leucophrys	Willie Wagtail	Widespread	
		Rhipidura rufifrons	Rufous Fantail	Widespread	
	Estrildidae	*Neochmia temporalis*	Red-browed Finch	Widespread	
	Hirundinidae	*Petrochelidon nigricans*	Tree Martin	Widespread	
	Maluridae	*Malurus cyaneus*	Superb Fairy-wren	Widespread	
	Meliphagidae	*Acanthagenys rufogularis*	Spiny-cheeked Honeyeater	Widespread	
		Acanthorhynchus tenuirostris	Eastern Spinebill	Widespread	
		Anthochaera carunculata	Red Wattlebird	Widespread	
		Caligavis chrysops	Yellow-faced Honeyeater	Widespread	
		Certhionyx variegatus	Pied Honeyeater	Widespread	
		Entomyzon cyanotis	Blue-faced Honeyeater	Widespread	
		Manorina melanocephala	Noisy Miner	Widespread	
		Melithreptus lunatus	White-naped Honeyeater	Widespread	
		Nesoptilotis leucotis	White-eared Honeyeater	Widespread	
		Philemon citreogularis	Little Friarbird	Widespread	
		Philemon corniculatus	Noisy Friarbird	Widespread	
		Ptilotula penicillata	White-plumed Honeyeater	Widespread	
	Motacillidae	*Anthus novaeseelandiae*	Australian Pipit	Widespread	
	Neosittidae	*Daphoenositta chrysoptera*	Varied Sittella	Widespread	
	Oriolidae	*Oriolus sagittatus*	Olive-Backed Oriole	Widespread	
	Pachycephalidae	*Colluricincla harmonica*	Grey Shrike-Thrush	Widespread	
		Falcunculus frontatus frontatus	Eastern Shrike-tit	Widespread	
		Pachycephala pectoralis	Golden Whistler	Widespread	
		Pachycephala rufiventris	Rufous Whistler	Widespread	

	Pardalotinae	*Pardalotus punctatus*	Spotted Pardalote	Widespread	
		Pardalotus striatus	Striated Pardalote	Widespread	
	Petroicidae	*Eopsaltria australis*	Eastern Yellow Robin	Widespread	
		Petroica boodang	Scarlet Robin	Widespread	
		Petroica goodenovii	Red-capped Robin	Widespread	
		Petroica phoenicea	Flame Robin	Widespread	
		Petroica rosea	Rose Robin	Widespread	
	Sturnidae	**Sturnus vulgaris*	Common Starling	Widespread	
	Turdidae	**Turdus merula*	Common Blackbird	Widespread	
	Zosteropidae	*Zosterops lateralis*	Silvereye	Widespread	
Psittaciformes	Cacatuidae	*Cacatua galerita*	Sulphur-crested Cockatoo	Widespread	
		Calyptorhynchus funereus	Yellow-tailed Black-cockatoo	Widespread	
		Eolophus roseicapillus	Galah	Widespread	
	Psittacidae	*Alisterus scapularis*	Australian King-Parrot	Widespread	
		Glossopsitta concinna	Musk Lorikeet	Widespread	
		Neophema pulchella	Turquoise Parrot	Widespread	
		Platycercus elegans	Crimson Rosella	Widespread	
		Platycercus eximius	Eastern Rosella	Widespread	
Strigiformes	Strigidae	*Ninox novaeseelandiae*	Southern Boobook, Morepork	Widespread	
		Ninox (Rhabdoglaux) strenua	Powerful Owl	Widespread	
MAMMALIA					
Artiodactyla	Bovidae	**Capra hircus*	Goat	Widespread	
	Cervidae	**Cervus elaphus*	Red Deer	Widespread	
	Suidae	**Sus scrofa*	Pig	Widespread	
Carnivora	Canidae	**Canis lupus familiaris*	Dog	Widespread	
		**Vulpes vulpes*	Red Fox	Widespread	
Chiroptera	Emballonuridae	*Saccolaimus flaviventris*	Yellow-bellied Sheathtail-bat	Widespread	
	Miniopteridae	*Miniopterus schreibersii oceanensis*	Eastern Bent-wing Bat	Widespread	Westernmost [outliers Balranald & Narrabri]

	Molossidae	*Austronomus australis*	White-striped Freetail-bat	Widespread	
		Mormopterus (Ozimops) planiceps	Little Mastiff-bat	Widespread	
		Mormopterus (Ozimops) ridei	Ride's Free-tailed Bat	Widespread	
	Vespertilionidae	*Chalinolobus gouldii*	Gould's Wattled Bat	Widespread	
		Chalinolobus morio	Chocolate Wattled Bat	Widespread	
		Falsistrellus tasmaniensis	Eastern False Pipistrelle	Widespread	
		Nyctophilus geoffroyi geoffroyi	Lesser Long-eared Bat	Widespread	
		Scotorepens orion	Eastern Broad-nosed Bat	Widespread	
		Vespadelus darlingtoni	Large Forest Bat	Widespread	
		Vespadelus regulus	Southern Forest Bat	Widespread	
		Vespadelus vulturnus	Little Forest Bat	Widespread	
Dasyuromorphia	Dasyuridae	*Antechinus agilis*	Agile Antechinus	Widespread	Northernmost
		Antechinus stuartii	Brown Antechinus	Widespread	Westernmost
Diprotodontia	Acrobatidae	*Acrobates pygmaeus*	Feathertail Glider	Widespread	
	Macropodidae	*Macropus giganteus*	Eastern Grey Kangaroo	Widespread	
		Macropus rufogriseus	Red-necked Wallaby	Widespread	
		Osphranter robustus robustus	Wallaroo	Widespread	
		Wallabia bicolor	Swamp Wallaby	Widespread	
	Petauridae	*Petaurus australis*	Yellow-bellied Glider	Widespread	Westernmost
		Petaurus breviceps breviceps	Sugar Glider	Widespread	
	Phalangeridae	*Trichosurus vulpecula*	Australian Brushtail Possum	Widespread	
	Pseudocheiridae	*Petauroides volans*	Greater Glider	Widespread	Westernmost
		Pseudocheirus peregrinus	Common Ringtail Possum	Widespread	
	Vombatidae	*Vombatus ursinus*	Bare-nosed Wombat	Widespread	
Lagomorpha	Leporidae	*Oryctolagus cuniculus*	Rabbit	Widespread	
Monotremata	Tachyglossidae	*Tachyglossus aculeatus*	Short-beaked Echidna	Widespread	
Perissodactyla	Equidae	*Equus caballus*	Horse	Widespread	

Rodentia	Muridae	**Mus musculus*	House Mouse	Widespread	
		Rattus fuscipes	Southern Bush Rat	Widespread	
		**Rattus rattus*	Ship Rat	Widespread	
REPTILIA					
Squamata	Agamidae	*Amphibolurus muricatus*	Jacky Lizard	Widespread	
		Rankinia diemensis	Mountain Dragon	Widespread	Westernmost
	Elapidae	*Austrelaps ramsayi*	Highland Copperhead	Widespread	Westernmost
	Scincidae	*Acritoscincus platynotus*	Red-throated Skink	Widespread	
		Ctenotus robustus	Robust Ctenotus	Widespread	
		Ctenotus taeniolatus	Copper-tailed Skink	Widespread	
		Egernia cunninghami	Cunningham's Skink	Widespread	
		Egernia striolata	Tree Skink	Widespread	
		Eulamprus heatwolei	Yellow-bellied Water Skink	Widespread	Westernmost
		Eulamprus quoyii	Eastern Water-skink	Widespread	
		Hemiergis decresiensis	Three-toed Earless Skink	Widespread	
		Lampropholis delicata	Dark-flecked Garden Skink	Widespread	
		Lampropholis guichenoti	Pale-flecked Garden Sunskink	Widespread	
		Liopholis whitii	White's Skink	Widespread	
		Menetia greyii	Common Dwarf Skink	Widespread	
		Pseudemoia entrecasteauxii	Tussock Cool-skink	Widespread	Westernmost
		Saproscincus mustelinus	Weasel Skink	Widespread	Westernmost
		Tiliqua rugosa	Shingle-back	Widespread	
		Tiliqua scincoides	Eastern Blue-tongue	Widespread	
	Varanidae	*Varanus gouldii*	Gould's Goanna	Widespread	

Miocene Central Volcanoes, NW New South Wales: Genesis over a Lithospheric Cavity (?)

F. Lin Sutherland[1]
with illustrative contributions by B.E. Cohen[2] and M.B. Duggan[3].

[1]Australian Museum, 1 William Street, Sydney, NSW 2010 (Lin.Sutherland@austmus.gov.au);
[2]School of Geographical and Earth Sciences, University of Glasgow, Scotland, G12 8QQ, UK;
[3]519 Mulquinneys Road, Braunstone, NSW 2460

Sutherland, F.L. (2019). Miocene central volcanoes, NW New South Wales: genesis over a lithospheric cavity (?). *Proceedings of the Linnean Society of New South Wales* **141,** S85-S114.

Basalt fields and central volcanoes form a curved south-migrating trace through NW New South Wales. A segment of East Australian intraplate volcanism, it traces Australia's northern plate motion north over a mantle plume system. This created the western New England basalt field (24 – 21 Ma), Nandewar central volcano (19 – 18 Ma), Warrumbungle central volcano (18 – 15 mya), Mount Canobolas central volcano (13 – 11 Ma) and minor alkaline eruptions near Oberon (10 – 9 Ma). This 'boomerang-shaped' segment initially swelled south-westerly with increasing mantle melting and basaltic evolution. After initial fluid basaltic outpourings in New England, it formed two large central volcanoes along its outward curve before bending southerly to form a smaller central volcano and a scattered tail of small late-eruptions. This volcanic trace did not match Australia's linear plate motion trend between 24 – 9 Ma. Neither did it correspond with adjacent plume trend seen in the leucititic lavas to the west, the coastal NSW plume volcanoes and Tasman Sea submarine plume chains to the east. Recent seismic tomography has revealed 'cavities' within the underlying lithosphere-asthenosphere boundary (LAB). The anomalous NW New South Wales plume upwelling underwent diversion by its interaction along the western edge of a LAB 'cavity'.

Manuscript received 10 June 2019, accepted for publication 1 October 2019.

KEY WORDS: age-dating, basalt fields, Cenozoic volcanism, central volcanoes, East Australia, lithospheric cavity, magmatic fractionation, mantle melting, plate motion, plume trace.

INTRODUCTION

This paper surveys Miocene volcanic rocks, their distribution, age, petrology, genesis, tectonic setting, geomorphic development, and features of general interest within north-western New South Wales. It is based on a presentation given at the 2018 Linnean Society of NSW on this theme at Coonabarabran, 25-26 September, 2018. The symposium also explored further relationships between geology, flora, fauna and fires, which were not pursued in this volcanic survey. The Symposium presentation was greatly enhanced by inclusion of extra material in the form of images of volcanic features and geological diagrams, particularly by Dr Ben Cohen, from his 2007 PhD thesis study, School of Physical Sciences, University of Queensland, and by Dr Morrie Duggan, from his studies and writings on the area, when employed at the Australian Geological Survey Organisation, now Geoscience Australia, Canberra, ACT. Many of these illustrations are included in this paper, with the permission and acknowledgement of the contributors, and add greatly to its illustrative content. Some volcanic content in this study appeared in a previous Linnean Society of New South Wales Symposium volume, on Geodiversity, Geoheritage and Geotourism, (Sutherland 2011). Those parts related to NW New South Wales volcanic areas, however, are revisited and updated with further relevant literature.

Geological setting

Eastern Australia has an extensive record of intraplate basaltic volcanism. Its latest prolonged cycle has continued in quasi-continuous mode for ~ 100 Ma, after initial early Cretaceous break-up events at ~ 125 Ma split Australia and New Zealand (Matthews et al. 2016 a, b). This episode initiated widespread elevated heat flows, leading to volcanic activity and

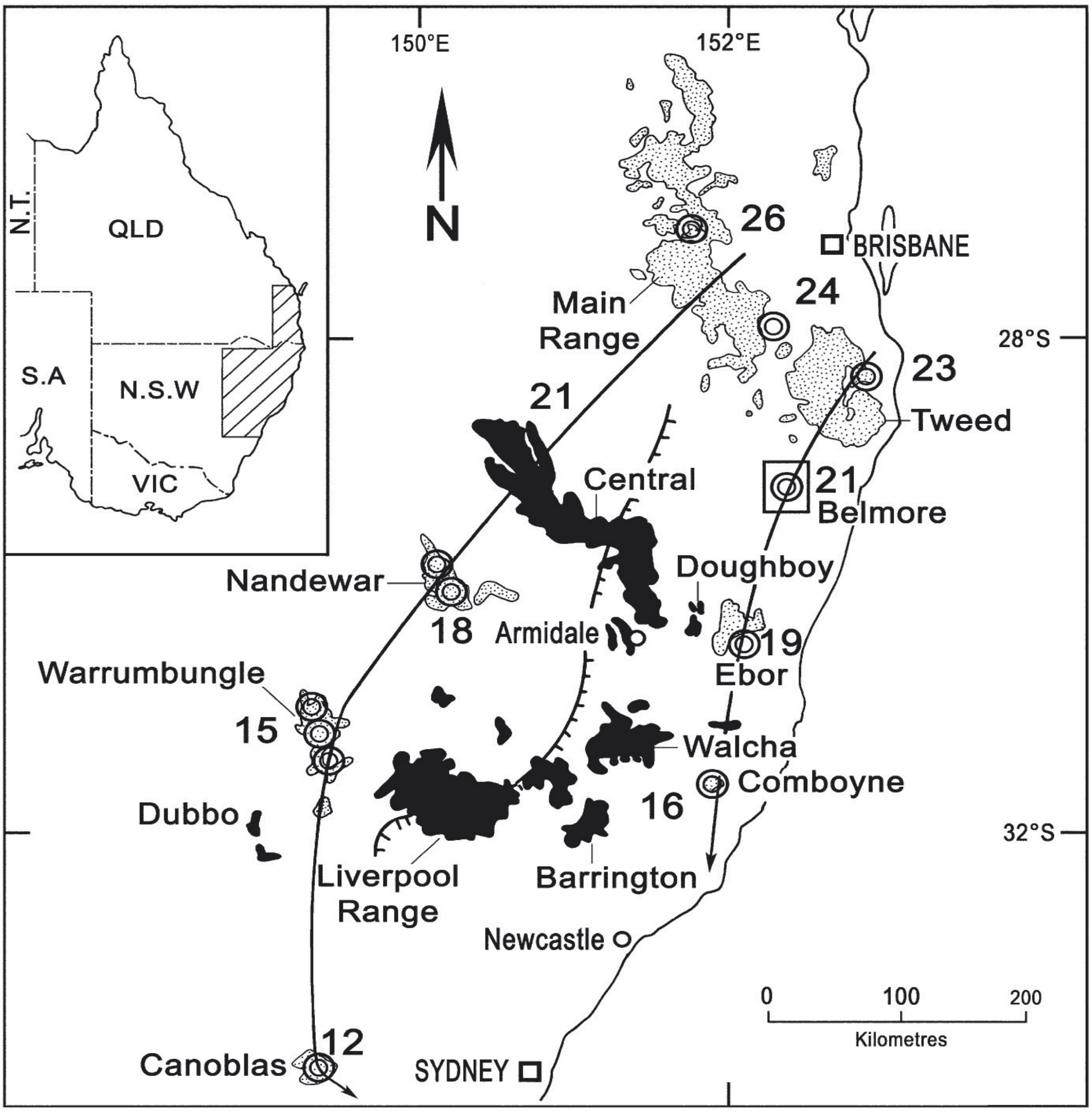


Figure 1. Distribution of central volcanoes (stippled areas) and basalt lava fields (black areas), Qld – NSW 26 – 36o S. Map shows main ages in Ma (based on available Ar – Ar and K- Ar ages), general age-progressive trends (arrowed lines) and western edge of the Sydney Basin (hatched line) The Belmore central volcano is outlined by a box to indicate its unusual silicic nature. The diagram is modified from Sutherland et al. (2005).

sea floor spreading events that dismembered the Gondwa margin into fragmented continental slivers (Higgins et al. 2015). The disruptions led to the rise of long-term asthenosphere-derived magmatic plume systems that developed migratory 'hot spot' volcanic chains over migrating lithosphere (Johnson 1989; Sutherland 2003; Sutherland et al. 2012; Cohen et al. 2013; Jones et al. 2017). Three types of volcanic fields were initially distinguished within eastern Australian volcanism, basaltic lava fields, central volcanoes which include both basaltic and evolved felsic components, and rarer leucititic lavas (Johnson 1989). The latter two types were associated with migratory plume-related activity, while basaltic lava fields were considered more random rift-related melting events. Later studies, however, have identified basaltic lava fields that appear to be associated with the migratory plume-derived fields (Sutherland 2003; Jones et al. 2017). The main NW New South Wales Miocene volcanic fields include basaltic lava fields, some plume-related, and well developed central volcanoes (Fig. 1), while age-progressive leucititic migratory volcanoes are confined to outer western fringes (Cohen 2007; Hansma and Tover 2018).

The term ‘Volcanoes of Northwest New South Wales’ used in the Coonabarabran Symposium needs definition here, as some volcanoes are variously designated north-eastern or central NSW in previous literature. This study covers the migratory Miocene age-linked North West NSW volcanic fields mapped west of Inverell (Brown and Stroud 1997; Vickery et al. 2007), and to the south-east includes the large Nandewar Range and Warrumbungle Range central volcanoes, all of which fall within the Brigalow Belt South Bioregion (Dawson et al. 2003). The lesser-sized Canobolas central volcano and minor Abercrombie basalt field (Pogson and Watkins 1998), however, lie south of the Brigalow Belt South Bioregion (Dawson et al. 2003). The fields overall extend between 149° 30’– 151° E and 29° – 33° 45’S. The Brigalow Belt South Bioregion also covers the eastern voluminous Oligocene-Eocene Maybole and Liverpool Range basaltic shields (up 1000 m in thick; Johnson 1989; Middlemost 2013), which are not considered here.

The feeder systems for the described migratory volcanoes penetrated a range of crustal basement units (Pogson and Watkins 1998; Dawson et al. 2003; Vickery et al. 2007). The underlying Paleozoic basement includes parts of the Lachlan and New England fold-belts (Glen 2013; 2015). The fold-belt rocks underlie an unconformity below late Permian mafic rocks and the following sedimentary beds of Gunnedah Basin (Ward and Kelly 2013). Westward, these beds are overlapped by late Triassic-Jurassic-early Cretaceous deposits of the Surat Basin.

The western New England basalt field (Fig. 2), was re-named the Delungra Volcanic Suite by Vickery et al. (2007). It includes older flows and plugs northwest of Inverell, which transgress Jurassic Surat Basin beds. West of Inverell younger lavas overlie the older basalts and were erupted from plugs that ascended through the early Permian Bundarra Batholith in the New England Fold Belt (Vickery et al. 2007). Smaller separate basalt fields around Bingara overlie Devonian-Carboniferous beds of the New England Fold Belt. The Delungra Volcanic Suite flows buried alluvial deposits of the Miocene drainage (Fig. 3), which carried unusual diamonds of unknown source (MacNevin 1977; Meyer et al. 1997; Barron et al. 2008).

Nandewar central volcano shows complex relationships to the underlying geology (Dawson et al. 2003). The northern part volcanics both intruded and overlie dissected Gunnedah and Surat Basin beds, although its northern nose volcanics overlie Cretaceous marine beds. Basaltic lavas in its northeastern extent overlie Cenozoic alluvial gravels, sands and silts. The central and southern parts of the volcano intrude through and overlie thrust-faulted Devonian and Carboniferous fold belt beds to the east side. Its west side largely overlies a dissected terrain of basal Permian mafic volcanic rocks and Permian-Triassic sedimentary beds within the Gunnedah Basin. In places, Nandewar extrusions overlie eroded sills of teschenite, an analcime-bearing dolerite. These are unrelated to Nandewar Volcano and were dated at 198 ± 2 Ma (Cohen 2007). Small basaltic flow remnants of Nandewar Volcano’s original outreach continue along a N-S length of 120 km and an E-W width of 75 km (Geological Drive across the Nandewar Volcano. Bob and Nancy’s Geotourism Site: http://ozgeotours.yolasite.com/ ; accessed 26/09/2019).

Many eruptive units of Warrumbungle Volcano are now remapped in greater detail (Troedson and Bull, 2018). Most overlie Jurassic sedimentary beds of Surat Basin, largely the braided stream deposits, but in places extend over mid-Jurassic alluvial and lake deposits (Dawson et al. 2003). The north western edge of the volcanic apron, however, rests on upper late Jurassic to early Cretaceous stream and coastal deposits. The feeder system in the central vent ascended into the Surat Basin sequence through the underlying Lachlan Fold Belt. Flows entered former radial drainages and extended flows travelling SSE intersected and infilled a former SW channel of Castlereagh River, diverting the river farther south (Dawson et al. 2003).

The rise and fall of Canobolas Volcano through growth and erosion in relation to the surrounding geology and regolith is outlined in Chan (2003). The feeder system erupted through the Lachlan Fold Belt and its outflowing lavas descended into drainages cut extensively in weathered plateau surfaces. In places, lavas flowed over Surat Basin beds infilling radial drainages to the northeast and reached exposed Bathurst Granite to the southeast.

Young zircon grains appear in alluvial deposits adjacent to basalts in the Abercrombie province (Sutherland 1993). These deposits lie ESE well beyond the older Canobolas eruptive apron. They suggest minor eruptions around Oberon after cessation of Canobolas activity.

VOLCANIC FIELDS, GEOCHRONOLOGY AND PETROLOGY

Delungra Volcanic Suite

Four separate areas of eruption were mapped within the basaltic suite (Fig. 4). These comprise two areas of largely silica-saturated tholeiitic basalts, the

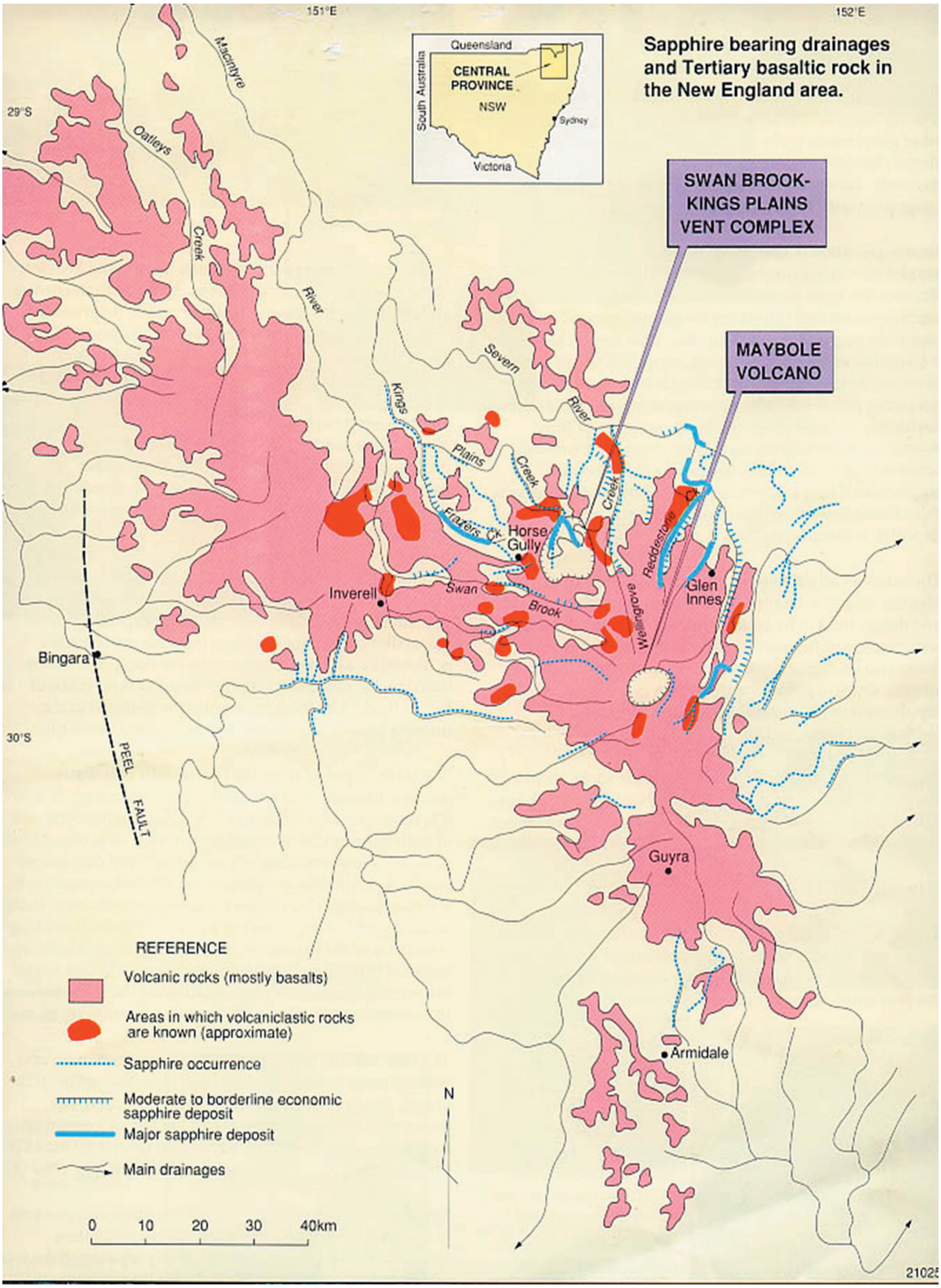


Figure 2. New England, NSW, basalt fields (pink), volcaniclastic deposits (red) and alluvial gem leads (blue). The basalts east of a line through Inverell are mostly alkaline basalts with older ages > 30 Ma, while those to the west include tholeiitic and alkaline basalts mostly with younger ages < 30 Ma. Map courtesy of Gemmological Association of Australia.

