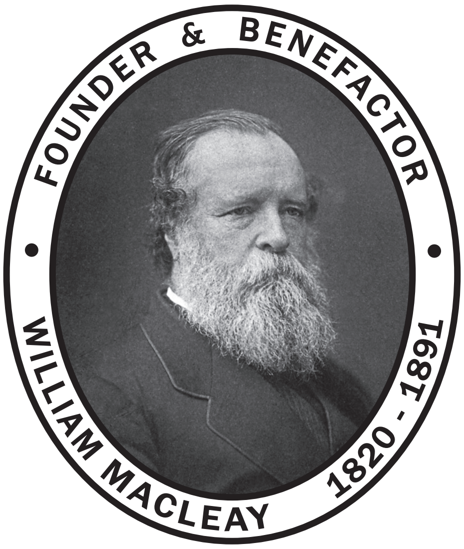
PROCEEDINGS
of the
LINNEAN
SOCIETY
of
NEW SOUTH WALES

VOLUME 136

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 82, Kingsford, N.S.W. 2032, Australia.
Telephone and Fax +61 2 9662 6196.
Email: linnsoc@iinet.net.au
Home page: www.linneansocietynsw.org.au/

Cover motif: *Palaeoxyris duni* holotype MMF 42697a (left) and paratype MMF 42697b (right) on a single slab shown in Figure 2 in the paper by Graham McLean, pages 201-218, this volume.

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 136
December 2014

Minerals of Jenolan Caves, New South Wales, Australia: Geological and Biological Interactions

R. E. Pogson[1], R. A. L. Osborne[1,2], and D. M. Colchester[1]

[1]Geoscience and Archaeology, Australian Museum, 6 College St, Sydney NSW 2010 (ross.pogson@austmus.gov.au); [2]Faculty of Education and Social Work, University of Sydney, NSW 2006

Pogson, R.E., Osborne, R.A.L. and Colchester, D.M. (2014). Minerals of Jenolan Caves, New South Wales, Australia: geological and biological interactions. *Proceedings of the Linnean Society of New South Wales* **136**, 1-18.

Geological and biological processes in the Jenolan Caves have formed a range of mineral species spanning several chemical groups. So far 25 mineral species have been either confirmed, or identified for the first time at Jenolan. Their chemical groups include carbonates: (calcite, aragonite, hydromagnesite, huntite, dolomite, ankerite); silicates: (kaolinite, K-deficient muscovite ('illite'), montmorillonite clays); phosphates, (ardealite, hydroxylapatite, taranakite, leucophosphite, variscite, crandallite, montgomeryite, kingsmountite); sulfate: (gypsum); oxides: (quartz, cristobalite, amorphous silica, hematite, romanèchite); hydroxide**:** (goethite); nitrate: (niter); and chloride: (sylvite). Dolomitised limestone bedrock and ankerite veins can be recognised as a magnesium source of some magnesium carbonate minerals, as well as supplying a calcite inhibitor favouring aragonite formation. The cave clays have diverse origins. Some are recent sedimentary detritus. Older clays of Carboniferous age contain components of reworked altered volcaniclastics washed or blown into the caves, so these clays may represent argillic alteration of volcanic products. Some of the clays may have formed as alteration products of ascending hydrothermal fluids. The phosphates and some gypsum formed when bat guano reacted chemically with limestone and cave clays. Gypsum has also been formed from the breakdown of pyrite in altered bedrock or dolomitic palaeokarst. The niter and sylvite have crystalized from breakdown products of mainly wallaby guano.

Manuscript received 9 August 2013, accepted for publication 23 April 2014.

KEYWORDS: biology, geology, guano, Jenolan Caves, minerals

INTRODUCTION

The Jenolan Caves, 182 km west of Sydney in the Greater Blue Mountains World Heritage Area, are developed in the folded, steeply dipping, Late Silurian Jenolan Caves Limestone (Carne and Jones 1919; Chalker 1971; Allan 1986), and in places intersect stratified Palaeozoic marine carbonate palaeokarst deposits, termed caymanite (Osborne 1991, 1993, 1994). The Jenolan Caves Limestone extends 7 km in a NW direction, in the valley of McKeown's Creek, having a maximum thickness of 265 m. The caves are developed on the northern and southern sides of the Grand Arch, a natural tunnel cutting the limestone.

From the discovery of Jenolan Caves by Europeans after 1838, the calcite speleothems have been admired for their beauty and variety, but other minerals were not recognised until the late 19th Century, when niter was first reported by Wilkinson (1886), and gypsum and phosphate minerals by Mingaye (1898). An Australian Museum-Sydney University project to characterise the minerals of Jenolan Caves has been active for over 25 years, and so far has either confirmed, or identified for the first time at Jenolan, 25 mineral species. Some of the minerals have been formed by completely inorganic chemical processes, but others have involved chemical interactions with biological materials such as marsupial and bat guano. Mineral species in the nitrate, chloride, carbonate, phosphate, sulfate, silicate, oxide and hydroxide chemical groups are described.

MATERIALS AND METHODS

The studied mineral specimens, collected by the authors over the last 25 years, are lodged in the Australian Museum Geoscience collections. Earlier cave mineral specimens were donated to the Australian Museum by J.C. Wiburd in 1898 and by others in the late 19th and early 20th centuries. Specimen registration numbers prefixed by 'D' or 'DR' are in the Australian Museum Mineralogy and Petrology collections respectively, and other designations are specimen field collection numbers.

The minerals were identified using a variety of methods, including field observations and analytical methods. Most of the identifications were carried out at the Australian Museum using X-ray diffraction (XRD) equipment (PANalytical X'Pert Pro) with a graphite monochromator, proportional counter, and 45 kV, 40 mA Cu-Kα radiation. Scans were run from 5-70° 2θ with 1° divergence slit, 2° antiscatter slit, 0.1 mm receiver slit and 0.02° steps, with additional scans 2-15° 2θ with 0.125° divergence slit and 0.25° antiscatter slit. Peak patterns were processed using PANalytical X'Pert HighScore software.

X-ray fluorescence analysis was carried out at the University of Technology, Sydney, using an Rh target at 60 kV, 40 mA, LiF 420, LiF 220, Ge 111 and TlAP analysing crystals, and Siemens UniQuant software. Energy dispersive X-ray spectrometry (EDS) was carried out at the Australian Museum, with an Oxford Instruments Link Isis 200 EDS coupled with a Cambridge Stereoscan 120 SEM, with internal Co standard, in backscatter electron mode. Spectra were accumulated for 100 seconds at 20 kV, 18 – 25 x magnification, and 20 microsecond processing time. SEM imaging was performed at the Australian Museum with a Leo 435VP and later a Zeiss EVO LS 15, using gold coated samples mounted on standard SEM stubs, at 15-20 kV and 18 – 23 mm working distance.

Laser Raman spectroscopy was performed at the Queensland University of Technology using a Renishaw 1000 Raman system, with a monochromator, filter system, CCD detector (1024 pixels) and Olympus BHSM microscope equipped with 10x, 20x, and 50x objectives. The spectra were excited by a Spectra-Physics model 127 He-Ne laser producing highly polarised light at 633 nm and collected at a nominal resolution of 2 cm^{-1} and precision of ± 1 cm^{1} in the range between 200 and 4000 cm^{-1}. Repeated acquisitions using a 50 x microscope objective were accumulated to improve the signal to noise ratio of the spectra. Raman Spectra were calibrated using the 520.5 cm^{-1} line of a silicon wafer. The spectra of at least 10 crystals were collected to ensure the consistency of the data. Infrared spectra were collected at the Queensland University of Technology using a Nicolet Nexus 870 FTIR spectrometer with a smart endurance single bounce diamond ATR cell. Spectra over the 4000 - 525 cm^{-1} range were collected with a resolution of 4 cm^{-1} and a mirror velocity of 0.6329 cm s^{-1}. Spectra (128 scans) were co-added to improve the signal to noise ratio.

Other methods used were polarized light microscopy, ultraviolet fluorescence, K-Ar dating (CSIRO Petroleum) and fission track dating (Geotrack International), inductively-coupled plasma mass spectrometry (University of Cape Town), and sulfur and oxygen isotope determinations (Environmental Isotopes, Sydney, and University of Barcelona).

RESULTS

The following species catalogue documents the rich mineralogical diversity of Jenolan Caves, including physical descriptions and mode of occurrence for those minerals known up to July 2013. The species and their formulae are listed in Table 1.

Calcite

Calcite is the trigonal form of calcium carbonate. It is the main mineral in the Jenolan Caves Limestone, which has an average composition of 97.6% $CaCO_3$ (Sussmilch and Stone 1915; Carne and Jones 1919; Chalker 1971; Allan 1986). It also contains small and variable amounts of Mg and Fe. It forms the majority of cave speleothems in an incredible variety of forms, including stalactites, stalagmites, columns, straws, shawls, shields, canopies, helictites, cave pearls, rim pools, pool crystal, rafts, cave coral and flowstone. The spectacular calcite speleothems are the main features of Jenolan Caves, and a selection is shown in Fig. 1:a,b,c,d,e. Calcite is also deposited through interaction between colonies of blue-green algae (cyanobacteria) and drip water, forming rounded, crenulated stalagmites (stromatolites or 'craybacks') found in Nettle Cave (Fig. 2) and the Devil's Coach House. A speleothem classification is presented in Hill and Forti (1997).

Calcite also forms curious fluffy growths of tangled microcrystalline filaments. They form light insubstantial masses of 'fairy floss' or cotton wool appearance (Fig. 3a) and have been observed up to 5 – 6 cm diameter. When damp the masses are coherent, but fall apart to a white powder when dry. SEM images of these fluffy growths from Wilkinson Branch of Chifley Cave show microcrystalline aggregates of tangled filaments 0.5–1 micron diameter (Fig. 3b). It often grows on a porous mud or clay substrate, but can also cover rock, flowstone and stalactites. It is mainly calcite, with minor silica and water. They have been aptly described by (Mingaye 1899:330):

Table 1: Identified Jenolan Caves mineral species
Chemical formulae are from the International Mineralogical Association Commission on New Minerals, Nomenclature and Classification approved list. The 'illite series' chemical formula is from Rieder et al. (1998).

ankerite	$Ca(Fe,Mg,Mn)(CO_3)_2$
aragonite	$CaCO_3$
ardealite	$Ca_2(PO_3OH)(SO_4).4H_2O$
calcite	$CaCO_3$
crandallite	$CaAl_3(PO_4)_2(OH)_5.H_2O$
cristobalite	SiO_2
dolomite	$Ca(Mg,Fe)(CO_3)_2$
goethite	$Fe^{3+}O(OH)$
gypsum	$CaSO_4.2H_2O$
hematite	Fe_2O_3
huntite	$CaMg_3(CO_3)_4$
hydromagnesite	$Mg_5(CO_3)_4(OH)_2.4H_2O$
hydroxylapatite	$Ca_5(PO_4)_3(OH)$
kaolinite	$Al_2Si_2O_5(OH)_4$
kingsmountite	$(Ca,Mn^{2+})_4\ (Fe^{2+},Mn^{\ 2+})Al_4(PO_4)_6(OH)_4.12H_2O$
leucophosphite	$KFe^{3+}{}_2(PO_4)_2(OH)\ .2H_2O$
montgomeryite	$Ca_4MgAl_4(PO_4)_6(OH)_4.12H_2O$
montmorillonite	$(Na,Ca)_{0.3}(Al,Mg)_2Si_4O_{10}(OH)_2.nH_2O$
muscovite, K-deficient	("illite series") $K_{0.65}Al_{2.0}\square Al_{0.65}Si_{3.35}O_{10}(OH)_2$
niter	KNO_3
quartz	SiO_2
romanèchite	$(Ba,H_2O)_2(Mn^{4+},Mn^{3+})_5O_{10}$
sylvite	KCl
taranakite	$K_3Al_5(PO_3OH)_6(PO_4)_2.18H_2O$
variscite	$AlPO_4.2H_2O$

"Two samples of this substance were received. The first, which weighed 1½ grammes, Guide Wiburd states, was compressed into a small match-box, and would fill your hat in its natural state. It is so light that, when you blow on it, it falls off the roof and sides like snow".

Aragonite

Aragonite, the orthorhombic form of calcium carbonate is the second most common cave mineral world-wide (Hill and Forti 1986, 1997), although its occurrence is still relatively rare. Aragonite crystal groups are highly regarded for their aesthetic value and can form some of the most spectacular of all speleothems (Fig. 4).

At Jenolan, aragonite forms white stalactites, straws, columns, helictites, needles, 'flos ferri' and anthodites (quill-like crystal sprays). It is found in a number of caves, including Ribbon (the Lyrebird's Nest), Pool of Cerberus (the Arabesque), River (the Furze Bushes), Jubilee, Red, Chevalier, Wiburd's Lake, Mammoth, Spider, Glass, Contact and Barralong Caves (Rowling 2004, 2005a,b). It occurs on limestone cave walls, palaeokarst deposits and cave clays.

Dolomite

Veins of iron-bearing dolomite intersect the Jenolan Caves Limestone and one bed towards the top of the Limestone is extensively dolomitised. An Fe-rich dolomite mass can be seen just in front of the entrance to the Lyrebird's Chamber, Ribbon Cave. Near the western edge of the Jenolan Caves Limestone in Contact Cave, dolomitic stalactites are currently forming. Dolomitic palaeokarst (caymanite) occurs extensively in the Mud Tunnels section of River Cave.

Ankerite

Ankerite forms thin yellow to brown branching veins up to several tens of centimetres length in the limestone (Fig. 5), and can also form larger zones of replacement. Ankerite also mantles some of the fossils in the limestone. Much of the veining has a surface alteration to goethite and clays, sometimes with minor silica. The unaltered material has a sugary texture due to small rhombohedral crystals of ankerite up to 0.3 mm.

Huntite and hydromagnesite

These two minerals are the major components of a Mg-carbonate-rich 'moonmilk', a white, structureless, plastic, spongy mass with high water content, sometimes with a 'cauliflower' appearance, and having the consistency of cottage cheese when damp, but falling apart as a white powder when dry. Huntite and hydromagnesite with minor calcite, aragonite, and silica have been observed as a 4 cm mass growing on an aragonite stalactite in the Lyrebird's Nest, Ribbon Cave. Under SEM, this moonmilk shows rosettes of platy crystals up to about 5 microns (Fig. 6). Traces of huntite and hydromagnesite have been found in Wiburd's Lake Cave (Rowling 2005b).

Clays (Kaolinite, K-deficient muscovite ("illite"), montmorillonite)

Cave clays of plastic consistency and white, yellow, brown and red colours are widespread. Most

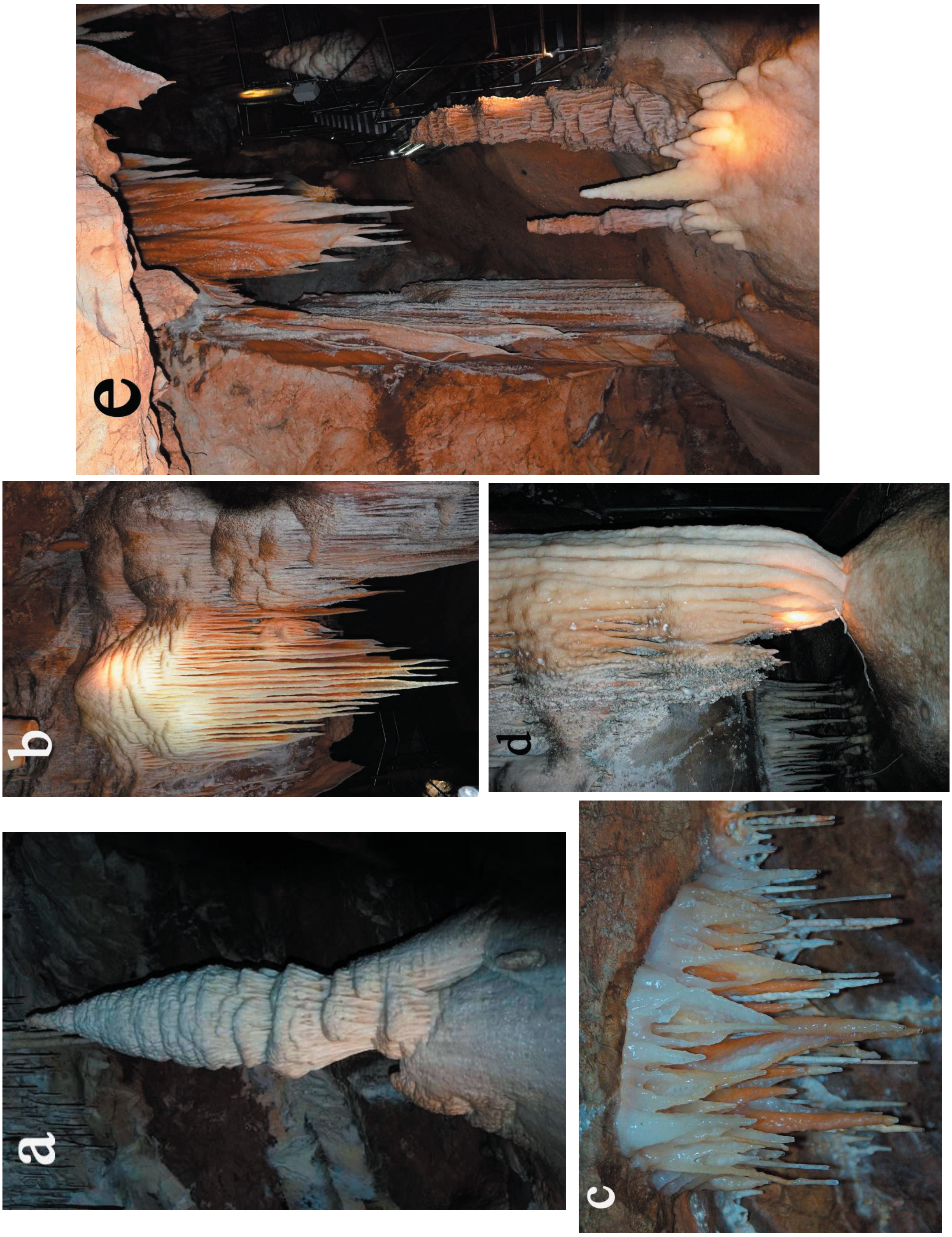


Figure 1a,b,c,d,e: Calcite speleothems a: Minaret, River Cave; b: Indian Canopy, Orient Cave; c: Stalactites, Ribbon Cave; d: Fluted Column, Imperial Cave; e: Indian Chamber, Orient Cave. Images: Ross Pogson, Australian Museum

Figure 2: Stromatolites ('craybacks'), Nettle Cave, width approx. 1.5 m. Image: Ross Pogson, Australian Museum

are kaolinite/illite mixtures, often with quartz, and sometimes with minor calcite or montmorillonite, and coloured by hematite or goethite.

As well as massive forms, kaolinite can also form pseudo-hexagonal crystals up to 3 microns (Fig. 7a), and also pseudomorphs tiny feldspar crystals of possible volcanic origin, in pink clay (DCH4) from the Devils Coach House. Illite forms delicate fluffy or hairy growths on kaolinite (Fig. 7b).

Ardealite

Rounded yellow bosses up to about 9 cm high, called 'potatoes' by Foster (1890); Trickett (1905); and Havard (1928), form the "Potato Patch" of Dunlop (1979), in the Bone Cave section of Lucas Cave (Fig. 8a,b). Similar deposits occur in the Grotto Cave section of Chifley Cave (Fig. 8c), and were reported by Mingaye (1898, 1899). He analysed but did not name the ardealite, identified the accompanying gypsum, and noted that similar deposits were seen in the Bone Cave, Lucas Cave. The 'potatoes' have a thin outer shell of gypsum, but their interiors are filled with softer cream-coloured powdery ardealite, and minor calcite. They sit on a layer of mixed ardealite, gypsum and hydroxylapatite. Although they sit on a sloping surface, they display a vertical growth axis and may have been deposited under subaerial conditions by vertically-drawn solutions (Pogson et al. 2011). Ardealite is uncommon in Australia, but Bridge (1967) and Bridge et al. (1975) reported ardealite with brushite from Marooba Cave, Jurien Bay, Western Australia, and Grimes (1978) identified ardealite from Texas Caves, Queensland, all with guano associations.

Hydroxylapatite

Hydroxylapatite is found in a number of places as thin white coatings and small nodules. In the Grotto Cave chamber of Chifley Cave, hydroxylapatite has formed under ardealite 'potatoes', and occurs with crandallite. It is part of a complex phosphate mineral mixture in Katie's Bower, Chifley Cave. In Lucas Cave, traces are present on walls near The Slide; in layers below the 'potatoes'; lining a solution tube in limestone above the 'potatoes'; and with crandallite in Bone Cave. It has also been found on cave earth

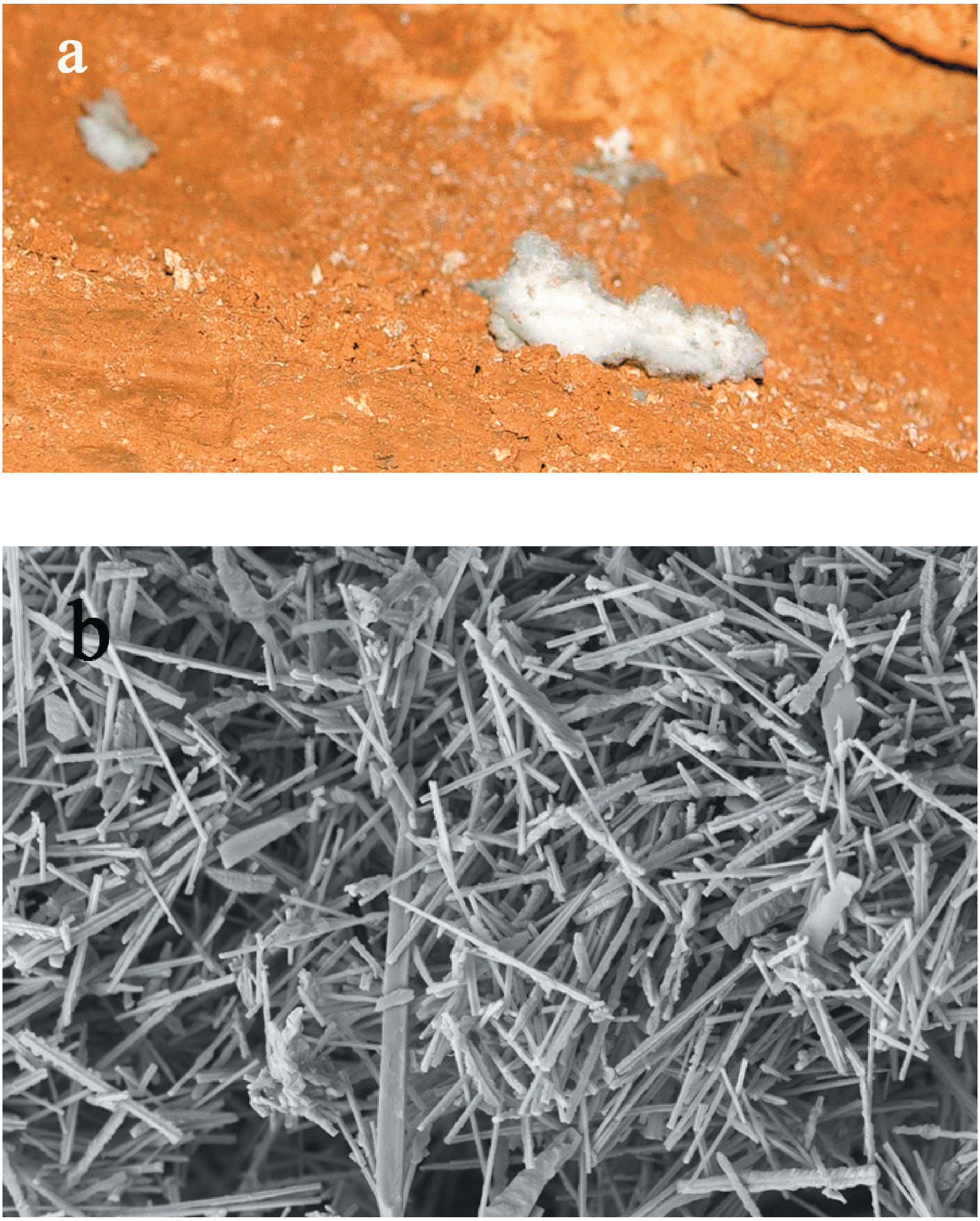


Figure 3a,b: a: Calcite fluffy growth, Wilkinson Branch of Chifley Cave, width 6 cm. Image: Ross Pogson; b: SEM image, calcite fluffy growth, Wilkinson Branch, Chifley Cave. Field of view 141 x 98 microns. Image: Sue Lindsay, Australian Museum

Figure 4: Aragonite, Chevalier Cave. Image: Ted Matthews, Jenolan Caves

Figure 5: Ankerite veins in limestone, 30 m south of eastern entrance to Grand Arch. View approx. 20 x 15 cm. Image: Ross Pogson, Australian Museum

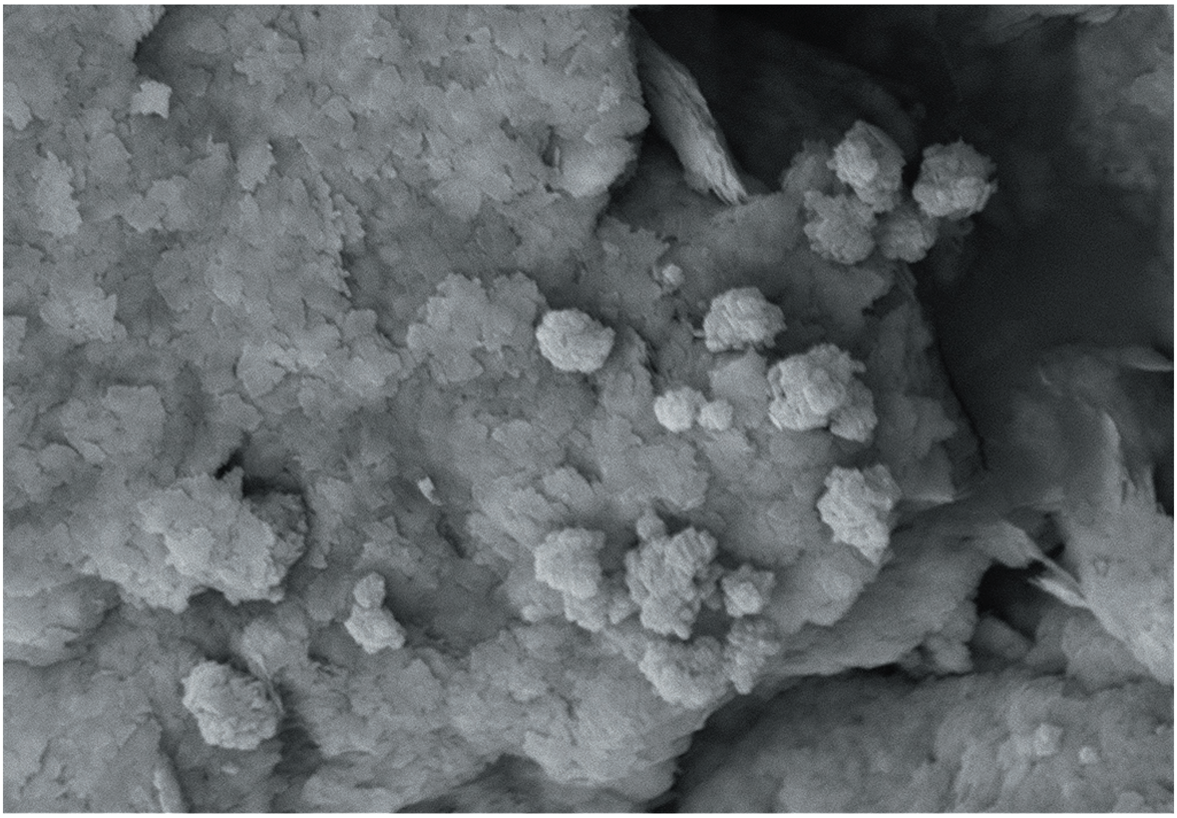


Figure 6: SEM image, Mg-rich moonmilk, Lyrebird's Nest Chamber, Ribbon Cave. Field of view 50 x 35 microns. Image: Sue Lindsay, Australian Museum

coating limestone in Queen Esther's Chamber, River Cave. The CO_2-rich variety ('carbonate-hydroxylapatite') occurs in Katie's Bower, Chifley Cave, as amber botryoidal crusts of 0.5 mm spherules. Hydroxylapatite is present in altered bat guano collected by Wiburd in 1898 from Lucinda Cavern, Chifley Cave (DR12132) and in altered guano collected more recently from the Exhibition Chamber of Lucas Cave. It is also intermixed with other phosphate minerals elsewhere.