Figure 3 (left). A western New England basalt flow capping diamond-bearing alluvial beds. Round Mountain Mine, Copeton area. Photo F. Lin Sutherland.

extensive Mount Russell Volcanics and restricted Dera Dera Volcanics, and two small regions of silica-undersaturated basalts, the Inverell Volcanics and Bingara Volcanics (Vickery et al. 2007). Previous dating results were largely K-Ar ages. McDougall and Wilkinson (1967) cited a range of 20.9 ±2 to 18.5 ± 2 Ma for the tholeiitic Mount Russell – Inverell basanite sequence, while Vickery et al. (2007) reported 23.9 ± 0.3 Ma for a Derra Derra basanite and 22.6 ± 0.5 Ma for a Bingara hawaiite. An Inverell basanite, re-examined by Cohen (2007), gave a more precise

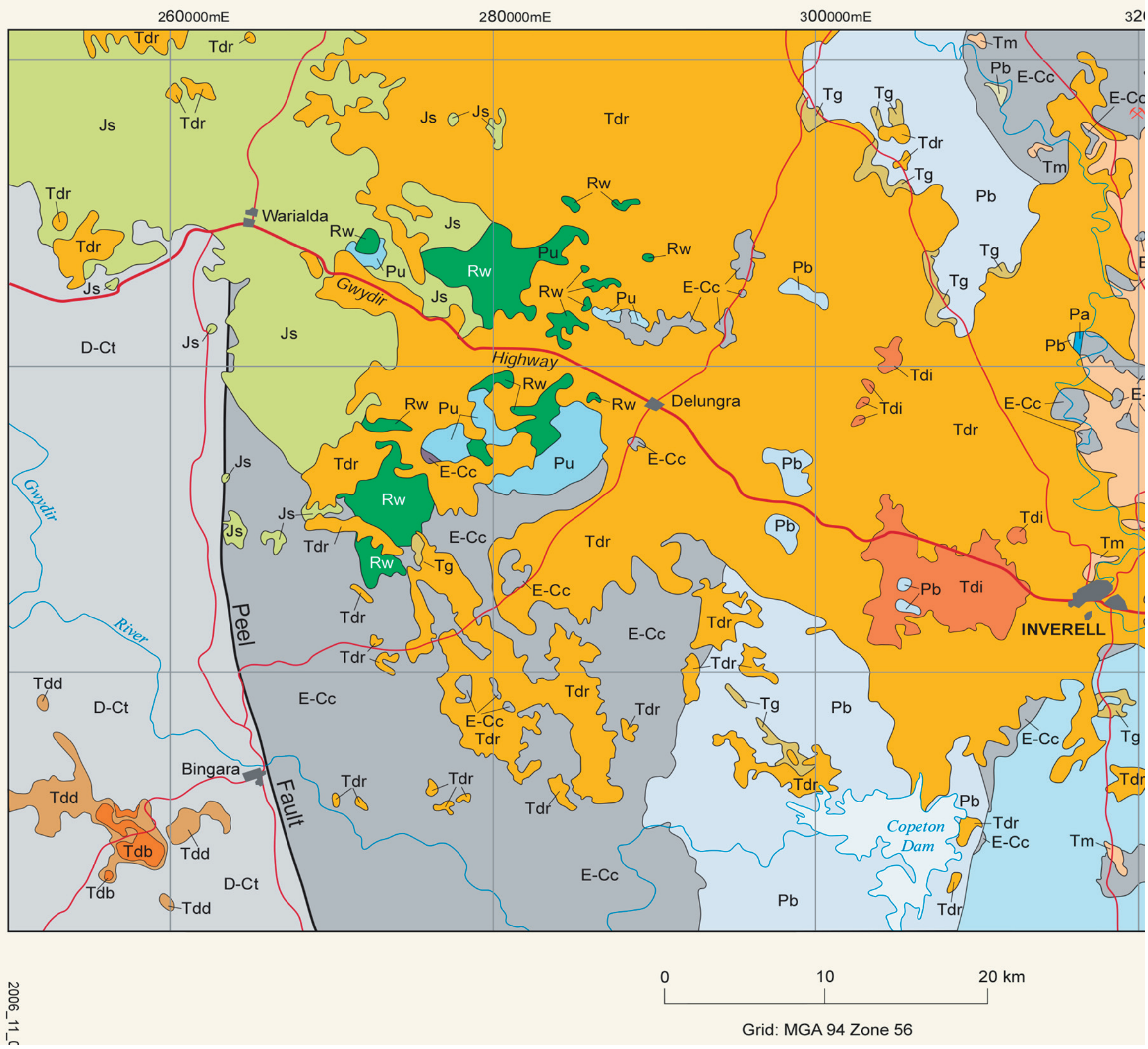


Figure 4. Portion of Inverell 1:250 000 Geological Map Sheet (Vickery et al. 2007), showing details of the Delungra Volcanic Suite basalts (Tdr Russell Volcanics, Tdi Inverell Volcanics, Tdd Derra Derra Volcanics,Tdb Bingera Volcanics) and underlying geological units (Tg Cenozoic gravels, Tm Maybole Volcanic Suite, Js Surat Basin, Rw Warialda Trough, Pu Uralla Supersuite, Pb Bundarra Supersuite, E-Cc Central Block, D-ct (Tamworth Belt), with red lines (roads), blue lines (rivers and dams). Other rock units east of Inverell are not designated. The three latitudinal grid lines lie at 6740000nN, 6720000mN and 6700000mN in descending order.

^{40}Ar-^{39}Ar age of 21.3 ± 0.4 Ma. These results suggest Delungra volcanism was active from ~ 24 to 21 Ma.

The extensive Mount Russell Volcanics in microscope sections exhibit sub-ophitic intergrowth of clinoproxene and plagioclase within a crystallisation sequence of olivine-plagioclase-clinopyroxene-magnetite (Vickery et al. 2007). Chemically, the rocks are quartz tholeiites, with normative quartz ~ 1 –25 %, hypersthene 44–63 % and diopside 33–37 %. They have relatively high SiO_2, Al_2O_3, and Zr/Nb and low TiO_2, MgO, Zr , La/Yb_N and Dy/Yb_N in comparison to the more undersaturated Inverell and Bingara basalts. The smaller Derra Derra Volcanics field shows similar tholeiitic petrology to the Mount Russell field, although slightly lower in SiO_2 and higher in Al_2O_3, while some transitional basalts lack normative qz. Trace element profiles are less elevated than in Mount Russell suites, apart from a distinct high Rb content, while REE profiles show slight enrichment.

The restricted low-silica Bingara and Inverell Volcanic Fields contrast markedly in their petrology from the tholeiitic fields. They are richer in olivine, typically in embayed phenocrysts and microcrysts, and contain feldspathoidal minerals in the groundmass. Analcime in Bingara Volcanics hawaiites can form up to 40 % of the rocks. In Inverell Volcanics basanites, nepheline with associated analcime, cancrinite, zeolites and alkali feldspar can form some 50 % of the rock. The accessory Fe-Ti oxide mineral in these Si-difficient rocks is largely ilmenite rather than the magnetite-ulvospinl series found in the tholeiitic suites.

Trace element and isotope results on the Delungra Volcanic Suite provide insights into the genesis of its basalt fields (Vickery et al. 2007). Normalised REE ratios suggest that the low-Si Bingara and Inverell basalts with the highest Dy/Yb_N (2.5 – 3.2) and La/Yb_N (34 – 57) values represent small volume partial mantle melts from deeper garnet-bearing peridotitic mantle. In contrast lower Yb_N (1.4 – 2.5) and La/Yb_N (4 – 6) values in the Mount Russell Si-rich basalts indicate larger volumes of partial mantle melting of spinel- bearing peridotite mantle, with other trace elements suggesting incorporation of crustal materials. Measurements of isotope ratios of ^{87}Sr/^{86}Sr and ^{143}Nd/^{144}Nd in the rocks showed that the Bingara and Inverell basalt ^{87}Sr/^{86}Sr (~ 0.7040 – 0.7043) and ^{143}Nd/^{144}Nd (0.5127) fall within the main field for East Australian central volcano plume signatures. The Mount Russell basalt values (^{87}Sr/^{86}Sr 0.7048; ^{143}Nd/^{144}Nd 0.5127) lie slightly outside the plume signature field, but along the same trend line for the Bingara-Inverell basalts. The data suggest all these fields are derived from a similar plume source, although Mount Russell basalts show crustal contamination effects.

Nandewar Central Volcano

The Nandewar volcano has a NNW – SSE trend, probably partly controlled by faulting in the Devonian-Carboniferous basement (Dawson et al. 2003; Cohen 2007; Fig. 5). Considerable erosion of the original structure has revealed much of its basaltic and felsic extrusions and feeders (Figs 5 – 9). Alkali rhyolite flows occupy much of the central region and include an alkali monzonite intrusion, while the northern shield exposes plugs and domes of comenditic rhyolite. Evolved flows in the southern flank are punctuated by a cluster of plugs and flows of alkali trachyte, which includes the high point of Mount Kapatur. A surface reconstruction of the original volcano (Sutherland 1995), depicted two main craters remaining at the north and south ends. These would mark eruptive vents above the two plug and dome sites.

The most accurate dating of the volcanic sequence within the Nandewar volcano and its felsic centres rests on four ^{40}Ar-^{39}Ar ages determined by Cohen (2007), given in a summary plot of the volcano's migratory relationships with the leucititic migratory line to the west (Cohen et al. 2008). A high level basalt, three trachytes and a rhyolite gave a restricted age range of 18.9 – 18.5 ± 0.2 Ma (Figure 5).This restricts activity compared with the K-Ar age range of 21.1 ± 1.5 – 17.4 ± 0.8 Ma (Cohen 2007). The only mafic ^{40}Ar/^{39}Ar age lies in the upper volcanic levels, which probably confines basal basalt eruptions to within 21– 18.7 Ma.

Several studies describe Nandewar mineralogy, petrology and genesis of the alkaline rock suites. Abbott (1969) listed an evolution from rare olivine basalt through intermediate rocks such as hawaiites, mugearites and benmorites into silicic end member rhyolites. Low oxygen fugacities in the magmas controlled the compositions of crystallising mafic minerals. Pyroxenes included Ca-rich augite, Na-rich hedenbergite and hedenbergite, while more evolved rocks crystallised sodic amphiboles of the riebeckite – arfvedsonite series Feldspar ranged from calcic-plagioclase into anorthoclase and alkali feldspars in compositions near Ab_{65} $Or_{35.}$ Extreme crystal fractionation processes were invoked for producing the observed rock compositions.

The role of fractional crystallisation in the magmas to produce the assemblages was further investigated by Stolz (1985). He studied slightly saturated hawaiite through trachyandesite and tristanite into comendite. Tristanite is a type of K-

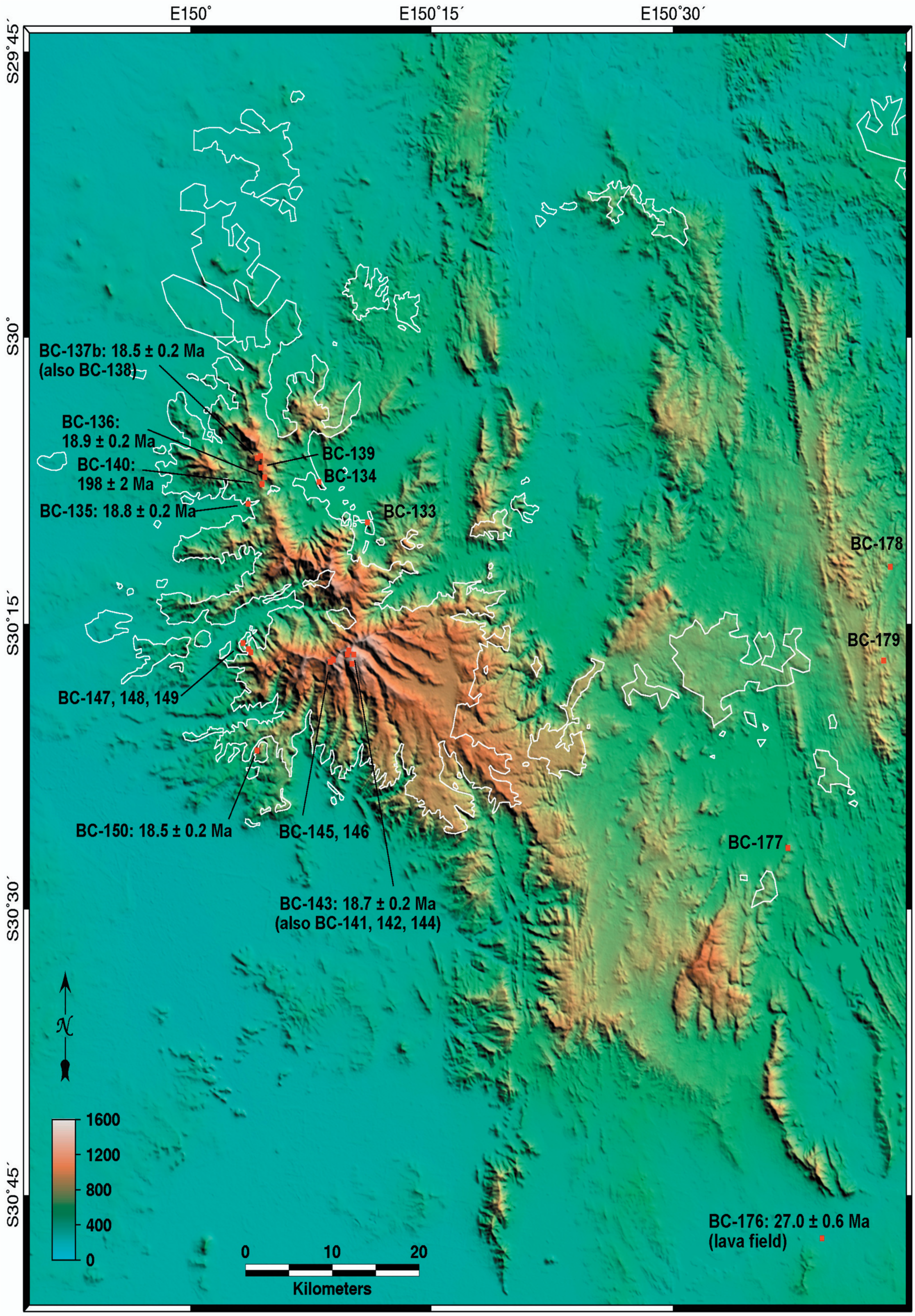


Figure 5. Nandewar Volcano, showing topographic relief based on Digital elevation modelling (DEM), used for locating sites of Ar – Ar ages (Ma), image Cohen (2007).

Figure 6. View of northern profile of Nandewar Volcano, looking north westerly from Killarney Gap, Bingara- Narrabri Road, towards Castle Top Mountain a flow remnant with a dyke outcrop on its eastern side. Photo Ben Cohen.

Figure 7. Sawn Rocks, showing an alkali rhyolite exposure, with well-developed cooling columns, Killarney Gap, S side Bingara- Narrabri Road. Photo Ben Cohen.

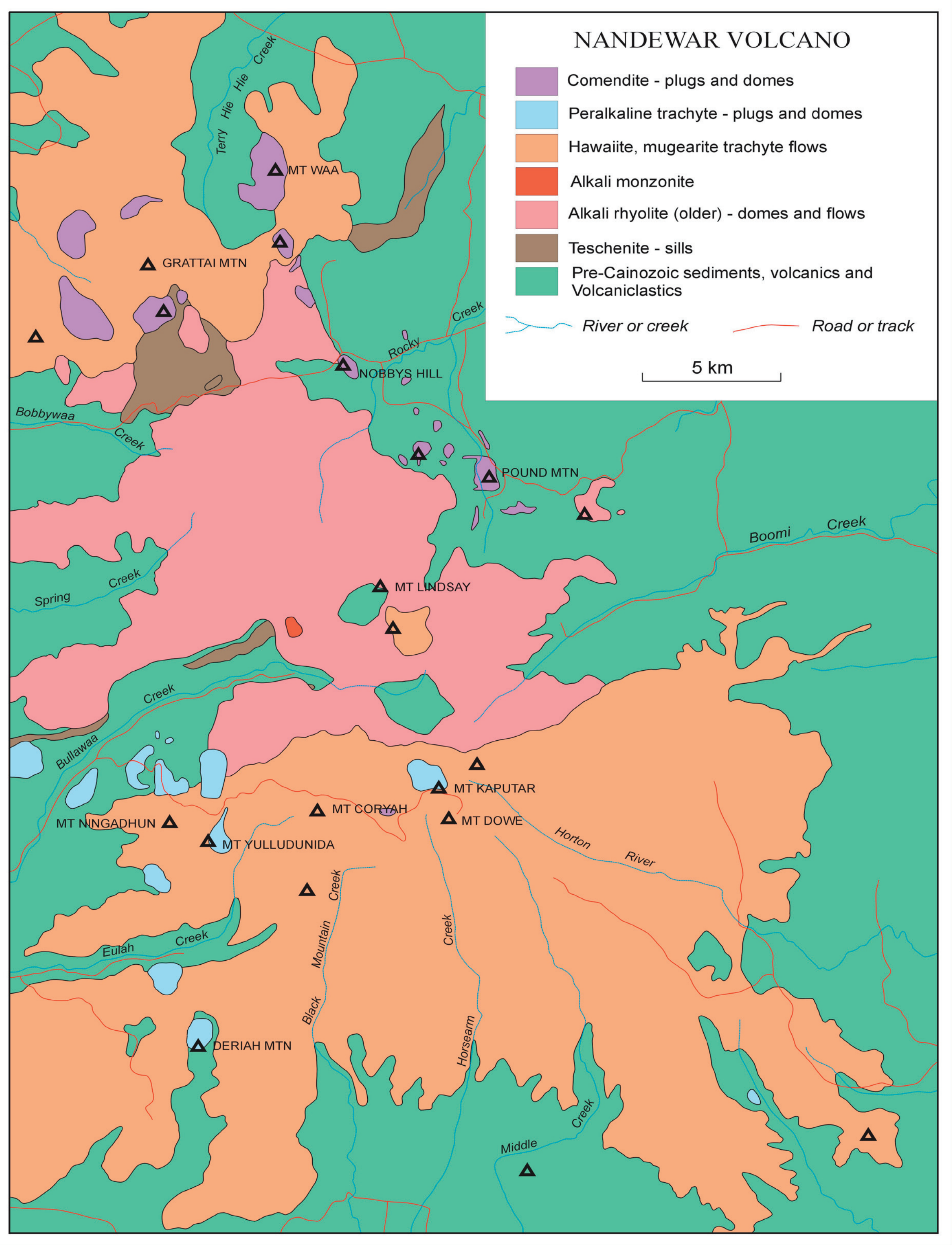


Figure 8. Nandewar Volcano, simplified geological map, with legend. Image Morris Duggan.

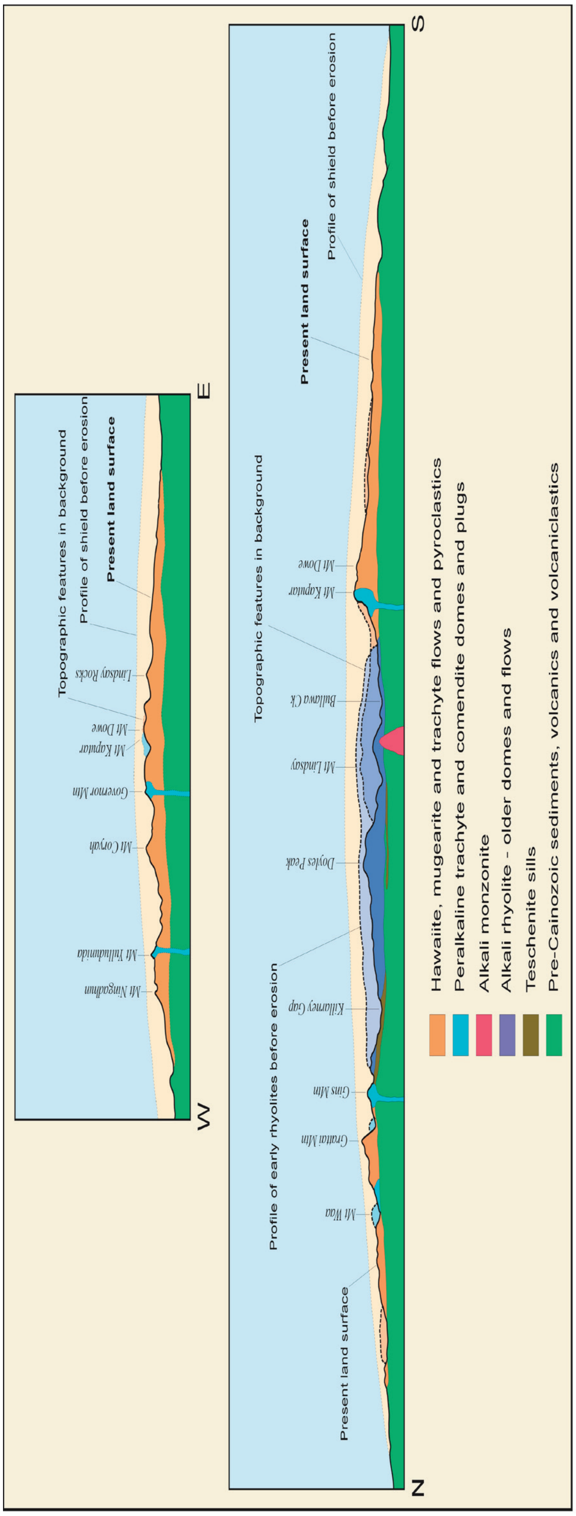


Figure 9. Nandewar Volcano, N-S and W-E profiles, present and past. Image Morris Duggan.

rich trachyte between trachyandesite and trachyte in composition, typical in silica-saturated alkali suites often associated with hot spot-related provinces (Whitaker et al. 2007). At Nandewar, parental magmas were regarded as partial melts of mantle peridotites containing varying amounts of accessory amphibole, mica and apatite. The range of trachytes and rhyolites, however, was difficult to replicate from the mineralogy in the less fractionated rocks. An alternative model was proposed where changes in the melt chemistry took place in the liquid state. Late-stage additions and loses of volatile components were considered as significant modifiers in abundances of alkali elements and trace element contents in magmas during volcanic growth.

Mineral compositions in the volcanic suites were closely studied by Stolz (1986), in relation to magmatic genesis. Olivines, calcic pyroxenes and amphiboles in suites evolving from hawaiite, through trachyandesite to comendite show marked decreases in Mg values (100 Mg / Mg+Fe) within the sequence. Sub-calcic clinopyroxenes and Al-enriched orthopyroxenes indicated crystallisation of hawaiites at pressures between 0.6 – 0.8 GPa. Some trachyandesites contain crystals of plagioclase and Ti-bearing magnetite that suggest crystallisation as cumulates at moderate pressures. Evolution of comendites took place at lower pressures. The Fe-Ti oxide minerals in trachyandesites and comendites indicate trends of cooling temperatures and a decreasing oxygen activity in the crystallising magmas. Some Ti-bearing magnetite and ilmenite developed rims of aenigmatite, in more alkaline-rich rhyolites, suggesting periodic cessation of the oxide crystallisation. Rhyolites in the lower central part of the volcano, however, contain Fe-Ti oxides formed under more highly oxidising conditions.

A summary on Nandewar Volcano petrology included details of field outcrops and settings (Duggan et al. 1993). The volcanic suite was subsequently investigated using a petrogenetic experimental simulation of the Nandewar rocks (Nekvasil et al. 2004). Rock powders were run at various pressure and temperature (PT) conditions under different bulk water contents. Nandewar compositions could arise from a hy-normative hawaiite starting point and fractionate it into sodic rhyolite at P (0.93 GPa), T (1200 – 1100^{o} C), bulk water content at ~ 0.5 wt% and low oxygen activity below the fayalite-magnetite-quartz buffer. The mildly alkaline hawaiite, matching a partial mantle melt at ~ 60 km depth, became increasingly alkaline through strong early clinopyroxene crystal fractionation, with suppression of the feldspar crystallisation. Dominant crystallisation of Ti-rich amphibole, kaersutite, at

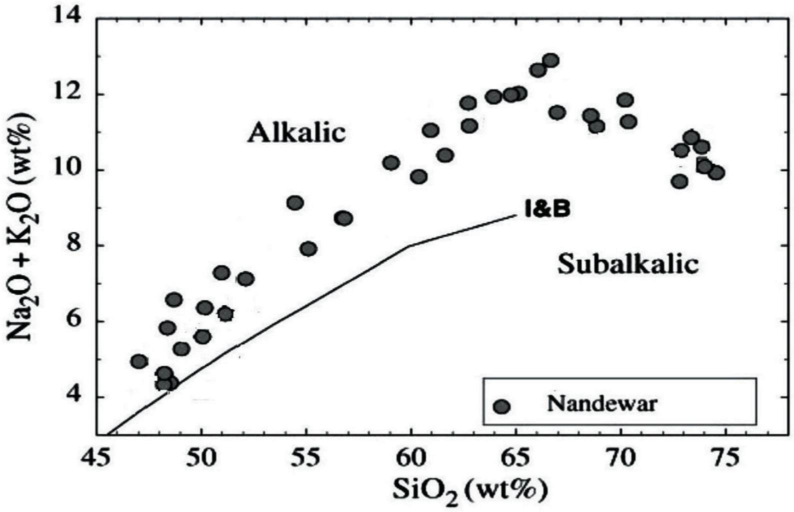


Figure 10. Total Alkalis (Na2O + K2O) –SiO2 diagram showing plots of Nandewar suite analyses from Abbott (1969) and Stolz (1985). Note trend of increasing Alkali content with turn around and slight decline at higher silica levels typical of many hot spot related suites. Diagram modified from Nekvasil et al. (2004). Dividing line I & B between alkalic and subalkalic fields is from Irvine and Baragar (1971)

mid-crustal PT in the middle stages (~ 30 km in depth and ~1100 – 1050^{o} C), pushed compositions towards rhyolitic melts. The changes were pressure sensitive and at mid-crustal values generated K-enrichments in melts. Evidence for multi-stage ponding and crystallisation stages within the melts themselves helps to explain the difficulties Stolz (1985) had in calculating matching assemblages. Nandewar alkali enrichment with SiO$_2$ (Fig. 10) and other oxide trends (not shown) matches patterns found in alkali shield volcanoes elsewhere, as in the Azores, Atlantic, Clarion Island, Mexico, and Ascension Island, Southern Ocean (Nekvasil et al. 2004).

The full story of Nandewar Volcano activity awaits further resolution. A mantle-derived nephelinite sill with ultramafic inclusions and high pressure megacrysts intrudes the Permian sequence below its northeast side (Wilkinson 1975). Such rocks appear in the nearby plume-related late nephelinites in the Inverell Volcanics, west New England. The Nandewar nephelinite may mark early low-volume deep melting as the area encroached over the hotspot plume, or even late activity as it passed beyond plume influence. The nephelinite's actual relationship to Nandewar Volcano activity, will need precise dating.

Warrumbungle Central Volcano

This is the best age-controlled central volcano in the NW New South Wales chain, where results have clarified many relationships between various landmark volcanic exposures within its landscape features (Figs 11, 12). The volcanic features (Fig.

Figure 11. Warrumbungle Volcano, view of Grand High Tops circuit, looking southward, showing intrusive features in the central region. Prominent features include Needle Mountain, extreme left, Crater Bluff (far left), Belougery Spire (left), The Breadknife (left centre), Bluff Pyramid (right) and Bluff Mountain (far right). The Breadknife and Bluff Mountain have Ar –Ar age dates, at 15.2 ± 0.3 and 15.5 ± 0.2 Ma. Photo Ben Cohen.

Figure 12. Crater Bluff (foreground), looking south to Tonduron Spire. Photo Ben Cohen.

13) largely intrude and/or overlie the Jurassic basin cover (Dugan and Knutson 1993; Dugan et al. 1993; Dawson et al. 2003). A cross section of the volcano with suggested structure and possible original profile is presented in Fig. 14. Sixteen K-Ar ages ranged between ~17 – 13 Ma for the sequence. The ^{40}Ar/ ^{39}Ar dating at 9 sites (Fig. 15) constrained the age range to 18.0 ± 0.2 – 15.2 ± 0.2 Ma (Cohen 2007). Cohen confirmed the activity spanned a magnetic polarity reversal switch from normal, through transitional to reversed magnetism. He also suggested some domal features (Duggan and Knutson 1993; Duggan et al.1993) were probably plugs. Further ^{40}Ar/^{39}Ar dating by Crossingham et al. (2018) on trachybasalt and trachyandesite rocks gave ages from 17.8 ± 0.1 to 16.8 ± 0.1 Ma. These ages lie within the overall ^{40}Ar/ ^{39}Ar range for Warrumbungle Volcano, but preceded the recorded late silicic activity between 16.3 ± 0.1 and 15.2 ± 0.3 Ma (Cohen 2007).

Figure 13 (Left). Trachyte dyke intruding pyroclastic beds, lower section Mount Woorut sequence, Siding Springs Road, 0.7 km NE of John Renshaw Drive junction. Photo Ben Cohen.

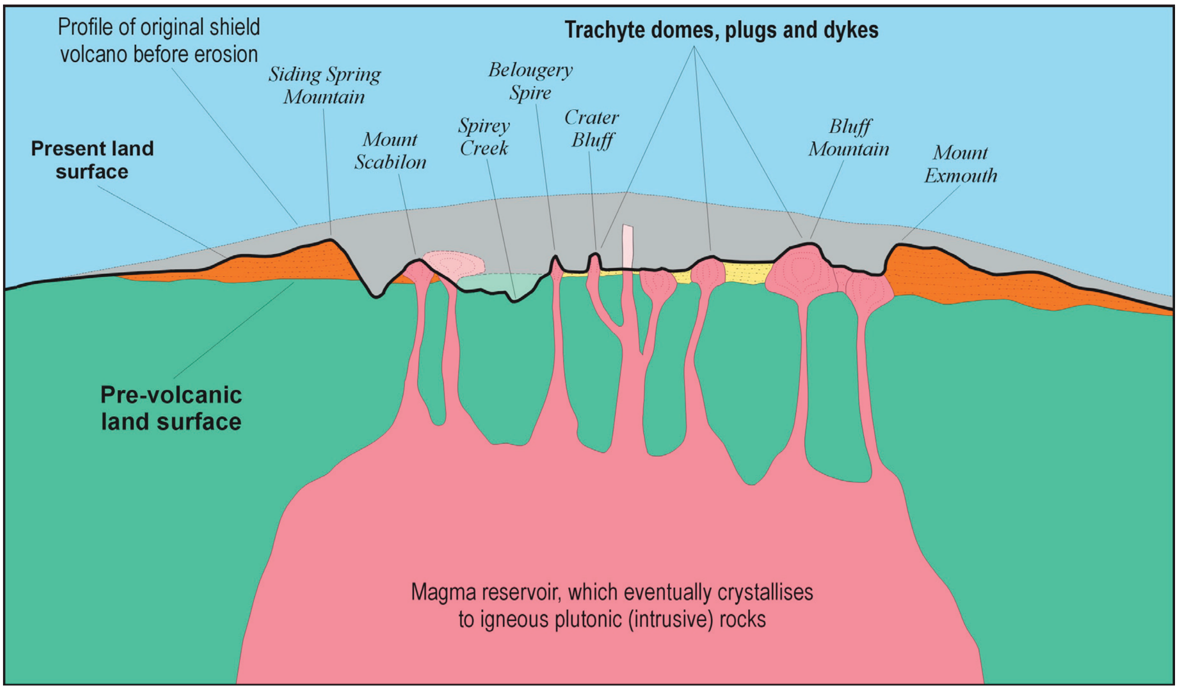


Figure 14. Warrumbungle Volcano, showing simplified geological section interpretation of present structure and original surface profile. Image from Duggan and Knutson (1993). This section pre-dates recent re-mapping of the volcano geology and possible modifications in its interpretation (Bull and Troedson, 2018; Troedson and Bull, 2018).

A comprehensive survey of Warrumbungle Volcano petrology (Duggan et al. 1993), indicated a strongly bimodal distribution with peaks in the hawaiite-mugearite and trachytic ranges. The more mafic rocks dominated in the outer north and south flanks and contain forsterite, Mg-rich olivine, as an early crystallisation mineral. A few hawaiites contain ultramafic inclusions, mostly pyroxenites and megacrysts of Al-bearing and Fe-rich augitic clinopyroxene. Less evolved alkali basalt and more evolved benmoreite are rare types among the mafic series. Trachytes dominate the central part of the volcano, where flows up to 50 m thick form the main shield lavas, and also compose small lava domes elsewhere. Plugs, dykes and domes of such rocks are prominent in the central vent area, such as around the Grand High Tops circuit (Fig. 11), but also form isolated peaks in the east and south flanks.

The trachyte suite typically contains Fe-rich olivine, the mineral fayalite, and includes both alkali and meta-aluminous compositional types. The Warrumbungle petrological evolution was considered to mostly represent compositional magma fluctuations across a critical thermal divide that directed crystallisation into silica-saturated and silica-under saturated feldspathoidal-crystallising paths. Peralkaline felsic magmas dominated the abundant explosive pyroclastic deposits through the sequence. Overall, these magmas typically crystallised sodic clinopyroxene, minerals in the hedenbergite-acmite series, which may contain abnormally high values of Zr (Duggan 1988). The sodic amphibole arfvedsonite is also common in the peralkaline rocks. In addition, the sodium, titanium, iron silicate mineral, aenigmatite, is present in many trachytes. Some exceptionally Ti-poor, silica-understurated trachytes contain wilkinsonite $Na_2 Fe^{2+}_4 Fe^{3+}_2 Si_6 O_{20}$ (Fig. 16). This is a new member of the aenigmatite group first described from Mount Bingie Grumble in the Warrumbungles by Duggan (1990). It was named after an Australian petrologist, the late Professor John Wilkinson from the University of New England, Armidale, NSW, for his seminal studies on the nature and evolution of alkaline rocks, especially in eastern Australia.

Detailed geochemical analyses on two Warrumbungle peralkaline trachytes were compared with Nandewar, Canobolas and other such East Australian Mesozoic-Cenozoic examples (Ewart et al. 1985; Ewart 1985). The O isotope values for feldspars in Warrumbungle trachytes were noticeably higher than in a Nandewar, Mount Kapatur rock. Subsequent detailed petrological studies on

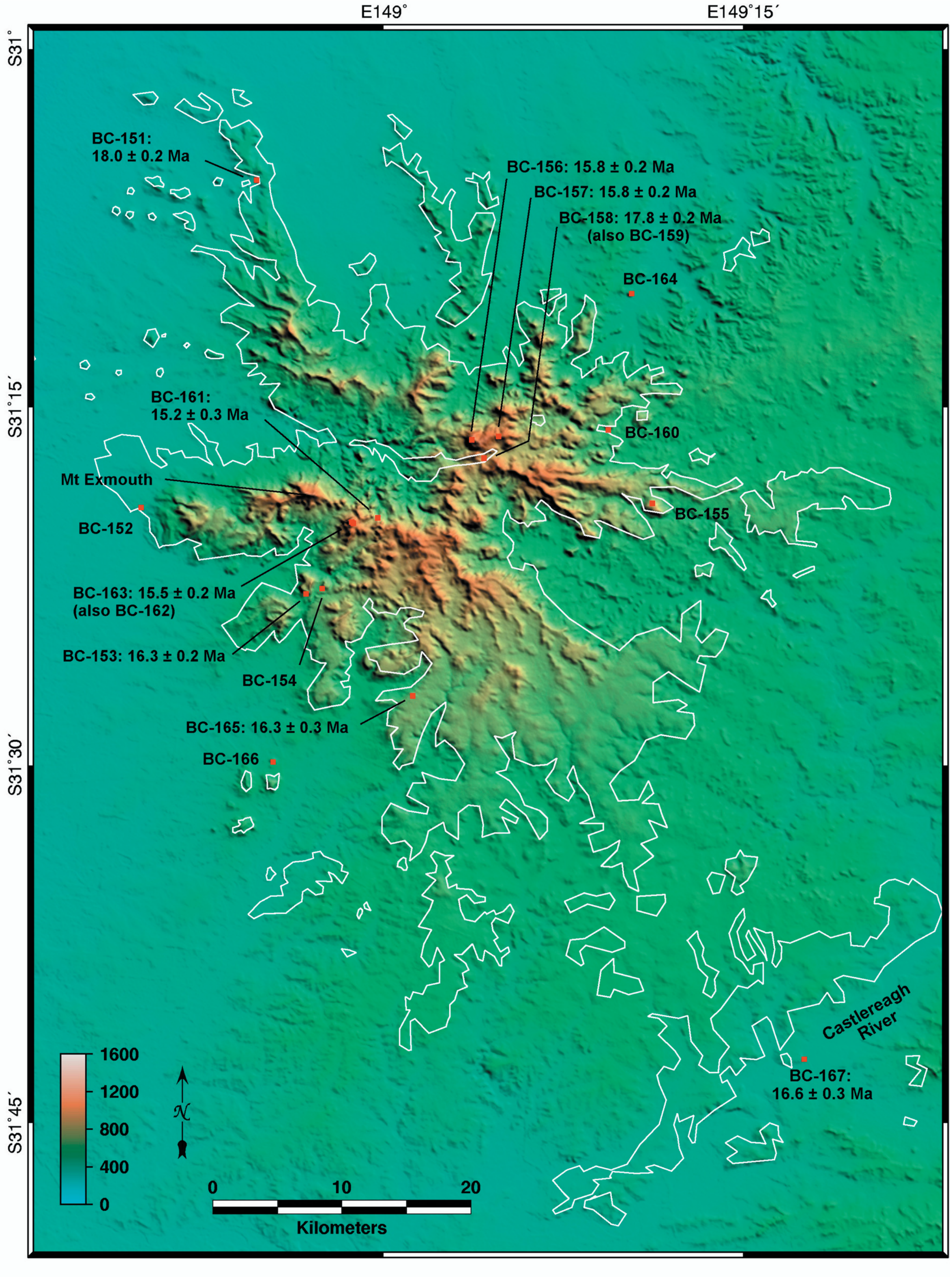


Figure 15. Warrumbungle Volcano, showing topographic relief based on DEM modelling, with sites used in Ar –Ar age dating (Ma). Image Ben Cohen.

Figure 16. Photomicrograph of wilkinsonite-bearing trachyte in thin section. The large white crystals are phenocrysts of anorthoclase feldspar and the dark crystals in the groundmass include both the sodic pyroxene aegirine and the new mineral species wilkinsonite. Field of view is 100 mm in width. Photo Morris Duggan.

Warrumbungle Volcano included close attention to its phonolitic and trachytic suites (Ghorbani 1999; 2003). Warrumbungle Volcano is the most investigated central volcano in the NW New South Wales migratory chain. The pyroxenes were used by Ghorbani and Middlemost (2000) to unravel the complex magmatic petrogenesis, which identified a high pressure, depleted mantle peridotite source and Al- and Fe-enriched crustal magma chambers. One nepheline-normative mafic rock included omphacitic pyroxene with very high K contents (up to 2.3 wt %), which suggested a deep mantle source.

Mafic to intermediate petrology in the Warrumbungle sequence was targeted recently by Crossingham et al. (2018). They examined crystallisation processes in the feeder systems below the volcano. The hawaiite and mugearite lavas ranged from aphanitic to glomeroporphritic in texture. The macrocrysts in the rocks included both antecrysts that represent earlier crystallisations in the volcano, brought up and recycled into the later magma, and phenocrysts that grew within the erupting magma. Macrocrystic minerals were commonly plagioclase, and clinopyroxene, which included pink Ti-rich augite and lower Ti- and Mg- content green augite. Olivine macrocrysts are rare, except in one lava in which crystal cores are Mg-rich, although some are zoned to Fe-rich rims. Clinopyroxene macrocrysts range from pinkish Ti-rich augite to greenish augite with lower Mg and Ti contents and commonly show spongey textures. Magnetite macrocryts are usually present.

In synthesising their data, Crossingham et al. (2018) concluded that Warrumbungle Volcano grew in three stages. Initial-stage magmas fractionated olivine and some clinopyoxene and evolved during ascent. Second stage crystallisation became more complex. Magmas divided into separate batches of different ages and compositions and sampled materials from crystal mushes formed in melts at depths of ~ 40 km. This led to a final stage of magma mingling and increased mixing of antecrysts and phenocrysts in ascending recharges of magma at higher levels. The Mg content in the studied lavas differed during the stages of growth and fractional crystallisation of mineral phases. First stage growth lavas showed the highest MgO range (~ 3.5 – 7.5wt %), second stage lavas the widest MgO range (~ 0.5 – 7.5 wt %) and the final stage had a slightly restricted range (~ 2 – 5 wt %). These growth stages, their timing and various depths of magma generation and recharging, and their associated mineral crystallisations are summarised in Fig.17 (after Crossingham et al. 2018). This Figure also shows differences in growth and crystallisation in Warrumbungle Volcano and its migratory twin, Comboyne Volcano, east of the Dividing Range.

The geological story of Warrumbungle Volcano is far from finished. Exposures found after the ravages of fire and flood in 2013, allowed more detailed mapping of their features and are listed in the 2018 Symposium abstracts. They include stratigraphic refinements (Troedson and Bull, 2018), detailed studies on pyroclastic deposits and evaluation of late radial trachytic dykes in the magmatic and inflation uplift history (Bull and Troedson 2018), geophysical observations of signature responses from airborne and satellite surveying (Carlton and Bull 2018), erosional expressions in alluvial depositions and mass waste movements (Thompson 2018; Tulau et al. 2018) and descriptions of embedded fossiliferous horizons (Holmes 2018). An informed stage now exists for other flora, fauna, environmental, educational and recreation projects within the time-honoured volcanic edifice.

Canobolas Central Volcano

The smallest and youngest central volcano in the NW New South Wales chain, Canobolas, retains a subdued summit core rising above its remanent basaltic shield outflows (Cohen 2007; Figs 18, 19). Initial K-Ar dating gave 13.0 ± 2 – 11.2 ± 0.3 Ma, while 5 Ar–Ar ages gave a similar range 13.2 ± 0.3 – 11.2 ± 0.3 Ma (Cohen 2007). Mafic samples gave both early (13.2 Ma) and late (11.6 Ma) ages, while

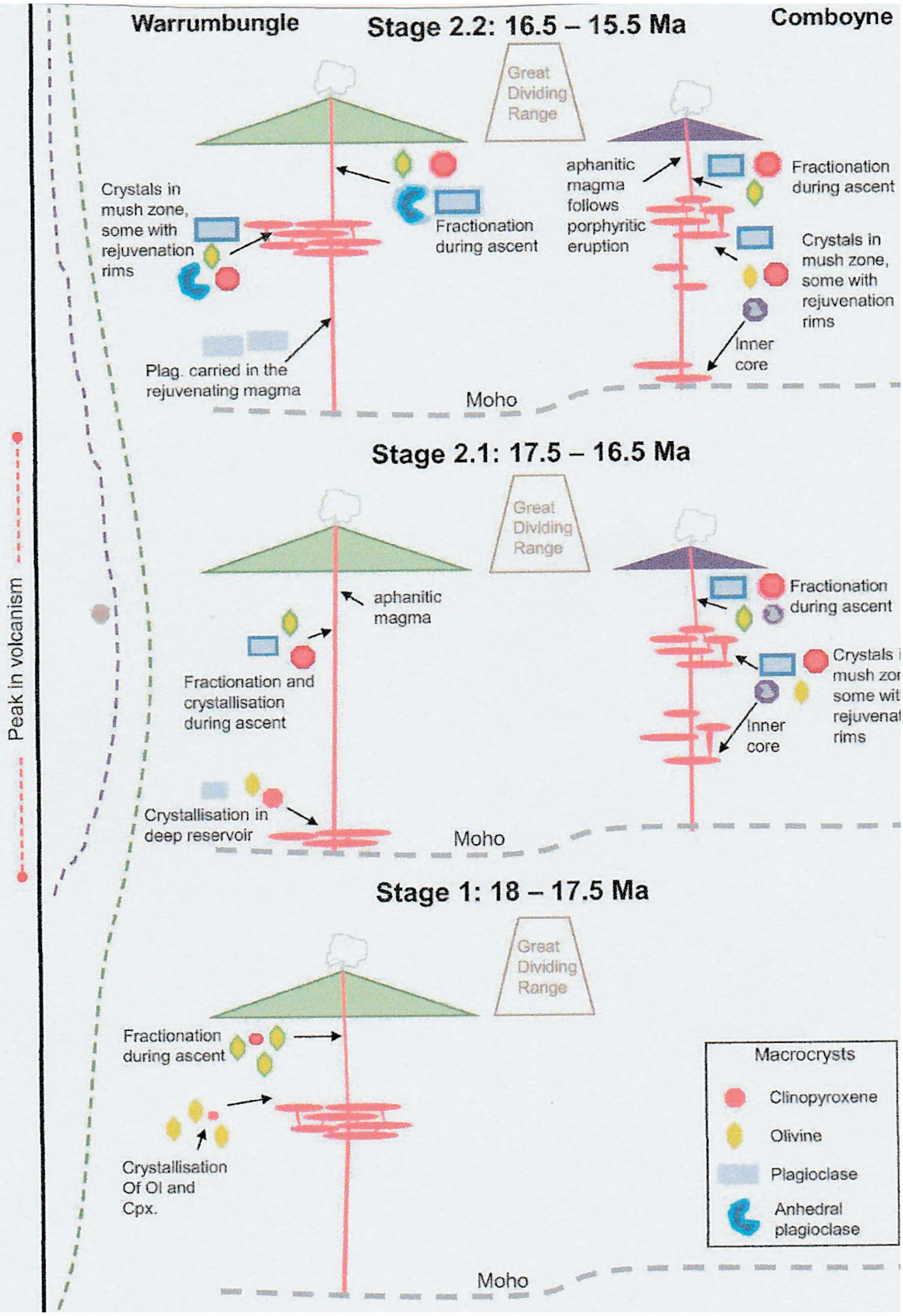


Figure 17. Magmatic and eruptive growth history of Warrumbungle Volcano, compared with the co-eval Comboyne migratory volcano, east of Dividing Range (Crossingham et al. 2018).

Figure 18.Canobolas Volcano in profile, showing summit region (centre distance) rising above flanking outcrops of eroded flows of its former basaltic shield. Photo Ben Cohen.

felsic ages (11.9 – 11.6 Ma) suggest overlap with the mafic eruptive range, as supported by field data (Middlemost 1981; Cohen 2007).

Previous petrological studies on the volcano were summarised by Middlemost (1981). His studies revealed a complete series of evolved members from hawaiite to rhyolite. Initial eruptions of mafic shield lavas preceded growth of a central complex as more evolved melts became admixed with further mafic events. The early mafic flows and pyroclastic deposits were mostly hawaiite and flow sheets up to 150 m thick built voluminous south easterly sequences. Mafic flows descending north western volcanic flanks flowed into a SE tributary drainage of the Lachlan River. Flows descending northern flanks travelled up to 70 km from the vent region into tributary drainages flowing north into the ancestral Macquarie drainage (Cameron et al. 1999; Tompkins and Hesse 2004). The Canobolas central summit growth included emplacements of felsic domes, dykes, plugs, flows, pyroclastic and volcanoclastic deposits (Figs 20 – 22).

Middlemost (1981) depicted the fractionation sequence using plots of MgO + CaO against $Na_2O + K_2O$. Representative proportions of analysed rock types (given here as %), included hawaiite (25%), mugearite (6%), bemoreite (8%), trachyte (47%) and rhyolite (14%). A trend of decreasing (MgO + CaO) from hawaiite to trachyte levelled out at low values and then trended into the rhyolite field. This trend mirrored the Total alkalis vs Silica diagram trend for Canobolas and also Nandewar evolution (Figure 10), but instead uses a mafic component rather than silica. At Canobolas voluminous trachyte generation dominated the central summit growth. A massive trachyte flow remnant 8 km long, 3 km wide and 30 m thick descended the southern extremities of the central vent apron (Panuara flow). Less voluminous silicic end member rhyolites, mostly comendites, formed an annular domal ring around the central trachytic plug complex. Middlemost suggested the silicic melts were derived by filter pressing and/or volatile release processes within underlying pools of trachytic magma.