Crandallite

Crandallite forms a white, chalky, crumbly deposit in the Bone Cave section of Lucas Cave, collected by guides from floor deposits (D58074). In Chifley Cave it occurs as a white crumbly nodular deposit (D56949) (Fig. 9) on red-brown clay on limestone, above the 'potatoes' alcove in the Grotto Cave (Pogson et al. 2011), and as a component of phosphates in Katie's Bower.

Other phosphates – Katie's Bower, Chifley Cave (Taranakite, Variscite, Montgomeryite, Kingsmountite, Leucophosphite)

These five phosphate minerals, together with hydroxylapatite, CO_2-rich hydroxylapatite, crandallite, calcite, silica, and horizontally-stratified clays (kaolinite, illite) have been identified in Katie's Bower, Chifley Cave, as complex intergrowths in a prominent poorly-consolidated, unstable outcrop. This deposit has slumped downwards and forward, obscuring contacts and extending under the path and down a gentle slope to the opposite cave wall. Many of the phosphates fluoresce pale yellow under short-wave ultraviolet light.

Mingaye (1898) reported and analysed phosphates from this location, including taranakite (then called 'minervite') in 'Left and Right Imperial Caves'. As to their origin, Wiburd found mineralised bat guano in Lucinda Cavern, Chifley Cave (his donated specimen DR12132). Taranakite, hydroxylapatite, leucophosphite and variscite (D58072) form crumbly, fine-grained white to cream-coloured chalky masses and irregular veins and coatings. An iron-bearing variety of variscite is also present (KB19). A taranakite specimen (misidentified at the time as 'sulphate of alumina') (D10948) was found in 'New Cave' (probably Jubilee Cave) by Robert Etheridge,

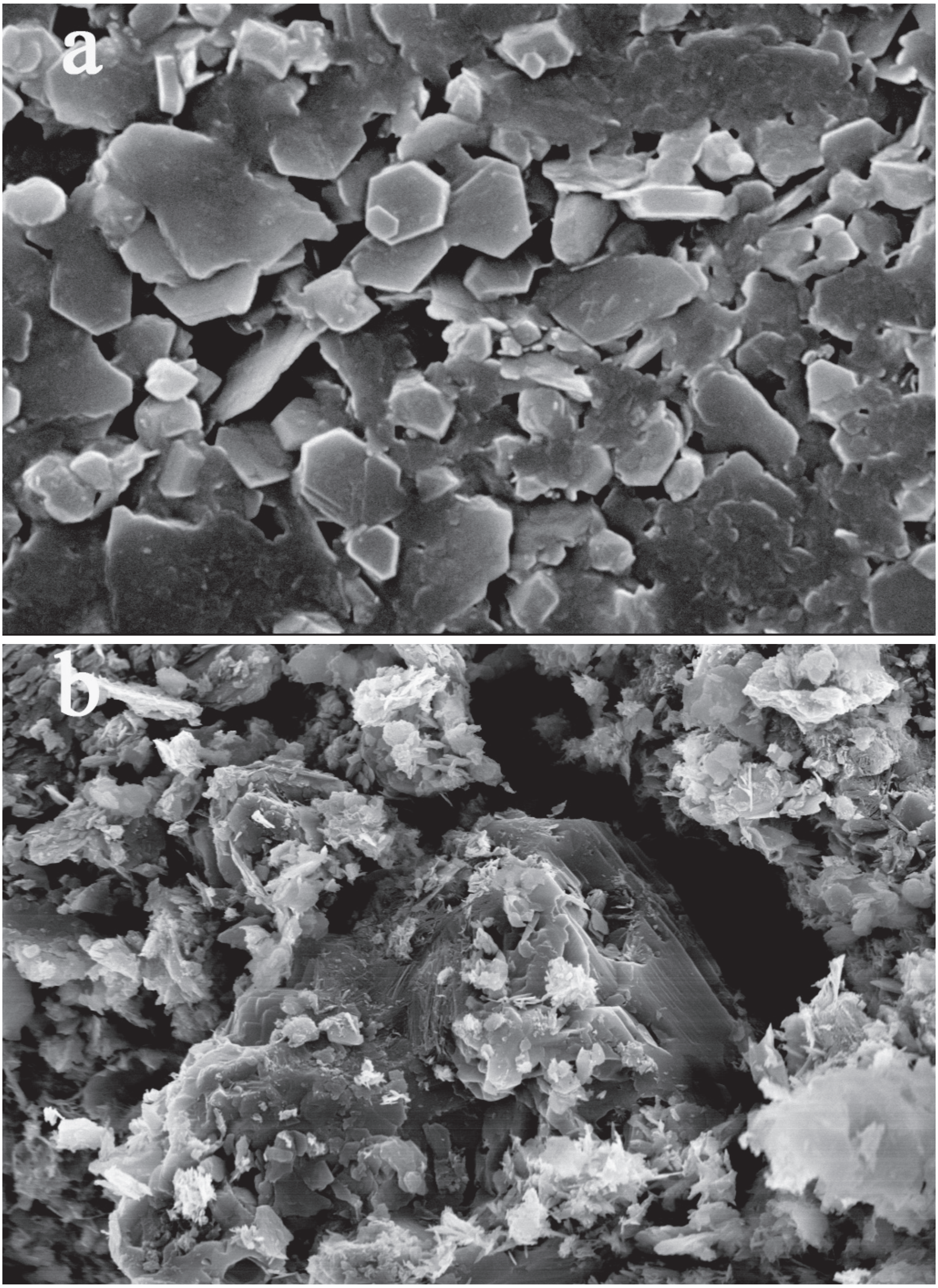


Figure 7a,b: SEM images, a: Kaolinite crystals (JRV7), River Lethe, River Cave, field of view 20 x 14 microns; b: Illite on kaolinite (JRV9), The Junction, River Cave, field of view 48 x 34 microns. Images: Sue Lindsay, Australian Museum

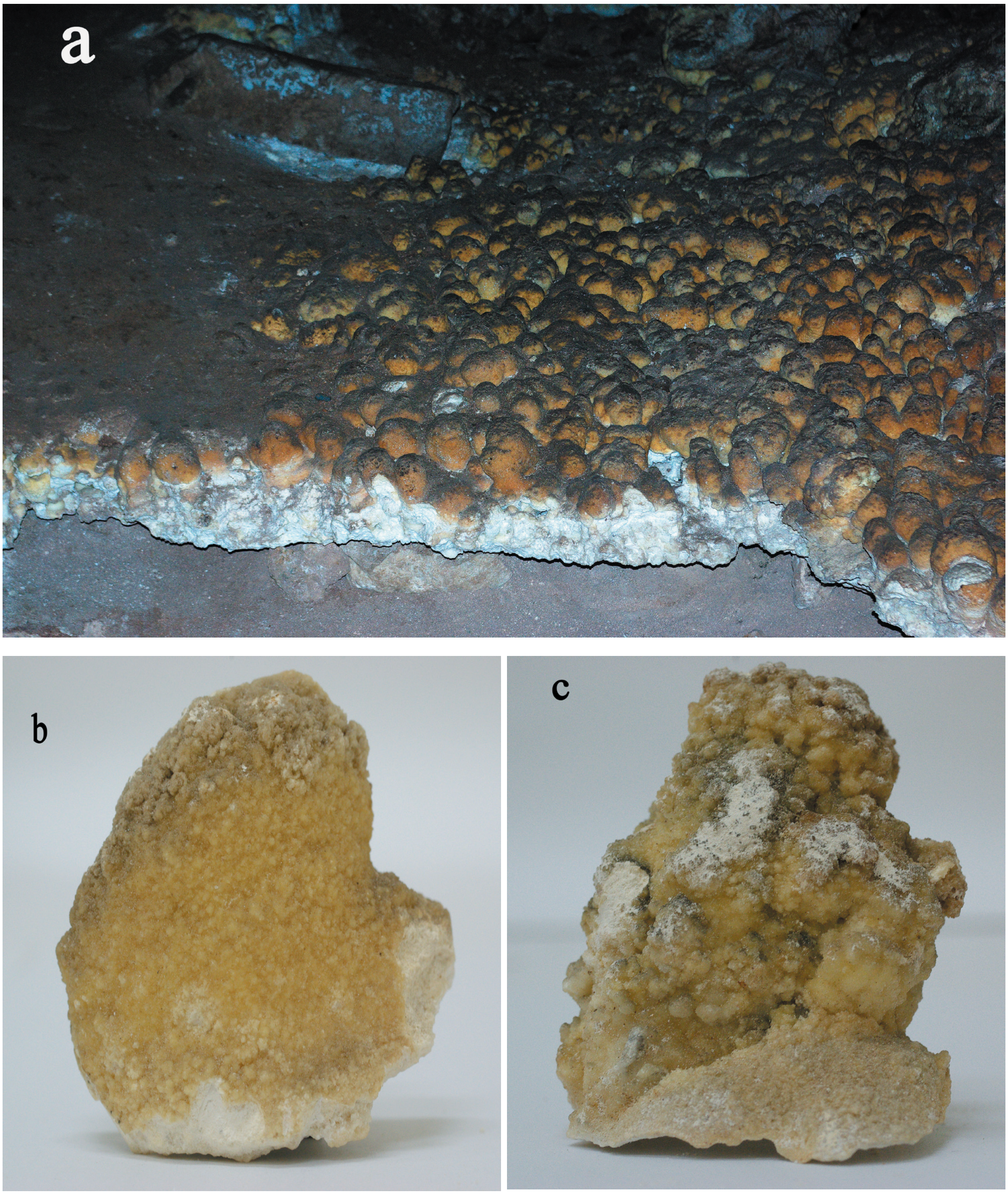


Figure 8a,b,c: a: 'Potatoes', Bone Cave, Lucas Cave; b: Ardealite 'potato', Lucas Cave (D49535), size 60 mm;. c: 'Potatoes', Chifley Cave (D57257), size 70 mm. Images: Ross Pogson, Australian Museum

Australian Museum in 1896. Taranakite is uncommon in Australia, but Bridge (1967) reported it from caves near Jurien Bay, and on the Nambung River, Western Australia.

Montgomeryite is the Mg-analogue of kingsmountite (Anthony et al. 2000). Montgomeryite forms tiny rosettes of pale yellow platy crystals 0.05 – 0.3 mm and micro-botryoidal aggregates similar to those of kingsmountite, in small crystal-lined cavities in white chalky matrix, and as a minor component of massive, crumbly, chalky mixed phosphates. Additional tests by Frost et al. (2012a) confirmed the identification as montgomeryite (D58702, D58703).

Kingsmountite forms white radiating thinly bladed to acicular microcrystals with silky lustre, in compact aggregates of spherules 2 – 3 mm. It also forms larger bladed microcrystals in crusts up to a 4 mm thick (D58703). Blocky fawn-coloured crystals less than 0.5 up to 1 mm line small vughs in fine-grained crumbly, chalky matrix. It is closely associated with montgomeryite. SEM images show the kingsmountite rosettes are made of 2 – 3 micron crystal plates (Fig. 10).

Gypsum

Gypsum forms the yellow outer shell of the 'potatoes' in Lucas Cave (Bone Cave section) and in Chifley Cave (Grotto Cave section). Mingaye (1898, 1899) analysed the Grotto Cave deposit and identified the material as gypsum. It is also found as white to colourless deposits elsewhere in small cavities in upper Bone Cave, and crusts in Centenary Cave, in Lucas Cave. Minor deposits also occur in other caves. In the past, gypsum has been found as white to clear masses and curved, fibrous crystal groups (gypsum 'flowers') associated with palaeokarst (D19994) in the Devil's Coach House. Their original collection site in the Devil's Coach House is unknown but gypsum specimens from this locality are preserved in the Australian Museum collections (D19994, D12021) (Fig. 11a,b).

Silica (quartz, cristobalite, amorphous)

Silica is present as small quartz grains in many clays and cave sediments. It also occurs as minor poorly crystalline cristobalite and amorphous silica in mixed phosphates; in fluffy calcite growths in the Wilkinson Branch of Chifley Cave; and in Mg-rich moonmilk in Ribbon Cave.

Romanèchite

Romanèchite is present as thin black to brown-black surface coatings in many places. It is also present as tiny rounded black nodules to 1.5 mm in clays.

Goethite and hematite

Goethite and hematite are widespread. They are present in red, brown and yellow clays, and also stain calcite speleothems in a variety of colours. Extensive concretionary goethite deposits, often as 'pipe concretions' are seen near the far end of Jubilee Cave.

Niter and sylvite

Niter was reported by Wilkinson (1886) from the Grand Arch, and by Mingaye (1898, 1899) from the Devil's Coach House. More recently, Sydney University researchers (J. James pers. comm.) found niter and tiny cubic crystals of sylvite in dust from the SW side of the Grand Arch. Jenolan Caves staff found thick crusts of white material, later identified as niter, from Dust Cave high up on the south side of Grand Arch. Dust Cave is a 9 x 7 x 2 m cavity just to the right of the top of the Lucas Cave path, partly in between large limestone boulders fallen from the roof. The cave walls consist of limestone boulders and bedrock, conglomerate cave fill and lithified palaeokarst.

The niter crusts in Dust Cave are horizontal deposits on the cave floor, partly covered by a large pile of fine grey-brown dust. Small crusts and stalactites of niter occur on the cave walls, especially on porous conglomeratic cave fill. These niter crusts are up to 5 cm thick (D52263) and have a corroded appearance, best seen in cross-section (Fig. 12). The corrosion channels run perpendicular to the horizontal crust surface. The crusts contain skeletal crystals of sylvite 0.1 - 3 mm (average 0.3 mm), sometimes occurring in long strings perpendicular to the horizontal surface of the crusts. The sylvite content of the crusts is variable, ranging from 5–15 % by volume (Colchester et al. 2001). Crevice fillings of niter occur in several places in the Grand Arch.

DISCUSSION

Carbonates

The calcite speleothems are usually very pure calcium carbonate but can be stained various colours by iron oxides and hydroxides, manganese oxides and organic material. Calcite can also contain magnesium, manganese, strontium and iron in its crystal structure.

Formation of the calcite-rich fluffy growths is still a matter for debate. Suggestions have been: it formed as a part of the life cycle of bacteria, fungi or algae; it is a disintegration product of bedrock or other cave formations; or it is a precipitation directly from ground water, but special conditions promote fibrous crystal aggregates. It has also been suggested the flat calcite lamellae are pseudomorphs after metastable monohydrocalcite (hexagonal $CaCO_3.H_2O$), or that the calcite needles are paramorphs after aragonite (Onac and Ghergari 1993; Ghergari et al. 1994). These growths also occur in Chevalier, Glass, Mammoth, and Wiburd's Lake Caves. A chemical analysis of fluffy calcite growths from Wilkinson Branch, Chifley Cave, is given in Table 2 (analysis 3).

Figure 9: Crandallite, Grotto Cave, Chifley Cave. Size 10 x 25 cm. Image: Ross Pogson, Australian Museum

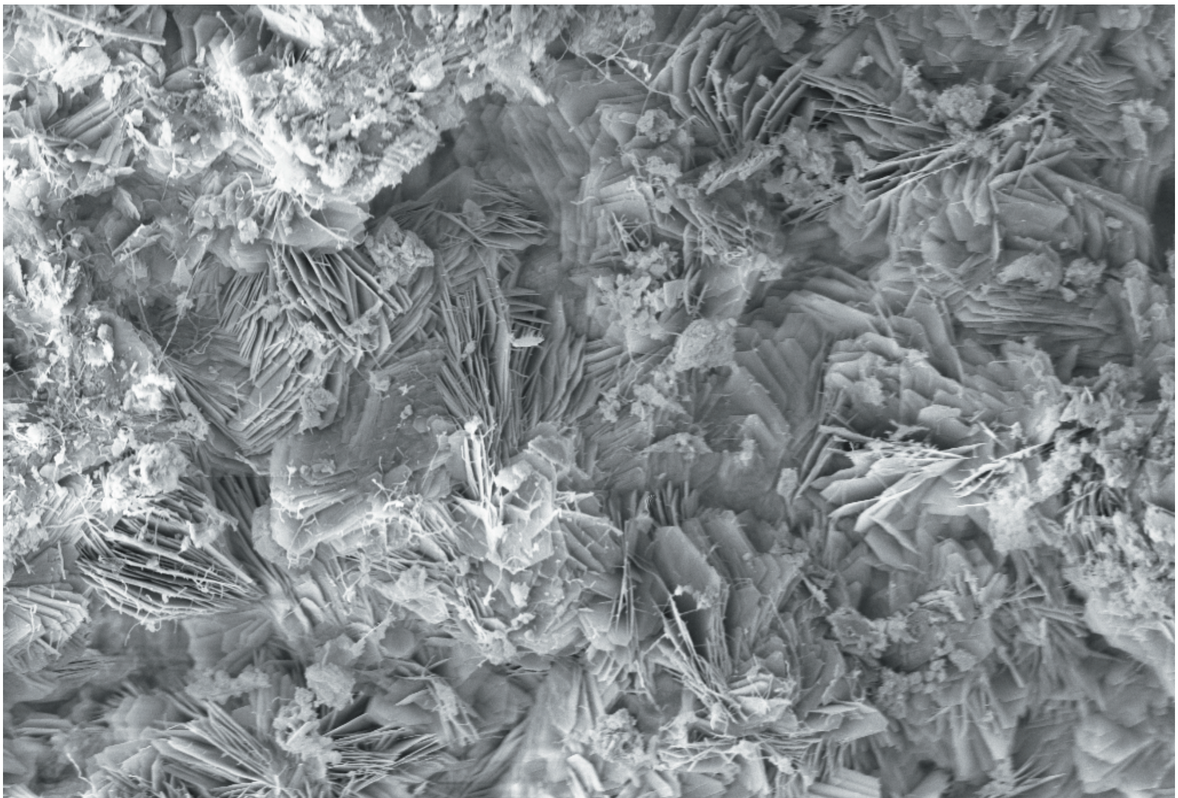
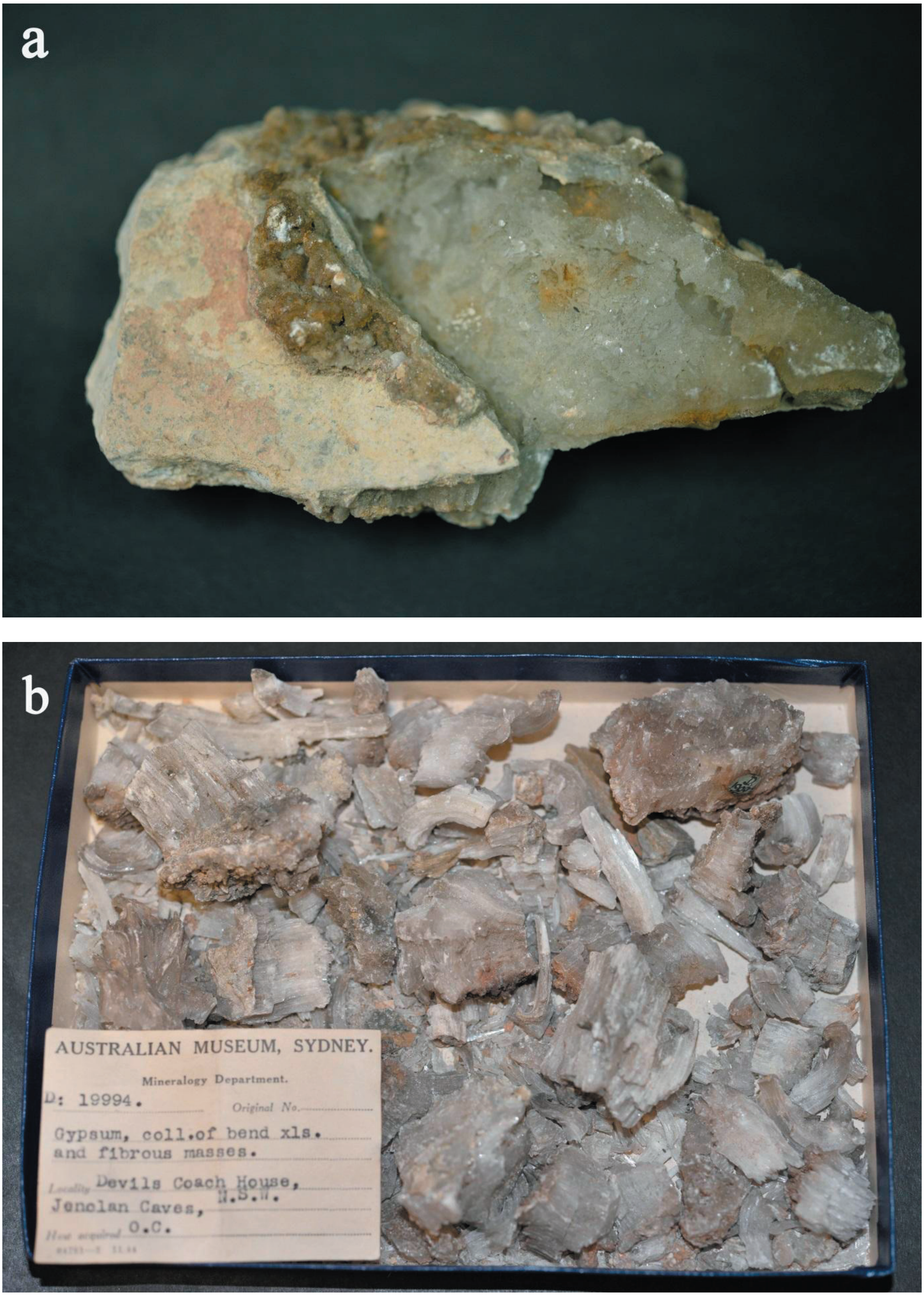


Figure 10: SEM image, Kingsmountite (D58703), Katie's Bower, Chifley Cave. Field of view 280 x 190 microns. Image: Sue Lindsay, Australian Museum



AUSTRALIAN MUSEUM, SYDNEY.

Mineralogy Department.

D: 19994. Original No.

Gypsum, coll.of bend xls.
and fibrous masses.

Locality Devils Coach House,
Jenolan Caves, N.S.W.

How acquired O.C.

Figure 11a,b: a: Gypsum, Devils Coach House, D12021, 14 x 7 x 5 cm (with attached palaeokarst); b: Gypsum 'flowers' to 80 mm (D19994). Images: Ross Pogson, Australian Museum

Fig. 12: Niter/sylvite crust (D52263), Dust Cave, Grand Arch. Size 7 x 5 x 5 cm. Image: Stuart Humphreys, Australian Museum

Aragonite is normally stable at higher temperatures and pressures over 3 kbar (MacDonald 1956). However, it forms in caves at ambient pressures and temperatures, (approximately 15°C and 1 bar), which is outside its thermodynamic stability field. Based on P/T data alone, only calcite should be present, and aragonite will very slowly alter to calcite but seems to persist for a long time in caves. It is widely thought that aragonite is formed when calcite precipitation is inhibited by structural poisons like Sr, Fe, Mg, phosphate and sulfate ions, but other factors, such as low drip rates, low evaporation rates, and variations in temperature, atmospheric humidity and carbon dioxide concentration may be involved. If the presence of Mg ions is a factor in its formation, possible Mg sources are nearby dolomite or ankerite. Jenolan aragonite has approximately 0.3% SrO as well as minor Mg, Fe, P etc. (Table 2, analyses 1 and 2).

The ankerite and dolomite have variable chemistry. They are more susceptible than limestone to alteration, and it is possible that much of the soggy goethite-bearing clay deposits in caves along McKeown's Valley, near the western limestone contacts were formerly iron-bearing dolomites. Much of the horizontally-bedded Carboniferous carbonate palaeokarst (caymanite) in The Mud Tunnels, River Cave is dolomitic. Some of this palaeokarst contained pyrite (now altered to goethite), and square crystal outlines can be seen in thin-section. Compositions of Fe-rich dolomite from near the entrance of the Lyrebird's Nest Chamber, Ribbon Cave; and from Contact Cave near the western edge of the Jenolan Caves Limestone, are shown in Table 2, analyses 4 and 5.

Mg-rich 'moonmilk', a mixture of microcrystalline magnesium-bearing carbonates, is often found in close proximity to aragonite, or dolomite and ankerite. The dolomite is often decomposed to a goethite or hematite-rich clay, obscuring its carbonate origins. The decomposition of these Mg-rich minerals provides the sources of Mg^{2+} ions in solution required for formation of huntite and hydromagnesite. These minerals are precipitated when magnesium ion concentration increases with evaporation (Hill and Forti 1997).

Clays

The clay deposits appear to represent different ages and origins. Younger clays may originate from wind-blown dust (loess), or water-borne sediments brought in by streams or floodwaters. However, some of the older clays appear to have components of altered, reworked volcanic ash detritus washed or blown into the caves. This volcanic detritus is present in River Lethe clay, River Cave. Some of the clay deposits may have formed as alteration products resulting from ascending hydrothermal fluids. The evidence for presence of upwelling hydrothermal fluid activity is based on the analysis of cupola morphology by Osborne (1999). Large deposits of water-bearing goethite-rich clays occurring in caves along McKeown's Valley, near the western edge of the Jenolan Caves Limestone may represent altered dolomitised limestone bedrock.

The potassium content of K-deficient muscovite ('illite') made Potassium-Argon dating possible, and a range of illite-bearing clays gave Carboniferous dates of 320-357 Ma (mean 337 Ma) (Visean to Namurian). Details of the K-Ar dating results are presented in Osborne et al. (2006, Table 5). Fission track dating of zircon grains extracted from clay from The Junction, River Cave, gave a central age of 308.9+/-25.6 Ma with two age groups with pooled ages of 435.9+/- 19.1 Ma (Carboniferous) and 207.2 +/- 18.5 Ma (Late Triassic to Early Jurassic) (Green

Table 2: Analyses of some Jenolan Caves aragonite, calcite and dolomite (XRF wt%)

1. **Aragonite (JRV2) from a stalactite near the Furze Bush chamber, Mud Tunnels, River Cave.**
2. **Aragonite (JR7A) from crystal spheres, Lyrebird's Nest Chamber, Ribbon Cave.**
3. **Calcite fluffy growth (W1), from Wilkinson Branch, Chifley Cave.**
4. **Dolomite, iron-bearing (J167), near entrance of Lyrebird's Chamber, Ribbon Cave.**
5. **Dolomite, iron-bearing (JC3), from a stalactite in Contact Cave.**

Analyst: Marie Anast, University of Technology, Sydney, by X-ray fluorescence (total Fe as Fe_2O_3)

	1	2	3	4	5
SiO_2	0.14	7.1	0.79	5.8	11.7
TiO_2		0.35	0.02	0.37	0.11
Al_2O_3	0.07	3.5	0.35	3.64	5.1
MnO		0.46	0.02	0.87	0.07
Fe_2O_3	0.08	3.29	0.45	6.8	2.47
MgO		0.86	0.23	9.2	5.7
K_2O	0.02	1.4	0.11	1.62	1.58
CaO	99.3	82.6	97.5	71.3	72.4
BaO	0.02	0.03			0.27
SrO	0.26	0.28	0.03	0.06	0.35
P_2O_5		0.15	0.29	0.24	0.09
SO_3		0.04	0.10	0.10	0.04
Total	99.9	100.0	99.9	100.0	99.9

2003). Details of the fission track dating results are presented in Osborne et al. (2006, Table 6). It is suggested in Osborne et al. (2006) that some of these Carboniferous clays and their associated sand-size fraction (pyroclastic rock fragments, pyroxenes, zircons and illite pseudomorphs after feldspar) have a common origin, likely derived from reworked local Carboniferous volcaniclastics. The pristine crystal forms of both kaolinite and illite in several Jenolan clay deposits indicate that they have been allowed to grow in situ, undisturbed (Figs 7a,b).

Phosphates

Pogson et al. (2011) suggested that the ardealite 'potatoes' in Lucas and Chifley Caves have grown vertically from a sloping surface, under subaerial conditions, growing upwards from their porous substrate base by evaporation of vertically-drawn pore water (wicking). Their morphology and mode of occurrence make formation in a pool or by dripping water less likely. Sulfur isotopes in ardealite gave $\delta^{34}S$ of +11.12 to +12.8 $^0/_{00}$ (Pogson et al. 2011, Table 3), suggesting that sulfate-rich solutions came from leaching of bat guano deposits (at Jenolan from the bent-wing bat, *Miniopterus schreibersii*). These mineralised solutions reacted with limestone (Pogson et al. 2011). Most cave phosphate minerals originate from guano, which can also be a source of sulfur (Hill and Forti 2004). There is currently no visible bat guano near the 'potatoes' in Lucas Cave, although old deposits do occur in the Exhibition Chamber in another part of the Lucas Cave system. Ardealite chemical analyses are presented in Pogson et al. (2011, Table 2). Identification was confirmed by additional analytical methods (Frost et al. 2011a, 2012b).

Hydroxylapatite was probably a precursor mineral in the formation of other phosphates from leached bat guano (Marincea et al. 2004), being altered by changes in ion concentrations, Eh, pH and temperature of the percolating solutions. Crandallite is often an earlier-formed phosphate. Additional confirmatory tests for this Jenolan crandallite are detailed in Frost et al. (2011b, 2012c).

The complex aluminium, calcium and potassium-bearing phosphate minerals of Katie's Bower, Chifley Cave formed from reaction of acidic phosphatic solutions leached from bat guano, with limestone and cave clays. The phosphate deposits are complex mixtures of fine-grained minerals, making XRD identification difficult. Although bat guano was found in the 19th Century in the Lucinda Cavern of Chifley Cave, no recognisable guano traces remain in Katie's Bower. This suggests the mineral assemblage represents the final stage of guano alteration, consistent with pH levels approaching neutral (Vince et al. 1993). The chemical reactions have also released amorphous silica.

Variscite can be formed by leaching of montgomeryite with the loss of calcium (Hill and Forti 1997). Kingsmountite (Dunn et al. 1979) is a rare mineral. It is even rarer in cave environments, being previously reported only from Rossillo Cave, Mexico (Forti et al. 2006), although it occurs in USA, Russia, Portugal, Germany, and South Australia in other types of phosphate deposits (Anthony et al. 2000).

Onac and Veres (2003) and Marincea et al (2004) discussed formation of phosphates in Romanian caves, finding that ardealite could form from pre-existing hydroxylapatite. In general, the phosphates were formed from phosphate-rich, then sulfate-rich solutions, accompanied by pH changes reflecting the degree of carbonate dissolution. Hydroxylapatite usually forms at higher pH, and is destabilised for pH values up to 5.5, but if sulfur is available under those conditions, ardealite formation is favoured. Taranakite forms early under damp conditions in the presence of excess potassium, from solutions with pH < 6. Vince et al. (1993) studied the paragenesis of phosphate minerals at the Parwan Cave in Victoria, Australia, finding that taranakite and clay formed early, with apatite later, and finally montgomeryite. An additional confirmatory test for Jenolan taranakite is detailed in Frost et al. (2011c).

Sulfates

Gypsum was considered the second most common cave mineral by White (1976) and Onac (2005), and the third most common after calcite and aragonite by Hill and Forti (1997). Gypsum sulfur isotope signatures from Lucas and Chifley Cave 'potatoes' gave a $\delta^{34}S$ of +11.3 to +11.8 $^{0}/_{00,}$ indicating an organic origin, derived from bat guano (possibly via sulfur-oxidising bacteria in the guano). Sulfur isotopes from gypsum in the Devil's Coach House deposits ($\delta^{34}S$ of +1.4 to +4.9 $^{0}/_{00}$) indicate an inorganic origin, probably from breakdown of pyrite in carbonate palaeokarst. This interpretation of the isotope data is discussed in Pogson et al. (2011, Table 2).

Oxides and hydroxides

Apart from quartz sand grains, silica is widespread as a minor microcrystalline or cryptocrystalline component of many cave minerals, and it has also been released by chemical alteration of clays by acidic phosphatic solutions, giving rise to poorly crystalline cristobalite, as well as amorphous silica. Hematite and goethite in the caves may have originated from a variety of processes, including the breakdown of iron-bearing carbonates and pyrite, ferruginous wind-blown dust, and deposition from percolating iron-rich solutions. The high barium content of the clays (0.05 – 0.096 wt%) is due to the presence of romanèchite, which occurs as small rounded concretionary nodules, and is also common as thin films and coatings elsewhere (Osborne et al. 2006).

Nitrates and chlorides

The dust pile in Dust Cave is leached, powdery dung from the brush-tailed rock wallaby *Petrogale penicillata*. Waters percolating through the dung have leached nitrates and chlorides and redeposited them as niter and sylvite. The Grand Arch is very dry, and in winter cold, dry westerly winds blow straight through, promoting evaporation and deposition of the niter and sylvite crusts. The sylvite was deposited after the niter, filling some of the vertical cavities between the niter crystals (Colchester et al. 2001).

ACKNOWLEDGEMENTS

The authors are grateful to the Jenolan Caves Reserve Trust, the Karst and Geodiversity Unit of National Parks and Wildlife Service, and the Manager, Jenolan Caves, for providing access to the Caves and for permission for the mineral sampling. The Jenolan Caves guides gave invaluable assistance and advice at all times. This study included specimens collected under provisions of Scientific Licences S12664 and SL100197 of NSW National Parks and Wildlife Service, for Jenolan Karst Conservation Reserve. Sue Lindsay, Manager, SEM Unit, Australian Museum, provided the SEM images. The authors thank both Reviewers for their helpful comments, which have clarified and improved the manuscript.

REFERENCES

Allan, T.L. (1986). Geology of Jenolan Caves Reserve. BSc (Hons) Thesis, University of Sydney (unpubl.).

Anthony, J.W., Bideaux, R.A., Bladh K.W. and Nichols M.C. (2000). 'Handbook of Mineralogy – Vol. IV (Arsenates, Phosphates, Vanadates)'. (Mineral Data Publishing: Tucson, Arizona).

Bridge, P. (1967). Mineral, Mineral Technology and Geochemistry Division. In 'Report of the Western Australian Government Chemical Laboratories for the Year 1966', 42-43. (Western Australian Government: Perth).

Bridge, P., Hodge, L.C., Marsh, N.L., Thomas, A.G. (1975). Chiropterite deposits in Marooba Cave, Jurien Bay, Western Australia. *Helictite* **13**, 19-34.

Carne, J.E. and Jones, L. J. (1919). The Limestone Deposits of New South Wales. *Mineral Resources of New South Wales*, **25**, 1-383.

Chalker, L.E. (1971). Limestone in the Jenolan Caves area. *Records of the Geological Survey of New South Wales*. **13**(2), 53-60.

Colchester, D.M., Pogson, R.E. and Osborne, R.A.L. (2001). Niter and sylvite from Jenolan Caves, New South Wales, Australia. *Proceedings of the 13th International Congress of Speleology, Brasilia D.F., Brazil, July 15-22, 2001. Session (S1) Geospeleology*. 133-S1, 4p. Published on CD.

Dunlop, B.T. (1979). 'Jenolan Caves'. (New South Wales Department of Tourism: Sydney). 11th edition.

Dunn, P.J., Pecor D.R., White, J.S. and Ramik, R.A. (1979). Kingsmountite, a new mineral isostructural with montgomeryite. *Canadian Mineralogist* **17**, 579-582.

Forti, P., Galli, E. and Rossi, A. (2006). Peculiar minerogenetic cave environments of Mexico: the Cuatro Ciénegas area. *Acta Carsologica* **35**(1), 79-98. (Ljubljana, Slovenia).

Foster, J. J. (1890). 'The Jenolan Caves'. (New South Wales Government Printer: Sydney).

Frost, R.L., Palmer, S., Henry, D.A. and Pogson, R. (2011a). A Raman spectroscopic study of the 'cave' mineral ardealite $Ca_2(HPO_4)(SO_4).4H_2O$. *Journal of Raman Spectroscopy 42(6),* 1447-1454.

Frost, R.L., Xi, Y., Palmer, S.J. and Pogson, R. (2011b). Vibrational spectroscopic analysis of the mineral crandallite $CaAl_3(PO_4)_2(OH)_5.(H_2O)$ from the Jenolan Caves, Australia. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy* **82,** 461-466.

Frost, R.L., Xi, Y., Palmer, S.J. and Pogson, R. (2011c). Vibrational spectroscopic analysis of taranakite $(K,NH_4)Al_3(PO_4)_3(OH).9H_2O$ from the Jenolan Caves, Australia. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy* **83**(1), 106-111.

Frost, R.L., Xi, Y., Palmer, S.J. and Pogson, R. (2012a). Identification of montgomeryite mineral [$Ca_4MgAl_4(PO_4)_6(OH).12H_2O$] found in the Jenolan Caves, Australia *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy* **94**, 1-5.

Frost, R.L., Palmer, S.J. and Pogson, R.E. (2012b). Thermal Stability of the 'cave' mineral ardealite $Ca_2(HPO_4)(SO_4).4H_2O$. *Journal of Thermal Analysis and Calorimetry* **107**(2), 549553.

Frost, R.L., Palmer, S.J. and Pogson, R.E. (2012c). Thermal Stability of crandallite $CaAl_3\ (PO_4)_2(OH)_5.H_2O$: a 'cave' mineral from the Jenolan Caves. *Journal of Thermal Analysis and Calorimetry* **107**(3), 905-909.

Ghergari, L., Onac, B.P. and Sântămărian, A. (1994). Mineralogy of moonmilk formation in some Romanian and Norwegian caves. *Theoretical and Applied Karstology* **6**, 107-120.

Green, P.F. (2003). 'Fission Track Dating of a zircon concentrate from Jenolan Caves. Geotrack Report # 872'. Uunpublished report to the Australian Museum, March 2003. (Geotrack International Ltd: Brunswick West, Victoria, Australia).

Grimes, K.G. (1978). The geology and geomorphology of the Texas Caves, Southeastern Queensland. *Memoirs of the Queensland Museum* **19** (1), 17-59.

Havard, W.L. (1928). 'The Lucas Cave, Jenolan Caves: a practical guide to the regulation Route'. (New South Wales Government Tourist Bureau: Sydney, Australia). Facsimile edition (Jenolan Caves Historical and Preservation Society, 2011).

Hill, C.A. and Forti, P. (1986). 'Cave Minerals of the World', (National Speleological Society: Huntsville, Alabama USA).

Hill, C.A. and Forti, P. (1997). 'Cave Minerals of the World', Second Edition. (National Speleological Society: Huntsville, Alabama USA).

Hill, C.A. and Forti, P. (2004). Minerals in Caves. In 'Encyclopedia of Caves and Karst Science' (Ed. J. Gunn), 511-514.

MacDonald, G.J.F. (1956). Experimental determination of calcite-aragonite equilibrium relations at elevated temperatures and pressures. *American Mineralogist* **41**(9-10),744-756.

Marincea, A., Dumitras, D-G., Diaconu, G. and Bilal, E. (2004). Hydroxylapatite, brushite and ardealite in the bat guano deposit from Pestera Mare de la Meresti, Persani Mountains, Romania. - *Neues jahrbuch fur mineralogie- monatshefte* **10**, 464-488.

Mingaye, J.H. (1898). On the occurrence of phosphate deposits in Jenolan Caves, New South Wales. *Australasian Association for the Advancement of Science, Report* **5,** 423-425

Mingaye, J.H. (1899). On the occurrence of phosphate deposits in Jenolan Caves, New South Wales. *Records of the Geological Survey of New South Wales* **6**(2), 11-116.

Onac, B.P. and Ghergari, L. (1993). Moonmilk mineralogy in some Romanian and Norwegian caves. *Cave Science* **20**(3), 107-111.

Onac, B.P. (2005). Minerals. In 'Encyclopedia of Caves' (Eds. D. Culver and W.B. White), 371-378.

Onac, B.P. and Veres, D.A. (2003). Sequence of secondary phosphates deposition in a karst environment: evidence from Magurici Cave (Romania). *European Journal of Mineralogy* **15**, 741-745.

Osborne, R.A.L. (1991). Palaeokarst deposits at Jenolan Caves, New South Wales. *Journal and Proceedings of the Royal Society of New South Wales* **123**, 59- 73.

Osborne, R.A.L. (1993). Cave formation by exhumation of Palaeozoic palaeokarst deposits at Jenolan Caves, New South Wales. *Australian Journal of Earth Sciences* **40**, 591-593.

Osborne, R.A.L. (1994). Caves, dolomite, pyrite, aragonite & gypsum: The karst legacy of the Sydney and Tasmania Basins. In 'Twenty-Eighth Newcastle Symposium on Advances in the Study of the Sydney Basin', *University of Newcastle Department of Geology Publication* **606**, 322-324.

Osborne, R.A.L. (1999). The origin of Jenolan Caves: elements of a new synthesis and framework chronology. Presidential Address for 1998 – 1999. *Proceedings of the Linnean Society of New South Wales* **121**, 1-27.

Osborne, R.A.L., Zwingmann, H., Pogson, R.E. and Colchester, D.M.. (2006). Carboniferous clay deposits from Jenolan Caves, New South Wales: implications for timing of speleogenesis and regional geology. *Australian Journal of Earth Sciences* **53**(3), 377-405.

Pogson, R.E., Osborne, R.A.L., Colchester, D.M. and Cendon, D.I. (2011). Sulfate and phosphate speleothems at Jenolan Caves, New South Wales, Australia. *Acta Carsologica* **40**(2), 239-254. (Ljubljana, Slovenia).

Rieder, M., Cavazzini, G., D'Yakonov, Y.S., Frank-Kamenetskii, V.A., Gottardi, G., Guggenheim, S., Koval, P.V., Müller, G., Neiva, A.M.R., Radoslovich, E.W., Robert, J.-L., Sassi, F.P., Takeda, H., Weiss, Z., and Wones, D.R. (1998). Nomenclature of the micas. *The Canadian Mineralogist* **36**, 905-912.

Rowling, J. (2004). Cave aragonites of NSW. Master of Science Thesis (unpubl.). (The School of Geosciences, Division of Geology and Geophysics, The University of Sydney).

Rowling, J. (2005a). Studies on aragonite and its occurrence in Caves, including New South Wales Caves. *Journal and Proceedings of the Royal Society of New South Wales* **137(**3-4), 123-149.

Rowling, J. (2005b). Cave aragonite in NSW, Australia. *Proceedings of the International Union of Speleology Congress, Greece, Session 18, Mineralogy in Caves II, Talk O-88.*

Sussmilch, C.A. and Stone, W.G. (1915). Geology of the Jenolan Caves district. *Journaland Proceedings of the Royal Society of New South Wales* **49**(3), 144-148.

Trickett, O. (1905). 'Guide to the Jenolan Caves, New South Wales'. (New South Wales Government Printer: Sydney).

Vince, D., Hall, P. and Birch, W. (1993). Phosphate minerals in cave deposits. In 'Phosphate Minerals of Victoria' (Eds W.D. Birch and D.A. Henry) 121-151. (The Mineralogical Society of Victoria Inc.: Melbourne)

White, W.B. (1976). Cave minerals and speleothems. In 'The Science of Speleology' (Eds T.D. Ford and C.H.D. Cullingford) 267-327.

Wilkinson, C.S. (1886). 'Railway Guide to New South Wales'. (New South Wales Government Printer: Sydney).

The Jenolan Environmental Monitoring Program

Andrew C. Baker

Karst and Geodiversity Unit
National Parks and Wildlife Service
Office of Environment and Heritage
Level 2, 203-209 Russell Street, Bathurst, NSW 2795

Published on 30 May 2014 at http://escholarship.library.usyd.edu.au/journals/index.php/LIN

Baker, A.W. (2014). The Jenolan environmental monitoring program. *Proceedings of the Linnean Society of New South Wales* **136**, 19-34.

The Jenolan Environmental Monitoring Program reports on the condition of atmospheric and water parameters in and around the show caves at Jenolan. This paper summarises the key findings from four years (2009-2012) of monitoring cave atmosphere. The caves were typically characterised by high relative humidity, moderately stable air temperature (annual variation <2°C) and pronounced seasonal variation in the concentration of CO_2. A major exception was the Temple of Baal, where CO_2 was moderately elevated (~2,000 ppm) year round, with no apparent seasonal variation. The concentrations of CO_2 in the caves were generally well below the exposure limit and pose minimal risk to human health.

Abrupt increases in air temperature of up to 0.9°C in <12 minutes occurred in several of the caves, in particular the Imperial. These increases were characteristic of, and generally corresponded to, commercial tours, and rapidly stabilised back to the pre-tour temperature after the tour had passed. Similarly, increases in CO_2 associated with visitation were generally short lived, except in the Temple of Baal, where peak visitation elevated the CO_2 for extended periods of time. The merits and shortfalls of various options for managing the accumulation of CO_2 in the Temple of Baal are discussed.

Manuscript received 5 December 2013, accepted for publication 16 April 2014.

KEYWORDS: carbon dioxide, cave atmosphere; Jenolan Caves, temperature, tourist cave.

INTRODUCTION

The maintenance of natural processes within karst environments is highly dependant on the interactions between the soil, water and air (Watson et al. 1997). In recognition of these interactions, karst managers around the world are increasingly utilising air and water monitoring programs to examine the impacts of humans in show caves (e.g. Pulido-Bosch et al. 1997; Russell and MacLean 2008; Lario and Soler 2010). Indeed Cigna (2004) recommends that the atmosphere in all show caves should be monitored to determine whether cave operations are having adverse impacts on these unique and delicate environments.

Jenolan Caves are arguably Australia's best known show caves, attracting more than 200,000 visitors each year (Jenolan Caves Reserve Trust 2012). In 2004 the Jenolan Caves Reserve Trust (JCRT) received $4.2 million to undertake capital works within Jenolan Karst Conservation Reserve (JKCR). Of this funding, approximately $200,000 was allocated to the development of an air and water quality monitoring program. Sites for air and water monitoring and equipment were selected in 2006 in consultation with the Jenolan Scientific and Environmental Advisory Committee, with monitoring equipment purchased in 2007 and progressively installed in 2008-2009.

The Jenolan Environmental Monitoring Program (JEMP) measures air and water quality parameters that are of relevance to karst conservation, the maintenance of biological diversity and visitor safety. The measurement and reporting of such parameters enables an objective evaluation of the environmental performance of JCRT (or any future successor), with regards to air and water quality in the show caves. Specifically, the JEMP aims to achieve this by establishing and reporting trends in air quality and the relationship between these trends and anthropogenic activity (in particular commercial cave tours) and trends in water quality at a number of sites with the catchment of the tourist caves. This paper presents the key findings from four years (2009-2012) of monitoring cave atmosphere in the show caves at Jenolan.

METHODS

Sites

The Jenolan Karst Conservation Reserve (JKCR), is located approximately 180 km southwest of Sydney (33°49'S, 150° 02'E) and one of eight reserves that comprise the Greater Blue Mountains World Heritage Area (DECC 2009). Monitoring of cave atmosphere was conducted at seven sites within the show caves and one external reference site. Three monitoring sites were situated in the Northern Show Caves (Chifley, Diamond and Imperial) and four sites in the Southern Show Caves (Mafeking Branch of Lucas, Orient, River and Temple of Baal (Fig. 1, Table 1).

Equipment

Commercially available instruments manufactured by Vaisala were utilised to measure air temperature (Vaisala 'HMT 100', ± 0.2°C), relative humidity (Vaisala 'HMT 100', ±2.5% RH), barometric pressure (Vaisala 'PTB 110' ±0.3 hPa) and the concentration of carbon dioxide (CO_2) (Vaisala 'GM220' ±1.5% of range + 2 % of reading) at each monitoring site. Monitoring equipment was housed within a sealed case at each site and connected to the cave power supply. A data logger (ACR Systems Inc. 'SmartReader Plus 7') recorded each of the parameters every 6 minutes. This interval was chosen following preliminary trials in 2008, which found 6 minute intervals were a sufficient frequency to capture the influence of passing tour groups, whilst providing sufficient storage time (2 months 12 days) before the logger began to rewrite over the oldest data. Data were downloaded every 2 months for analysis and inclusion in bi-monthly Condition Reports that are provided to the JCRT by the OEH Karst and Geodiversity Unit.