Potential fractionation models were studied to establish Canobolas magmatic lineages (Middlemost 1981). This employed least squares calculation using the main mineral phase compositions in the various rock types. Starting with hawaiite, removal of augite (76 wt %), olivine (13%), magnetite (9%), and ilmenite (2%) produced mugearite. Then crystallising calcic plagioclase (52%), augite (27%), olivine (8%), and magnetite (7%) led to benmoreite. Further extraction of calcic plagioclase (75%), Fe-rich augite (13%), ilmenite (7%), and magnetite (6%) yielded trachyte. Alkali rhyolite could be attained with depletion of sanidine (88%), Fe-rich augite (7%), and magnetite (7%), or by removal of Fe-rich augite (88%) and magnetite (12%).

Further trace element (Pb, Rb, Sr, Sm, Nd) and isotope (Pb, Sr, Nd) data for Canobolas mafic lavas were presented by Ewart et al. (1988), who

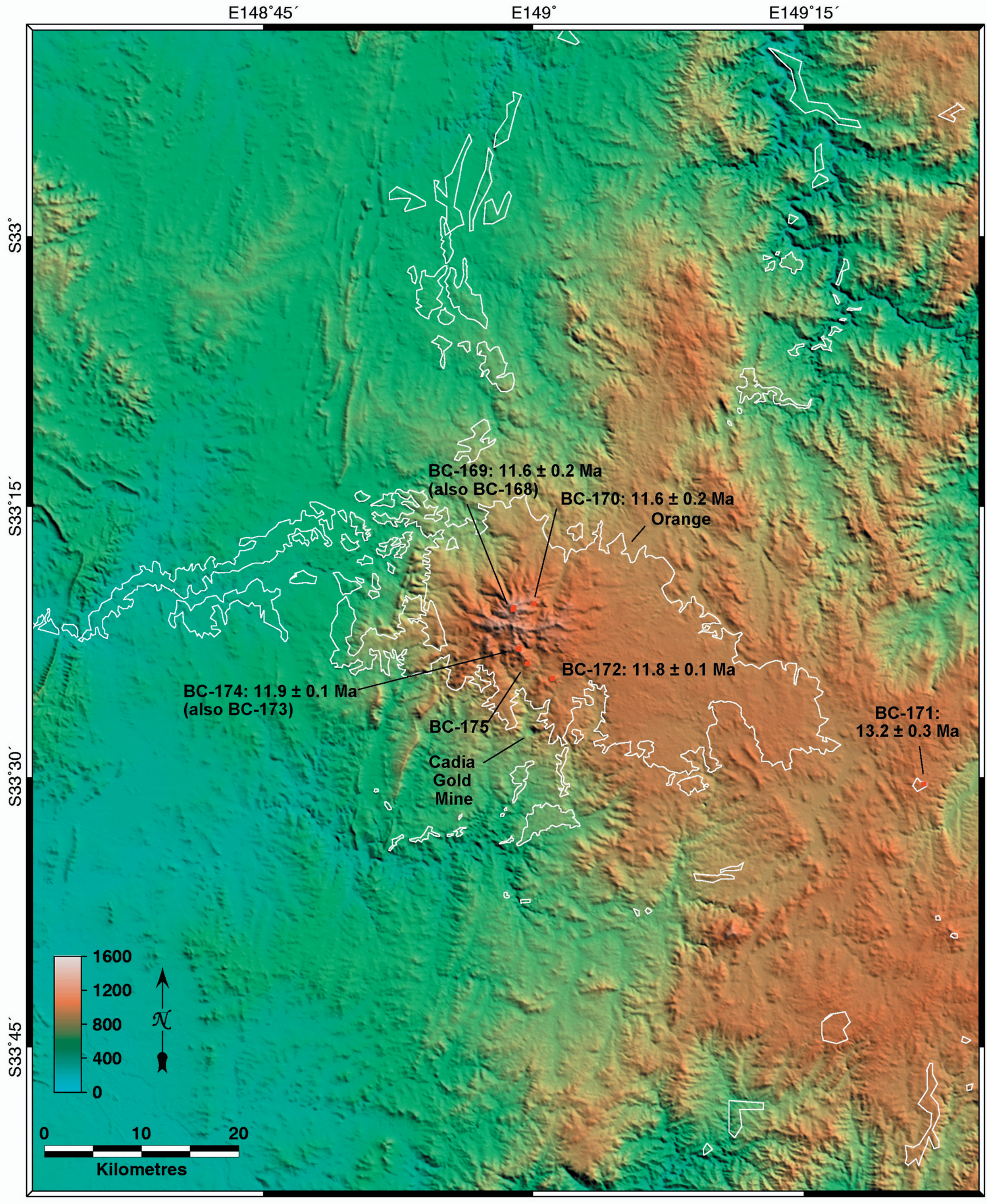


Figure 19. Canobolas Volcano, showing topographic relief based on DEM modelling, with sites used in Ar –Ar age dating (Ma). Image Ben Cohen.

introduced new mafic rock terms, quartz tholeiite and icelandite. End member alkali rhyolites were divided into two types (Pogson and Watkins 1998), a riebeckite-bearing rhyolite found in the larger domes on the volcano and arfvedsonite-bearing rhyolite that formed smaller remnant domes, cones and lavas.

Abecrombie zircon-bearing volcanic outburst

The Abercrombie Province 60 to 100 km SE of Mount Canobolas contains scattered flow remnants and small intrusions of alkali basalts that include

Figure 20. Lava domes of comendite, SE flank of Mount Canobolas. Photo Ben Cohen.

Figure 21. Small dyke, near summit, Mount Canobolas. Photo Ben Cohen.

mantle-derived types (Pogson and Watkins 1998). K-Ar age dating suggested several eruptive episodes between 20 and 16 Ma. A feature of the province is the presence of basalt-derived gem suites within adjacent alluvial deposits. Corroded crystals of gem zircon were dated by fission track counts from radiometric breakdown of U in their structure after thermal resetting during passage in hot magma. The zircons ages record several episodes that correspond with host basalt radiometric age-dates.

Figure 22. Scoriaceous mafic clast with chilled margins, in volcanic breccia, SE flank, Mount Canobolas. Photo Ben Cohen.

Figure 23. Zircon grains polished by magmatic corrosion, largest grain 0.25mm across, retrieved from fluvial sediments, Hopes Creek, Oberon area. Image Ross Pogson, Australian Museum.

One zircon age group stood out, with a young age range that matched the predicted latitudinal position for the East Australian hot spot at that time. The highly polished crystals show magmatic corrosion (Fig. 23), but there is little abrasion. This suggests minimal alluvial reworking of the grains, unlike that found in grains recycled from the older basalt sources. The young zircons were recovered from several sites around Oberon to Kings Plains near Blayney. Fission track ages (6 sites) ranged from 8.6 ± 2.3 to 9.4 ± 2.7 (av. 9.2 ± 2.1) Ma (Sutherland 1993, and Australian Museum Geotrack reports).

Further recent unpublished Ar-Ar dating on Warrumbungle and Canobolas volcanic rocks is available in Jones (2018). These extend the number of dated sites, although the age limits remain within the previous interval given by Cohen (2007).

DISCUSSION

Allied volcanic fields

Miocene volcanic fields in NW New South Wales include a dominant migratory chain of plume-related volcanoes. Three fields evolved into central volcanoes, while a low-volume basalt field to the SE, revealed a young ~ 9 Ma zircon-bearing event that may mark diminished plume activity. Other low-volume basaltic fields lie ~ 100 km SSW of Warrumbungle central volcano near Dubbo. There, they intrude and overlie Triassic-Jurassic Surat Basin beds (Cameron et al. 1999; Dawson et al. 2003). Farther west in NSW, a migratory chain of minor plume-related leucititic volcanoes kept pace with the large Nandewar – Canobolas central volcano migratory chain (Cohen et al. 2008).

The Dubbo basalts have limited K-Ar dating (12.3 – 14.3 Ma), and overlap basalt ages around Gulgong ~ 60 – 80 km east (14.2 –15.2 Ma; Cameron et al. 1999). Such basalt ages at latitudes between the main Warrumbungle and Canobolas central volcano activity prompt possibilities that this flanking basaltic activity may be linked to thermal effects from the nearby plume passage. Petrological study of Dubbo olivine tholeiites showed trace element and isotopic signatures similar to those in eastern Australian central volcanoes (Zhang and O'Reilly 1997). Such plume-related activity may extend back to 20 Ma, based on a K-Ar date on an olivine tholeiite body, 9 km WSW of Dubbo (Sutherland et al. 2012). Evolved K- rich hawaiites in the suite were considered to develop by high pressure fractionation and crustal contamination of the olivine tholeiite magmas. The accompanying basanite and alkali basalts, in contrast, required melting of a deeper source with a composition suggestive of a metasomatised lithospheric mantle.

Miocene leucititic volcanoes form a distinct petrological suite that extends south through outer NW New South Wales (Cundari 1973; Cundari et al. 1978; Johnson 1989). They are part of the longest known migratory continental hot spot chain (Sutherland 1981; Davies et al. 2015). The NSW leucitites formed small volcanic feeders, vents and flows (Figs 24, 25), with Ar-Ar ages between 18–15 Ma (McQueen et al. 2007; Cohen 2008). New high-quality paleomagnetic pole positions were calculated for the leucitites using the Ar-Ar age-dates (Hansma and Tohver 2018). Results confirmed earlier findings and showed the leucitite and Nandewar central volcano paleopole positions were indistinguishable, with a leucitite-related plume positon at 40.3 ± 3.0 °S.

The mineralogy, petrology and likely genesis of the plume-related leucitites are presented in Johnson (1989). Their plume source differed from the central volcano asthenospheric source and involved lithospheric melting and contamination along a rift line, activated by an underlying plume. Leucititic

Figure 24. Leucitite flow capping, El Capitan, looking from northwest. Photo Ken McQueen.

magma generation was constrained by lithospheric thickness, which exceeded ~ 135 km in depth (Rawlinson et al. 2017a). Unusual baryte-bearing hybrid basalt breccias occur north of Byrock leucitite volcano and included fragments of anorthoclase-nepheline basanite with fractionated pods of baryte-bearing trachyte (Sutherland et al. 2007). These vents may be plume-related, as they lie on the calculated track at ~30° S and show high Ba, a feature found in the leucitites (Davies et al. 2015). Such assignment, however, requires confirmation by dating.

Genesis of the Nandewar-Warrumbungle-Canobolas chain

The rise and fall of these central volcanoes took place within a bending plume trace (Fig. 26). After preliminary lava field activity in western New England, more voluminous magmatism created Nandewar Volcano (600 cubic km), then Warrumbungle Volcano (500 cubic km), before dwindled noticeably in forming Canobolas Volcano (50 cubic km) and finally tailed off into minor lava field activity (volume estimates from Duggan et al. 1993). Nandewar Volcano developed significant rhyolitic inputs, notably alkali rhyolites, whereas rhyolite is scarce in Warrumbungle Volcano and Canobolas only exhibits small rhyolitic events of comenditic type in its summit growth. A study of exposed central volcano feeders in the Glass House Mountains, SE Queensland (Shao and Niu 2015), focused on the genesis of peralkaline and peraluminous rhyolites. They suggested these suites reflected basaltic underplating and crustal contamination effects in their respective magmatic evolutions. Peralkaline trends are well developed in both Nandewar and Warrumbungle volcanoes, particularly in trachytes, which would suggest such underplating took place below those large volume volcanoes. This process also has solid support from earlier studies based on gravity and magnetic data (Wellman 1986; Johnson, 1989).

The West New England – Nandewar – Warrumbungle – Canobolas – Abercrombie trace (Fig.26), is anomalous. It does not correlate with an expected hot spot trace based on Australian plate motion during its eruption period (25 – 10 Ma), nor with the leucitite volcano line to the west or the coastal central volcano and oceanic hotspot chain trends to the east (Sutherland et al. 2012). This can be noted in the Australian and oceanic hot spot traces and plate motion tracks (Fig. 27). Various causes are given to account for bends in Australian central volcano traces, from tectonic shifts caused by former plate collision effects to the north and/or slab break-off effects on the eastern margin (Knesel et al. 2008; Sutherland et al. 2012; Cohen et al. 2013). These events created abrupt changes in the volcanism volumes and migration trends, which are less apparent in the NW New South Wales trace.

Figure 25. Leucitite flow margin, with inward dipping cooling joints, El Capitan. Photo Ken McQueen.

Recent studies show that plume activity can become incorporated into lithospheric edge-driven melting episodes, as in central-western Victoria (Sutherland et al. 2014; Oostingh et al. 2015; Rawlinson et al. 2017a). Studies of lithospheric thickness in eastern Australia above underlying plume sources show its depth can control the volume and nature of the plume-generated mantle melting (Davies et al. 2015). In this study, it is noticeable that the west New England basaltic – triple central volcano – Abercrombie basaltic migration follows the western curved edge of a lithospheric 'cavity' detected under the region (Rawlinson et al. 2017a; cavity C2). Neither the 'cavity' boundary, nor the subsequent volcanic migratory trace match the post- 24 Ma plate motion trend for eastern Australia (Rawlinson et al. 2017b), as shown in Fig. 28. To help explain this anomaly, it is surmised an underlying plume was over-ridden by the 'cavity' margin as plate motion carried the structure across the plume threshold. This diverted the plume and enhanced its activity through lithospheric edge-driven melting along the western 'cavity' margin. Plume activity dwindled and ceased as thicker lithosphere capped its track beyond the 'cavity' structure.

The northwest NSW plume activity was concentrated along the western side of the 'cavity' structure. This may reflect asthenospheric flow motion within the mantle upwelling. In sections modelled through such mantle upwells within the southern 'cavity' structure (C1), which triggered the plume-edge-driven Newer Volcanic basaltic activity, a westerly mantle flow of ~ 2 cm/yr was observed (Rawlinson et al. 2017a). A similar westerly mantle flow component may have directed the plume magmatic interaction towards the western edge of the underlying NW New South Wales lithospheric 'cavity'.

Where did the NW New South Wales central volcano plume originate?

The plume-dominated migratory volcanic trend lines in NW New South Wales all project back into Queensland. There, the central volcano lines extend northward to coastal exposures between Fraser Island and Cape Hillsborough (Sutherland et al 2012; Cohen

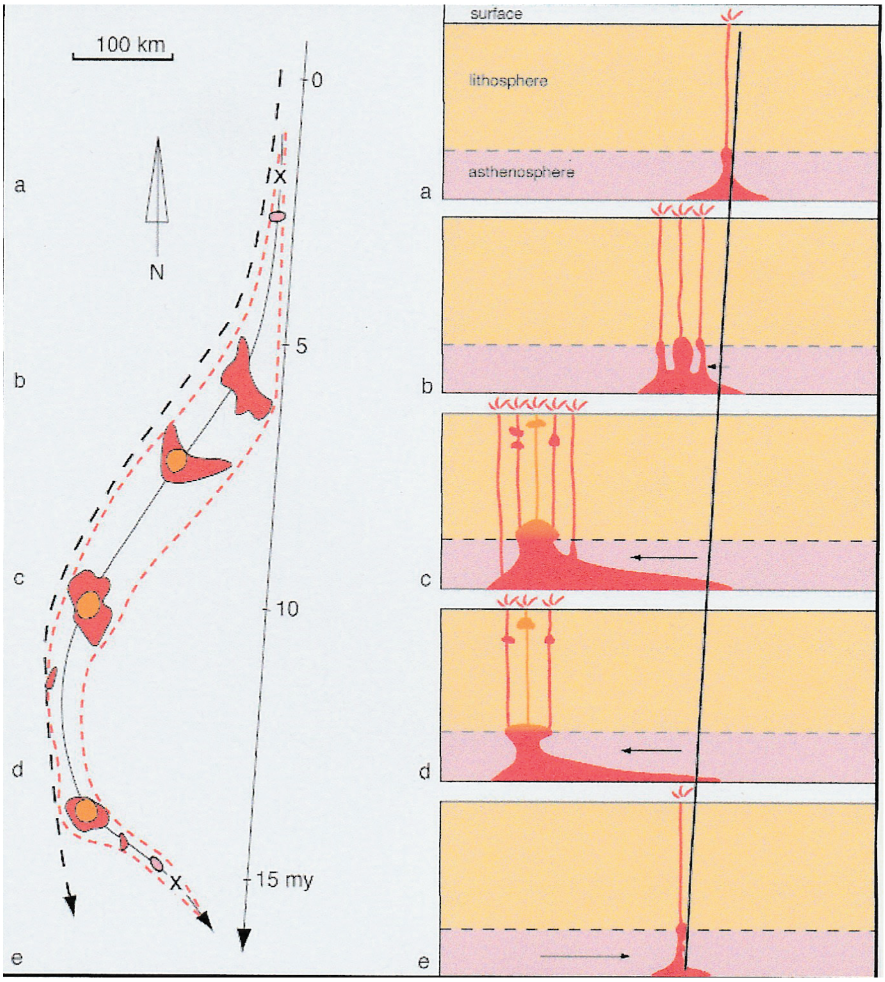


Figure 26. Idealised growth segment for relative New England-Nandewar-Warrumbungle-Canobolas migration. Left panel: Plan of migration growth relative to Australian plate motion trend over 15 Ma of migration, with basaltic areas (red), felsic cores (orange), minor alkaline fields (pink) and zircon megacryst-bearing eruptions (black crosses). Right panel: Lithosphere-asthenosphere cross sections (a – e), showing relative plume and surface volcanism from initiation to cessation (black trend line). Diagram from Sutherland (2003).

et al. 2013). This, central volcano activity is dated back to ~30 – 34 Ma, before its continuity vanishes offshore. Some modelling suggests that these plume trails project back to a major triple point rift-event that formed the Coral Sea – Louisiade – Cato Tough spreading segments (Sutherland et al. 2012). Figure 29 depicts plate motion paths for East Australia, generated from the present dormant locus of the plume system across Bass Strait and western Tasman Sea. The plate migration trends calculated at 10 Ma intervals from the plume locus suggest the NW New South Wales central volcano trends intersects the main thermal spreading arm of the Coral Sea Triple Point between 60 – 70 Ma. Some support for a major Coral Sea thermal event involvement in the past plume activity comes from dating of basalts dredged from the adjacent submerged Louisville Plateau at 55-56 Ma (Kalnins et al. 2015; Richards et al. 2018).

The NW New South Wales central volcano migratory plume track extrapolated northwards intersects the preceding voluminous basaltic-central volcano activity in SE Queensland (Brown et al. 2014). This presents a complicated task in determining its precise path for its earlier plume line connection. A thickened lithospheric spine protrudes eastwards below the connecting NSW border, which would inhibit the intervening plume melting (Davies et al. 2015). A possible link in this low-volume melt zone may be marked by an altered ‘leucititic’ lava remnant that overlies Mesozoic sandstones near Inglewood, SE Queensland (Wilkinson 1977). This lava, however, lacks precise dating. If plume-related, it would link the NSW trend towards the Main Range Volcano. Here, a small central volcano trace extends northerly from Toowoomba to eastern Bunya Mountain dated at 22–24 Ma (Sutherland et al. 2012). The trace, however, seems too young for migratory connection with Delungra NSW volcanism. A more easterly trend into Fassifern Valley central volcanoes connecting with the 26 Ma Flinders Peak volcano improves timing and links into the coastal SE Queensland plume line (Cohen 2007).

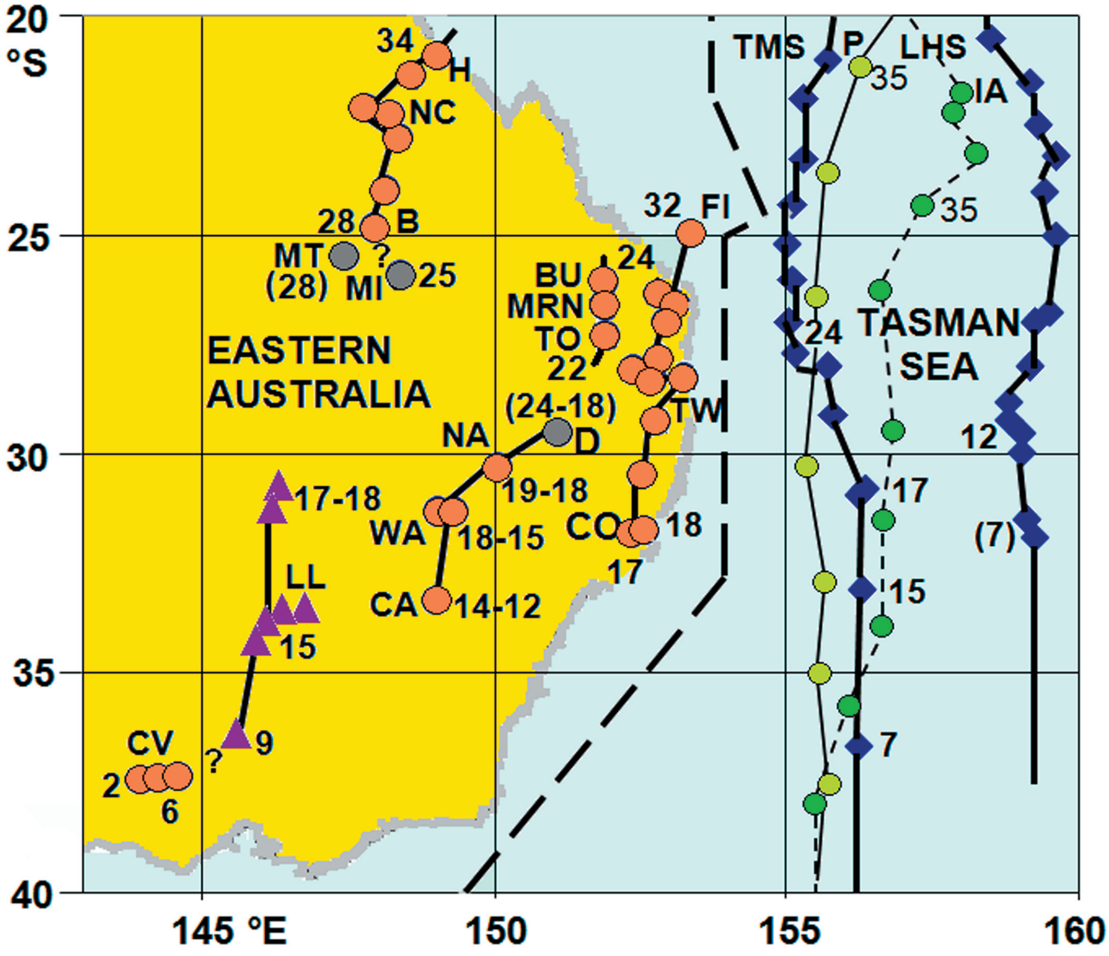


Figure 27. Eastern Australian and oceanic hot spot volcano traces (black connecting lines), with (Ma) and locality codes of central volcanoes (orange red circles), basalt lava fields (purple circles), leucitite volcanoes (purple triangles) and oceanic seamounts (dark blue diamonds). Plate motion tracks at 5 Ma intervals are fixed to Indian Ocean hot spots (thin black line with light green circles) and Pacific Ocean (thin dashed line with dark green circles). After Sutherland et al. (2012), which contains a full volcano code listing. Relevant codes here are D Delungra, NA Nandewar, WA Warrumbungle, CA Canobolas, and LL Leucitite Line.

CONCLUSIONS

The NW New South Wales volcanism is dominantly a mix of 'hotspot' plume-generated basaltic lava fields of both alkali and tholeiitc affinities, central volcanoes with basaltic shields and evolved felsic cores and low-volume leucitic intrusions and flows.

Three significant central volcanoes dominate the main plume-trace, the Nandewar, Warrumbungle and Canobolas Volcanoes, each showing well developed fractionation processes in their evolution, but each showing differences in their petrologic make up.

The plume lines represent surges in volcanic activity between 24 – 10 Ma. Subsequent post-eruptive erosion has exposed spectacular internal volcanic features. The scenic remnants have attracted considerable scientific studies, recreational use and preservation as National Parks and nature reserves.

Volcanoes along the main plume migratory track show an overall rise and fall in eruptive volumes associated with a curving swell and pinch path that does not correspond with the underlying paleo-plate motion of Australia. This suggests an additional eruptive control.

The volcanic rise and fall along the west New England –Abercrombie migration curve follows the western edge of a lithospheric 'cavity' revealed by seismic tomography, suggesting interaction of a plume and lithospheric 'cavity' edge that diverted the plume line.