Data analysis

Data were filtered using the 'macro' and 'IF' functions in Microsoft Excel to remove data that exceeded a maximum permissible temperature range between the temperature probe and the data logger (≤8°C) or maximum permissible change between two consecutive time internals (≤2°C change in six minutes). These values were determined from the results of preliminary trails in 2008, which ascertained the largest genuine difference between the temperature probe and the data logger (i.e. the

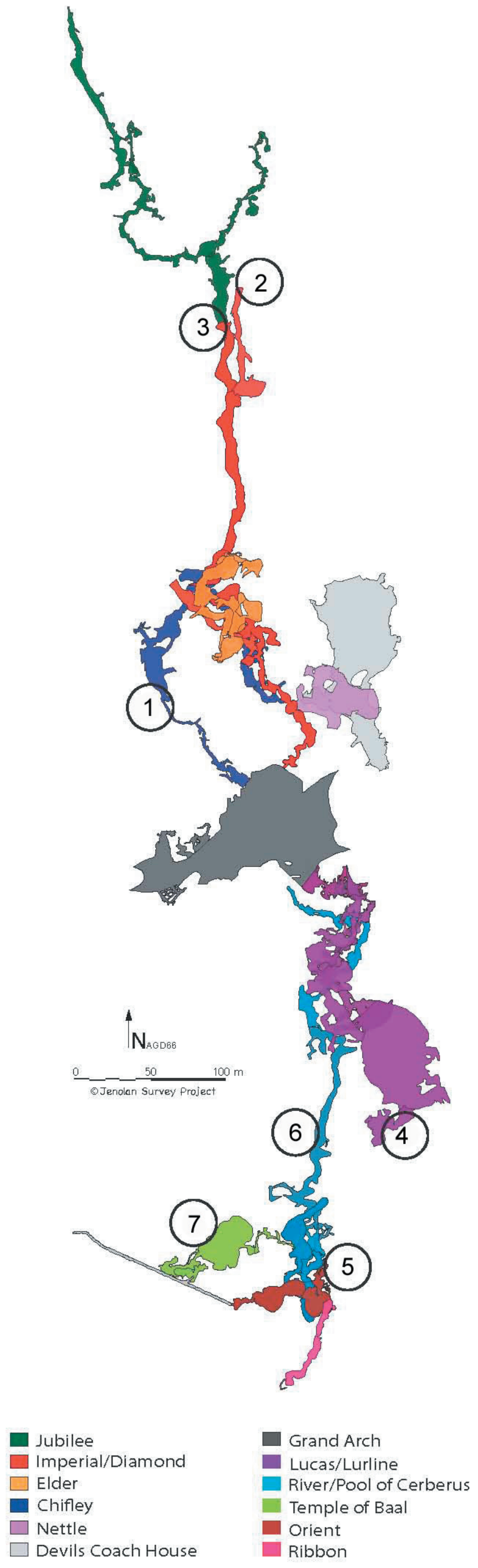


Figure 1. Map of the tourist cave system at Jenolan. Monitoring sites are numbered as per the description in Table 1. Image courtesy of the Jenolan Survey Project.

Table 1. Air monitoring sites

Name	Site number	Site description
Northern Show Caves		
Chifley Cave	1	In Katie's Bower, on the tourist platform above the mains power distribution
Diamond Cave	2	Approximately 5 m beyond the end of the public viewing area.
Imperial Cave	3	Nellie's Grotto
Southern Show Caves		
Lucas Cave	4	In the Mafeking branch approximately ten steps below the highest point of elevation
Orient Cave	5	In Lower Indian Chamber
River Cave	6	Under the bridge approximately 15 m before the Pool of Reflections
Temple of Baal	7	At the middle junction next to the switchboard
External site		
School House	8	On the south facing wall.

temperature in the sealed case), and largest change between consecutive temperature readings. Filtering the data was necessary to remove false values that occurred as a result of power outages and surges. Where temperature values at a site were false, it was assumed that all other parameters at that point in time were also false. The final step of filtering the data involved manually checking the graphed data for anomalies. For example, it was common for several sites to simultaneously experience an abrupt decrease of all parameters and such values were regarded as false and removed from the dataset.

Bimonthly datasheets were combined into a single spread sheet to determine the average, maximum and minimum values for each of the parameters for the four year period. The daily average air temperature, relative humidity and CO_2 were calculated for each day from January 1, 2009 to December 31, 2012 and graphed to examine any variation in cave atmosphere between seasons from one year to the next. Lastly, to ascertain the influence of commercial cave tours on the cave atmosphere, air temperature, relative humidity and CO_2 data, one week of continuous data (i.e. readings taken every six minutes) for April 5-11 2012 was graphed at a larger scale. This period was chosen as it included Easter (April 6-8), typically one of the busiest periods of visitation during the year.

RESULTS

Overview of cave atmosphere

The average air temperature in the caves ranged from 11.7°C in the Diamond Cave to 15.5°C in the Temple of Baal (Table 2, Fig. 2a). In comparison to the external site, where the average air temperature was 12°C and ranged from -4°C in winter to > 30°C summer, the air temperature within the caves was highly stable. The Temple of Baal had the least variation, with a temperature range of 0.6°C, while the Chifley experienced the largest range (3.2°C, Fig. 2a). Similarly for relative humidity (RH), while the external site experienced a highly degree of variability (6.9 - 99.6 % RH), the cave atmosphere was characterised by very high (98.8 - 99.9 %) and stable RH (Table 2, Fig. 2b). As with air temperature, the Chifley experienced the largest range in RH (9.7 %). However given the low variability of RH compared to the precision of the probes (± 2.5%), detailed analysis was not possible.

Whereas the caves experienced considerably less variation in air temperature and RH than the external site, this was not the case for CO_2, with the cave atmosphere recording a much larger range in CO_2 than the external atmosphere (Fig 2c). In comparison to the external atmosphere (~380 ppm) the average concentration of CO_2 at the monitoring sites within

Table 2. Average data (2009-2012) for air temperature, relative humidity and the concentration of CO_2 at each of the monitoring sites.

	Chifley	Diamond	Imperial	Lucas	Orient	River	Temple of Baal	External
Temperature (°C)								
Mean	12.98	12.65	13.04	14.24	14.94	13.36	15.49	12.01
SD	0.33	0.09	0.11	0.06	0.11	0.20	0.05	7.13
Range	3.22	1.02	1.57	2.03	0.94	1.66	0.63	-
Relative humidity (%)								
Mean	98.75	99.74	99.85	99.69	99.12	99.61	99.47	72.63
SD	0.59	0.17	0.10	0.01	0.31	0.31	0.06	18.61
Range	9.72	4.37	3.91	2.73	3.79	4.48	1.89	92.74
CO_2 (ppm)								
Mean	1,013.4	848.0	857.2	1,098.8	759.2	718.6	2,142.1	381.4
SD	853.1	275.6	413.5	461.3	347.1	333.4	425.3	35.2
Range	4,847.9	1,596.6	2,333.3	2,022.2	2,292.3	1,668.4	2,690.6	352.1

a)

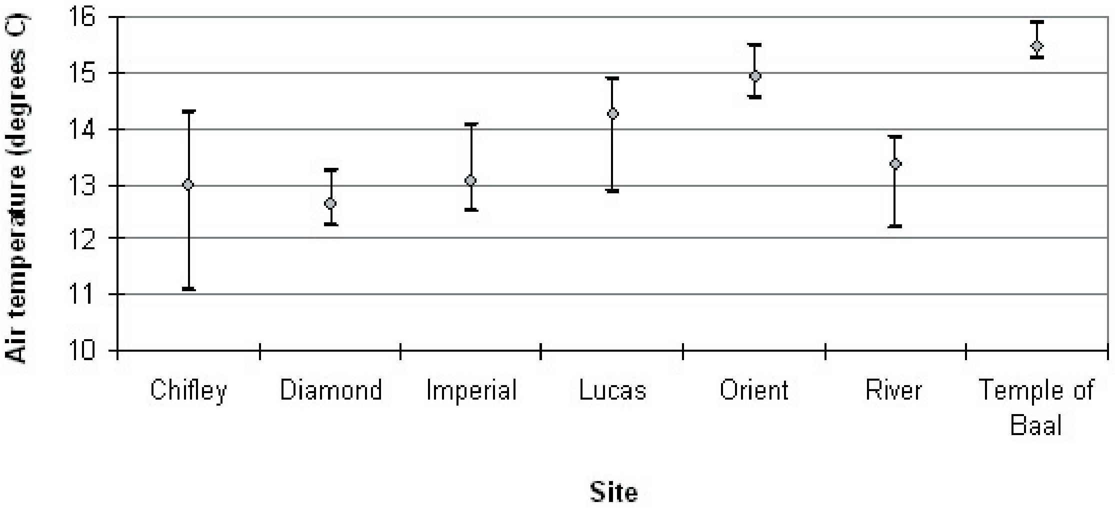
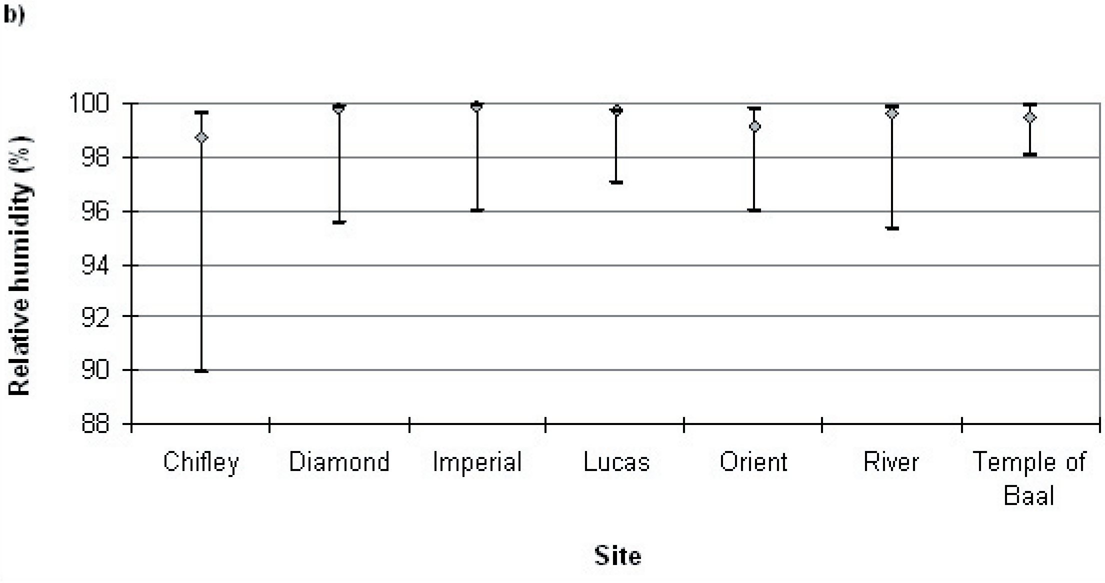
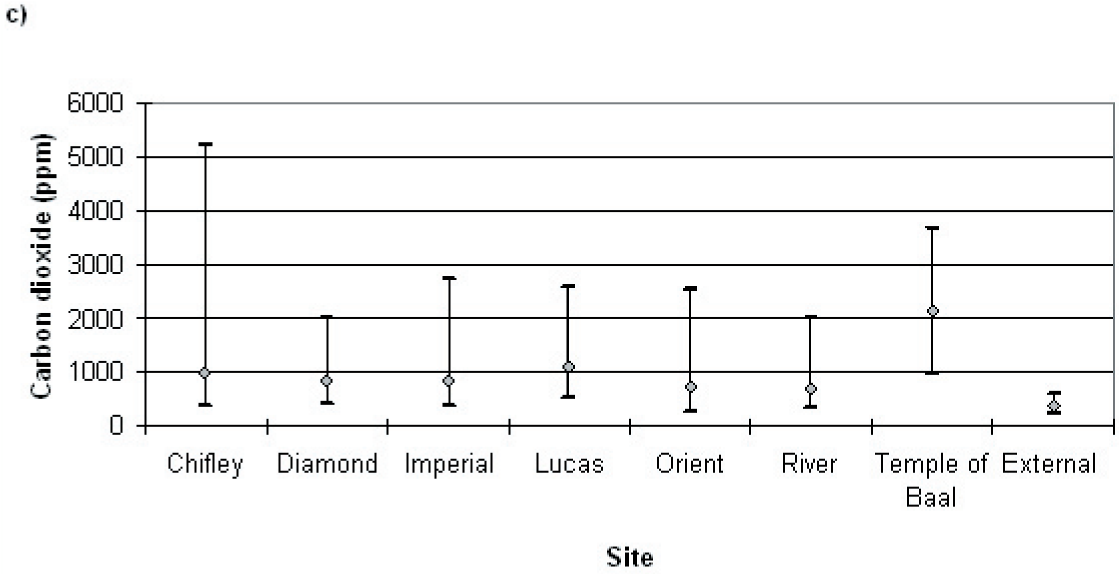


Figure 2. Average a) air temperature, b) relative humidity (RH) and c) CO_2 concentration at each of the monitoring sites from January 1 2009 to December 31 2012. The high-low lines show the range (maximum and minimum values). Temperature and RH data for the external site are not shown due to the high degree of variability. [b) and c) on following page].

Figure 2 continued





the caves ranged from 848 ppm in the Diamond to 2,142 ppm in the Temple of Baal. While the average concentration of CO_2 was markedly higher in Temple of Baal compared with the other caves, the highest concentration of CO_2 occurred in the Chifley (5,232 ppm). With the exception of the Chifley and Temple of Baal (maximum CO_2 = 3,662 ppm), the maximum concentration of CO_2 that occurred at any of the other sites within the caves was < 3,000 ppm (Fig. 2c).

Trends in cave atmosphere through time

Seasonal variation in the average daily air temperature was most pronounced in the Chifley and River caves, with the difference in the average air temperature between summer and winter of 0.8-1.2°C in the Chifley and 0.6-0.7°C in the River Cave (Fig. 3). In the River Cave, the minimum air temperature typically did not occur until the end of winter (mid-late August), whereas in the Chifley, the minimum air temperature occurred much earlier in winter. Seasonal variation in the Imperial was inconsistent, with the difference between summer and winter average air temperature ranging from ~0.4°C in 2009 to ~0.1°C 2012 (Fig. 3). Unfortunately the temperature-relative humidity unit in the Temple of Baal and data logger in the Orient required repair on several occasions.

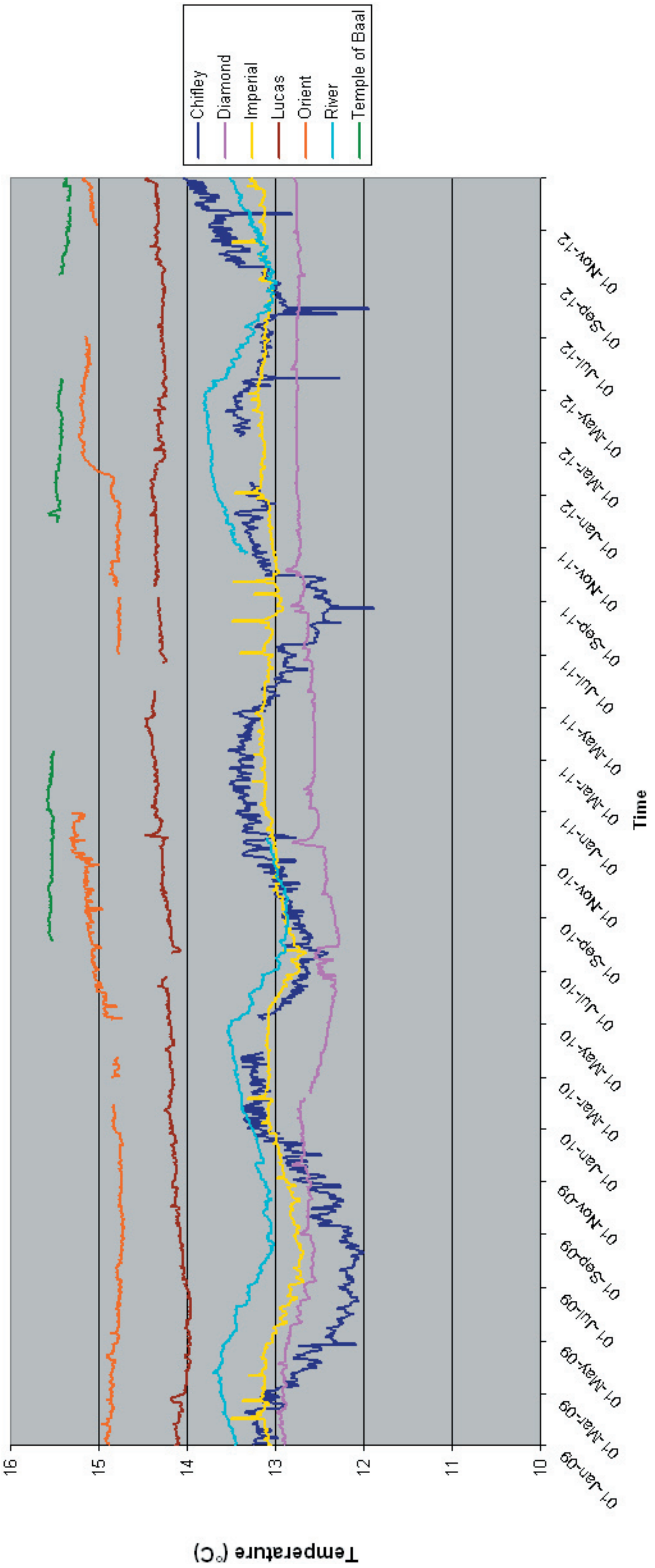


Figure 3. Average daily air temperature at each of the monitoring sites within the caves.

Consequently there are substantial gaps in the data for both these caves, although the data suggest these sites are characterised by generally highly stable air temperatures.

With the exception of the Temple of Baal, the concentration of CO_2 in the caves varied between seasons. CO_2 peaked during the summer months (December-January), decreased during autumn, was at a minimum during winter (June-August) and increased again in spring and summer (Fig. 4). During summer, the maximum average concentration of CO_2 in the caves was approximately 4-10 times that of the external site, whereas in winter, the CO_2 in the caves (excluding the Temple of Baal) was often only slightly elevated above the external atmosphere, with a maximum concentration 1.5-2 times that of the external atmosphere. CO_2 in the Temple of Baal showed no relationship with season, with major increases typically occurring during periods of peak visitation, as discussed in the following section.

Influence of visitors on cave atmosphere

Abrupt increases or “spikes” in air temperature occurred in several caves and were most pronounced in the Imperial, Lucas and Orient (Fig. 5a). Of these caves, the Imperial experienced the largest spikes in air temperature, with increases of up to 0.59°C in < 12 minutes during Easter 2012 (Fig. 5a). Increases of 0.5-0.7°C frequently occurred in the Imperial throughout the four years of monitoring (as noted in the Bimonthly reports prepared for JCRT), and this cave consistently recorded the largest spikes in air temperature. The largest single spike in air temperature, an increase of 0.9°C, occurred on the 10th March 2012. Spikes of between 0.2-0.5°C were typical in the Lucas Cave, as was evident during Easter 2012. Although spikes in the Orient were often smaller than those in the Imperial and Lucas (typically ~0.2°C), they generally occurred on a more frequent and regular basis (Fig. 5a). It is important to note that tours in the Imperial and Lucas frequently did not longer enter the sections of the caves containing monitoring sites, whereas every tour that entered the Orient entered the chamber where monitoring was conducted.

With the exception of the Chifley Cave, the RH in the other caves remained virtually constant throughout the week, irrespective of commercial tours (Fig 5b). In the Chifley Cave, RH, like air temperature was highly variable and typically increased when air temperature within the cave decreased, and decreased when air temperature increased.

The concentration of CO_2 in cave atmosphere generally increased midmorning each day, coinciding with the commencement of cave tours. Increased visitation over the Easter period had a pronounced influence on the concentration of CO_2 (Fig. 5c). On Thursday 5th April, most of the caves recorded only small increases in CO_2, in keeping with relatively low rates of visitation. Conversely over Easter, significantly increases in visitation led to higher concentrations of CO_2 for periods of time. For example in the Lucas Cave, an increase in visitation of between 500-1,000 people/day during April 6-8 resulted in substantially larger increases in CO_2 than April 5 (Fig. 5c), when only 140 people visited the cave.

Different caves experienced different trends in the accumulation of CO_2. As with air temperature, abrupt spikes in CO_2 occurred in the Imperial, Lucas and the Orient (Fig. 5c). These abrupt increases were usually relatively short-lived, however when tours were frequent, the concentration of CO_2 did not decrease to the pre-tour level before the next tour. This frequently resulted in elevated levels of CO_2 until there was a substantial gap between tours or after the last tour for the day. In the River Cave, CO_2 accumulation was more gradual, increasing mid-late morning and decreasing each evening (Fig. 5c).

Interestingly, the Temple of Baal exhibited very different trends in CO_2 compared to the other caves. During periods of increased visitation such as Easter 2012, the level of CO_2 in the Temple of Baal gradually increased with visitation during the day, plateaued or marginally decreased during the evening and until the commencement of tours the following day (Fig. 5c). Conversely on days when there were fewer visitors, such as April 5, 2012, there was a slight decrease in the average concentration of CO_2. Indeed throughout 2009-2012, periods of high visitation consistently resulted in peak levels of CO_2 (Fig. 6).

To examine the relationship between visitation, air temperature and CO_2 concentrations, these parameters were graphed side by side for the Orient Cave (Fig. 7). Simultaneous spikes in air temperature and CO_2 corresponded with each and every one of the tours through the cave. As could be expected, the size of each tour influenced the magnitude of the spikes in air temperature and CO_2. For example on April 5, four similar sized tours during the day resulted in four comparable spikes in air temperature and CO_2, while a smaller 8 pm “extended Orient” tour resulted in much smaller spikes in temperature and CO_2. During the Easter long weekend (April 6-9 2012), the frequency of tours was such that after a tour, the air temperature and CO_2 to did not decrease to the pre-tour level before the next tour, resulting in a period where temperature and CO_2 were elevated (Fig. 7).

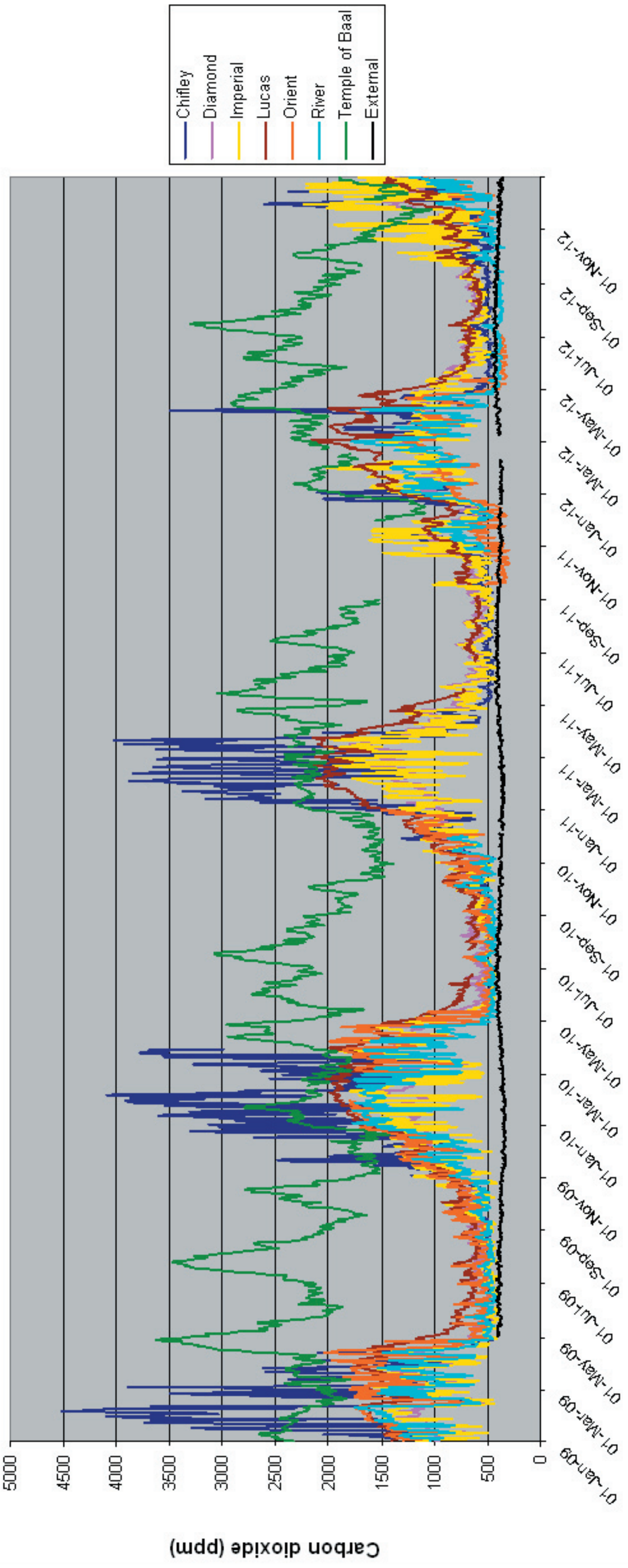


Figure 4. Average daily concentration of carbon dioxide at each of the monitoring sites.

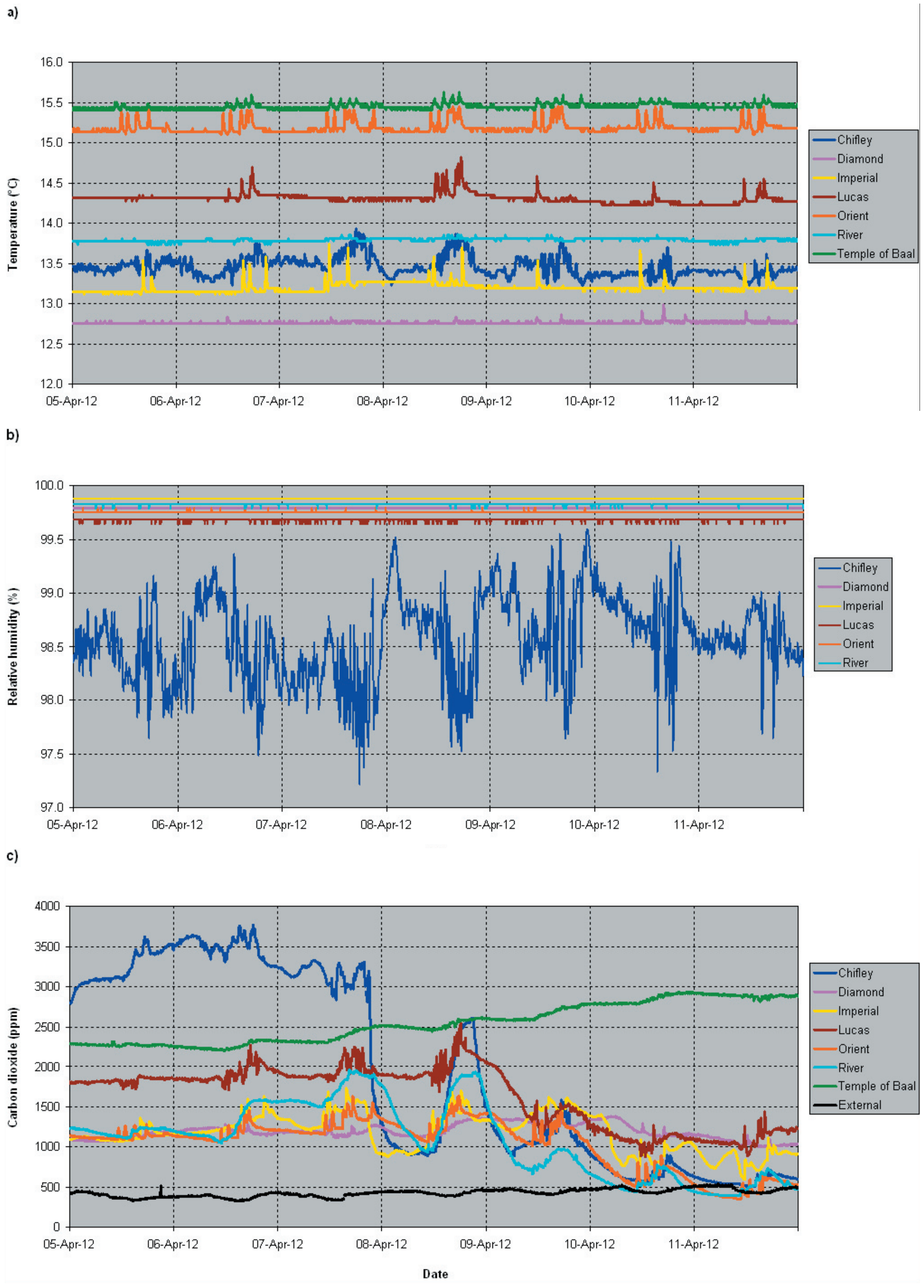


Figure 5. Daily variation in a) air temperature, b) relative humidity (RH) and c) CO_2 concentration at each of the monitoring sites from April 5 to 11 2012. Each parameter was recorded at 6 minutes intervals.

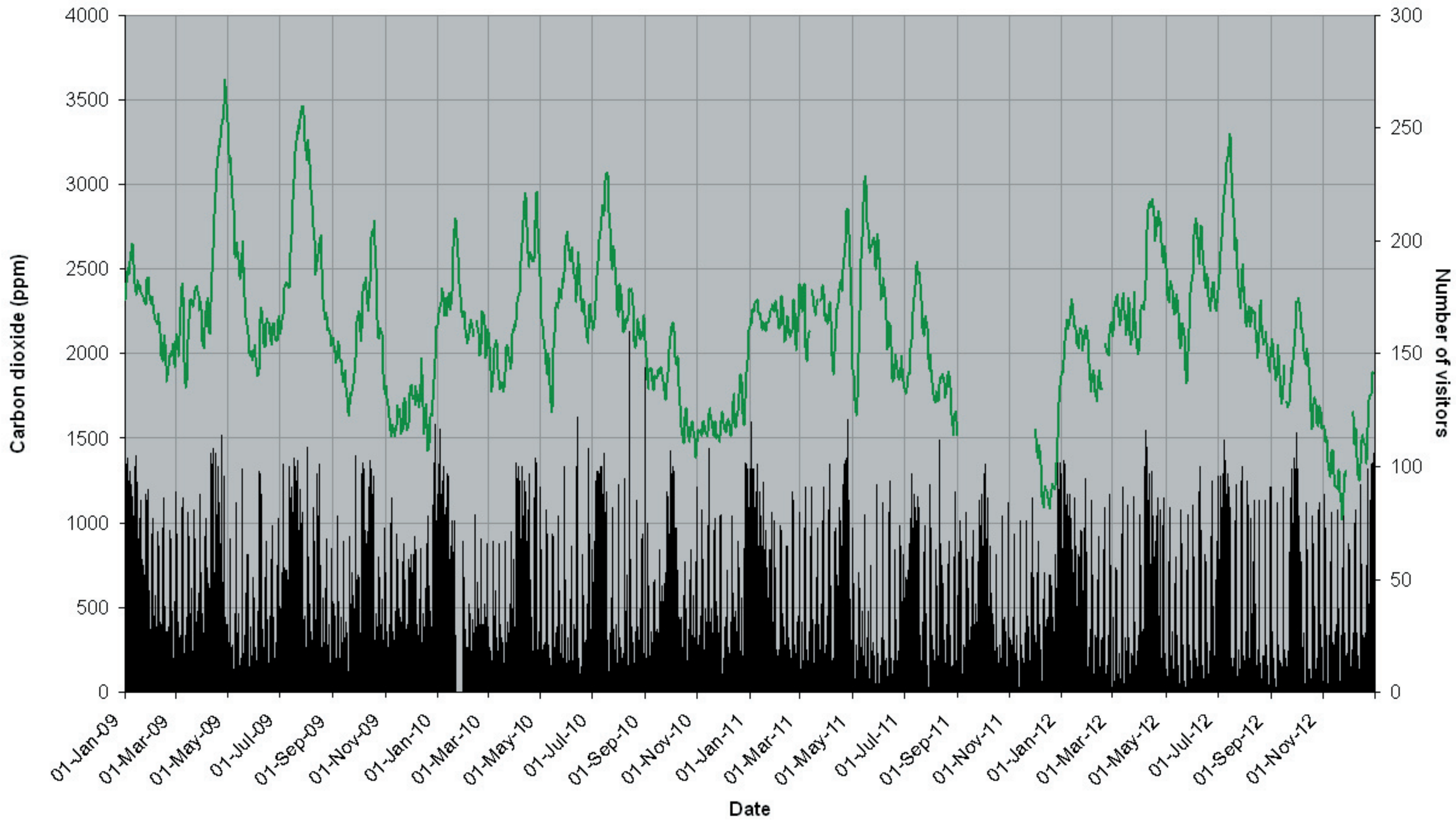


Figure 6. Relationship between the concentration of carbon dioxide in the Temple of Baal and number of visitors to the cave each day. Note: no visitor data were available for March 23-29 2010.

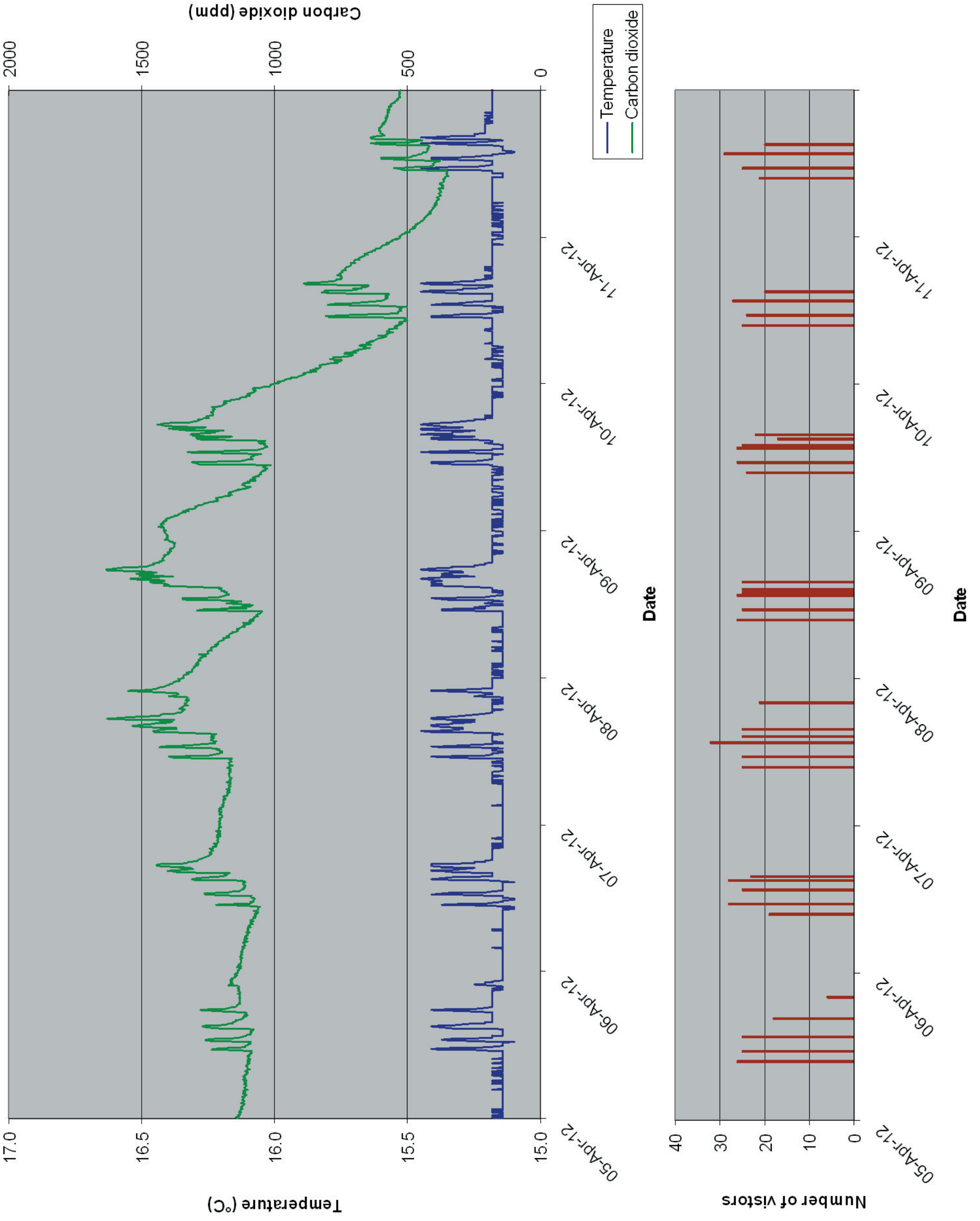


Figure 7. Relationship between commercial tour groups, air temperature and CO_2 concentration in the Orient.

DISCUSSION

Trends in cave atmosphere

Of all the caves, the Chifley had the most variable atmosphere, and experienced considerable day to day variation and pronounced seasonal trends in air temperature and CO_2. These trends are consistent with strong ventilation in the cave (Whittlestone et al. 2003) and current research by Waring and Hankin (2013), which has shown the occurrence of bi-directional airflow and daily cycles of ventilation through the upper (i.e. the Elder / Plug Hole) and lower entrances to the cave. Conversely, the most stable air temperature occurred in the Temple of Baal, a cave known to have limited ventilation (Whittlestone et al. 2003). As with air temperature, strong ventilation in the Chifley Cave accounts for greater variability of RH in the Chifley compared to the other caves.

The average (2009-2012) air temperature differed by up to 2.8°C between the sites within the caves. These differences were predominately attributed to the location of individual caves within the larger cave system. For example the warmest caves were the Temple of Baal, the Orient and Mafeking branch of the Lucas Cave, all of which are situated in the upper levels of the southern show caves, while the River Cave at a lower level was substantially cooler. In the northern show caves, the average air temperature in the Diamond was slightly cooler than the Chifley and Imperial. On the basis of elevation, this result would not be expected, since the Diamond is higher than the Imperial. However connections to other passages (e.g. the Jubilee Cave) create complex airflows through the cave (J. James pers. com.), which may explain this discrepancy. More broadly, since the air temperature of a cave is frequently influenced by the surface temperature of the ground, it is plausible that variations in the microclimate of the surface karst (e.g. due to differences in aspect, exposed bedrock and vegetation cover) contributed to the difference in air temperature between the caves (Domínguez-Villar et al. 2013)

With the exception of the Temple of Baal, all of the caves exhibited seasonal variation in CO_2, with a summer maximum and a winter minimum. These trends are consistent with Australian (e.g. Smith 1998; Eberhard et al. 2003) and international (Spötl et al. 2005; Fernandez-Cortes et al. 2006; Liñán et al. 2008) literature which report that CO_2 concentrations typically peak in summer and decrease to a minimum in winter. Although changes in barometric pressure can cause air to flow into or out of a cave (Cigna 2004), external air temperature is a likely driver of seasonal variation in CO_2 at Jenolan. During winter, the cave atmosphere is generally substantially warmer than the external air, which increases air circulation as warm, moist air rises out of the cave and is replaced by comparatively cold, dry external air. Conversely, when external temperatures are warmer, a temperature inversion does not form and the comparatively cool, moist air remains within in the cave (Fernandez-Cortes et al. 2006). This presumption is in accordance with contemporary research by Waring and Hankin (2013), who found external air temperature is the key driver of air circulation in the Chifley Cave.

Furthermore, higher concentrations of CO_2 during summer are also likely, due to increased production of CO_2 by natural processes (Baker and Genty 1998). These include the diffusion of CO_2 from within epikarst air (rich in CO_2 from root respiration and the breakdown of organic matter), degassing from cave waters, and biological productivity in the cave (Fairchild and Baker 2012). Indeed contemporary research by Waring and Hankin (2013) has shown that on hot days, the airflow in the Chifley Cave causes soil-air that is rich in CO_2 to seep into the cave, particularly at Katies Bower.

In the Temple of Baal, the gradual accumulation of CO_2 during periods of high visitation, gradual decrease in CO_2 during periods of lower visitation and lack of seasonal variation was indicative of low ventilation during 2009-2012. This notion is consistent with the findings of Whittlestone et al. (2003), who reported low ventilation rates, such that the difference between the summer and winter concentrations of radon in the Temple of Baal was only “marginally discernable” (Whittlestone et al. 2003). The increases and decreases in CO_2 during periods of high and low visitation confirm that visitation is an important factor in the determining CO_2 levels within this cave and is consistent with the hypothesis of Michie (1997), that visitors to the Temple of Baal caused the high concentrations of CO_2.

Implications for management

The Chifley was the only cave where the concentration of CO_2 exceeded 5,000 ppm, the limit specified in Carbon Dioxide Exposure Standards (time weighted average), which allow a person to work an 8 hour day for 40 hours per week in 5,000 ppm of CO_2 (Safe Work Australia 2013). The same standards also specify a short term exposure limit of 30,000 ppm (3 %) CO_2 for a duration of 15 minutes. Although the maximum concentration of CO_2 exceeded 5,000 ppm in the Chifley, this was never for an extended period of time, as evident by the average daily concentration, which only once exceeded 4,500 ppm and never 5,000 ppm (Fig. 4). Consequently, it is extremely unlikely that the concentrations of CO_2 reported at any of the monitoring sites would have impacted the health or safety of visitors, cave guides, or maintenance staff.

Commercial cave tours frequently increased the air temperature and concentration of CO_2 within the cave atmosphere. In most of the caves these increases were relatively short lived and rapidly returned to the pre-tour level (i.e. fast relaxation time) immediately after the tour when visitation was moderate or at the end of the day during periods of high visitation. Consequently, in these caves, the current rates of visitation and tour schedules did not have any apparent lasting impact on the cave atmosphere. However the same was not true for the Temple of Baal, where the number of visitors influenced the concentration of CO_2 and resulted in an accumulation of CO_2 during periods of high visitation.

CO_2 is a crucial factor in many of the processes that form caves and their speleothems. An increase in the concentration of CO_2 in the cave atmosphere may initially impact active speleothems by decreasing the rate of calcite deposition and ultimately the dissolution of speleothems (James 2004). Kermode (1979) proposed that concentrations of CO_2 above 2,400 ppm result in aggressive water that can dissolve speleothems, and as a result, is the maximum permissible level in Glowworm Cave, New Zealand (de Freitas and Banbury 1999; de Freitas 2010), although the reliability of this threshold as a universal guideline has been questioned (e.g. Michie 1997; de Freitas and Banbury 1999). Recent research suggests that there is no universal threshold, but rather that the equilibrium of CO_2 between the air and water ultimately determines if calcite is deposited or dissolved (Baker and Genty 1998; Cigna 2002; James 2004). Moreover, research examining the influence of CO_2 on calcite deposition within the tourist caves at Jenolan found corrosion thresholds ranged from 2,690 ppm in the River Cave to 28,000 ppm in the Ribbon Cave and did not exceed the maximum CO_2 measured in the caves (Failes 1997). It is important to note that these thresholds do not apply to inactive speleothems and bedrock, and corrosive condensates that form as a result of increased concentrations of CO_2 from visitors can be highly damaging (James 2004, 2013), although fortunately many of the speleothems in the Temple of Baal appear to be active.

It is beyond the scope of the JEMP to measure and quantify corrosion thresholds of CO_2 within the caves and further research on the impacts of CO_2 on the caves is required, especially in the Temple of Baal. Specifically, measurement of the partial pressure of CO_2 (P_{CO2}) of speleothem drip water and concentration of dissolved calcium could be used to accurately determine the sensitivity of speleothems to changes in the concentration of CO_2 in the cave atmosphere (Fairchild and Baker 2012). Nevertheless, in the Temple of Baal, visitation increased the concentration of CO_2 for lengthy periods of time, such that no seasonal variability was evident, and may in turn influence process such as the rates of calcite deposition. Furthermore, although the concentration of CO_2 in the Temple of Baal was below the limit specified by Safe Work Australia (2013), which allows a person to work an 8 hour day (40 hour week) in 5,000 ppm of CO_2, it has been suggested that visitors may experience discomfort from CO_2 concentrations < 2,500 ppm (Osborne 1981).

The most common methods of addressing issues of air quality in tourist caves are to limit visitor numbers and artificial ventilation (James 2004). Obviously if visitation causes an accumulation of CO_2 in a cave, a reduction in the number of people who visit that cave will lessen this accumulation. However, this is in direct conflict with commercial interests and is not a considered a realistic proposition. At the same time, given that visitors are elevating the concentration of CO_2 in the Temple of Baal, caution should be exercised when evaluating visitation rates and the possibility of increasing the number of people who visit the cave.

When considering the influence of visitation on the atmosphere and microclimate of Pozalagua Cave (Spain), Lario and Soler (2010) recommended closure of the cave one day per week during periods of "normal" visitation and two days per week after high visitation in order to minimise the cumulative effects of visitation. Given the low rates of ventilation and time taken for the concentration of CO_2 to decrease, it is unclear how successful a similar scenario would be in the Temple of Baal. Under the existing trends in visitation, the concentration of CO_2 gradually decreases with lower visitation following periods of peak visitation and accordingly, the environmental benefits of completely closing the cave would need to be weighed up against the economic benefits associated with visitation.

An alternative method of dealing with CO_2 is to ventilate the cave to prevent a build up of excessive CO_2. For example, careful manipulation of the airflow regimes is used to limit the accumulation of CO_2 in Glowworm Cave, New Zealand (de Freitas and Banbury 1999; de Freitas 2010; Gilles and de Freitas 2013). Similarly, Michie (1997) demonstrated that opening the airtight doors in the Binoomea Cut, an artificial tunnel that provides access to the Temple of Baal, can rapidly decrease the concentration of CO_2 in the cave atmosphere. However increased ventilation is likely to cause significant side effects that must be carefully considered. The maintenance of natural conditions is crucial to the conservation of a cave (Watson et al. 1997) and changes to the natural airflow frequently alter the microclimate of a cave (Gillieson 1996). Artificial ventilation often causes increased fluctuations in temperature and relative humidity (Russell and Maclean 2008) and is a major cause of desiccation of caves (Gillieson 1996; de Freitas 1997). Additionally, increased airflow circulates dust particles to a greater depth within the cave (Michie 2004) and is likely to discolour speleothems, thereby reducing their aesthetic value (James 2013). Consequently, any potential change to the air flow in a cave is potentially highly damaging and requires careful consideration (Michie 2004; Faimon et al. 2012).

The creation of artificial entrances modifies natural airflow, thereby altering the natural microclimate of a cave (Cigna 1993; Gillieson 1996). For this reason the International Show Cave Association (ISCA) states that "any new access into a cave must be fitted with an efficient system, such as double set of doors, to avoid creating changes in the air circulation" (ISCA 2010). The artificial entrance to the Temple of Baal, the Binoomea Cut, contains two air lock doors, which were installed after it was observed that the cave was drying out (J. James pers. com.). Prolonged opening of the airlock doors would undoubtedly increase airflow and decrease in $CO_{2,}$ but is also likely result in the desiccation of the cave, especially in winter, when the artificial entrance may act as a "chimney" (see de Freitas and Banbury 1999 and Russell and Maclean 2008) as warm moist air is drawn out of the Binoomea Cut, while cold air is drawn in from the River Cave. This scenario would be highly undesirable, as the potential befits associated with decreased levels of CO_2 would almost certainly be outweighed by unnatural variation in the microclimate and desiccation of speleothems.

Previous studies have noted the conflict between maintaining a stable microclimate (in particular temperature and RH) versus the need for ventilation to manage the accumulation of CO_2 (e.g. de Freitas 1997; Michie 1999; Liñán et al. 2008). One solution to this conflict may be a compromise whereby limited ventilation is permitted through the Binoomea Cut. This could be achieved by temporary opening of the airtight doors (e.g. two hours as per Michie 1997), although this would be expected to increase the variation of air temperature and RH in the cave. Additionally, the manual opening and closing of the doors, may be problematic as it could be expected that the doors would accidently be left open from time to time, to the detriment of the cave. An alternative approach could be the installation of a window in each of the airlock doors that could be opened during peak visitation to allow limited airflow into the cave. A more limited airflow may allow the temperature and RH of the external air to partially equalise with the cave atmosphere before reaching the cave, whilst minimising the potentially harmful accumulation of CO_2.

As previously discussed, the circulation of air in caves is influenced by a number of factors including season and weather conditions. These factors may have significant implications for ventilation, since the influence of ventilation on the cave microclimate as well as its effectiveness in removing CO_2 can be highly variable depending on season and local weather conditions, and require different ventilation regimes (de Freitas 1997). With this in mind, any study of the effectiveness and impacts of ventilation must include temporal variation in airflow associated with season and varying weather conditions. Finally, in considering the possibility of increasing the ventilation in caves such as the Temple of Baal, it must stressed that any change to airflow within a cave requires careful consideration, and must be guided by ongoing monitoring, if long term impacts are to be minimised. Such considerations highlight the importance and value of long term, baseline data collected in environmental monitoring programs such as the Jenolan Environmental Monitoring Program.

Monitoring of the cave atmosphere at Jenolan provides valuable baseline data for the air temperature, relative humidity and concentration of CO_2 in the tourist caves. Regular measurement of these parameters has ascertained the caves are typically characterised by high levels of relative humidity, moderately stable air temperature with seasonal variation of < 2°C, and highly seasonal variation in concentration of CO_2. Commercial cave tours frequently increased the air temperature and concentration of CO_2, although both parameters rapidly returned to the pre-tour level after the tour had passed. An exception occurred in the Temple of Baal, where peak visitation elevated the concentration of CO_2 for extended periods of time, such that seasonal variation was not apparent.

ACKNOWLEDGMENTS

Many people in NSW Office of Environment and Heritage and Jenolan Caves Reserve Trust have played a crucial role in the JEMP. In particular, thanks to Stephen Meehan (OEH) for his efforts in establishing and managing the JEMP and Russell Cummins (formerly OEH) for his preliminary work during the establishment of the Program. Thanks also to Dan Cove and Grant Cummins (JCRT) for the logistical support at Jenolan. Dr. Julia James kindly commented on a draft of the manuscript. Prof. Andy Baker and an anonymous reviewer provided valuable comments on the manuscript.

REFERENCES

Baker, A. and Genty, D. (1998). Environmental pressures on conserving cave speleothems: effects of changing surface land use and increased cave tourism. *Journal of Environmental Management* **53,** 165-175.

Cigna, A.A. (1993). Environmental management of tourist caves. *Environmental Geology* **21,** 173-180.

Cigna, A.A. (2002). Modern trend in cave monitoring. *Acta carsologica* **31**, 35-54.

Cigna, A.A. (2004). Climate of Caves. In ‘Encyclopaedia of caves and karst science’ (ed. J. Gunn) pp. 228-230. (Fitzroy Dearborn: New York).

Department of Environment and Climate Change (2009). ‘Greater Blue Mountains World Heritage Area: strategic plan’. (Department of Environment and Climate Change (NSW)).

de Freitas, C.R. (1997). Cave monitoring and management: The Glowworm Cave, New Zealand. In: ‘Proceedings of the 12th ACKMA Conference, Waitomo, NZ, 1997.’ (ed. D.W. Smith) pp. 55-66. (Australasian Cave and Karst Management Association: Carlton South, Victoria, Australia).

de Freitas, C.R. (2010). The role and importance of cave microclimate in the sustainable use and management of show caves. *Acta carsologica* **39**, 477-489.

de Freitas, C.R. and Banbury, K. (1999) Build up and diffusion of carbon dioxide in cave air in relation to visitor numbers at the Glowworm Cave, New Zealand. In: ‘Proceedings of the Thirteenth Australasian Conference on Cave and Karst Management, Mount Gambier, South Australia, 1999.’ (eds. K. Henderson and P. Bell) pp. 84-89. (Australasian Cave and Karst Management Association: Carlton South, Victoria, Australia).