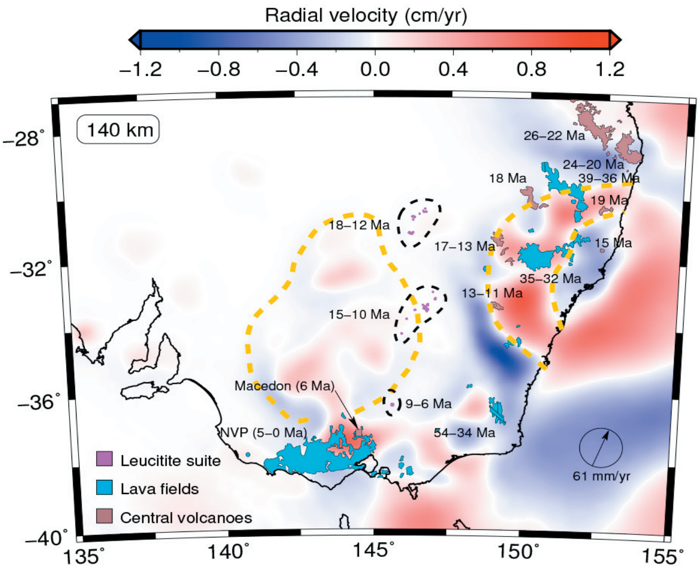


Figure 28. Radial seismic velocity map of East Australian lithosphere at 140 km depth. The eastern coastal lithospheric 'cavity' (152 – 153o E; 29.5o – 35.5 o S) enclosed by a pair of yellow dashed curved lines enclosing faster radial velocities (0.0 – + 1.0 cm/yr). Note its western boundary forms the locus for the NW New South Wales migratory basaltic and central volcano rise and fall between 24 – 11 Ma. Diagram after Rawlinson et al. (2017b; Fig. S8).

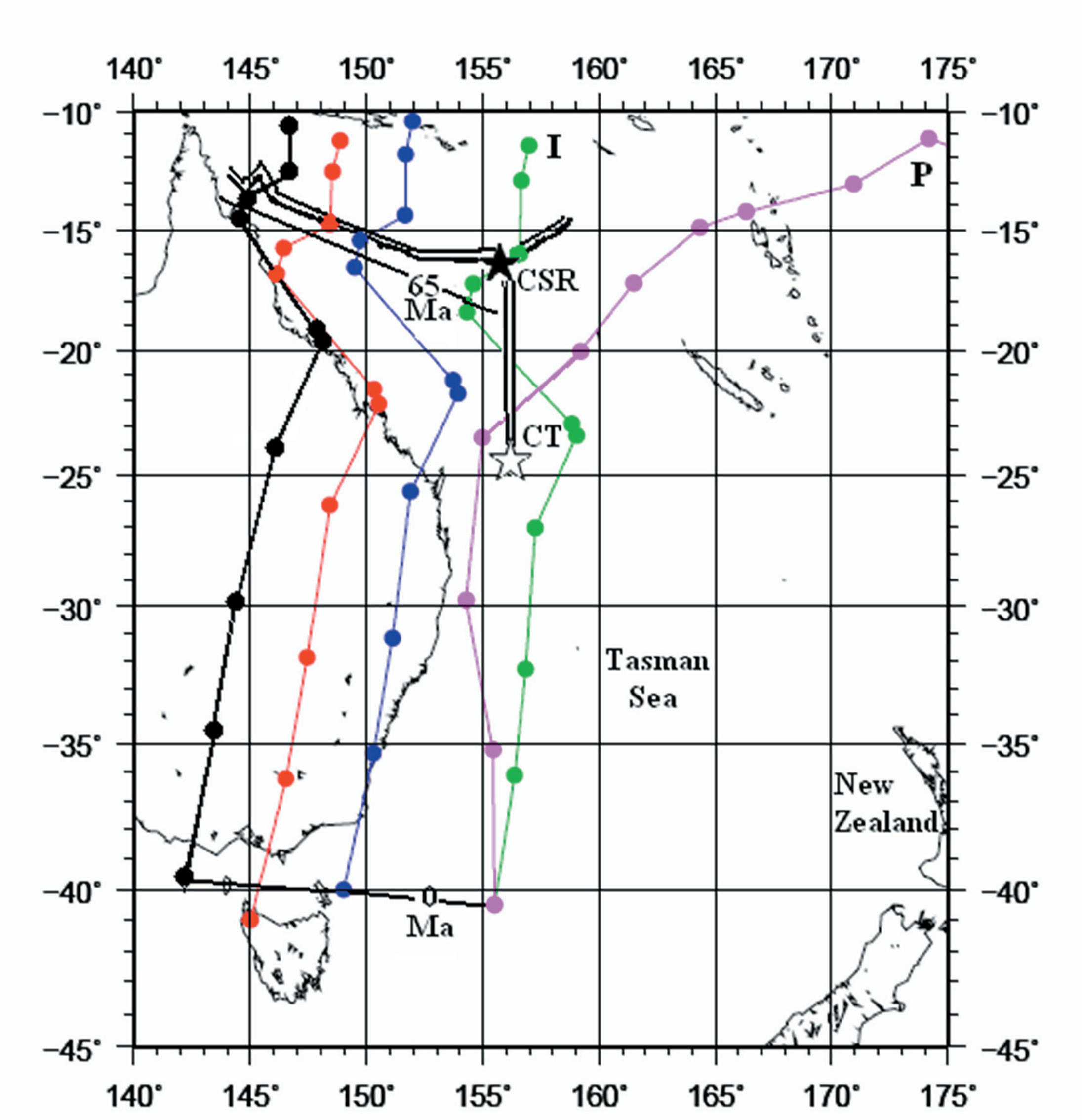


Figure 29 (preceding page). East Australia-Tasman Sea-Coral Sea plate motion tracks generated from present plume line array (Bass Strait-Western Tasman Sea). Tracks based on fixed Indian – Atlantic hotspots (I) are represented by black, red, blue and green lines with spots at 10 Ma intervals (0 – 100 Ma). The NW New South Wales central volcano line (~150o – 149o E, 30o – 34o S) lies adjacent to the blue line track. A Pacific hotspot track (P) is shown for comparison (pink line). The Coral Sea (CSR) – Cato Trough (CT) spreading rift system (double lines) indicates triple-point locations (black filled and unfilled stars respectively). Computer plot, Maria Seton.

Plume-driven NW New South Wales volcanism is only a strand within a broader plume system that erupted across moving eastern Australian lithosphere. An ultimate origin may lie within late Cretaceous Coral Sea rifting, with the original plumes now in dormant repose below the southern Bassian – Tasman basins.

ACKNOWLEDGEMENTS

The Linnean Society of New South Wales and organising committee for staging the ‘Volcanoes of Northwest New South Wales’ Natural History Field Symposium, Coonabarabran, 24 – 27 th September , 2018, and providing for publication of Symposium presentations. Dr Ben Cohen, University of Glasgow, Scotland and Dr Morrie Duggan, Braunstone, NSW, made substantial contributions of illustrative materials, and provided invaluable comments on the ms. Dr Michael Bruce, Petrology and Geochemistry, NSW Department of Planning, Industry and Environment, Sydney, made a constructive critique on the ms. Professor Ken McQueen, University of Canberra, ACT, and Ross Pogson, Geoscience, Australian Museum, Sydney, NSW, provided additional field and specimen photography. Professor Nick Rawlinson, Department of Earth Sciences, University of Cambridge, UK provided and gave permission to use seismic tomographic figures from his 2017 Geophysical Research Letter study. Dr Tracey Crossingham, School of Earth and Environmental Sciences, University of Queensland, Brisbane provided and permitted use of her Warrumbungle volcano PhD study. Terry Coldham, Gemmological Association of Australia, provided a map of the New England basalt fields. Joan Henley and The Geological Survey of New South Wales provided 1: 250 000 northern New England, NSW and SE Queensland map sheets in connecting areas. Simone Meekin, Geological Survey New South Wales and Larry Barron, Sydney, aided with literature search. Dr Maria Seton, Earth Sciences, Sydney University, provided Australian Plate movement modelling

REFERENCES

Abbott, M.J. (1969). Petrology of Nandewar Volcano, N.S.W., Australia. *Contributions to Mineralogy and Petrology* **20** (2), 115-134.

Barron, L.M., Barron, B.J., Mernagh, T.P. and Birch, W.D. (2008). Ultra high pressure macro diamonds from Copeton, (New South Wales, Australia), based on Raman spectroscopy of inclusions. *Ore Geology Reviews* **34**, 76 - 85.

Brown, R.E. and Stroud, W.J. (1997). *Inverell 1: 250 000 Metallogenic Map SH/56-5: Metallogenic study and Mineral Deposit Data Sheets*, 576pp. Geological Survey of New South Wales, Sydney.

Brown, R.E., Cranfield, L.C., Denaro, T.J., Burrows, P.E., Henley, H.F. and Brownlow, J.W. (2014). *Warwick-Tweed Heads Special metallogenic map SH/56-2 and SH/56-3*, Geological Survey of New South Wales, Maitland.

Bull, K.F. and Troedson, A.L. (2018). Permian pumice to Miocene Magmas: volcanology of Warrumbungle National Park. Program, Abstracts and Field Guide, 2018 Linnean Society of NSW Natural History Field Symposium, Coonabarabran 25th-27th September 2018, p 4.

Cameron, R.G.,Barron, L.M., Meakin,N.S., Warren, A.Y.E., Raymond, O.L., Morgan, E.J., Henderson, G.A.M. and Pogson, D.J. (1999). Cainozoic. In ‘Dubbo 1: 250 000 Geological Sheets SI/55-4, 2nd edition. Explanatory Notes’ (Compilers N.S. Meakin and E.J. Morgan) pp. 336-356. (Geological Survey of New South Wales: Sydney).

Carlton, A. and Bull K. (2018). Geophysical signatures of the Warrumbungle National Park. Volcanoes of North West New South Wales. Program, Abstracts and Field guide, 2018 Linnean Society of NSW Natural History Field Symposium, Coonabarabran 25th-27th September 2018, p 5.

Chan, R.A. (2003). Bathurst and Forbes 1: 250 000 Map Sheets, New South Wales. CRC LEME, Geoscience Australia, Canberra, 5pp.

Cohen, B.E. (2007).High- resolution ^{40}Ar/^{39}Ar geochronology of intraplate volcanism in eastern Australia. PhD thesis, School of Physical Sciences, University of Queensland, Brisbane.

Cohen, B.E., Knesel, K.M., Vasconcelos, P.M. and Schellart, W.P. (2013). Tracking Australian plate motion through the Cainozoic: Constraints from ^{40}Ar/^{39}Ar geochronology. *Tectonics* **32**, 1371-1383.

Cohen, B.E., Knesel, K.M., Vasconcelos , P.M., Theide, D.S. and Hergt, J.M. (2008). ^{40}Ar/^{39}Ar constraints on the timing and origin of Miocene leucitite volcanism in south eastern Australia. *Australian Journal of Earth Sciences* **55**, 407-418.

Crossingham, T.J. Ubide, T., Vasconcelos, P.M. and Mallmann, G. (2018). Parallel plumbing systems feeding a pair of co-eval volcanoes in eastern Australia. *Journal of Petrology* **59** (6), 1035 - 1066.

Crossingham, T.J., Vasconcelos, P.M., Cunningham, T. and Knesel, K.M. (2017). ^{40}Ar/^{39}Ar geochronology and volume estimates of the Tasmantid Seamounts: support for a change in motion of the Australian plate. *Journal of Volcanological and Geothermal Research* **343**, 95 - 108.

Cundari, A. (1973). Petrology of the leucite-bearing lavas in New South Wales. *Journal of the Geological Society of Australia* **20**, 456-492.

Cundari, A., Renard, J.G.R. and Gleadow, A.J.W. (1978). Uranium-potassium relationships and apatite fission-track ages for a differentiated leucitite suite from New South Wales (Australia). *Chemical Geology* **22**, 11-20

Davies, D.R., Rawlinson, N., Iffaldano, N. and Campbell, L.H. (2015). Lithospheric controls on magma composition along Earth's longest continental hotspot track. *Nature* **525**, 511-514.

Dawson, M.W., Spiller, F.C. P., Brownlow, J.W. and Barnes, R.G. (2003). Brigalow Belt South Bioregion geological map. Geological Survey of New South Wales, New South Wales Department of Mineral Resources, Sydney.

Duggan, M.B. (1988). Zirconium-rich sodic clinopyroxenes in felsic volcanics from the Warrumbungle Volcano, central New South Wales. *Mineralogical Magazine* **52**, 491-496.

Duggan, M.B. (1990). Wilkinsonite $Na_2\ Fe^{2+}{}_4\ Fe^{3+}{}_2\ Si_6\ O_{20}$, a new member of the aenigmatite group from the Warrumbungle volcano, New South Wales, Australia. *American Mineralogist* **75**, 694 -701.

Duggan, M.B. and Knutson, J. (1991). The Warrumbungle Volcano, central New South Wales. *Bureau Mineral Resources Record 1991/44*. Bureau of Mineral Resources, Canberra, ACT.

Duggan, M. B. and Knutson, J. (1993).*'The Warrumbungle Volcano: a geological guide to the Warrumbungle National Park'*. Australian Geological Survey Organisation, Canberra, ACT.

Duggan, M.B., Knutson, J. and Ewart, A. (1993). *'Warrumbungle, Nandewar and Tweed Volcanic Complexes' Excursion guide C4. IAVCEI Meeting, Canberra*. Australian Geological Survey Organisation, Canberra, ACT.

Edwards, J. (1988). Geology of the alkaline volcanic complex of the Canobolas Mountains, Orange, N.S.W. Hons Thesis, University of Melbourne.

Ewart, A. (1985). Aspects of the mineralogy and chemistry of the intermediate – silicic Cainozoic rocks of Eastern Australia. Part 2: Mineralogy and Petrogenesis. *Australian Journal of Earth Sciences* **32** (4), 383-413.

Ewart, A., Chappell, B.W. and Le Maitre, R.W. (1985). Aspects of the mineralogy and chemistry of the intermediate – silicic Cainozoic rocks of Eastern Australia. Part 1: Introduction and Geochemistry. *Australian Journal of Earth Sciences* **32** (4), 359-382.

Ewart, A.E., Chappell, B.W. and Menzies, M.A. (1988). An overview of the Geochemical and Isotopic Characteristics of the Eastern Australian Cainozoic Provinces. *Journal of Petrology, Special Lithospheric Issue*, pp 225-273.

Ghorbani, M.R. (1999). Petrology and Geochemistry of the Warrumbungle Volcano, New South Wales. PhD thesis, University of Sydney.

Ghorbani, M.R. (2003). Phonolitic and trachytic rocks from Warrumbungle volcano, different sources and conditions. *EGS-AGU Joint Assembly, Niece, France, 6 – 11 April 2003, abstract # 9241.*

Ghorbani, M.R. and Middlemost, E.A.K. (2000). Geochemistry of pyroxene inclusions from Warrumbungle Volcano. *American Mineralogist* **85**, 1349 – 1367.

Glen, R.A. (2013). Refining accretionary orogen models for the Tasmanides of eastern Australia. *Australian Journal of Earth Sciences* **60**, 315-370.

Glen, R.A. (2015). 'The Tasmanides of eastern Australia' (Eds A.P.M Vaughn, P.T. Leat and R.J. Pankhurst) pp. 23-96. *Geological Society of London Special Publication* **246**.

Hansma, J. and Tover, E. (2018). Paleomagmatism of mid- Miocene leucitite volcanics in eastern Australia. *Geophysics Journal International* **215**, 303 -313.

Holmes, K. W. B. (2018). The Mid Miocene flora preserved in the diatomite beds of the Chalk Mountain Formation, Warrumbungle Volcano complex. Program, Abstracts and Field guide, 2018 Linnean Society of NSW Natural History Field Symposium, Coonabarabran 25th-27th September 2018, p 8.

Higgins, K., Hashimoto, T., Rollet, N., Colwell, J., Hackney, R., & Milligan, P. (2015). Structural analysis of extended Australian continental crust: Capel and Faust Basins, Lord Howe Rise. In 'Sedimentary Basins and Crustal processes at Continental Margins: From Modern Hyper-extended Margins to and in Deformed Ancient Analogues' (Eds G.M. Gibson, F. Roure and G. Manatschal) pp. 9–33. *Geological Society of London Special Publication* **413**.

Irvine, T. N. and Baragar, W. R. A. (1971). A guide to the chemical classification of the common volcanic rocks. *Canadian Journal of Earth Sciences* **8**, 523–548.

Johnson, R. W., Compiler and Editor (1989). '*Intraplate Volcanism in Eastern Australia and New Zealand*' (Cambridge University Press: Cambridge).

Jones, I.M. (2018). Evolution and migration of Cenozoic Australia: Precision 40Ar/39Ar geochronology and geochemistry and paleomagnetic data from east Australia Cenozoic magmas. PhD thesis, School of Earth and Environmental Sciences. University of Queensland, Brisbane.

Jones, I., Verdel, C., Crossingham, T. and Vasconcelos, P. (2017). Animated reconstruction of the Late Cretaceous to Cenozoic northward migration of Australia and implications for the generation of east Australian mafic magmatism. *Geosphere* **13** (2), 1-22.

Kalnins, L.M., Cohen, B.E., Fitton, J.G., Mark, D.F., Richards, F.D. and Barfod, D.N. (2015). The East Australian, Tasmantid and Lord Howe Volcanic Chains: Possible mechanisms behind a trio of hot spot trails. Abstract D141A-2591. AGU Fall Meeting, 14–18 Dec., San Francisco.

Knesel, K.M., Cohen, B.E., Vasconcelos, P.M. and Theide, S.M. (2008). Rapid change in the drift of the Australian plate records collision with Ontong Java Plateau. *Nature* **454**, 754-757.

McDougall, I. and Wilkinson, J.F.G. 1967. Potassium-argon dates on some Cainozoic volcanic rocks from northeastern New South Wales. *Journal of the Geological Society of Australia* **14** (2), 225-233.

MacNevin, A.A. (1977). Diamonds in New South Wales. Department of Mines, Geological Survey of New South Wales, Mineral Resources **42**.

Matthews, K.J., Maloney, K.T., Zahirovic, S., Williams, S.E. and Müller (2016b). Global boundary evolution and kinematics since the late Palaeozoic. *Global and Planetary Change* **146**, 226-250.

McQueen, K.G., González, O.R., Roach, I.C., Pillans, B.J., Dunlap, W.J. and Smith, M.L. (2007). Landscape and regolithfeatures related to Miocene leucitite lava flows, El Capitan north east of Cobar, New South Wales. Australian Journal of Earth Sciences 54(1), 1-17.

Matthews, K.J., Seton, M. and Müller (2016a). A global scale reorganization event at 105 – 95 Ma. *Earth and Planetary Science Letters* **355-356**, 283-293.

Meyer, H.O.A., Milledge, H.J. and Sutherland, F.L. (1997). Unusual diamonds and unique inclusions from New South Wales, Australia. *Russian Geology and Geophysics* **38** (2), 305 – 331.

Middlemost, E.A.K. (1981). The Canobolas Complex, N.S.W., an alkaline shield volcano. *Journal of the Geological Society of Australia* **28** (1-2), 33 – 49.

Middlemost, E.A.K. (2013). 'Magmas, Rocks and Planetary Development: A Survey of Magma/Igneous rock Systems', Chapter 10.8, p. 220. Routledge, London and New York.

Nekvasil, H., Dondolini, A., Horn, J., Filberto, H. and Lindsley, D.H. (2004). The Origin and Evolution of Silica-saturated Alkalic Suites: an experimental study. *Journal of Petrology* **45** (4), 693 -721.

Oostingh , K.F., Jourdan, F., Merle, R. and Chiardia, M. (2015). Spatio-temporal geochemical evolution of the SE Australian upper mantle deciphered from the Sr, Nd and Pb isotope compositions of Cenozoic intraplate volcanic rocks. *Journal of Petrology* **57**(8), 1509-1530.

Pogson D.J. and Watkins, J.J. (1998). Bathurst 1: 250 000 Geological Sheet SI/55-8: Explanatory Notes, CAINOZOIC, pp. 271-282. Geological Survey New South Wales, Sydney.

Rawlinson, N., Davies, D.R. and Pilia, S. (2017a). The mechanisms underpinning Cenozoic intraplate volcanism in eastern Australia: Insights from seismic tomography and geodynamic modelling. *Geophysical Research Letters* **44**, 9681-9690.

Rawlinson, N., Davis, D.R. and Pilia, S. (2017b). Supporting information for the "The mechanisms underpinning Cenozoic intraplate volcanism in eastern Australia from seismic tomography and geodynamic modelling". Grl 56337-supp-001-supplementary pdf, 1-14.

Richards, F.D., Kalnins, L.M., Watts, A.B., Cohen, B.E., and Beaman, R.J. (2018). The Morphology of the Tasmantid Seamounts: Interactions between tectonic inheritance and magmatic evolution. *Geochemistry, Geophysics, Geosystems* **19**, 3870- 3891.

Shao, F., Nui, Y., Regelous, M. and Zhu, D-C. (2015). Petrogenesis of peralkaline rhyolites in an intraplate setting: Glass House Mountains, southeast Queensland, Australia. *Lithos* **216-217**, 196-210.

Stolz, A.J. (1985). The Role of Fractional Crystallization in the evolution of the Nandewar Volcano, North-eastern New South Wales, Australia. *Journal of Petrology* **26** (4), 1002-1026.

Stolz, A.J. (1986). Mineralogy of the Nandewar Volcano, northeastern New South Wales. *Mineralogical Magazine* **50**, 241-255.

Sutherland, F.L. (1981). Migration in relation to possible tectonism and regional controls in eastern Australian volcanism. *Journal of Vocanology and Geothermal Research* **9**, 181-213.

Sutherland, F.L. (1993). Late thermal events based on zircon fission track ages in northeastern New South Wales and southeastern Queensland. Links to Sydney Basin Seismicity? *Australian Journal of Earth Sciences* **40**, 461- 470.

Sutherland, F. L. (1995). '*The Volcanic Earth*'. UNSW Press, Sydney.

Sutherland, F.L. (2003). 'Boomerang' migratory intraplate volcanism, eastern Australian rift margins and Indian-Pacific mantle boundary. *Geological Society of Australia Special publication* **22** and *Geological Society of America Special Paper* **372**, 203-221.

Sutherland, F.L. (2011). Diversity within geodiversity, underpinning habitats in New South Wales. *Proceedings of the Linnean Society of New South Wales* **132**, 37-54.

Sutherland, F.L., Graham, I.T., Zwingmann, H., Pogson, R.E. and Barron , B.J. (2005).Belmore Volcanic province , northeastern New South Wales, and some implications for plume variations along Cenozoic migratory trails. *Australian Journal of Earth Sciences* **52**, 897-919.

Sutherland, F.L., Barron, B.J., Colchester, D.M. and McKinnon, A.R (2007). Unusual baryte-bearing hybrid basalt, Bourke-Byrock area, northern New South Wales. *Journal & Proceedings of the Royal Society of New South Wales* **140**, 27-46.

Sutherland, F.L., Graham, I.T., Meffre, S., Zwingmann, H. and Pogson, R.E. (2012). Prolonged passive margin volcanism, East Australian Plate: outbursts, progressions, plate controls and suggested causes. *Australian Journal of Earth Sciences* **57**, 983-1005.

Sutherland, F.L., Graham, I.T., Hollis, J.D., Meffre, S., Zwingmann, H., Jourdan, F. and Pogson, R.E. (2014).

Multiple felsic events within post-10 Ma volcanism, Southeast Australia: inputs in appraising proposed magmatic models. *Australian Journal of Earth Sciences* **61**, 241-267.

Thompson, P. (2018). Field observations of cobble and boulder stream deposits from the erosion of the Warrumbungle Volcano. Program, Abstracts and Field guide, 2018 Linnean Society of NSW Natural History Field Symposium, Coonabarabran 25th-27th September 2018, p 10.

Tomkins, K.M. and Hesse, P.P. (2004). Evidence of Late Cenozoic uplift and climate changein the stratigraphyof the Macquarie River valley, New South Wales. *Australian Journal of Earth Sciences* **51**, 273-290.

Troedson, A.L. and Bull, K.F. (2018). A new geology map of Warrumbungle National Park and environs. Program, Abstracts and Field guide, 2018 Linnean Society of NSW Natural History Field Symposium, Coonabarabran 25th-27th September 2018, p 5.

Tulau, M.J., McInnes-Clark, S. and Morand, D. (2018). Mass movements in Warrumbungle National Park, NSW. Program, Abstracts and Field guide, 2018 Linnean Society of NSW Natural History Field Symposium, Coonabarabran 25th-27th September 2018, p 11.

Vickery, N.M., Dawson, Sivell, W.J., Malloch, K.R. and Dunlap, W.J. (2007) Cainozoic igneous rocks in the Bingera to Inverell area, northeastern New South Wales. *Quarterly Notes of the Geological Survey of New South Wales* **123**, 1 – 31.