Eberhard, S., Michie, N., McBeath, R. and Bell, P. (2003). Carbon dioxide and climate in Jewel Cave. In ‘Proceedings of the Fifteenth Australasian Conference on Cave and Karst Management, Chillagoe Caves and Undara Lava Tubes, North Queensland, 2003.’(ed. K. Henderson) pp. 73. (Australasian Cave and Karst Management Association Incorporated: Carlton South, Victoria, Australia).

Failes, T. (1997). Carbon dioxide and its influence on calcite deposition and solution. Honours Thesis, University of Sydney, Sydney.

Faimon, J., Troppová, D., Baldík, V. and Novotný, R. (2012). Air circulation and its impact on microclimatic variables in the Císařská Cave (Moravian Karst, Czech Republic). *International Journal of Climatology* **32,** 599-623.

Fairchild, I.J. and Baker, A. (2012) ‘Speleothem science: From processes to past environments’ Wiley-Blackwell, Oxford, UK.

Fernandez-Cortes, A., Calaforra, J.M. and Sanchez-Martos, F., (2006). Spatiotemporal analysis of air conditions as a tool for the environmental management of a show cave (Cueva del Agua, Spain). *Atmospheric Environment* **40,** 7378–7394.

Gilles, M.J. and de Freitas, C.R. (2013). Environmental Management of the Waitomo Glowworm Cave: Effects of visitors and ventilation on carbon dioxide concentrations. In ‘Proceedings of the Fifteenth Australasian Conference on Cave and Karst Management, Waitomo Caves, New Zealand, 2013’ (eds R. Webb and S Webb) pp 173-191. (Australasian Cave and Karst Management Association Incorporated: Mount Compass, South Australia, Australia).

Gillieson, D. (1996) ‘Caves: processes, development and management’. Blackwell, Oxford, England.

International Show Cave Association (2010) ISCA management guidelines – draft. http://www.i-s-c-a.com/documents

James, J.M. (2004). Tourist caves: air quality. In ‘Encyclopaedia of caves and karst science’ (ed. J. Gunn) pp. 730-731. (Fitzroy Dearborn: New York).

James, J.M. (2013). Atmosheric processes in caves. In ‘Treatise on Geomorphology, Vol 6, Karst Geomorophology’ (Editor in Chief J.F.Shroder, Volume Editor A. Frumkin) pp 304-318. (Acedemic Press, San Diego).

Jenolan Caves Reserve Trust (2012). Jenolan Caves Reserve Trust: annual report 2011-2012. http://www.jenolancaves.org.au/imagesDB/wysiwyg/AnnualReport2011-12.pdf

Kermode, L.O. (1979). Cave corrosion by tourists. In ‘Cave Management in Australia III: Proceedings of the third Australian conference on cave tourism and Management, Mt Gambier, South Australia, 1979.’ pp. 97-104. (Australasian Cave and Karst Management Association, Carlton South, Victoria, Australia).

Lario, J. and Soler, V. (2010). Microclimate monitoring of Pozalagua Cave (Vizcaya, Spain): application to management and protection of show caves. *Journal of Cave and Karst Studies* **72,** 169–180.

Liñán, C., Vadillo, I. and Carrasco, F. (2008). Carbon dioxide concentration in air within the Nerja Cave (Malaga, Andalusia, Spain). International Journal of Speleology **37,** 99-106.

Michie, N. (1997). An investigation of the climate, carbon dioxide and dust in Jenolan Caves, NSW. PhD thesis, Macquarie University, Sydney.

Michie, N. (1999). Management of carbon dioxide in show caves. In ‘Cave Management in Australasia 13: Proceedings of the 13th ACKMA Conference, Mt Gambier, South Australia, 1999.’ (eds K. Henderson and P. Bell). (Australasian Cave and Karst Management Association, Carlton South, Victoria, Australia).

Michie, N. (2004). Tourist caves: air debris. In 'Encyclopaedia of caves and karst science' (ed. J. Gunn) pp. 731-732. (Fitzroy Dearborn: New York).

Osborne, R.A.L. (1981). Towards an air quality standard for tourist caves: studies of carbon dioxide enriched atmosphere in Gaden-Coral, Wellington Caves, NSW. *Helictite* **19,** 48-56.

Pulido-Bosch, A., Martín-Rosales, W., López-Chicano, M., Rodríguez-Navarro C.M., and Vallejos, A. (1997). Human impact in a tourist karstic cave (Aracena, Spain). *Environmental Geology* **31,** 142-149.

Russell, M.J. and MacLean, V.L. (2008). Management issues in a Tasmanian tourist cave: Potential microclimatic impacts of cave modifications. *Journal of Environmental Management* **87,** 474-483.

Safe Work Australia (2013) Hazardous Substances Information System
http://hsis.safeworkaustralia.gov.au/ExposureStandards

Smith, G.K. (1998). Foul air at Bungonia. In 'Under Bungonia' (eds J., Bauer and P., Bauer) pp. 85-92. (JB Books: Oak Flats, NSW, Australia).

Spötl, C., Fairchild, I.J. and Tooth, A.F. (2005). Cave air control on dripwater geochemistry, Obir Caves (Austria): Implications for speleothem deposition in dynamically ventilated caves. *Geochimica et Cosmochimica Acta* **69,** 2451-2468.

Waring, C.L. and Hankin, S.I. (2013). How weather and climate drives Chifley Cave speleothem growth. In 'The Science of Jenolan Caves: What do we know?' Abstracts of presented papers and posters (Jenolan Caves, May 23-24, 2013).

Watson, J., Hamilton-Smith, E. Gillieson, D. and Kiernan K. (eds) (1997). 'Guidelines for cave and karst protection'. (International Union for Conservation of Nature and Natural Resources: Cambridge, UK).

Whittlestone, S., James, J. and Barnes, C. (2003). The relationship between local climate and radon concentrations in the Temple of Baal, Jenolan Caves, Australia. *Helictite* **38,** 39-44.

Invertebrate Cave Fauna of Jenolan

Stefan M. Eberhard[1], Graeme B. Smith[2], Michael M. Gibian[3], Helen M. Smith[4] and Michael R. Gray[4]

[1] Subterranean Ecology Pty Ltd, Perth; [2] Australian Museum Entomology Dept., 6 College St, Sydney 2010 and author for correspondence (le_gbsmith@optusnet.com.au); [3] SC Johnson and Son Inc., Sydney; [4] Australian Museum Arachnology Dept.

Eberhard, S.M., Smith, G.B., Gibian, M.M., Smith, H.M. and Gray, M.R. (2014). Invertebrate cave fauna of Jenolan. *Proceedings of the Linnean Society of New South Wales* **136**: 35-67.

The invertebrate fauna known from within the caves at Jenolan is inventoried and summarised. At least 136 individual taxa have been identified although less than one-half (43%) are assigned to described species, the rest are either undescribed (8%) or have only been identified to genus level (31%) or higher taxa (18%). The collected fauna is dominated by arachnids (47%) and collembolans (24%) followed by insects (15%) and crustaceans (6%) with three or fewer taxa identified in each of the remaining groups comprising molluscs, diplopods, chilopods, annelids, platyhelminths and nematodes. In terms of ecological dependence on caves, 53% of collected taxa comprised typically epigean species with the remainder considered to be habitual cave-dwellers. Eight species (revised from 14 previously) are considered to be obligate hypogean species (terrestrial troglobites or aquatic stygobites) comprising three species of springtail, two spiders, a pseudoscorpion and two aquatic crustaceans. The diversity of troglobite species is fairly typical for karst areas in the eastern highlands of NSW but higher unrecorded diversity of stygobite species is predicted. While the invertebrate cave fauna of Jenolan has received more attention from biologists than any other karst area in NSW, substantial knowledge gaps remain. Research and conservation priorities are: (1) identify existing collections and describe new species, focussing on troglomorphic taxa which are likely to be locally endemic and of conservation significance; (2) targeted field surveys for rare troglomorphic taxa which are under-represented in existing collections; (3) sample for aquatic micro-crustacea and other stygofauna in vadose zone, phreatic zone and interstitial habitats; (4) sample for troglobites in meso-cavern and other cryptic terrestrial habitats.

Manuscript received 23 October 2013, accepted for publication 11 December 2013.

KEYWORDS: cave fauna, Jenolan, stygobite, troglobite

INTRODUCTION

The purpose of this paper is fourfold: (1) to provide an historical inventory of the invertebrate cave fauna recorded from the Jenolan karst, which to date, has largely existed in unpublished reports; (2) to summarise the current state of taxonomic and collection knowledge; (3) to identify knowledge gaps and priorities for further research and conservation; (4) to briefly re-assess the significance of the Jenolan cave fauna in a regional and national context.

The Jenolan Caves have attracted the attention of European scientists since first being visited in the 1830s, however little attention was paid to the invertebrate fauna, either above or below ground, until guide Joseph C. Wiburd initiated collections from the 1880s until around 1903. Many of Wiburd's specimens are in the Australian Museum collections. Most specimens appear to be surface collections although two species of cave-dwelling spider (*Cycloctenus abyssinus* and *Laetesia weburdi*) described by Urquhart (1890), are historically important, being the first cave dwelling invertebrates described from New South Wales.

After Wiburd and Urquhart's pioneering efforts, further documentation of Jenolan's invertebrate cave fauna lapsed until the 1960s when collections were reinitiated by John Polesson, Barbara Dew, Elery Hamilton-Smith, Ted Lane and Aola Richards. Their efforts identified ten named species of spider, pseudoscorpion, harvestman, springtail and beetle, plus several other unidentified species of millipede, cricket and moth (Hamilton-Smith 1967).

The next era of systematic survey occurred between 1986 and 1988, when Michael Gibian, Louise Wheeler and Graeme Smith, with further involvement from Mike Gray, Glenn Hunt, Penelope Greenslade, Mia Thurgate and Ernst Holland, sampled the fauna by hand as well as netting streams and taking samples of leaf litter and guano for Tullgren funnel extractions. These efforts increased the number of recorded taxa (most undescribed) from 26 to 67 including Jenolan's first troglobitic spiders and aquatic cave fauna (Gibian et al. 1988).

Systematic collection efforts were continued by Eberhard (1993) with emphasis on aquatic macrofauna and interstitial habitats using baits, nets and pumping methods. These collections and other previous accessible records were part of a wider survey of New South Wales cave fauna which established Jenolan as one of the better sampled karsts in the State and possessing a comparatively rich invertebrate cave fauna (Eberhard and Spate 1995). Since this last survey and inventory at Jenolan, which remains unpublished in the scientific literature, further field collection efforts have been very limited.

As is typical of invertebrate surveys, and subterranean fauna especially, the taxonomic (Linnaean) shortfall means that much of the Jenolan material remains incompletely identified, awaiting specialist attention. Some progress has however been made with descriptions of four mite species (Halliday 2001), one spider (Forster et al. 1987), one amphipod (Bradbury and Williams 1997), redescription of the Jenolan harvestman (Hunt 1992), and further identification of springtails (Greenslade 2011); descriptions of an additional four mite species are in preparation (Halliday in litt. 2013).

The survey and inventory by Eberhard and Spate (1995) informed the stance taken in a subsequent paper by Thurgate et al. (2001a) who applied the metaphor 'from rags to riches' to highlight subterranean biodiversity in New South Wales and 'dispel former erroneous perceptions of a depauperate fauna'. Since this paper was published, a great amount of field survey and taxonomic research has been undertaken in other states, mostly in Western Australia and South Australia (Eberhard et al. 2009; Guzik et al. 2011), the results of which reinforce the need and timeliness for formal documentation and reappraisal of Jenolan's cave fauna as presented herein.

DEFINITIONS

Biospeleologists classify subterranean species according to their degree of ecological association and dependence upon subterranean environments. Frequently this association is presumed or inferred, especially in the case of obligate subterranean forms, on the basis of morphological modifications, typically a reduction or loss of pigmentation and eyes, elongation of appendages and compensatory enhancement of non-optic sensory structures.

Accidentals: Typically surface dwelling species whose occurrence underground is incidental, having 'accidentally' wandered or fallen in, or been carried underground by sinking water (e.g. flood), gravity or air currents

Epigean: Surface dwelling

Hypogean: Subterranean

Guanophile/Guanobite: Species that are associated with the guano of cave roosting bats or birds. Species associations with guano may be facultative (guanophile) or obligate (guanobite).

Meso-cavern: Subsurface cavity generally too small for a human to enter. Underground voids in the size range 0.1-20 cm, especially in karst and volcanic substrates. cf. macro-cavern which are voids > 20 cm, especially caves large enough for human entry.

Stygophile/Stygobite: Terms equivalent to troglophile and troglobite for aquatic cave fauna

Trogloxene: Species that habitually occupy caves for a part of their life cycle but frequently return to the surface for food. e.g. bats and cave crickets.

Troglophile: Species that can complete their whole life cycle in hypogean environments but populations of the same species also occur in epigean environments. They usually do not possess typical morphological modifications, but in some cases the cave-dwelling populations may show some degree of modification (e.g. lighter pigmentation or reduced eye size) compared to their surface-dwelling conspecifics.

Troglobite: Species that are obligate cave dwellers and entirely restricted to the subterranean environment and showing typical troglomorphic traits (see next).

Troglomorphy: Any morphological, physiological, or behavioural feature that characterizes subterranean fauna. Common morphological traits include: reduction of eyes, pigment, wings; elongation of appendages; specialization of non-optic sensory structures.

OVERVIEW

An overview of the systematic composition and current state of taxonomic knowledge appears in Fig. 1 and Table 1 and a more comprehensive list of the faunal records and the location of specimens is in the appendix. At least 136 individual taxa have so far been collected within the caves at Jenolan. In terms of recorded diversity, the collected invertebrate fauna is dominated by arachnids (47%) and collembolans (24%) followed by insects (15%) and crustaceans (6%) with three or fewer taxa identified in each of the remaining groups comprising molluscs, diplopods, chilopods, annelids, platyhelminths and nematodes (Fig. 1).

Springtails (Collembola) were very abundant and diverse with 33 recognised taxa including three troglobites and seven undescribed species (Table 1). Although a naturally diverse group, their disproportionate representation in Jenolan cave collections partly reflects the survey and identification efforts applied to this group by Greenslade (2002) and which contrasts with most of the insect groups excepting the beetles (Coleoptera) which are reasonably well known. The arachnid collections are dominated by terrestrial mites (Acarina) and spiders (Araneae) with 28 and 31 recognised taxa respectively. This also partly reflects the survey and identification efforts for these groups applied by Halliday (2001) and Gray (1973) respectively. While eight crustacean taxa have been recorded to date, this is likely to under-represent the actual diversity because this group is typically diverse in karst groundwater. Moreover, Jenolan's deep groundwater habitats have been poorly sampled for aquatic micro-crustacea. In terms of taxonomic resolution, less than one-half (59 species, 43%) of the 136 taxa are currently assigned to described species, the rest are either undescribed (11 species, 8%) or have only been identified to genus level (42 taxa, 31%) or higher (24 taxa, 18%) (Table 1).

A systematic list of all invertebrate taxa recorded from inside caves at Jenolan is given in the appendix. In terms of ecological classification, many of the taxa are considered to be 'accidental' or incidental hypogean fauna (72 taxa), falling into caves or being washed in by flood events. Forty-nine (49) taxa are considered to be troglophiles (or stygophiles). Only

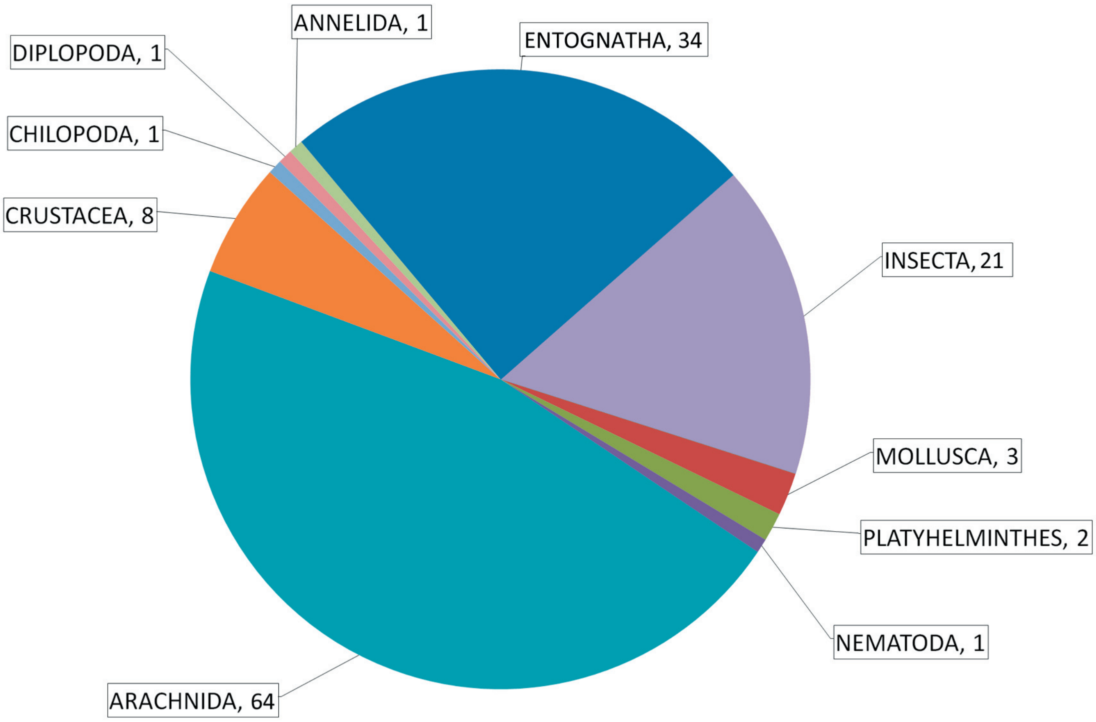


Figure 1. Systematic composition of Jenolan invertebrate cave fauna collections showing the number of taxa identified in major taxonomic groups.

Table 1. Overview of recorded diversity and taxonomic resolution in major selected groups of Jenolan cave invertebrates.

Higher Group	No. taxa	Described sp.	Undescribed n. sp.	Identified to genus	Not identified to genus	Troglobites / stygobites
Entognatha: Collembola	33	10	3	19	1	3
Entognatha: Other	1				1	
Insecta: Coleoptera	6	6				
Insecta: Others	15	2		5	8	
Arachnida: Araneae	31	12	3	13	3	2
Arachnida: Acarina	28	19	4	1	4	
Arachnida: Others	5	3		2		1
Crustacea	8	4	1	2	1	2
Diplopoda	1				1	
Chilopoda	1				1	
Mollusca	3	3				
Annelida	1				1	
Nematoda	1				1	
Platyhelminthes	2				2	
Totals	**136**	**59**	**11**	**42**	**24**	**8**

eight species are considered to be troglobites or stygobites, comprising three species of springtail, two spiders, a pseudoscorpion, and two crustaceans (Table 1, Figs 2, 3 and 4).

DETAILED SYSTEMATIC ACCOUNT WITH NOTES ON COLLECTIONS AND ECOLOGY

ENTOGNATHA

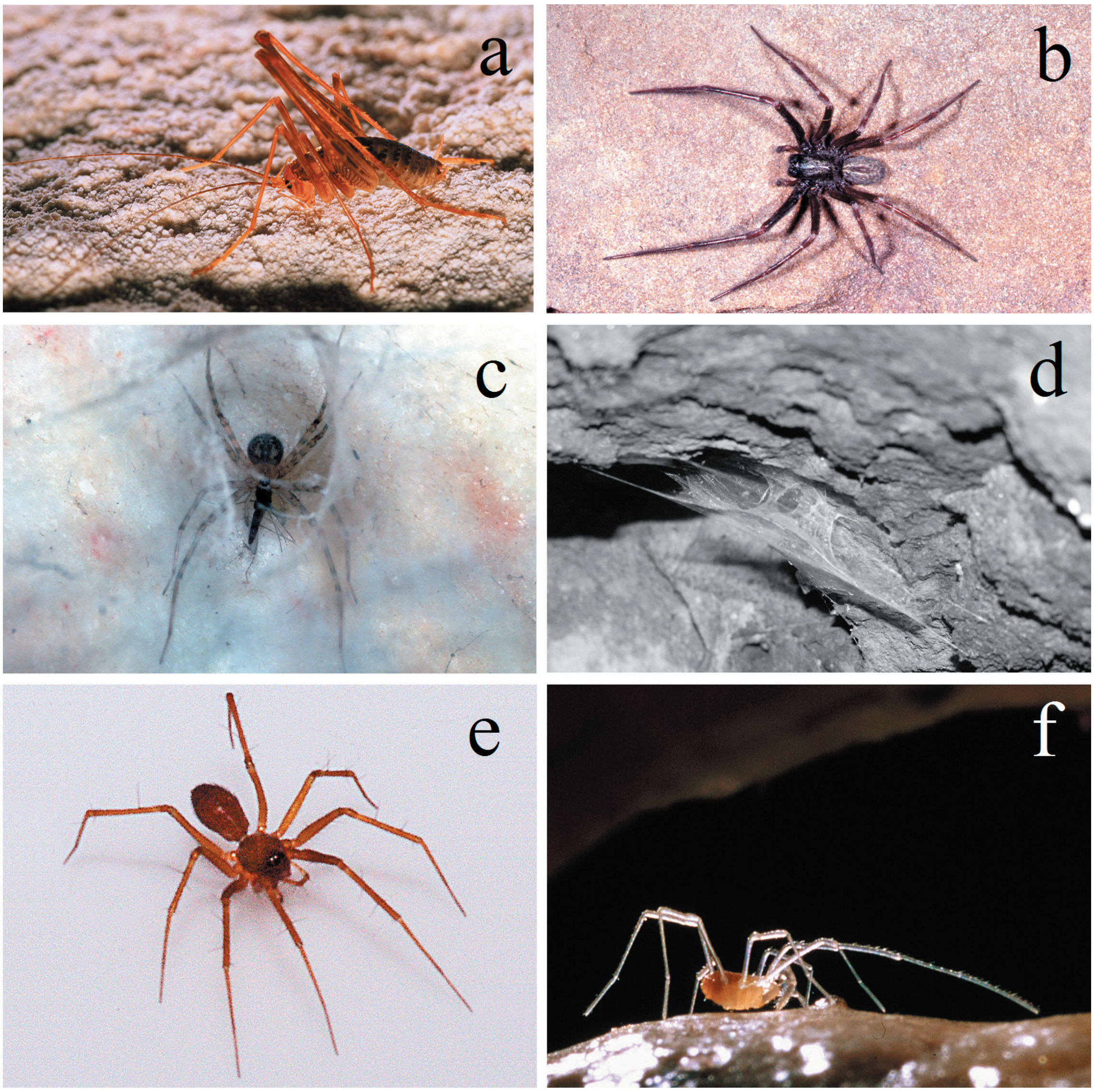
Subclass Collembola

Penelope Greenslade has tentatively identified 33 taxa from 11 families from material predominantly collected by Gibian, Smith, Wheeler, and Eberhard (Greenslade 2002). Collembola were mainly collected by hand from the surface of pools, from rock walls, stalagmites and other surfaces, but some Tullgren funnel extractions were taken of guano and flood debris, and some pitfall traps baited with arthropod remains. Collembola were observed to be very abundant on moist surfaces (e.g. stalagmites) in the humid and dark sections of caves developed for tourism (e.g. Orient Cave upper levels) (S. Eberhard personal observation, 1993). It is hypothesised that tourism activities have altered the ecology of these otherwise normally dark and energy-poor deep zone environments, via the introduction of artificial light and nutrients with associated growth of fungi and lampen-flora which provide a food source for grazing invertebrates to colonise deep zone habitats that would normally preclude them.

The most abundant species (*Onychiurus* sp. *fimetarius* group, *Ceratophysella* spp. *Mesophorura* sp. *krausbaueri* group and *Folsomia candida* (Willem, 1902)) also occur in Europe and are almost certainly introduced to Australia. The undescribed native *Adelphoderia* sp. was the most frequently occurring

Figure 2 (left). Scanning electron micrograph of *Adelphoderia* sp., < 1 mm (Penelope Greenslade)

Figure 3 (below). Examples of Jenolan cave fauna, approximate length (including legs) indicated (photographer). a. *Cavernotettix* cave cricket, 25 mm (Stefan Eberhard); b. *Badumna socialis* 16 mm (Mike Gray); c. *Stiphidion facetum* (with dipteran prey), 25 mm (Stefan Eberhard); d. Web of *S. facetum* (Helen Smith); e. *Laetesia weburdi*, 5 mm (Mike Gray); f. *Holonuncia* cave harvestman, 20 mm (Stefan Eberhard).