Ward, C.R. and Kelly, B.F.J. (2013). Background Paper on the New South Wales Geology, with a focus on Basins Containing Coal Seam Gas Resources, for the office of the NSW Chief Scientist and Engineer. UNSW Global, Australia, 28 August 2013. www.Chief.scientist.nsw.gov.au/_data/assets/pdf.file/009/31788/NSW - Geology- Background Paper Ward-and Kelly-unsw.pdf

Wellman, P. (1986). Intrusions beneath large alkaline intraplate volcanoes. *Exploration Geophysics* **17,** 30-35.

Whitaker, M.L., Nekvasil, H., Lindsley, D.H. and Difranesco, N.J. (2007). The role of pressure in in producing compositional diversity in intraplate basaltic magmas. *Journal of Petrology* **48** (2), 365 – 393.

Whitehead, J. (2014). '*The Geology of the Warrumbungle Range*'. 2nd Edition. Whitehead, John, Coonabarabran, NSW.

Wilkinson, J.F.G. (1975). Ultramafic inclusions and high pressure megacrysts from a nephelinite sill, Nandewar Mountains, north-eastern New South Wales, and their bearing on the origin of certain ultramafic inclusions in alkaline volcanic rocks. *Contributions to Mineralogy and Petrology* **51**, 235-262.

Wilkinson, J.F.G. (1977). Analcime phenocrysts in a vitrophric analcimite – primary or secondary? *Contributions to Mineralogy and Petrology* **64**, 1-10.

Zhang, M. and O'Reilly, S.Y. (1997). Multiple sources for basaltic rocks from Dubbo, eastern Australia: geochemical evidence for plume – lithospheric interaction. *Chemical Geology* **136**, 33-54.

Mass Movements of Warrumbungle National Park, New South Wales, Australia

Mitch J. Tulau[1], Petter Nyman[2], Mark Young[3], David Morand[4], Sally K. McInnes-Clarke[5] and Philip Noske[2]

[1]Department of Planning, Industry and Environment, PO Box 63 Port Macquarie, New South Wales, 2444
[2]School of Ecosystems and Forest Sciences, University of Melbourne, Carlton, Victoria, 3010
[3] Department of Planning, Industry and Environment, PO Box 644 Parramatta, New South Wales, 2124
[4] Department of Planning, Industry and Environment, PO Box 856 Alstonville, New South Wales, 2477
[5] Department of Planning, Industry and Environment, PO Box 1477 Gosford, New South Wales, 2250

Tulau, M.J., Nyman, P., Young, M., Morand, D.T., McInnes-Clarke, S.K. and Noske, P. (2019). Mass movements of Warrumbungle National Park. *Proceedings of the Linnean Society of New South Wales* **141**, S115-S130.

The Warrumbungle Range is the mountainous eroded remnant of an Early Miocene shield volcanic complex located in the central west of New South Wales. A high-severity wildfire in Warrumbungle National Park in January 2013 was followed by intense rain, causing a number of debris flows. Several flows impacted on infrastructure such as roads and culverts and posed a severe risk to public safety, prompting a broader assessment of mass movement hazard within the park. High resolution LiDAR DEM revealed 542 locations with evidence of mass movement processes that pre-date the fire. The most common types of mass movement visible in the DEM are rotational slumps (353, 65%). The distribution of these indicated stratigraphic control, with 50% of slumps within 440 m of the volcanics-sandstone geologic contact, and typically occurring within unconsolidated volcanic colluvium and/or in situ deeply weathered volcanics. Debris flows are the next most common mass movement type after rotational slumps. Debris flow scour channels generally occurred on colluvial slopes in more elevated sites, within the volcanic rocks. DEM-extracted morphometric data was used to identify areas of debris flow hazard in WNP. Several large mass movements are morphometrically different, with some evidence for formation under different hydro-climatic conditions. A simple conceptual model of how mass movements contribute to the evolution of the Warrumbungle Range is proposed involving groundwater, deep weathering, slope retreat by mass failure, colluvial deposition and periodic incision by debris flows.

Manuscript received 17 July 2019, accepted for publication 10 December 2019.

KEYWORDS: debris flows, fire impacts, mass movements, slumps.

INTRODUCTION

In January 2013, a wildfire in the Warrumbungle Range of NSW affected 56,290 ha, including 95% of the 23,312 ha Warrumbungle National Park (WNP). Seventy-two percent of the fire burnt with high or extreme fire severity. On 1 February 2013, an intense storm from the southwest delivered between 60 and 90 mm of rain within 30 minutes and was ranked the 19th most intense on record in WNP (Yu 2015). Further, this storm occurred over a fire ground with little groundcover, and caused flash flooding and massive erosion, including debris flows. In many locations, first- to second-order drainage lines were scoured, often to bedrock, and the eroded material deposited in drainage lines downstream. Several such flows impacted on infrastructure such as roads and culverts and posed a severe risk to public safety. This prompted a broader assessment of the incidence of debris flows and the hazard posed by mass movements more generally in WNP.

This is the first study on mass movements in this region. We therefore lack knowledge on fundamental processes that govern landscape evolution in the Warrumbungles and hazards to infrastructure and human life. The study set out to determine the dominant mass movement processes in WNP (excepting rock fall and topple) and whether these may be controlled by geological factors. Furthermore, the study uses radiocarbon dates from levees and colluvial hollows to evaluate the frequency of debris flow events in the region. Finally, we use the findings to propose a simple conceptual model of how mass movement processes contribute to the evolution of landscapes in WNP.

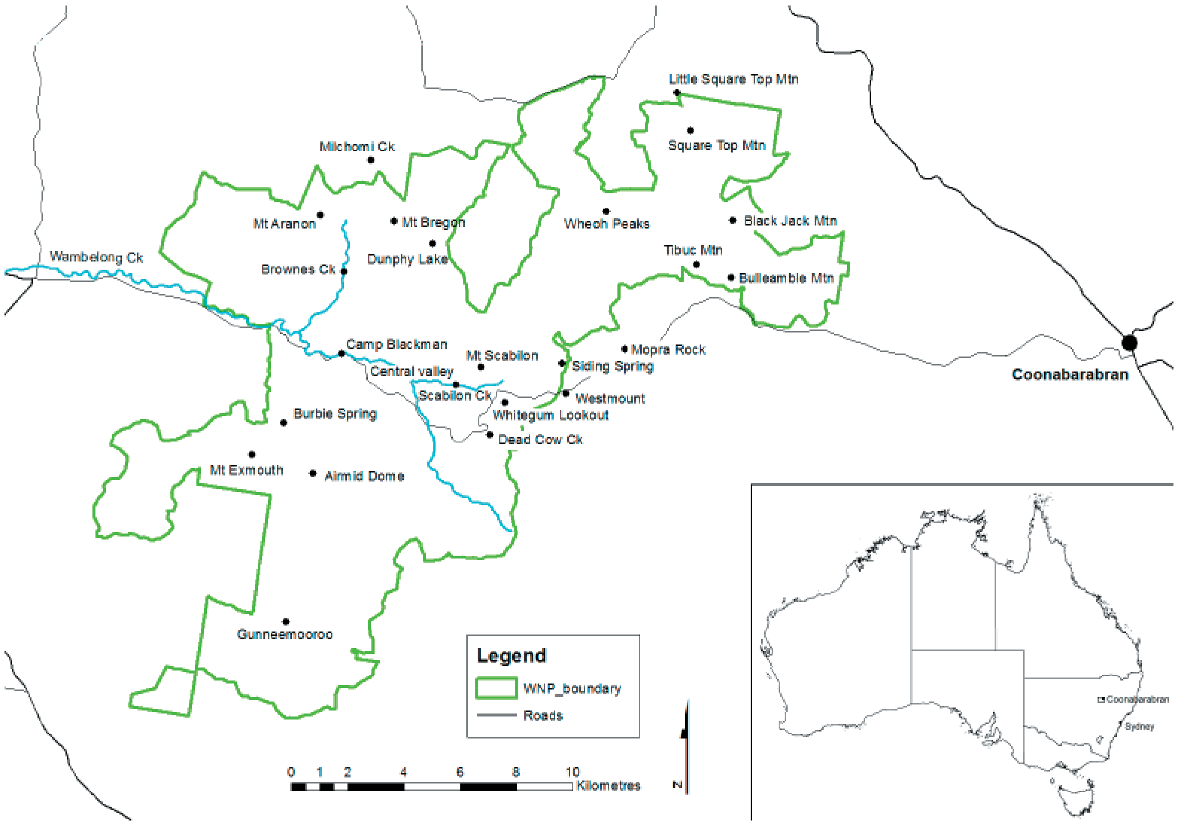


Figure 1. Study area.

Study Area

The study area (Fig. 1) is set in the WNP (23,312 ha) in the Warrumbungle Range in the central west of New South Wales (NSW). The study area is approximately 360 km northwest of Sydney and centred on the area approximately 25 km west of Coonabarabran.

The Warrumbungle Range is the eroded remnant of an Early Miocene shield volcanic complex. The range comprises rolling to steep hills and mountains, rising to 1,206m at Mount Exmouth and formed mainly of lava flow and volcaniclastic deposits punctuated by lava domes, plugs and dykes of the Warrumbungle Volcanics (Troedson and Bull 2018). A range of coherent volcanic rock types occur from mafic, through intermediate to felsic, with trachyte, trachyandesite and trachybasalt all common, and minor rhyolite also occurring. In the central part of the park, Wambelong Creek occupies a central valley, where Jurassic sandstones are exposed. Generally, the Warrumbungle Volcanics overlie relatively flat-lying Pilliga Sandstone; in parts of the northern section of the park the volcanics overlie Keelindi beds, comprising sandstones and conglomerates.

The climate in WNP is characterized by hot, humid summers and mild to cool winters. The mean maximum temperature at Coonabarabran Airport Automatic Weather Station (Bureau of Meteorology [BoM] station 064017) in January is 31°C, the mean minimum in July is 5°C. The mean annual rainfall at Westmount (BoM station 064046), on the eastern boundary of the park, is 1,034 mm.

The vegetation in WNP is generally open *Eucalyptus-Callitris* forest or Dry Sclerophyll Woodlands and Forests (Hunter 2008; Keith 2004), with a variable understory of shrubs and grasses.

The soils on trachytes are, in terms of the Australian Soil Classification (Isbell and NCST 2016), generally Brown to Red Dermosols. Soils on more felsic Warrumbungle Volcanics are generally Yellow and Brown Kandosols to Leptic Tenosols. Soils on Pilliga Sandstone are generally sandy Red to Yellow Kandosols and Chromosols. Approximately 16% of WNP is bare rock, being cliff lines in sandstone landscapes and as volcanic plugs.

Visitors are attracted to the Warrumbungles by the spectacular volcanic peaks, and WNP was established in several stages from 1953, attaining its present dimensions in 2010. The park has an annual visitation of ~35,000 (NPWS 2012).

Figure 2. Debris flow, February 2013, Dead Cow Creek.

Previous work

The Warrumbungle region has attracted the attention of geologists since the 19th and early 20th century (Edgeworth David 1896; Jensen 1907), and a great deal of work has been done in relation to petrogenesis (Faulks 1969; Hockley 1972; Duggan 1989; Duggan and Knutson 1991, 1993; Ghorbani 1999) and dating of the volcanic rocks (Dulhunty and McDougall 1966; McDougall and Wilkinson 1967; Dury et al. 1969; Dulhunty 1972; Wellman and McDougall 1974; Cohen et al. 2008). Troedson and Bull (2018) compiled, corrected and extended previous geology mapping (Offenburg 1968; Barnes et al. 2002), based on data within Honours theses and PhD theses (Hockley 1972, 1975; Timmers 1998), and interpretation of new field, petrographic, geochemical, and remotely-sensed data including aerial photography, Digital Elevation Model (DEM), and airborne geophysical data.

A number of workers have discussed the geomorphic evolution of the volcanic complex (Jensen 1907; Timmers 1998), but without recognising the ubiquity and significance of mass movements. Duggan and Knutson (1991) and Whitehead (2010) noted landslips, and the Burnt Area Assessment Team (BAAT) that reported on the 2013 fire noted debris flows in the Dead Cow and Scabilon Creeks (NPWS 2013) (Fig. 2). Troedson and Bull (2018) identified Neogene sedimentary deposits in the central valley that they regarded as mass movements. There have been no other mentions in literature of land instability in the Warrumbungle Range.

Similarly, there appears to be few studies of mass movements in nearby Cenozoic volcanic areas, although Melville (1976) addressed landslides on the north coast of NSW, Macgregor et al. (1990) noted landslips in the Border Ranges-Mt Warning area, and Erskine (2005) carried out a risk assessment for forestry in slip-prone areas near Mount Canobolas. Other studies in the region have been undertaken in areas of relatively flat-lying sedimentary (Sydney Basin) rocks. Blong and Dunkerley (1976) and Cunningham (1988) examined rockfalls in the Blue Mountains region, and Walker (1963), Bowman (1972) and Young (1978) assessed slope stability in the Wollongong escarpment.

A large body of research literature, particularly from the western USA, has been dedicated to evaluating the hazard posed by post-fire debris flows and their role in landscape processes (Riley et al. 2013). In Australia, research is more limited: Leitch et al. (1984) described a ‘mud torrent’ from a storm following the 1983 ‘Ash Wednesday’ fires in Warburton (Victoria); Rutherfurd et al. (1994) studied sediment delivery from debris flows in northeastern Victoria; and Ferguson et al. (2004) and Lyon and O’Connor (2008) examined the link between post-wildfire debris flows and poor water quality in northeast and central Victoria. Large debris flows also occurred in the Cotter River catchments near Canberra after the severe 2003 wildfire (Worthy 2006), and Nyman et al. (2011) documented the occurrence of post-fire runoff generated debris flows in dry sclerophyll forests in south-eastern Australia. More recently Nyman et al. (2019) demonstrated how mass movements in south-eastern Australia are linked to regional hydroclimatic conditions and the El Niño Southern Oscillation. However, debris flows have not previously been noted in the Warrumbungle Range.

The number of publications discussing the use of Light Detection and Ranging (LiDAR) in ‘landslide’ studies has grown considerably during the last decade (Jaboyedoff et al. 2012). High resolution DEMs have been used to map mass movements in many locations around the world (McKean and Roering 2004; Glenn et al. 2006 Ardizzone et al. 2007; Schulz 2007; Van Den Eeckhaut et al. 2007) and to provide insight into the material type, and to infer landslide behavior and activity.

MATERIALS AND METHODS

Mapping and field investigations

As part of the Warrumbungle Post-fire Recovery Project, LiDAR was acquired over WNP and a 1 m DEM prepared. The LiDAR data is available at https://elevation.fsdf.org.au/. This provided the base layer for terrain interpretation and analyses based on morphometric factors (Staley et al. 2006; Cavalli and Marchi 2008). Mass movements were identified and mapped using ArcMap 10.4 and classified according to Varnes (1978) and Cruden and Varnes (1996). Slumps were mapped where there was an identifiable headscarp on the DEM >5 m in breadth, and from the headscarp to the depositional lobe. Debris flows were mapped from the uppermost point of the erosion channel to proximal end of the fan at the base of the debris flow channel. For each mass movement, site and elevation data was extracted from the DEM for the uppermost point or headscarp, and the lowest point of the toe (slumps) or the lowest point of the erosion channel (debris flows). Slope data were extracted from a resampled 5 m DEM to negate data noise. Slow earthflows were mapped on the basis of large areas of hummocky ground and/or other evidence of movement such as burial of dykes.

Mass movement sites were inspected in the field, where accessible, although these comprised only a small proportion (~4%) of the total detectable on LiDAR. More detailed field investigations were undertaken at several debris flows and at other mass movement sites just above the Warrumbungle Volcanics - Pilliga Sandstone boundary to determine the depth of transported material and the degree of bedrock weathering. Sites inspected are discussed below and noted on Fig. 1.

Determining the age range and frequency of mass movements in WNP

The mass movements identified in WNP appear to span a wide age range, based on a range of morphometric, regolithic and other site variables, including: the clarity of mesotopographic features such as sharpness of a headscarp; any superimposition of movements; and any other evidence for post-depositional geomorphic processes within the transported material, such as formation of drainage lines.

The frequency and nature of movements under current hydroclimatic conditions was established by examination of the DEM and aerial photos. Aerial photos dating back to 1955 were examined to identify recent movements. Where accessible, recent movements may be confirmed by the degree of revegetation of disturbed or depositional areas. Information of recent landscape instability in the vicinity of WNP was also obtained from NPWS staff and other sources. As a result, the dates of certain historic mass movements are known.

Radiocarbon dates of charcoal from debris flow levees and colluvial hollows can provide data to help determine the erosion regime in headwaters. We sampled charcoal from three levees and two colluvial hollows in the Dead Cow Creek catchment in order to obtain an indication on how the post-fire event in 2013 sits within the longer-term geomorphic processes that have shaped the landscape (Fig. 3). Charcoal in colluvial hollows can be used to estimate the rate of colluvial deposition (Reneau et al. 1989; Hales et al. 2012). Radiocarbon dates of charcoal in levees (Fig. 4) can provide an indication of when debris flows occurred in the past (Lancaster and Casebeer 2007; Smith et al. 2012).

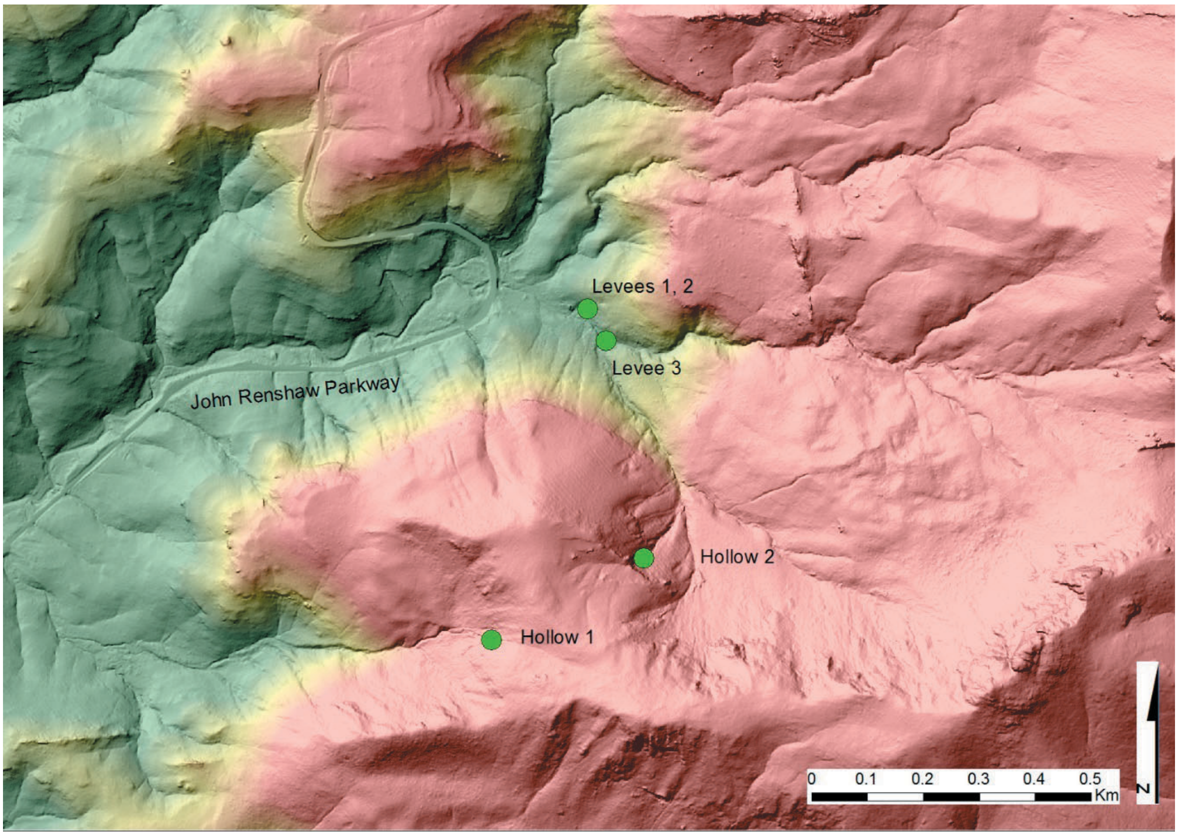


Figure 3. Sites in the Dead Cow Creek catchment where charcoal was sampled for radiocarbon dating. Figure prepared from 1 m DEM with hillshade.

Figure 4. Debris flow levee material at levee 3 site.

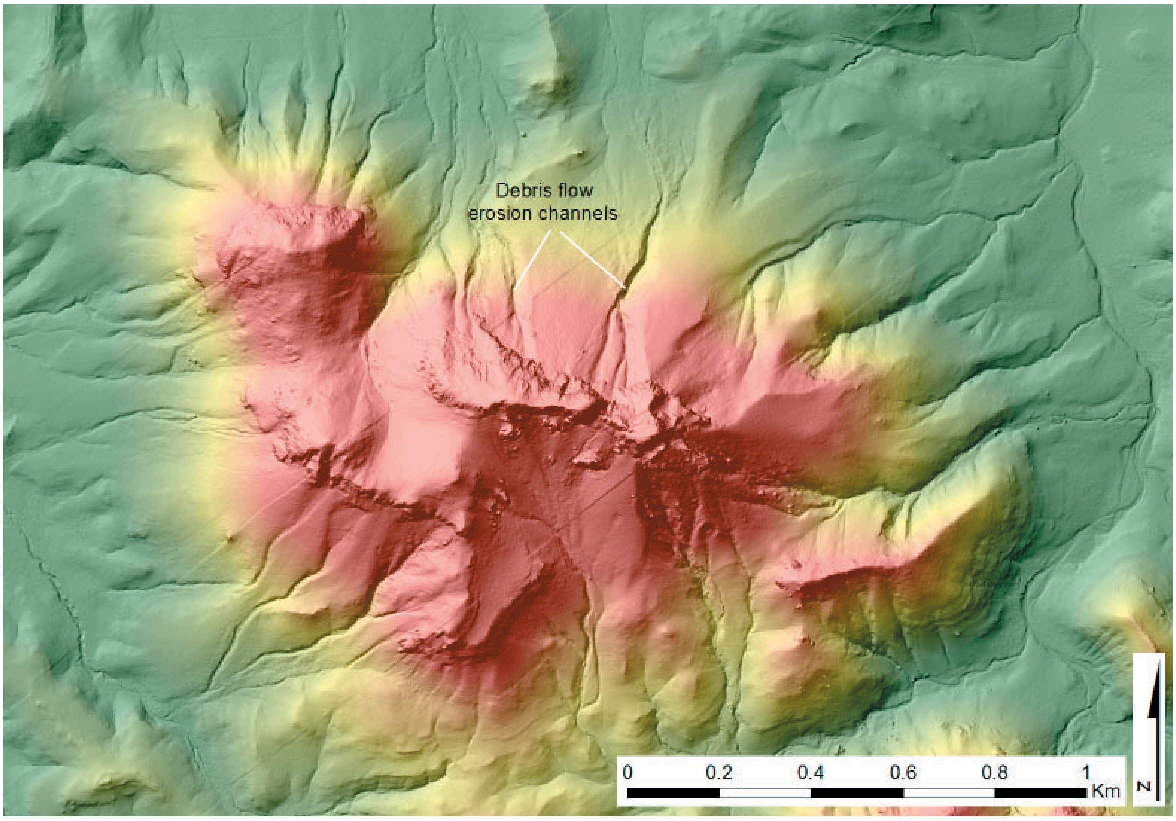


Figure 5. Debris flow scour channels, Wheoh Peaks.

RESULTS

Mapping

Five hundred and forty-two (542) individual mass movement locations totalling 408 ha were identified and mapped by examination of the high-resolution DEM. These data are available at https://www.environment.nsw.gov.au/eSpade2Webapp. Ninety-four per cent (94%) of the mass movements were located within areas mapped as Warrumbungle Volcanic Complex rocks, and <6% were on Pilliga Sandstone (17 ha, or 4.1% of the area of mass movements generally), based on geology data from Troedson & Bull (2018).

Debris flows

Seventy-seven (77) locations of mass movement processes were classified as debris flows. These were generally linear to sub-linear scour channels up to 700 m in length and 30 m in breadth, and found on steep (>92% average, 41% minimum) rectilinear colluvial slopes. The DEM revealed dozens of such channels associated with volcanic peaks, particularly in the north-west of WNP around Wheoh Peaks, Black Jack Mountain and the Tibuc-Bulleamble Mountain area (Fig. 5).

Historic aerial photographs and other remote imagery showed that the vast majority of such flows pre-dated the 2013 fire and storm. The only debris flows known to have been activated within the last 60 years were flows on Wheoh Peaks, Square Top Mountain, Little Square Top Mountain, Black Jack Mountain, and Airmid Dome (Fig. 6). The latter flow was dated to one of three intense rainfall events between December 2009 and February 2010, and therefore unrelated to fire or associated loss of groundcover. On 1 February 2013, several flows activated in the Dead Cow Creek area (Fig. 1) and one in Scabilon Creek.

Initiation and deposition slope angles for the 77 mapped debris flow scour channels are shown in Fig. 7. Debris flows were not observed to release on slopes <41% in WNP. Deposition may occur on slopes <27% on average, and the run-out, generally comprising a downstream fining sequence of boulders and logs to gravels and sands, can occur over several kilometres where the flow is valley-confined.

Radiocarbon dates of charcoal samples (shown in Table 1) from levees range from modern (calibrated radiocarbon age of 58 - 8 years BP) at 30 cm below the contemporary channel to much older for charcoal samples from levees deeper in the channel profile at

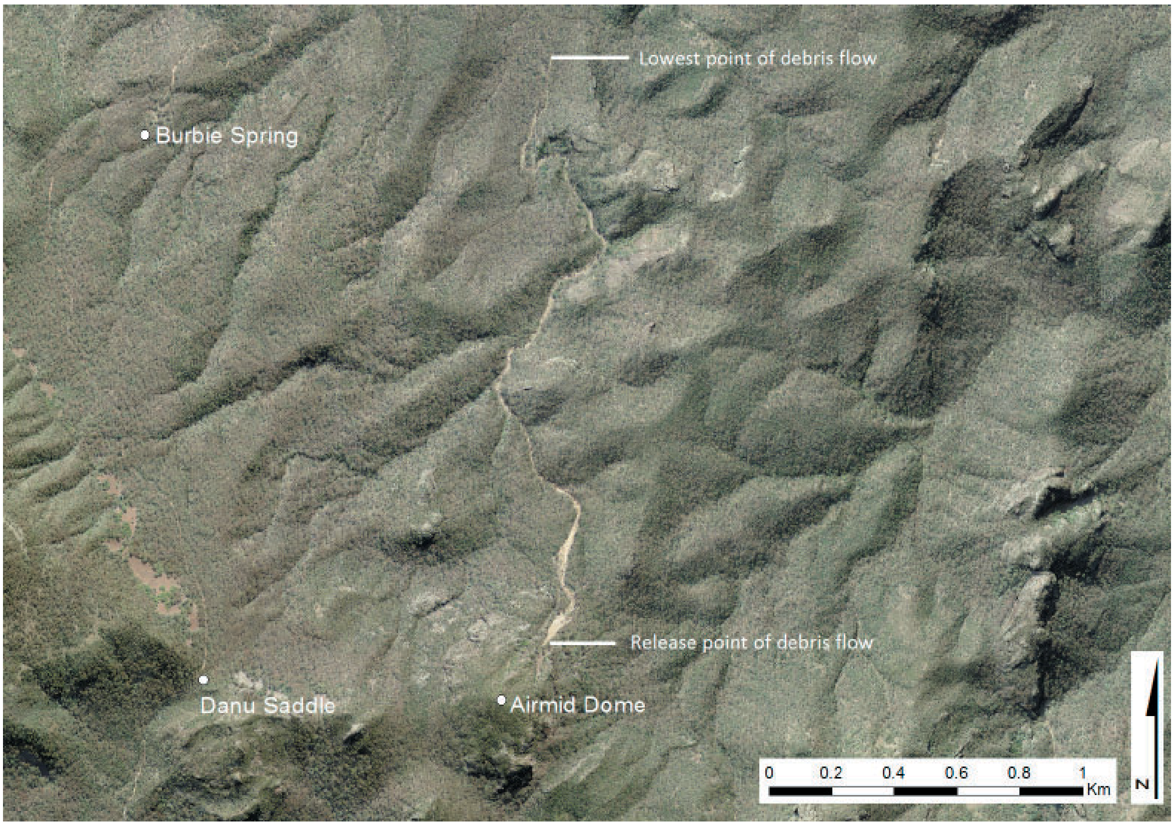


Figure 6. Airmid Dome debris flow.

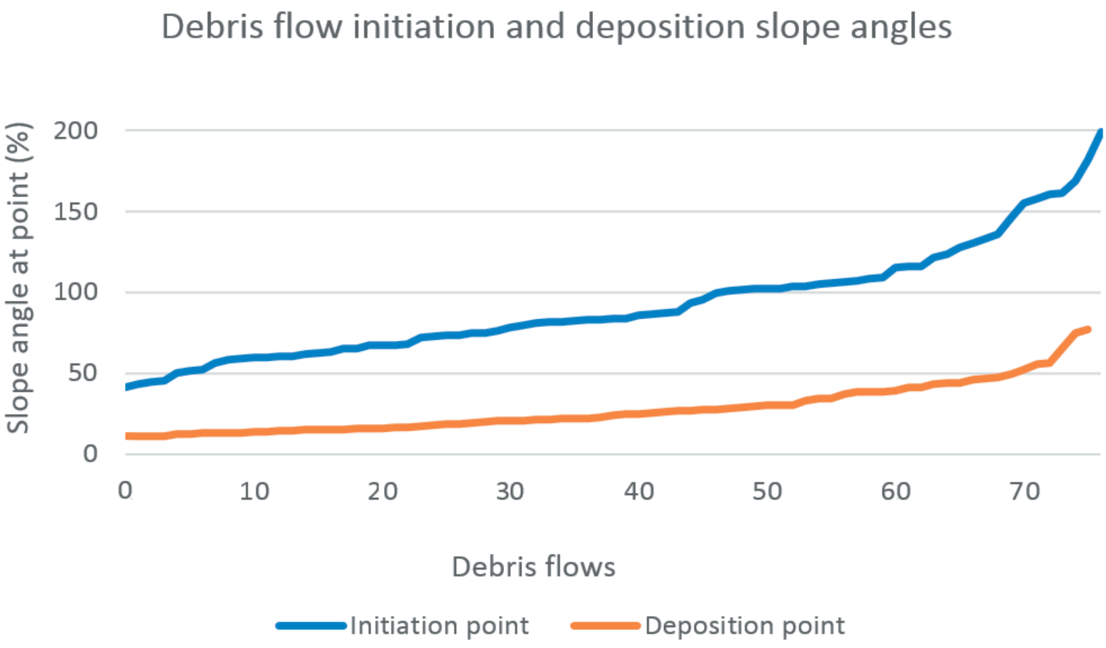


Figure 7. Frequency distribution plot of slope of debris flow release and deposition points.

Table 1. Radiocarbon dates from charcoal samples from old levees and colluvial hollows, reported as per standard convention (Millard, 2014). Dates were analysed at the Beta Analytic radiocarbon dating lab using Accelerator Mass Spectrometry (AMS). Charcoal was pre-treated using standard acid-alkali-acid method.

Sample code	Beta Analytics laboratory code	Sample location	Easting[1]	Northing[1]	Conventional radiocarbon age (BP) or Percent Modern Carbon (pMC)	δ13C from isotope-ratio mass spectrometry (o/oo)	Calibrated age (years BP) [2]
Levee 1 30 cm	522304	Old levee at 30 cm below bank of contemporary channel	694020	6535232	107.09 ± 0.40 pMC	-25.7	58 - 8
Levee 2 95 cm	522309	Old levee at 95 cm below bank of contemporary channel	694020	6535232	540 ± 30 BP	-24.8	525 - 500
Levee 3 125 cm	522308	Old levee at 125 cm below bank of contemporary channel	694054	6535175	1650 +/- 30 BP	-26.3	1492 - 1416
Hollow 1 140 cm	522307	Colluvium at channel head at 140 cm below contemporary hillslope surface	693846	6534638	880 +/- 30 BP	-26.3	738 - 683
Hollow 2 80 cm	522305	Colluvium at channel head at 80 cm below contemporary hillslope surface	694122	6534786	940 +/- 30 BP	-24.3	906 - 736
Hollow 2 110 cm	522306	Colluvium at channel head at 110 cm below contemporary hillslope surface	694122	6534786	4630 +/- 30 BP	-26.8	5254 - 5057

[1] Coordinates in MGA GDA94 zone 55.

[2] Dates calibrated by Beta Analytics (BetaCal3.21: HPD method: SHCAL13 (Hogg, et.al.,2013) using MatCal in Matlab (Lougheed et al, 2016). The date range is the 95.4% probability interval.

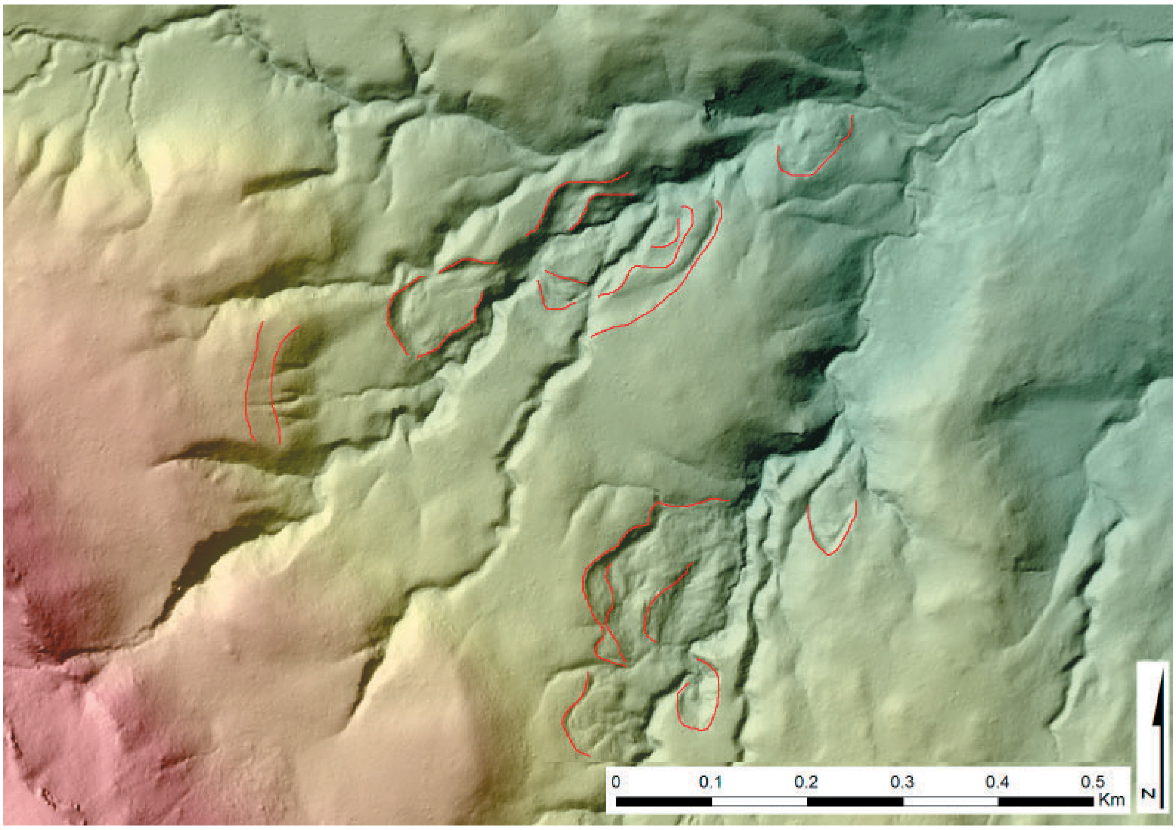


Figure 8. DEM image of rotational slumps, Milchomi Creek catchment. Figure prepared from 1 m DEM with hillshade.

125 cm (calibrated radiocarbon age of 1492 - 1416 years BP). The time interval between the radiocarbon dates in levee 1 and levee 2 (95 cm below contemporary channel bank) is ~500 years. There is an interval of ~1000 years between levee 2 and levee 3.

Calibrated radiocarbon dates from the base of exposed colluvial profiles indicate when the material was last eroded by debris flows or landslides. In hollow 1, which was located on a scree slope at the base of volcanic escarpments (the west oriented headwater in Fig. 3) the age of charcoal samples near the base of the eroded channel (at 140 cm below the surface) was 738 - 683 years BP. In hollow 2, which sits at the sandstone-volcanic boundary, the charcoal sample at the base of the profile (110 cm below the current hillslope surface), was dated to be 5254 - 5057 years BP. The radiocarbon date of charcoal from 80 cm below the surface was 906 - 736 years BP. With these dates, the rate of sediment accumulation in the hollows is in the order of 0.015 - 0.12 cm yr^{-1}. With hillslope lengths of 120 - 150 m, these infilling rates correspond to denudation of 2.5 - 20 mm kyr^{-1} which are within the range of values reported for hillslopes in southeast Australia (Smith et al. 2012).

Many debris flow channels, including most in the Wheoh Peaks, Black Jack Mountain and the Tibuc-Bulleamble Mountain areas, incised into colluvial and/or prior debris flow materials. The periodicity of debris flows may be set in part by the formation of indurated layers within the regolith of previous flows or colluvial deposits. Once permeability and transmissivity of the regolith is so limited, intense runoff is more likely to result in overlying unconsolidated surficial materials becoming hydraulically loaded to the point where slope stability is exceeded.

Slumps

The most common mass movement type in WNP evident in the DEM is the slump, of which 353 were identified. The smallest slump mapped was 19 m^2. Larger examples were up to 8.7 ha. The majority of slumps were identified as rotational, with a hummocky toe. Several revealed multiple headscarps and possibly, phases of activity (Fig. 8).

Fifty per cent (50%) of slump headscarps were initiated within the volcanic sequence within 440 m of the Warrumbungle Volcanics-Jurassic sandstones geologic boundary as determined by Troedson and

Bull (2018) (Fig. 9), with the inflection in Fig. 10 suggesting a causal relationship up to 1700 m from the boundary.

Field investigations were undertaken at several sites including Burbie Spring, Brownes Creek, Siding Spring, and Gunneemooroo to understand the processes involved at the volcanics-sandstone boundary. These revealed that the material immediately above the volcanic-sandstone boundary at these sites is typically unconsolidated volcanic colluvium and/or in situ deeply weathered volcanics (Fig. 11). In all cases mass failure was initiated in this material.

The elevations of the initiation points of slumps and that of the nearest sandstone contact were determined from the DEM and the difference calculated (Fig. 12); the inflection and sparse data on the right indicates that the elevation difference averages 81 m, but may be up to ~200 m.

Information regarding slump frequency is scarce, as slumps are generally difficult to detect beneath the vegetation on aerial photographs. A slump on Mopra Rock, just outside the park is known to have occurred in 1955 (P. Thompson, Coonabarabran Landcare, pers. comm), and a small slump in the upper Wambelong Creek valley occurred in 2018. A large rotational slump in the upper Wambelong Creek valley with a vertical headscarp with exposed soil is not known to have moved in several decades (A. Dow, NPWS, pers. comm.), suggesting a high degree of preservation on a decadal time scale. A presumed megaslump caused the formation of Dunphy Lake, a small intermittent wetland in a remote northern section of the park. This movement can be proxy dated from the palustrine sediments; Lobb (2015) retrieved two cores from the intermittent wetland, and dated the sediments using OSL and radiocarbon providing an age of 18.2 ka for initiation of wetland sediment accumulation at that site.

Slow Earthflows

Some areas exhibited hummocky, unstable terrain without a headscarp. The largest such area was 26 ha, near Gunneemooroo (Fig. 13). It is likely that further areas of undetected unstable surficial materials are present, older areas of instability being generally less detectable.

Other Movements

A Pleistocene age can be inferred for a 1.2 km long slow earthflow filling a former valley of the Dead Cow Creek catchment (Fig. 14), with an estimated volume of 2 x 10^6 m^3 of material. This material is indurated and has erosive drainage features developed within it, suggesting a Pleistocene age, and may relate to a climatic period with higher soil moisture regimes. A small intermittent 'lake' basin not unlike Dunphy Lake has developed towards the proximal end of the flow.

DISCUSSION AND CONCLUSIONS

Analysis of a high-resolution LiDAR DEM has revealed the large number, locations and types of hitherto largely unknown pre-historic to historic mass movements in WNP, features that were previously undetectable by aerial photographs or other remote imagery. Five hundred and forty-two (542) individual mass movements were mapped and classified: 353 were slumps; 58 were slips on hillslopes; 40 were slips in drainage lines; 81 were debris flows; and 9 were slow earthflows. Mass movements, especially slumps, are concentrated immediately above the volcanics-sandstone geological boundary and may occur on gentle slopes, as low as 4% with an average of 47%. In contrast, debris flow release points are located on steeper slopes, a minimum of 41% and an average of 102%. The large number of slumps that may be identified and which are therefore presumably younger than the 18.2 ka Lake Dunphy presumed megaslump gives an indication of the frequency of such events. In the Dead Cow Creek catchment, recurring debris flows can occur every few hundred years.

Mass movements appear to be a key process in long-term landscape evolution in the Warrumbungles, and probably have been since shortly after the eruption of volcanic materials. A model of landscape evolution is proposed, focusing on processes at the boundary (Fig. 15). In areas where unconsolidated volcanic colluvium and/or in situ deeply weathered volcanics directly overlies the sandstones, such as the Wheoh Peaks, Black Jack Mountain and Tibuc-Bulleamble Mountain areas, relatively rapid recession of colluvial slopes occurs from immediately above the boundary predominantly by land slippage and debris flows, leaving isolated caps of coherent volcanic rocks (Fig. 5).

In other areas with a deeper pile of coherent volcanics, rainfall enters groundwater via volcanic jointing, and appears to be impeded and directed laterally above the sandstone contact, resulting in greater weathering of the volcanics immediately above the contact, and the expression of artesian springs. A number of named springs or waterholes are located within a few hundred metres of the geological boundary (Jensen 1907; Hockley 1972; Troedson and Bull 2018). Weathered and unconsolidated volcanic

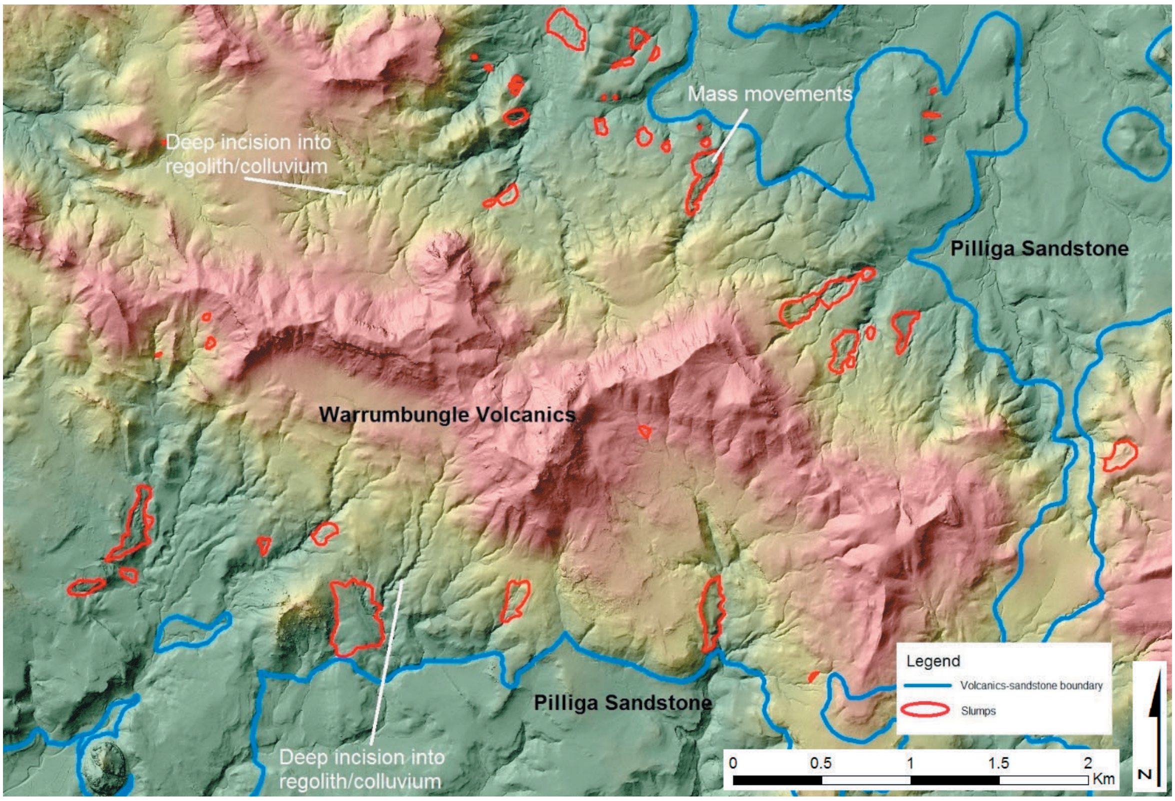


Figure 9. DEM image of slump distribution in the Mt Aranon-Bregon range, northwestern WNP, showing proximities to the mapped volcanics-sandstone geologic boundary. Figure prepared from 1 m DEM with hillshade.

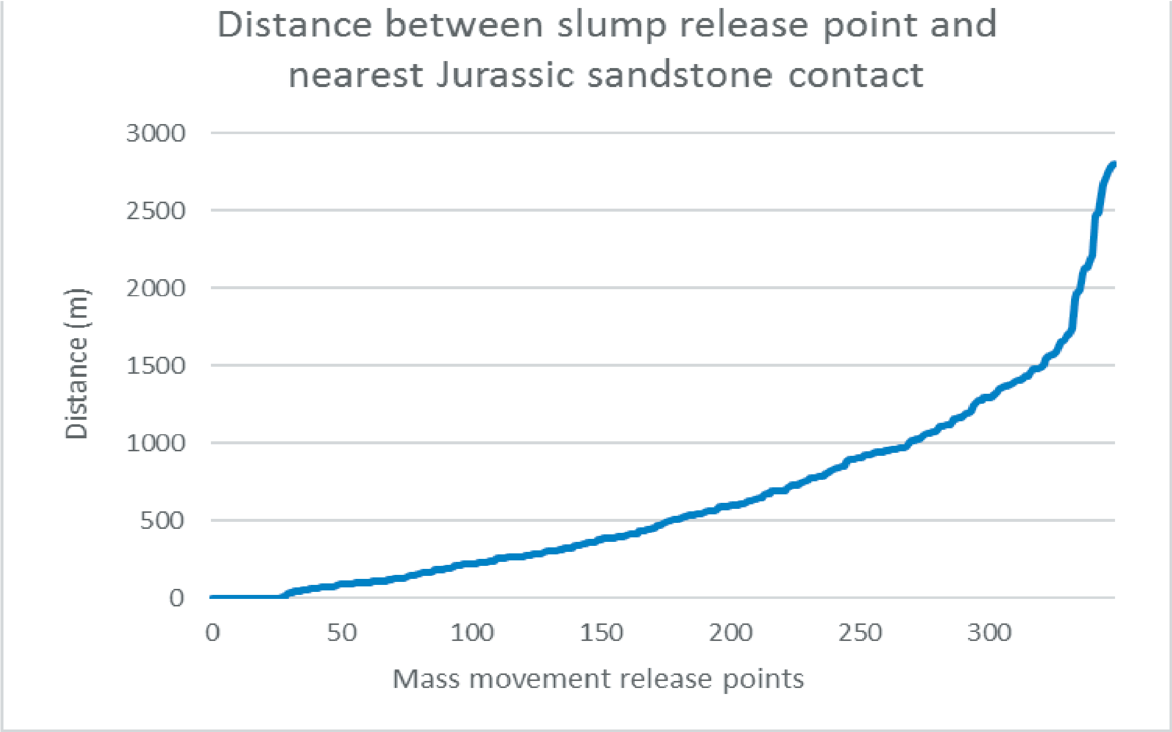


Figure 10. Frequency distribution plot of distances from slump release point to the volcanics –sandstones geologic boundary.

Figure 11. Deeply weathered in situ volcanics at Burbie Spring.