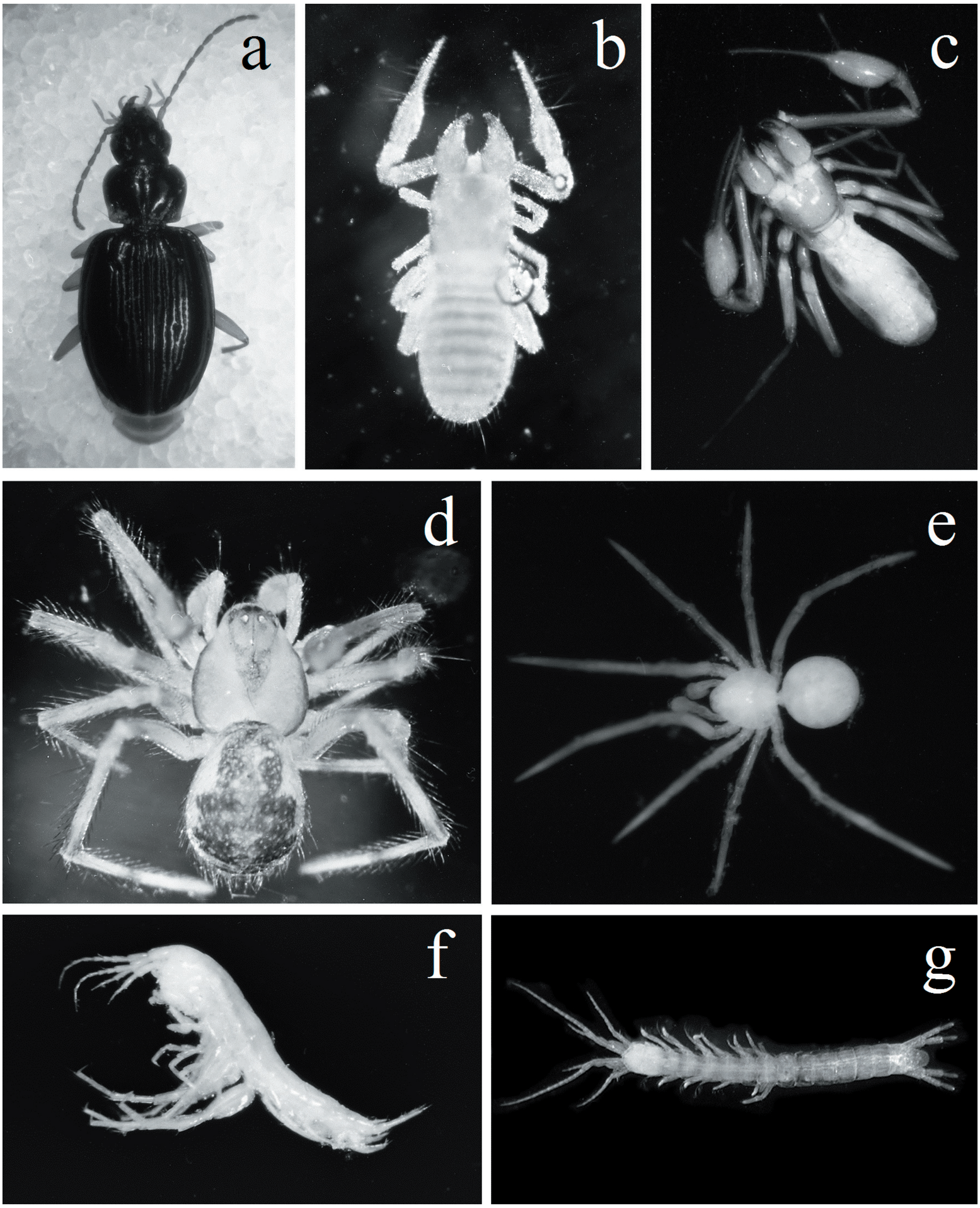


Figure 4. Examples of Jenolan cave fauna. a. *Trechimorphus diemenensis*, 5 mm; b. Pseudoscorpion *Sathrochthonius tuena*, 1.4 mm; c. Troglobitic pseudoscorpion *Pseudotyrannochthonius jonesi*, 3 mm; d. *Icona* sp., 8 mm, a troglophile with pigment and eyes; e. Troglobitic Theridiidae sp. (previously as *Icona* sp. 3), 3mm; f. Stygobitic amphipod *Neocrypta simoni*, 4 mm; g. Stygobitic crustacean, Psammaspididae gen. et sp. nov. 5mm (a.- f. Mike Gray; g. Peter Serov).

species (Fig. 2). Almost half the number of taxa were recorded only once or twice, mostly from extractions of flood debris and are almost certainly ‘accidentals’ washed in by flood waters. The Jenolan fauna was found to contain a greater number of genera with exotic species compared with the Tasmanian cave fauna (Greenslade 2002).

Greenslade considered that four of the Jenolan species were likely troglobites and another 10 species probable troglophiles. The troglobitic species of most interest from conservation and phylogenetic points of view (*Kenyura* sp.) is known, to date, only from a single cave. With the exception of *Coecobrya communis* (Chen and Christensen 1997) (an exotic introduced species previously incorrectly identified as *Lepidosinella armata*), none of these species has yet been described. *Coecobrya communis* was later reported by Chen et al (2005) to also occur in worm beds and is therefore considered in this work as a troglophile rather than a troglobite. Within the Jenolan Caves it has been collected from drains and gutters and on stalagmite.

All troglobitic Collembola, except *Adelphoderia* sp., were rare in the collections. *Kenyura* sp. was collected from mud banks and the surface of muddy pools; *Oncopodura* sp. from stalagmite, the surface of pools and from mud banks and *Arrhopalites* sp. from guano, although it may also be an exotic introduction (Greenslade in litt.). *Adelphoderia* sp. has been taken from stalagmite, the surface of pools, mud banks, flowstone, fungi, guano (1 record) and pitfall (one record). It was first collected by Hamilton-Smith around 1964 and was still present in 1988 surveys despite living in areas which are regularly cleaned and subject to high tourist visitation. It may be parthenogenetic as no males have been collected.

Greenslade considered the troglobitic species as the most important from a conservation standpoint and the collection sites of most importance as Mammoth, Orient and Imperial Caves (albeit probably biased by relative collecting effort).

INSECTA

Specimens belonging to the Blattodea, Orthoptera, Diptera, Lepidoptera, Hymenoptera and Psocoptera were deposited in the Entomology collections of the Australian Museum, however they do not appear to have been registered in the museum data base.

Order Coleoptera

At least seven beetle taxa belonging to four families were collected from caves. The carabid beetles were examined by Dr Barry Moore (then CSIRO) who identified three species, the most common being *Trechimorphus diemenensis* (Bates, 1878) (Fig. 4a). This species is widespread in southeast Australia, however cave forms possess shorter wings than surface forms (Moore 1964). The second species (*Meonis convexus* Sloane, 1900) has also been found in the nearby Tuglow Caves and is possibly troglophilic. The third species *Prosopogmus namoyensis* Sloane, 1895 is considered to be accidental. The pselaphid beetle *Tyromorphus speciosus* (King, 1865) was recorded by Hamilton-Smith (1966) from the Southern Limestone at Jenolan (and from caves in Victoria and Queensland). Several other pselaphids were collected by Gibian et al. (1988) which probably belong to this species, but this has not yet been confirmed. The introduced ptinine ‘spider’ beetle *Ptinus exulans* Erichson, 1842 has been reported from Jenolan (Hamilton-Smith 1967) as well as many other caves in most Australian states. The staphylinid beetle *Myotyphlus jansoni* (Matthews, 1878) was also reported by Hamilton-Smith (1967) in association with bat guano.

Other unidentified beetles or their larvae have been collected in Imperial, Mammoth, McKeowns Hole, Devil’s Coach House and Hennings Cave.

Order Orthoptera

Cave crickets (*Cavernotettix* sp.) are commonly encountered trogloxenes in the entrance, twilight and transition zones of caves (Fig. 3a). The species from Jenolan is closely related to those from other karsts in the region but remains undescribed.

Order Hemiptera

Dr Lionel Hill examined the material collected, noting some root feeding Coccoidea, one lygaeid nymph and two species of the dipsocoroid genus *Ceratocombus*. One may be *C. australiensis* Gross, 1950 but the other is undescribed. Both also occur on leaf litter in epigean habitats and are therefore regarded as troglophiles.

Order Diptera

Diptera collected or reported include sciarids (*Chaetosciara* sp. and *Corynoptera* sp.), tipulids and chironomids. They have not been identified and all are considered to be accidental or trogloxenes.

Order Lepidoptera

The guanophilic tineid moths *Monopis crocicapitella* (Clemens, 1859) and *Hofmannophila pseudosprettella* (Stainton, 1849) have been reported from within the caves associated with bat guano. Hamilton-Smith (1967) reported that *Monopis* sp.

moths have been “found in almost all bat-inhabited caves of eastern Australia, where the larvae develop on heaps of guano”. Both species of moth are cosmopolitan.

Order Hymenoptera

Ants collected in Hennings and Mammoth Caves remain unidentified.

Order Psocoptera

Booklice have been collected from detritus and guano in Mammoth, McKeowns Hole and Arch Caves. One cosmopolitan psocid (*Psyllipsocus ramburii* Selys-Longchamps, 1872) has been reported from many caves in Australia (Smithers 1964) as well as other situations and is considered to be a troglophile. The Jenolan material has not yet been identified.

ARACHNIDA

Order Acarina

Numerous mites belonging to four orders were collected both in and around the caves at Jenolan by Gibian et al., Eberhard and Holm. At least twenty-three mesostigmatid taxa (including Uropodina) were collected within the caves either in leaf litter accumulations or bat guano. Dr Bruce Halliday (2001) has published his findings on the Jenolan Mesostigmata (excluding Uropodina) and has provided preliminary information on a paper currently in preparation on the Uropodina. A single parasitic tick extracted from guano in Paradox Cave has been identified (considered to be a reptile parasite) but the remaining Jenolan mite fauna has not been further examined. This includes mites from three families of the suborder Prostigmata found in low numbers in various caves. Oribatids were present in most samples and were sometimes abundant. No work has been done on these two suborders at Jenolan.

Most of the mites collected are also known from surface habitats. Four species have been described from the Jenolan cave material (Halliday 2001) and descriptions of a further four Uropodina species are pending (Halliday in litt. 2013). None of the mites described displayed morphology associated with adaptations to subterranean life. We have tentatively classified about half of the recorded taxa as troglophiles on the basis of their being recorded, to date, only from within the caves or having been recorded in caves on several occasions, even though some are also well known from surface habitats.

Order Araneae

Spiders are the most commonly seen arachnids in surface and cave habitats at Jenolan. The best known species is the troglophilic ‘social spider’, *Badumna socialis* (Rainbow, 1905) (Desidae, Fig. 3b), whose sheet webs are common on the roof and walls of Jenolan’s Grand Arch through which the road passes. Their web density can be so great that individual webs merge to form a single large sheet, punctured by the entrance holes of each spider. Clumps of web periodically fall off the roof, and it was suggested that dust and chemical pollution from vehicles might be adversely affecting the population (James et al. 1990). While it was found that the webs were highly polluted by lead from vehicle exhaust fumes (Hose et al. 2002), direct effects on the spider population were not demonstrated, but continuing monitoring of the arch population was recommended. The species is also found in arch habitats at Colong, Abercrombie and Wombeyan. Few are seen in caves beyond the cave arch and entrance regions, where local air currents (and night lighting) probably bring in a steady supply of insect food. The genetic relationships between the different arch populations, and a close surface relative, *Badumna longinqua* (Koch, 1867) need testing to properly assess their taxonomic and conservation status. A limited protein electrophoretic study (Gray, unpublished) showed phylogeographic differentiation between the Jenolan and Wombeyan populations. *Stiphidion facetum* Simon, 1902, a widely distributed surface species, is also commonly seen in hammock-like sheet webs on the walls of the Grand Arch (Figs 3c and 3d).

The first spider described from Jenolan Caves was the troglophilic linyphiid, *Laetesia weburdi* named for the Head Guide, Joseph Wiburd (name misspelt by Urquhart). *Laetesia weburdi* (Fig. 3e) is a relatively small spider with slender legs and variable pigmentation (dark to pale). It is found in small sheet webs suspended from walls and formation. The species was originally placed in genus *Linyphia*, but in reassigning this species to *Laetesia,* van Helsdingen (1972) noted its close similarity to species from cave and surface habitats in south west Australia, notably, *L. mollita* Simon, 1908 (the type species of the genus). A second linyphiid, as yet undescribed, is a troglobitic species, lacking both pigment and eyes. It is smaller and much rarer than *L. weburdi* and is known only from one male (in poor condition) and juveniles. The webs are similar to those of *L. weburdi* and were associated with moist formation in Imperial and River Caves. Recent searching has so far failed to find the additional material necessary to properly describe the species.

An interesting group of theridiid spiders are tentatively placed in the genus *Icona*, otherwise only known from the subantarctic islands of New Zealand (Forster 1955a and 1964). They were originally placed in *Steatoda* (in Gray 1973), and subsequently reassigned to 'in or near' *Icona* following examination by H.W. Levi (pers. comm.). These spiders, currently undescribed, are distributed across southern Australia as troglophilic and troglobitic species. At Jenolan there is at least one unidentified species of this group (Fig. 4d), a relatively common troglophile with varying degrees of depigmentation (it was at first thought to represent two species). These troglophiles were described as having "scatty webs over mud or leaf litter deposits" (Gibian et al. 1988).

A small troglobitic species of theridiid from Hennings Cave (Fig. 4e) was also previously included under *Icona* (in Gibian et al. 1988, Eberhard and Spate 1995). The taxonomic placement of this eyeless and totally depigmented species must wait until adult specimens are available.

A troglophilic species of *Cryptachaea* is widely distributed in south-eastern Australia: *C. gigantipes* (Keyserling, 1890) is recorded from a number of NSW caves (Smith et al. 2012), including Jenolan (previously as *Achaearanea veruculata* (Urquhart, 1885) in Gibian et al. 1988, Eberhard and Spate 1995). This large species makes a typical theridiid 'gumfoot' capture web.

Like the linyphiids, the other web building troglophiles are very small. These include members of two surface litter dwelling families: Micropholcommatidae (0.5-1.5 mm) spiders found on mud banks, in litter debris and in small webs on stalagmites; Mysmenidae (up to 2 mm) where a male was taken from a 'small web'. On close examination these webs are usually seen to be modified orb webs.

Small theridiosomatid spiders (*Baalzebub* sp.) are often seen in cave entrance, twilight and transition zones in their distinctive cone-shaped orb webs. These spiders use a central tension line to maintain this web shape; they release the tension when prey approaches allowing the sticky orb web to rebound over it.

The non web-building spider fauna includes several vagrant troglophilic hunters often associated with loose rock, soil bank, guano deposit, litter detritus and root mass habitats. Most belong to genera endemic to Australia and New Zealand. *Cycloctenus abyssinus* (family Cycloctenidae) has been periodically recorded in cave habitats. The original description (by Urquhart 1890) was of a female and subadult males; Rainbow (1893) described an adult male and referred to several female specimens, but the whereabouts of these are unknown, and today there are no pre-1900 specimens or males currently recorded in the Australian Museum collections. These spiders are well pigmented and have large eyes and are probably conspecific with a surface species. The spiders are not often seen, but are probably an important predator in the caves ecosystem.

Kaiya terama Gray, 1987 (Gradungulidae) has been found in several caves at Jenolan, and is a common epigean log and litter dwelling species.

Tasmanoonops spp. (Orsolobidae) are much smaller spiders that are found in similar surface habitats. They have been collected in Elder and Hennings caves associated with moist habitats, including hanging root masses.

Order Opiliones

One troglophilic species, the triaenonychid *Holonuncia cavernicola* (Fig. 3f) was originally described from "Jenolan Caves" (Forster 1955b) and re-described by Hunt (1992) based on the holotype and additional material collected by Gibian et al. (1988), Hunt and others. While the species regularly occurs in caves at Jenolan, specimens are also found in epigean habitats. The harvestman in caves at Tuglow is tentatively assigned to *H. cavernicola*. Other species in the genus *Holonuncia* are found within multiple karsts in southern New South Wales. Pigmentation and eye size varied between cave and surface populations but also within cave populations (Hunt 1992).

A second species of harvestman, the neopilionid *Megalopsalis* sp. is known from two specimens collected from the entrance chamber of Mammoth Cave and is probably accidental in caves.

Order Pseudoscorpiones

Three species have been collected at Jenolan. One is probably an accidental; the other two were described by Chamberlin (1962) with only vague locality data but have since been confirmed to occur at Jenolan. *Sathrochthonius tuena* (Fig. 4b) is a guanophile from Bow and Paradox Caves as well as from Wombeyan Caves. The other is a troglobite, *Pseudotyrannochthonius jonesi* (Fig. 4c) known from Imperial Cave and the Chevalier extension.

MYRIAPODA

Order Geophilomorpha

A geophilomorph centipede seen on flowstone in Hennings may be an accidental.

Order Polydesmida

Polydesmid millipedes collected from several caves are considered to be troglophiles. No further work has been carried out.

CRUSTACEA

Gibian et al. (1988) recorded the first aquatic cave fauna from Jenolan, reporting amphipods (Crangonyctidae), copepods (Harpacticoida, Cyclopoida) and ostracods. This material, augmented by the more extensive collections of Eberhard (1993), has been re-examined and some identifications amended to at least six aquatic taxa.

Order Cyclopoida

At least two, possibly three, species of copepod have been collected in Mammoth and Lucas caves. The two species that have been identified are well known surface copepods and may be accidentals or stygophiles. The third putative species remains unidentified.

Order Isopoda

Two species of terrestrial oniscid slaters have been collected, one strongly pigmented and eyed from Elder Cave, the other is a single weakly pigmented specimen (*Styloniscus* sp.) from Mammoth Cave. We have been unable to locate the Elder Cave specimen and the *Styloniscus* specimen has not been further studied.

One species of aquatic phreatoicoid isopod (*Crenoicus* sp.) has been netted in both the Imperial resurgence and in Paradox Cave by Eberhard. It is likely stygophilic but has not been further studied.

Order Amphipoda

Eberhard trapped the eusirid amphipod *Pseudomoera fontana* (Sayce, 1902) in both the Northern Stream sink and the Imperial Cave resurgence; it is a common species in southeast Australian streams and is either an accidental or stygophile.

Neoniphargid amphipods were trapped in both Paradox Cave and the Imperial streamway. Bradbury and Williams (1997) described the stygobitic *Neocrypta simoni* based on the material collected by Stefan Eberhard in Paradox Cave (Fig. 4f); five specimens netted in the Imperial River by Gibian, Smith and Wheeler have not been identified as yet.

Order Anaspidacea

Eberhard (1993) collected stygobitic syncarids (Psammaspididae) by placing baits (kippers in brine) in the Imperial and Spider Cave rivers and in perched seepage fed pools well above the river level. Mia Thurgate collected more from the Pool of Reflections in River Cave in 2000. Psammaspidids (Fig. 4g) are a primitive group of eyeless crustaceans recorded from ground waters in eastern Australia. No further taxonomic work has been conducted on this interesting material.

MOLLUSCA

Class Gastropoda

Pommerhelix depressa (Hedley, 1901) and *Elsothera sericatula* (Pfeiffer, 1849) have been collected in Casteret Cave and caves in the southern limestone. Eberhard collected the aquatic snail *Glacidorbis hedleyi* Iredale, 1943 at the Imperial resurgence. Snails collected by Gibian et al. (1988) have not been examined.

ANNELIDA

Terrestrial and aquatic oligochaetes were reported by Gibian et al. (1988) and Eberhard (1993) but not further identified.

NEMATODA

Terrestrial and aquatic nematodes were reported by Gibian et al. (1988) and Eberhard (1993) but not further identified.

PLATYHELMINTHES

Flatworms of the Orders Paludicola and Terricola were reported by Eberhard from Wiburds Lake, Mammoth and Serpentine Caves.

DISCUSSION

Comparisons of biodiversity patterns between different karst areas can be fraught with biases including, inter alia, area effects and differences in survey effort, methods and taxonomic biases, as well as bias towards troglobitic/stygobitic species, incorrect ecological classification, provincialism and other fallacies (see Culver et al. 2013). Nevertheless we consider it timely to undertake a brief re-appraisal of Jenolan's cave fauna to place its significance in a regional and national context, especially because a great deal of subterranean fauna research has occurred elsewhere in Australia (see Guzik et al. 2011) since the previous Jenolan and New South Wales inventory by Eberhard and Spate (1995); Thurgate et al. (2001a, 2001b).

Jenolan retains its status with the highest recorded subterranean taxonomic diversity (136 taxa) of any karst area in New South Wales, which is at least partly an artefact of high survey effort, with Jenolan drawing the attention of biologists over many decades. Notwithstanding, we hypothesise that other environmental factors may be responsible. Firstly, Jenolan is highly karstified and hosts the most extensive cave system in New South Wales with over 40km of surveyed cave passage. This subsurface 'area effect' is consistent with studies elsewhere (e.g. Graening et al. 2006) which show increasing cave length correlates with increasing species richness. Secondly, Jenolan is a topographically diverse fluvial karst with many large-sized cave entrances (vertical and horizontal) and multiple sinking streams which facilitate active colonisation of caves by animals, but also particularly, their passive transport underground (by gravity, water or air), which may partly account for the high proportion (53%) of taxa classified as 'cave accidentals' in our inventory. This ratio is not dissimilar to 42% recorded in a desktop bio-inventory of the Nullarbor which is a significantly larger karst area (by > 2 orders magnitude) but similarly characterised by multiple large-sized cave entrances where collecting efforts have historically tended to focus (Eberhard in litt.).

While the classification of taxa as 'accidentals' or otherwise (trogloxene, troglophile, troglobite) is often necessarily inferred owing to limitations in survey data and knowledge of species taxonomy and ecology, ambiguous classification or misinterpretation of troglomorphic traits may skew interpretation of site 'significance' when assessed in terms of total species richness. For this reason, many comparisons between karst areas in the literature are restricted (arguably biased) towards troglomorphic species (presumed troglobites and stygobites, see Culver and Sket (2000). Notwithstanding, troglobites and stygobites are more typically short-range endemic species and therefore more vulnerable to threats and extinction from environmental changes. On this basis a high conservation significance may be attributed to troglobites and stygobites.

In paving the way for standardized and comparable subterranean biodiversity studies, Culver et al. (2013) concluded that it is necessary to treat troglobites and stygobites differently from non-obligate species, because differences of opinion exist as to which species are troglobites and stygobites. In our opinion the eight species considered likely to be troglobites or stygobites at Jenolan (revised from 14 troglomorphic species earlier reported by Thurgate et al. 2001a) ranks as fairly typical for karst areas in the eastern highlands (Eberhard and Spate 1995). At this point in discussion it is appropriate to correct an error in the Jenolan Karst Conservation Reserve Draft Plan of Management (Department of Environment and Conservation NSW, undated, p. 49) which mistakenly reports 147 species of troglobitic [sic] fauna.

We consider it likely that additional obligate subterranean species remain to be discovered at Jenolan, especially in the poorly sampled epikarst, vadose, deep phreatic and interstitial aquatic habitats, and terrestrial meso-cavern habitats. Our prediction is based partly on the diversity known from Wombeyan Caves, located 55 kilometres south of Jenolan, which has a high diversity (11 species) of stygobitic amphipods (Bradbury and Williams 1997). For comparison, the richest obligate cave fauna recorded from eastern Australia is Bayliss Cave, a lava tube in north Queensland, with 20 species of troglobites (Culver and Sket 2000). Tasmania is also relatively diverse with 15 or more obligate species recorded from well-developed karst areas (Eberhard 1996).

The fallacy of provincialism as termed by Culver et al. (2013) occurs when data from one 'favoured' place is treated differently than data from other places. In applying the metaphor 'from rags to riches' to highlight subterranean biodiversity in New South Wales, Thurgate et al. (2001a) may have been justifiably optimistic, however, this paradigm deserves to be reappraised in the national context considering subsequent discoveries of remarkably diverse subterranean faunas in other states. Recently in Western Australia sampling of deep groundwater aquifers has revealed the existence of diverse (> 60 species) stygobite communities (e.g. Eberhard et al. 2009). Sampling of terrestrial meso-cavern habitats in iron-ore and calcrete rocks has also revealed highly diverse troglobite communities comprising > 45 obligate species (S. Eberhard in litt.).

FUTURE RESEARCH AND CONSERVATION PRIORITIES

The Jenolan Karst Conservation Reserve Draft Plan of Management (Department of Environment and Conservation NSW, undated) recognises that cave fauna is highly susceptible to disturbance and recommends further investigation into the potential impacts of human activities on the conservation of these species. The material from the 1986-1993 collections represent a reasonable baseline survey for Jenolan Caves. Nevertheless cave fauna, especially the highly adapted species, are usually rare and it is highly likely that further intensive collection efforts would result in new taxa being found. Alternative collection techniques used for aquatic micro-fauna and terrestrial meso-cavern habitats e.g., damp leaf litter packs (Weinstein and Slaney, 1995) should be evaluated as they may effectively sample taxa that were not collected using the methods previously employed. The current state of knowledge, gaps and research priorities are summarised in Table 2.

A great deal of the material collected has not yet been sorted to species level. New species still await formal description due to the very limited funding and diminishing taxonomic resources available in Australia. Future collection efforts could concentrate on obtaining specimens of groups where a funded taxonomist is available, or aim to increase the number and quality of specimens of certain important troglobitic and stygobitic representatives (e.g. by obtaining more mature material, including both sexes) or seek information on their biology and ecology, about which virtually nothing is known.

The species of most conservation interest are those species restricted to the subterranean environment, especially the troglobites and stygobites. The physical extent and degree of karstification at Jenolan, and the hypothesised presence of undiscovered troglobitic and stygobitic taxa in the mesocavern and other cryptic aquatic habitats, emphasises the importance of the continuing biological exploration of this significant subterranean ecosystem.