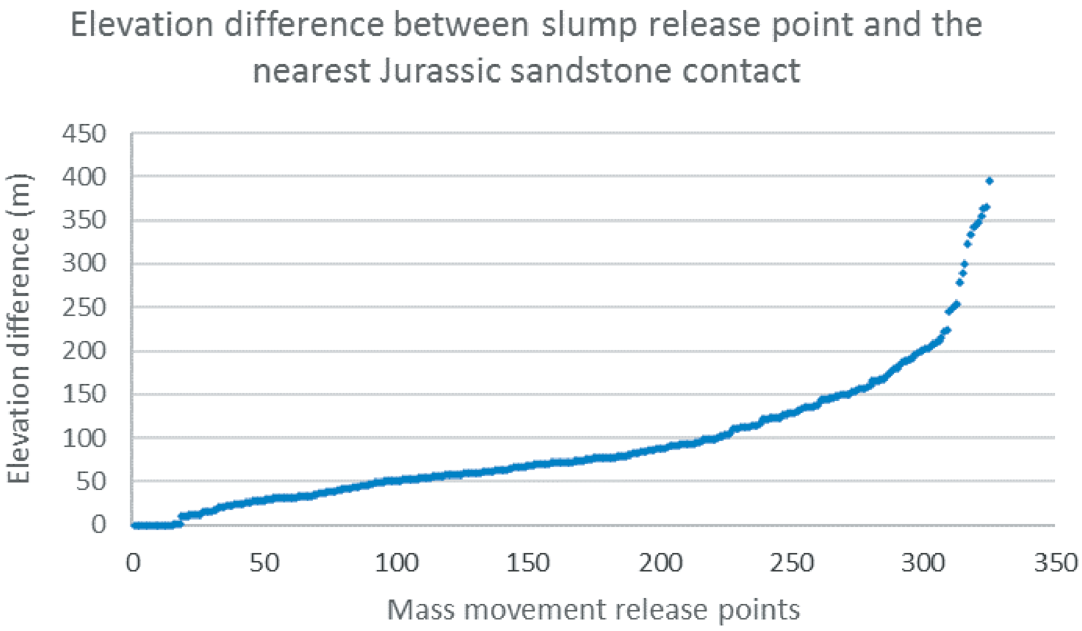


Figure 12. Frequency distribution plot of elevation difference between slump release points and the volcanics-sandstones geologic boundary.

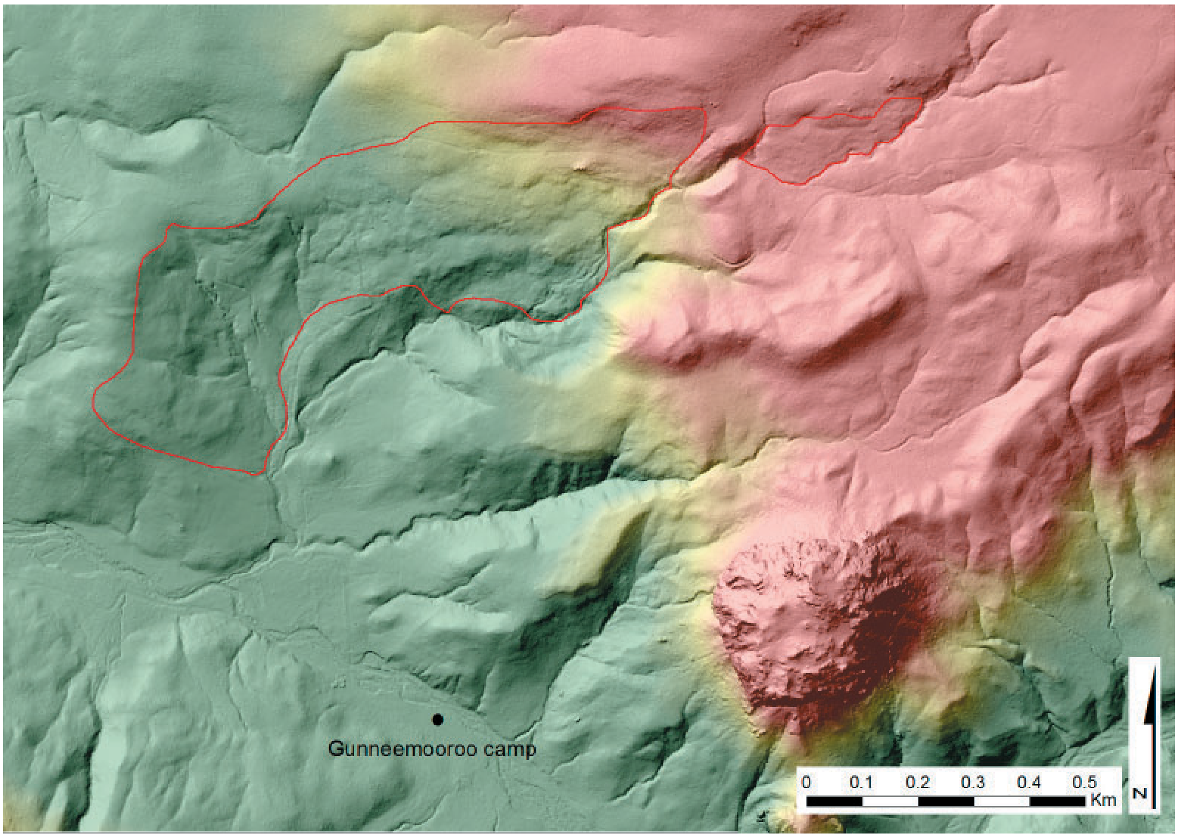


Figure 13. DEM image of hummocky, unstable terrain, Gunneemooroo area.

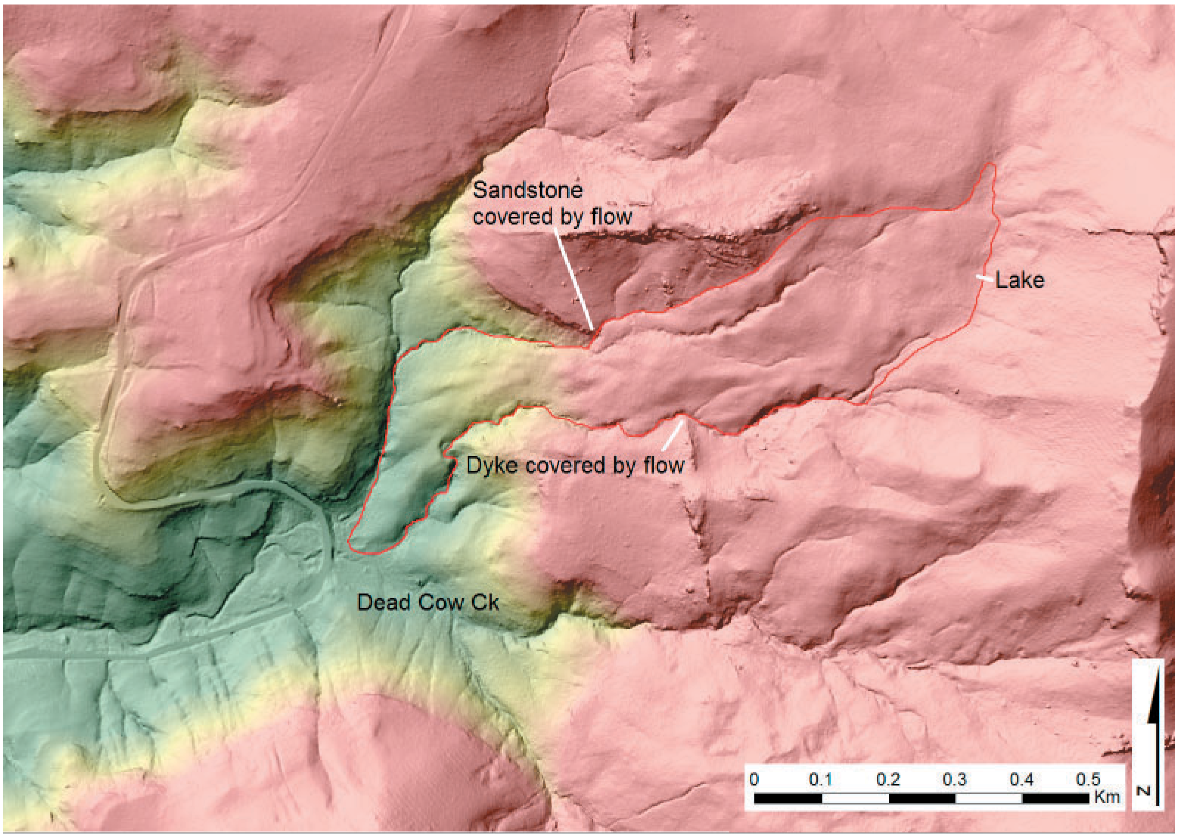


Figure 14. Dead Cow Creek catchment slow earthflow.

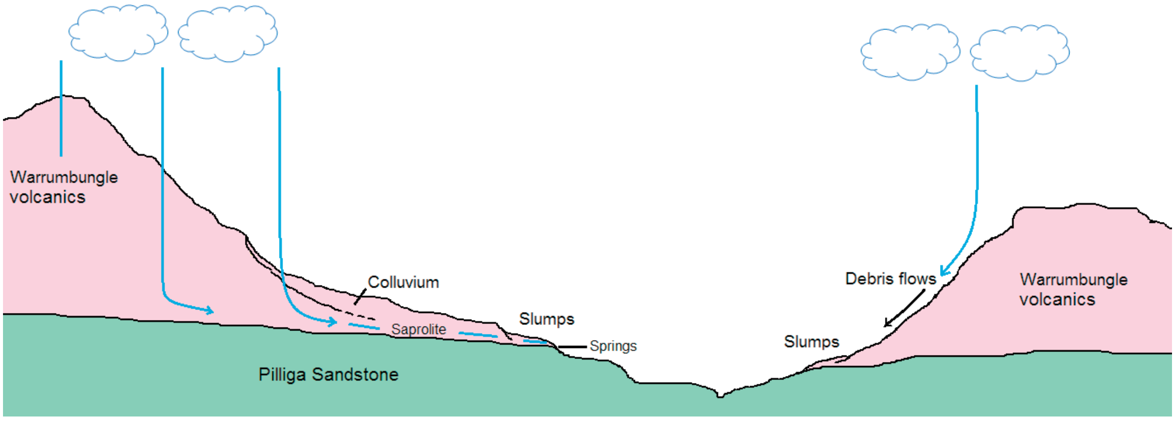


Figure 15. Conceptual model of processes at the sandstone-volcanic boundary.

regolith directly above the contact becomes deeply incised by stream action (Fig. 9) and periodically fails by slumping (Fig. 8). Stratigraphic undermining may also occur from higher within the volcanic sequence, leaving a larger 'apron' of volcanic colluvium and deeply weathered volcanic regolith (Fig. 9).

This study relied on the geological mapping of Troedson and Bull (2018). However both this work and the present study were constrained by lack of access to many areas of WNP. In these areas, much of the geological mapping was carried out by interpretation of aerial photography and other remotely sensed data. Similarly, more detailed inspection of more sites near the volcanics-sandstones contact, particularly in relation to groundwater hydrodynamics and weathering patterns would inform a more robust model of landscape evolution. Further, work on debris flows could be extended beyond the limited number of sites in this study to examine timing and possible synchronicities with other sites, such as the north-eastern part of WNP.

Mass movements appear to have been a significant process of landscape evolution in the Warrumbungles since at least the late Pleistocene, with one movement (Dunphy Lake) dated to the Last Glacial Maximum. Certain features, such as the Dead Cow Creek deposit, and the central valley Neogene sedimentary deposit, have few modern identified analogues. The processes responsible for their formation do not appear to operate under current hydro-climatic conditions.

This work has direct relevance to park planning and hazard management. It has highlighted the hazards posed by mass movements to the public and to infrastructure, identified slopes and areas at risk of debris flows and slumps, and outlined the processes and conditions under which mass movements may be active. Furthermore, the dating of debris flow deposits and colluvial sediments provide an early indication on the frequency with which these types of events can be expected to occur. The results may also have wider implications beyond WNP, to post-volcanic landscape evolution in other Cenozoic volcanic areas in NSW.

ACKNOWLEDGMENTS

We thank: Craig Wall, Rebecca Cass and Arthur Dow (NPWS) for their interest and assistance and for access to the park; Scott Taylor (DPIE) for spatial imagery; Peter Thompson (Coonabarabran Landcare) for local information.

Petter Nyman received funding from the Australian Research Council (Linkage project: LP150100654).

REFERENCES

Ardizzone, F., Cardinali, M., Galli, M. and Guzzetti, F. (2007). Identification and mapping of recent rainfall-induced landslides using elevation data collected by airborne Lidar. *Natural Hazard and Earth System Science* **7**, 637-650.

Barnes, R.G., Dawson, M., Spiller, F.C.P and McDonald, K.M. (2002). Interpreted and re-compiled geology of the Brigalow Belt South Bioregion – Digital Data Set. NSW Department of Mineral Resources, for NSW Resource and Conservation Assessment Council.

Blong, R.J. and Dunkerley, D.L. (1976). Landslides in the Razorback area, New South Wales, Australia. *Geographiska Annaler* **58A**, 139-147.

Bowman, H.N. (1972). Natural slope stability in the City of Greater Wollongong. *Records of Geological Survey of NSW* **14**(1), 159-222.

Bull K.F., Troedson A.L., Bodorkos S., Blevin P.L., Bruce M.C. & Waltenberg K. (in review). Geology of Warrumbungle National Park: new insights into volcanic facies architecture and evolution of Warrumbungle Volcano. *Australian Journal of Earth Sciences*.

Burnt Area Assessment Team (2013). Post-fire rapid risk assessment and mitigation

Wambelong fire Warrumbungle National Park 2 February 2013. Final report. NSW National Parks and Wildlife Service and ACT Parks, Conservation and Lands.

Cavalli, M. and Marchi, L. (2008). Characterisation of the surface morphology of an alpine alluvial fan using airborne LiDAR. *Natural Hazard and Earth System Science* **8**, 323-333.

Cohen, B. E., Knesel, K.M., Vasconcelos, P. M., Thiede, D. S. and Hergt, J.M. (2008). ^{40}Ar/^{39}Ar constraints on the timing and origin of Miocene leucitite volcanism in southeastern Australia. *Australian Journal of Earth Sciences* **55**, 407-418.

Cruden, D.M. and Varnes, D. J. (1996). In 'Landslides: Investigation and Mitigation' (Eds A.K. Turner and R.L. Shuster). *Transportation Research Board, Special Report* **247**, 36-75.

Cunningham, D.M. (1988). A rockfall avalanche in a sandstone landscape, Nattai North, NSW. *Australian Geographer* **19**, 221-229.

David, T.W.E. (1896). Note on the occurrence of diatomaceous earth at the Warrumbungle Mountains, New South Wales. *Proceedings of the Linnean Society of NSW* **21**, 261-268.

Duggan M.B. (1989). Warrumbungle. In R.W. Johnson & J. Knutson (eds.) 'Intraplate Volcanism in Eastern Australia and New Zealand'. Cambridge University Press, 121-122.

Duggan, M.B. and Knutson, J. (1991). The Warrumbungle Volcano, central New South Wales. An outline of the geology and petrology of the Warrumbungle Volcano. Bureau of Mineral Resources (BMR) Record 1991/44, Canberra.

Duggan, M.B. and Knutson, J. (1993). The Warrumbungle Volcano: a geological guide to the Warrumbungle National Park. Australian Geological Survey Organisation, Canberra, 51 pp.

Dulhunty, J.A. (1972). Potassium-argon dating and occurrences of Tertiary and Mesozoic basalts in the Binnaway district. *Royal Society of NSW, Journal and Proceedings* **105**, 71-76.

Dulhunty, J.A. and McDougall, I. (1966). Potassium argon dating of basalts in the Coonabarabran-Gunnedah district, New South Wales. *Australian Journal of Science* **28**, 393-394.

Dury, G.H., Langford-Smith, T. and McDougall, I. (1969). A minimum age for the duricrust. *Australian Journal of Science* **31**, 362-363.

Erskine, W.D. (2005). Mass movement hazard assessment associated with harvesting of the 1962 age class of Monterey pine (Pinus radiata D. Don) in Canobolas State Forest, New South Wales. Forest Resources Research, NSW Department of Primary Industries Sydney.

Faulks, I.G. (1969). The geology of the southern slopes of the Warrumbungle Mountains. In 'IX Mesozoic and Cainozoic Rocks' (Eds T.G. Vallance, J.F.G. Wilkinson, M.J. Abbott, I.G. Faulks, J.R. Stewart and K.J.M. Bean), *Journal of the Geological Society of Australia* **16**, 536-537.

Ferguson, R., Dwyer, C., Loffler, T. and Hardie, R. (2004). Fire Recovery Pilot Study: Buckland River and Omeo District Catchments. Technical Report by Earth Tech Engineering Pty Ltd for the Northeast Catchment Management Authority, Wangaratta, Australia, 57 pp.

Ghorbani, M.R. (1999). Petrology and geochemistry of the Warrumbungle volcano, N.S.W., Australia. PhD thesis, University of Sydney.

Glenn, N.F., Streutker, D.R., Chadwick, J., Thackray, G.D., Dorsch, S.J. and Dorsch, N. F. (2006). Analysis of LiDAR-derived topographic information for characterizing and differentiating landslide morphology and activity. *Geomorphology* **73**, 131-148.

Hales, T., Scharer, K. and Wooten, R. (2012). Southern Appalachian hillslope erosion rates measured by soil and detrital radiocarbon in hollows. *Geomorphology* **138**(1), 121-129.

Hockley, J.J. (1972). The petrology of the Warrumbungle volcano, New South Wales Australia. PhD thesis, University of New England, Armidale.

Hockley, J.J. (1975). The geology of the Warrumbungle Mountains, explanatory notes and map. Self-published.

Hogg, A.G., Hua, G., Blackwell, P.G., Niu, M., Buck, C.E., Guilderson, T.P., Heaton, T.J., Palmer, J.G., Reimer, P.J., Reimer, R.W., Turney, C.S.M. and Zimmerman, S.R.H. (2013).

SHCal13 Southern Hemisphere Calibration, 0–50,000 Years cal BP. *Radiocarbon*, **55**(4): 1889-1903.

Hunter, J.T. (2008). Vegetation and floristics of Warrumbungle National Park. A Report to the New South Wales National Parks and Wildlife Service.

Isbell, R.F. and the National Committee on Soil and Terrain (2016). The Australian Soil Classification. Australian Soil and Land Survey Handbooks Series, Second Edition. (CSIRO Publishing).

Jaboyedoff, M., Oppikofer, T., Abella´n, A., Derron,M., Loye.A., Metzger, R. and Pedrazzini,A. (2012). Use of LIDAR in landslide investigations: a review. *Natural Hazards* **61**,5-28.

Jensen, H.I. (1907). The geology of the Warrumbungle Mountains. *Proceedings of the Linnean Society of NSW* **32**, 557-626.

Keith, D. (2004) *Ocean Shores to Desert Dunes. The native vegetation of New South Wales and the ACT.* Department of Environment and Conservation (NSW), Hurstville.

Lancaster, S.T. and Casebeer, N.E. (2007). Sediment storage and evacuation in headwater valleys at the transition between debris-flow and fluvial processes. *Geology* **35**(11), 1027-1030.

Leitch, C., Flinn, D. and van de Graaff, R. (1984). Erosion and nutrient loss resulting from Ash Wednesday (February 1983) wildfires: a case study. *Australian Forestry* **46**, 173-180.

Lobb, J. (2015). A palaeoenvironmental and palaeofire record from Dunphy Lake, Warrumbungle Mountains, south-eastern Australia. Thesis submitted in accordance with the requirements of the Master of Research Department of Environmental Sciences Macquarie University October 2015.

Lougheed, B. and Obrochta, S. (2016). MatCal: Open Source Bayesian 14 C Age Calibration in Matlab. *Journal of Open Research Software*, **4**. 10.5334/jors.130.

Lyon, J.P. and O'Connor, J.P. (2008). Smoke on the water: can riverine fish populations recover following a catastrophic fire-related sediment slug? *Austral Ecology* **33**, 794-806.

Macgregor, J.P., McManus, K.J. and Fell, R. (1990). Management of protected lands subject to mass movement in the Richmond River catchment. Unisearch Ltd, University of NSW.

McDougall, I. and Wilkinson, J.F.G. (1967). Potassium-argon dates on some Cainozoic volcanic rocks from northeastern New South Wales. *Journal of the Geological Society of Australia* **14**(2), 225-233.

McKean, J. and Roering, J. (2004). Objective landslide detection and surface morphology mapping using high-resolution airborne laser altimetry. *Geomorphology* **57**, 331-351.

Melville, A.R. (1976). Landslides on the far North Coast. *Journal of the Soil Conservation Service of NSW* **32**, 181-186.

Millard, A.R. (2014). Conventions for Reporting Radiocarbon Determinations. *Radiocarbon* **56**(2), 555-559.

National Parks and Wildlife Service (2012). Warrumbungle National Park Plan of Management.

Nyman, P., Sheridan, G.J., Smith, H.G. and Lane, P.N.J. (2011). Evidence of debris flow occurrence after wildfire in upland catchments of south-east Australia. *Geomorphology* **125**(3), 383-401.

Nyman, P., Rutherfurd, I. D., Lane, P. N. J., and Sheridan, G. J. (2019). Debris flows in southeast Australia linked to drought, wildfire, and the El Niño–Southern Oscillation. *Geology* **47**(5): 491-494.

Offenberg A. (1968). Gilgandra 1:250 000 Geological Sheet SH/55-16, New South Wales Department of Mines.

Reneau, S.L., Dietrich, W.E., Rubin, M., Donahue, D.J. and Jull, A.J.T. (1989). Analysis of hillslope erosion rates using dated colluvial deposits. *Journal of Geology* **97**(1), 45-63.

Riley, K.L., Bendick, R., Hyde, K.D., Gabet, E.J., 2013. Frequency–magnitude distribution of debris flows compiled from global data, and comparison with post-fire debris flow in the western US. *Geomorphology* **191**, 118-128

Rutherfurd, I.D., Bishop, P. and Loffler, T. (1994). Debris flows in northeastern Victoria, Australia: occurrence and effects on the fluvial system. In 'Variability in stream erosion and sediment transport' (Eds L.J. Olive, R.J. Loughran and J.A. Kesby). Proceedings of the Canberra Symposium, December 1994, pp 359-369. International Association of Hydrological Sciences, Wallingford.

Schulz, W. H. (2007). Landslide susceptibility revealed by LIDAR imagery and historical records, Seattle, Washington. *Engineering Geology* **89**, 67-87.

Smith, H.G., Sheridan, G.J., Nyman, P., Child, D.P., Lane, P.N.L., Hotchkis, M.A.C. and Jacobsen, G.E. (2012). Quantifying sources of fine sediment supplied to post-fire debris flows using fallout radionuclide tracers. *Geomorphology* **139–140**(0), 403-415.

Staley, D.M., Wasklewicz, T.A. and Blaszczynski, J.S. (2006). Surficial patterns of debris flow deposition on alluvial fans in Death Valley, CA using airborne laser swath mapping data. *Geomorphology* **74**,152-163.

Timmers, A.J. (1998). The geomorphic evolution of the Warrumbungle Volcanic Complex, New South Wales, Australia. PhD thesis, University of New England.

Troedson, A.L. and Bull, K.F. (2018). Geological mapping of Warrumbungle National Park and surrounds, final report. Prepared for the New South Wales Office of Environment and Heritage. Geological Survey of New South Wales Report GS2018/0575.

Van Den Eeckhaut, M., Poesen, J., Verstraeten, G. and Vanacker, V. (2007). Use of LIDAR-derived images for mapping old landslides under forest. *Earth Surface Processes and Landforms* **32**, 754-769.

Varnes D. J. (1978). Slope movement types and processes. In: 'Landslides, analysis and control' (Eds R.L. Schuster and R.J. Krizek). Transportation Research Board Special Report No. 176, National Academy of Sciences, 11-33.

Walker, P.H. (1963). Soil history and debris avalanche deposits along the Illawarra scarpland. *Australian Journal of Soil Research* **1**, 223-230.

Wellman, P. and McDougall, I. (1974). Potassium-argon ages on the Cainozoic volcanic rocks of New South Wales. *Geological Society of Australia Journal* **21**, 247-271.

Whitehead, J. (2010). The Geology of the Warrumbungle Range. Self-published.

Worthy, M. (2006). Major Erosion Events and Past Fires in the Cotter River Catchment. Technical Report, the Australian National University, Centre for Resource and Environmental Studies for the ACTEW Corporation Ltd, Project No. WF-30034, Canberra, 7 pp.

Young, A.R.M. (1978). The influence of debris mantles and local climatic variations on slope stability near Wollongong, Australia. *Catena* **5**, 95-107.

Yu, B. (2015). An assessment of characteristics and rainfall erosivity of the Feb 2013 storm event in the Warrumbungle National Park, NSW. School of Engineering, Griffith University. Report prepared for the NSW Office of Environment and Heritage.

The Linnean Society of New South Wales publishes in its proceedings original papers and review article dealing with biological and earth sciences. Intending authors should contact the Secretary (PO Box 291, Manly NSW 1655, Australia) for instructions for the preparation of manuscripts and procedures for submission. Instructions to authors are also available on the society's web page (http://linneansocietynsw.org.au/).

Manuscripts not prepared in accordance with the society's instructions will not be considered.

PROCEEDINGS OF THE LINNEAN SOCIETY OF NSW

VOLUME 141

CONTENTS

Volume 141
Papers published in 2019, compiled 31 December 2019

Published at http://escholarship.library.usyd.edu.au/journals/index.php/LIN
(date individual papers were published online at eScholarship)

General papers

Supplement

Papers from the symposium "Volcanoes of northwest NSW: exploring relationships among geology, flora, fauna and fires" held in September 2018.