ACKNOWLEDGEMENTS

We would like to thank Louise Smith (previously L. Wheeler), the Jenolan Caves Reserve Trust and the Australian Museum for their support with the 1986-93 collection work and especially Ernest Holland for his supervision, support and advice. We are indebted to the following taxonomists who have worked on the Jenolan fauna: Dr Chris Allen, Dr Max Beier, Dr John H. Bradbury, Dr Cathy Car, Dr Peter Cranston, Dr Alison Green, Dr Penelope Greenslade, Dr Bruce Halliday, Mr Danilo Harms, Dr Mark Harvey, Dr Lionel Hill, Dr Glenn Hunt, Dr Tomislav Karanovic, Dr Robert Mesibov, Mr Graham Milledge, Dr Barry Moore, Dr Ebbe Nielsen, Dr Winston Ponder, Mr Peter Serov, Dr John Stanisic, Dr Michael Rix, Professor William (Bill) Williams, Dr George (Buz) Wilson.

REFERENCES

pdf files of unpublished reports denoted with asterix(*) are available from the author for correspondence

Barnard, J.L. and Karaman, G.S. (1982). Classificatory revisions in gammaridean Amphipoda (Crustacea), Part 2. *Proceedings of the Biological Society of Washington* **95**, 167–187.

Beier, M. (1966). On the Pseudoscorpionidea of Australia. *Australian Journal of Zoology* **14**, 275–303.

Beier, M. (1967). Some Pseudoscorpionidea from Australia, chiefly from caves. *The Australian Zoologist* **14**, 199–205.

Bradbury, J. H. and Williams, W. D. (1997). The amphipod (Crustacea) stygofauna of Australia: description of new taxa (Melitidae, Neoniphargidae, Paramelitidae), and a synopsis of known species. *Records of the Australian Museum* **49**, 249–341.

Chamberlin, J. (1962). New and little known false scorpions, principally from caves, belonging to the families Chthoniidae and Neobisiidae. *Bulletin of the American Museum of Natural History* **123**, 301–352.

Chen, J., Leng, Z, and Greenslade, P. (2005). Australian species of *Sinella* (*Sinella*) Brook (Collembola: Entomobryidae). *Australian Journal of Entomology* **44,** 15–21.

Clark, S.A. (2009). A review of the land snail genus *Meridolum* (Gastropoda: Camaenidae) from central New South Wales, Australia. *Molluscan Research* **29**, 61–120.

Culver, D.C. and Sket, B. (2000). Hotspots of subterranean biodiversity in caves and wells. *Journal of Cave and Karst Studies* **62,** 11–17.

Culver, D.C., Trontelj, P., Zagmajster, M., and Pipan, T. (2013). Paving the way for standardized and comparable subterranean biodiversity studies. *Subterranean Biology* **10,** 43–50.

Dew, B. (1963). Cave animals. *Journal of the Sydney University Speleological Society* **6**, 10–28.

*Eberhard, S. (1993). Survey of fauna and human impacts in the Jenolan Caves Reserve. Unpublished report produced for the Jenolan Caves Reserve Trust, New South Wales, Australia. April 1993. 16pp.

Eberhard, S.M. (1996). Tasmanian cave fauna. In 'Encyclopedia Biospeologica Tome III.' (Eds. C. Juberthie and V. Decu) pp. 2093-2103. (Societe Internationale de Biospeleologie, Moulis– Bucarest).

*Eberhard, S. and Spate, A. (1995). Cave invertebrate survey: Toward an atlas of NSW Cave Fauna. 112pp. (A report prepared under the New South Wales Heritage Assistance Program NEP 94 765. November 1995).

Eberhard, S.M., Halse, S.A., Williams, M., Scanlon, M.D., Cocking, J.S. and Barron, H.J. (2009). Exploring the relationship between sampling efficiency and short range endemism for groundwater fauna in the Pilbara region, Western Australia. *Freshwater Biology* **54**, 885–901.

Forster, R. R. (1955a). Spiders from the subantarctic islands of New Zealand. *Records of the Dominion Museum Wellington* **2,** 167–203.

Forster, R.R. (1955b). Further Australian harvestmen (Arachnida: Opiliones). *Australian Journal of Zoology* **3**, 354–411.

Forster, R. R. (1964). The Araneae and Opiliones of the subantarctic islands of New Zealand. *Pacific Insects Monograph* **7,** 58–115.

Table 2. State of knowledge, gaps and research priorities.

Higher Group	Relative Diversity	Taxonomic Resolution	Comments	Research Priorities
Entognatha: Collembola	High	Good	Well sampled and identified, includes troglobites and undescribed n. sp.	Describe n. sp. especially troglobites
Insecta: Coleoptera	Moderate	Good	Well sampled and identified in macro-cavern habitats but meso-cavern habitats poorly sampled	Sample meso-cavern habitats
Insecta: Others	Moderate	Poor	Poor taxonomic resolution	Identify existing collections
Arachnida: Araneae	High	Good	Generally well sampled and identified, but includes rare troglobites and undescribed n. sp.	Targeted sampling of troglobites and describe n. sp.
Arachnida: Acarina	High	Good	Well sampled and identified	Describe n. sp.
Arachnida: Others	Low	Good	Well sampled and identified in macro-cavern habitats but meso-cavern habitats poorly sampled	Sample meso-cavern habitats
Crustacea	Moderate	Moderate	Poorly sampled, likely to be more diverse, especially micro-crustacea	Sample deep aquatic habitats, identify and describe n. sp.
Myriapoda	Low	Poor	Poor taxonomic resolution	Identify existing collections
Gastropoda	Low	Excellent	Terrestrial snails sampled and identified, aquatic snails poorly sampled (Hydrobiidae)	Sample deep aquatic habitats
Annelida, Nematoda, Platyhelminthes	Low	Poor	Poorly sampled, likely to be more diverse, especially aquatic Oligochaeata	Sample deep aquatic habitats

Forster, R.R., Platnick, N.I. and Gray, M.R. (1987). A review of the spider superfamilies Hypochiloidea and Austrochiloidea (Araneae, Araneomorphae). *Bulletin of the American Museum of Natural History* **185,** 1–116.

*Gibian, M., Smith, G. and Wheeler, L. (1988). Interim report on the survey of the invertebrate fauna of Jenolan Caves 3rd August, 1988. 12 pp. Unpublished.

Graening, G. O., Slay, M.E. and Bitting, C. (2006). Cave fauna of the Buffalo National River. *Journal of Cave and Karst Studies* **68(3)**, 153–163.

Gray, M. (1973). Survey of the spider fauna of Australian Caves. *Helictite* **11**, 47–75.

Gray, M.R. (1983). The taxonomy of the semi-communal spiders commonly referred to the species *Ixeuticus candidus* (L. Koch) with notes on the genera *Phryganoporus, Ixeuticus* and *Badumna* (Araneae, Amaurobioidea). *Proceedings of the Linnean Society of New South Wales* **106**, 247–261.

Greenslade, Penelope (1992). The identity of Australian specimens recorded as *Lepidosinella armata* Handschin 1920 (Collembola: Entomobryidae) with a key to Australian *Sinella* and *Coecobrya*. *Journal of the Australian Entomological Society* **31**, 327–330.

Greenslade, Penelope (2002). Systematic composition and distribution of Australian cave collembolan faunas with notes on exotic taxa. *Helictite* **38**, 11–15.

*Greenslade, Penelope (2011). Collembola from Jenolan caves. *Unpublished report to the New South Wales National Parks Service. November 1989,* amended July 1993, corrected May 2011.

Guzik, M., Austin, A., Cooper, S., Harvey, M., Humphreys, W., Bradford, T., Eberhard, S.M., King, R., Leys, R., Muirhead, K., Tomlinson, M. (2011). Is the Australian subterranean fauna uniquely diverse? *Invertebrate Systematics* **24(5),** 407–418. http://dx.doi.org/10.1071/IS10038.

Halliday, R.B. (2001). Mesostigmatid mite fauna of Jenolan Caves, New South Wales (Acari: Mesostigmata). *Australian Journal of Entomology* **40**, 299–311.

Halliday, B. and Mašan, P. (2008). *Pachydellus hades* (Halliday) (Acari: Pachylaelapidae), a European mite species described from Australia. *Australian Journal of Entomology* **47**, 225–226.

Hamilton-Smith, E. (1966). Pselaphidae from Australian Caves. *Journal of the Entomological Society of Queensland* **5**, 70–71.

Hamilton-Smith, E. (1967). The Arthropoda of Australian Caves. *Journal of the Australian Entomological Society* **6**, 103–118.

Hamilton-Smith, E. and Adams, D.J.H. (1966). The alleged obligate ectoparasitism of *Myotyphlus jansoni* (Matthews) (Coleoptera: Staphylinidae). *Journal of the Australian Entomological Society* **5**, 44–45.

Harms, D. and Harvey, M.S. (2009). A review of the pirate spiders of Tasmania (Arachnida, Mimetidae, *Australomimetus*) with description of a new species. *Journal of Arachnology* **37**, 188–205.

Harms, D. and Harvey, M.S. (2013). Review of the cave-dwelling species of *Pseudotyrannochthonius* Beier (Arachnida: Pseudoscorpiones: Pseudotyrannochthoniidae) from mainland Australia, with description of two troglobitic species. *Australian Journal of Entomology* **52,** 129–143.

Heimer, S. (1986). Notes on the spider family Mimetidae with description of a new genus from Australia (Arachnida, Araneae). *Entomologische Abhandlungen. Staatliches Museum für Tierkunde Dresden* **49**, 113–137.

Helsdingen, P.J. van (1972). An account of money spiders from down under (Araneida, Linyphiidae). *Zoologische Mededelingen* **47**, 369–390.

Hose, G.C., James, J.M. and Gray, M.R. (2002). Spider webs as environmental indicators. *Environmental Pollution* **120,** 725–733.

Hunt, G.S. (1992). Revision of the genus *Holonuncia* Forster (Arachnida: Opiliones: Triaenonychidae) with description of cavernicolous and epigean species from Eastern Australia. *Records of the Australian Museum* **44**, 135–163.

James, J.M., Gray, M. and Newhouse, D.J. (1990). A preliminary study of lead in cave spider's webs. *Helictite* **28**, 37–40.

Moore, B. P. (1964). Present day cave beetle fauna in Australia: a pointer to past climate change. *Helictite* **3,** 69–74.

Office of Environment & Heritage NSW (October 2013). Draft Plan of Management Jenolan Karst Conservation Reserve. NSW National Parks and Wildlife Service. 102 pp. http://www.environment.nsw.gov.au/parkmanagement/JenolanKCRdraftPOM.htm

Rainbow, W. J. (1893). Descriptions of some new Araneidae of New South Wales. No. 1. *Proceedings of the Linnean Society of New South Wales* (2) **7,** 471–476.

Rainbow, W. J. (1904). Studies in Australian Araneidae III. *Records of the Australian Museum* **5**, 326–336.

Rainbow, W. J. (1905). Studies in Australian Araneidae IV. *Records of the Australian Museum* **6**, 9–12.

Rainbow, W. J. (1911). A census of Australian Araneidae. *Records of the Australian Museum* **9,** 107–319.

Richards, A.M. and Lane, E.A., (1966). Exotic Collembola from Jenolan Caves, N.S.W. *Helictite* **4**, 88–89.

Rix, M. G. and M. S. Harvey. (2010). The spider family Micropholcommatidae (Arachnida, Araneae, Araneoidea): a relimitation and revision at the generic level. *ZooKeys* **36,** 1–321.

Smith, H., Vink, C.J., Fitzgerald, B.M. and Sirvid, P.J. (2012). Redescription and generic placement of the spider *Cryptachaea gigantipes* (Keyserling, 1890) (Araneae: Theridiidae) and notes on related synanthropic species in Australasia. *Zootaxa* **3507**, 38–56.

Smithers, C.N. (1964). New records of cave and mine-dwelling Psocoptera in Australia. *Australian Journal of Entomology* **3**, 85.

Thurgate, M.E., Gough, J.S., Spate, A. and Eberhard, S. (2001a). Subterranean biodiversity in New South Wales: from rags to riches. *Records of the Western Australian Museum Supplement* **64**, 37–47.

Thurgate, M.E., Gough, J.S., Clarke, A.K., Serov, P. and Spate, A. (2001b). Stygofauna diversity and distribution in Eastern Australian cave and karst areas. *Records of the Western Australian Museum Supplement* **64**, 49–62.

Urquhart, A. T. (1890). On two species of Araneae new to science, from the Jenolan Caves, New South Wales. *Transactions of the New Zealand Institute* **22,** 236–239.

Weinstein, P. and Slaney, D.P. (1995). Invertebrate faunal survey of Rope Ladder Cave, North Queensland: a comparative study of sampling methods. *Journal of the Australian Entomological Society* **34**, 233–236.

Appendix
(next 18 pages)
Invertebrate fauna collected within the caves at Jenolan

*** Specimens identified by Dr C.B. Allen (CA), Dr M. Beier (MB), Dr J.H. Bradbury (JB), Dr C. Car (CC), Dr P. Cranston, Dr M. Gray (MG), Dr A. Green (AG), Dr P. Greenslade (PG), Dr B. Halliday (BH), Dr M. Harvey (MH), Dr L. Hill (LH), Dr G. Hunt (GH), Dr T. Karanovic (TK), Dr H.W. Levi (HL), Dr R. Mesibov (RM), Mr G. Milledge (GM), Dr B. Moore (BM), Dr E. Nielsen (EN), Dr W. Ponder (WP), Dr M. Rix (MR), Mr P. Serov (PS), Dr H. Smith (HS), Dr J. Stanisic (JS), Prof. W. Williams (WW), Dr G. Wilson (GW). Typ = type specimen(s). References to Smith as collector are G. Smith unless indicated otherwise.**

**** Native or introduced/cosmopolitan**

***** Ecological Status: Accidental (Ac), Guanophile (Gp), Stygophile (Sp), Stygobite (Sb), Troglophile (Tp), Troglobite (Tb), Trogloxene (Tx)**

****** Institutional abbreviations: Australian Museum, Sydney (AMS), American Museum of Natural History, New York (AMNH), Australian National Insect Collection, Canberra (ANIC), National Museum of New Zealand, Wellington (NMNZ), South Australian Museum, Adelaide (SAMA)**

PHYLUM or CLASS **Subclass** **Order** **Family** Taxa	**ID. by** *	**N or I/C** **	**ES** ***	**Comments on identification and name**	**Caves**	**Reference(s) and/or Location of specimens** ****
CLASS ENTOGNATHA						
Subclass Collembola						
Family Hypogastruridae						
Triacanthella sp.	PG	N	Tp?	Not further identifiable	Bow, Mammoth; terrestrial soil species	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Ceratophysella denticulata (Bagnall, 1941)	PG	I/C	Ac		Orient; Bow, Mammoth; cosmopolitan species very common in disturbed habitats in SE Australia; easily washed into caves	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Ceratophysella gibbosa (Bagnall, 1940)	PG	I/C	Ac		Orient; Bow, Mammoth; cosmopolitan species very common in disturbed habitats in SE Australia; easily washed into caves	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Mesogastrura libyca (Caroli, 1914)	PG	I/C	Tp		Imperial, single collection behind Lot's Wife; originally described from Tripoli and known in Europe from both terrestrial and cave habitats	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Family Oncopoduridae						
Oncopodura n.sp.	PG	N	Tb	New troglobiont so far only known from Jenolan Caves although a few specimens of *Oncopodura* from Jaunter and Bungonia are in collections	Imperial, Mammoth, Hennings, Wiburds Lake (stalagmite, surface of pools, mud bank)	Gibian et al. (1988), Thurgate et al. (2001a); Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Family Sminthuridae						
Adelphoderia n.sp.	PG	N	Tb	A troglobiont species belonging to an Australian endemic genus	Imperial, Orient, Lucas, Barralong, Chifley, Elder, Hennings, Mammoth, Paradox, Wiburds Lake (pool surfaces, mud banks, stalagmite, flowstone, fungi, guano)	Greenslade (2002); Greenslade (2011); Thurgate et al. (2001a); SAMA and/or ANIC
Arrhopalites sp.	PG	I/C?	Tp		Single specimen from Paradox; other species of genus found in caves in North America and Europe (guano)	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC

Temeritas sp.	PG	N	Ac	Not further identifiable	Mammoth; native terrestrial species; genus occurs in eucalypt forests and is associated with fungi on rotting logs	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Family Onychiuridae						
Onychiurus sp. *fimetarius* (Linnaeus) group	PG	I/C	Tp		Imperial, Orient, Mammoth, Elder, Devil's Coach House, Bow; cosmopolitan soil species, probably introduced	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Family Tullbergidae						
Mesophorura sp. *krausbaueri* Börner group	PG	I/C	Tp	Not further identifiable	Orient, Mammoth, Devil's Coach House, Serpentine, Bow; cosmopolitan terrestrial species	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Tullbergia sp.	PG	N	Tp	Not further identifiable	Orient, Bow, Mammoth, Wiburds Lake; terrestrial native soil species	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Dinaphorura sp.	PG	N	Tp	Not further identifiable	Mammoth; terrestrial native soil dwelling species	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Family Odontellidae						
Odontella sp. 1, sp. 2, sp. 3	PG	?	Ac		Bow (all 3 species from Bow)	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
gen. nov. nr *Odontella*	PG	N	Ac	Not further identifiable	Bow	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Family Neanuridae						
Neanura muscorum (Templeton, 1835)	PG	I/C	Ac		Orient, Mammoth, Bow; cosmopolitan species found in improved pasture in SE Australia	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Australonura sp. nr *meridionalis* Stach, 1951	PG	?	Tp		Mammoth, Devil's Coach House, Bow	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Undetermined Lobellini	PG	N	Tp	Not further identifiable	Mammoth, Bow; terrestrial native species	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Kenyura n.sp.	PG	N	Tb?	May belong to a new genus or to *Kenyura* which has not previously been recorded in Australia, but is known to exist in Qld and NE Tasmania; possibly true troglobite as some setae elongated	Mammoth (mud bank, surface of muddy pools)	Thurgate et al. (2001a); Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Ceratrimeria sp.	PG	?	Ac		Bow	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC

Family Neelidae					
Megalothorax sp.	PG	N	Tp	Not further identifiable	Serpentine; all species in genus live in soil and moss in humid habitats	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Family Brachystomellidae						
Brachystomella sp.	PG	?	Ac		Mammoth, Bow	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Subclavontella sp.	PG	?	Ac		Bow	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Family Entomobryidae						
Coecobrya communis (Chen and Christensen, 1997)	PG	I/C	Tp	First reported as *Lepidosinella armata* (Richards and Lane 1966). Greenslade (1992) later considered original and additional material from Orient Cave as *Coecobrya* nr *hoeffti*. Greenslade (2002) later records the species as *Sinella* (*Coecobrya*) *communis*, an exotic introduction	Orient (drain and gutter; stalagmite); also known from worm beds as well as caves overseas	Richards and Lane (1966); Thurgate et al. (2001a); Greenslade (1992); Greenslade (2002); pre-1989 specimens in NMNZ; more recent material in SAMA and/or ANIC
Lepidocyrtus sp.	PG	N?	Ac	Immature; not further identifiable	Devil's Coach House, Serpentine, Paradox; probably a native terrestrial species	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Ascocyrtus cinctus Schaeffer, 1898	PG	N	Ac		Serpentine; common, native terrestrial species with widespread distribution in forest leaf litter of SE Asia and SW Pacific	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Family Isotomidae						
Folsomia candida (Willem, 1902)	PG	I/C	Tp		Imperial, Orient, Barralong, Mammoth, Chifley, Devil's Coach House, Serpentine, Bow, Wiburds Lake, Paradox; cosmopolitan species, rare in terrestrial habitats. First described from caves in Belgium; frequently encountered in animal cultures and pot plants	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Folsomides exiguus Folsom 1932	PG	N	Ac		Bow; native terrestrial species; soils in humid forests	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Isotoma sp.	PG	?	Ac		Bow	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC

Parisotoma sp.	PG	?	Ac		Bow	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Cryptopygus caecus Wahlgren, 1906	PG	N	Ac	Initially determined as *Isotomodes* by Salmon	Guano, cave not specified; common soil and humus species in SE forests and subantarctic islands	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
cf. *Cryptopygus* sp.	PG	N	Ac	Not further identifiable	Bow; native terrestrial species	Greenslade (2002); Greenslade (2011); SAMA and/or ANIC
Order Protura						
Undetermined	PG	?	Ac		Mammoth	Gibian et al. (1988); whereabouts unknown, probably SAMA and/or ANIC
CLASS INSECTA						
Order Blattodea						
Undetermined		N	Ac			Gibian et al. (1988); whereabouts unknown, probably AMS
Order Orthoptera						
Family Rhaphidophoridae						
Cavernotettix sp.		N	Tx		Arch, Orient, Mammoth	Gibian et al. (1988); photocopied page titled Jenolan NSW 24-25 Oct 1987 (Eric Holm) probably never published; whereabouts unknown, probably AMS
Order Hemiptera						
Undetermined Coccoidea	LH	N	Ac?		Devil's Coach House (flood debris)	Gibian et al. (1988); Lionel Hill (in litt. 1989); specimens currently with LH but will be deposited in AMS
Undetermined Hemiptera						Gibian et al. (1988); whereabouts unknown, probably AMS
Family Lygaeidae						
Undetermined Rhyparochrominae	LH	N	Ac	Single nymph	Devil's Coach House (flood debris)	Lionel Hill (in litt. 1989); specimens currently with LH but will be deposited in AMS
Family Ceratocombidae						

Ceratocombus 2 spp.	LH	N	Ac	Lionel Hill (in litt. 1989) suggests one of these species may be *Ceratocombus australiensis* Gross	Mammoth, Devil's Coach House, Serpentine (surface or edges of pools, mud banks, flood debris); both species known to occur in epigean leaf litter — probably washed into caves	Lionel Hill (in litt. 1989); specimens currently with LH but will be deposited in AMS
Order Psocoptera						
Undetermined Psocoptera	GC	?	Tp?		Mammoth, McKeowns Hole, Arch (guano, litter, mud bank)	Gibian et al. (1988); whereabouts unknown, probably AMS
Order Diptera						
Undetermined flies			Ac?		Hennings, Wiburds Lake, Devil's Coach House (flood bypass), Mammoth, Serpentine, Elder, McKeowns Hole, Bow	Gibian et al. (1988); T. Moulds (in litt. 2013) whereabouts unknown, probably AMS
Family Tipulidae						
Undetermined			Ac?			Gibian et al. (1988); whereabouts unknown, probably AMS
Family Chironomidae						
Undetermined			Ac?			Gibian et al. (1988); whereabouts unknown, probably AMS
Family Sciaridae						
Chaetosciara sp.	PC	?	Ac?		Lucas (pool of water)	Photocopied page titled Jenolan NSW 24-25 Oct 1987 (Eric Holm), probably never published; whereabouts unknown, probably ANIC
Corynoptera sp.	PC	?	Ac?		Chifley (wood fragments by river)	Photocopied page titled Jenolan NSW 24-25 Oct 1987 (Eric Holm), probably never published; whereabouts unknown, probably ANIC
Undetermined sciarids		?				Gibian et al. (1988); whereabouts unknown, probably AMS
Order Hymenoptera						
Family Formicidae						
Undetermined ants			Ac?		Hennings, Mammoth	Gibian et al. (1988); whereabouts unknown, probably AMS

Order Lepidoptera					
Undetermined moths				Serpentine, Nettle, McKeowns Hole	Gibian et al. (1988); whereabouts unknown, probably AMS
Family Tineidae					
Monopis crocicapitella (Clemens, 1859)	EN	I/C	Gp	Imperial, Arch	Photocopied page titled Jenolan NSW 24-25 Oct 1987 (Eric Holm), probably never published
Family Oecophoridae					
Hofmannophila pseudospretella (Stainton, 1849)	EN	I/C	Ac	No data	Dew (1963)
Order Coleoptera					
Undetermined beetles or larvae				Imperial, McKeowns Hole, Devil's Coach House, Hennings, Mammoth	Gibian et al. (1988); T. Moulds (in litt. 2013) whereabouts unknown, probably AMS
Family Carabidae					
Trechimorphus diemenensis (Bates, 1878)	BM	N	Tp	Mammoth (gravel, mud banks) also known from other NSW cave areas	Moore (1964); B. Moore (in litt. 1987) ANIC (?)
Meonis convexus Sloane, 1900	BM	N	Ac	Wiburds Lake, Mammoth (also known from Tuglow Caves)	B. Moore (in litt. 1987) ANIC?
Prosopogmus namoyensis Sloane, 1895	BM		Ac	Mammoth	B. Moore (in litt. 1987) ANIC?
Family Staphylinidae					
Myotyphlus jansoni (Matthews, 1878)		N	Tp	Un-named cave in Southern Limestone	Hamilton-Smith and Adams (1966); whereabouts of specimen unknown, probably in the Biospeleological Collection, SAMA
Undetermined staphylinid				Devil's Coach House (flood debris)	Gibian et al. (1988); whereabouts unknown, probably AMS
Family Anobiidae					
Ptinus exulans Erichson, 1842		I/C	Tp	Unspecified; occurs in caves around the country	Dew (1963); Hamilton-Smith (1967) citing B. Moore (pers. comm); whereabouts

						unknown
Family Pselaphidae						
Tyromorphus speciosus (King, 1865)		N	Tp		Cave in Southern Limestone	Hamilton-Smith (1966); SAMA (BS0624); further material in BP Moore collection now probably within ANIC
Undetermined Pselaphidae					Chifley, Orient, Elder, Mammoth Hennings, Serpentine (damp wall, mud/flood debris, litter Tullgren)	Gibian et al. (1988); whereabouts unknown, probably AMS
CLASS CHILOPODA						
Order Geophilomorpha						
Family Geophilidae						
Undetermined centipede		N?	Ac?		Hennings	Gibian et al. (1988); specimen not traced (photograph in cave only)
CLASS DIPLOPODA						
Order Polydesmida						
Undetermined polydesmids	CC GM	N			Serpentine, Mammoth (Sand Passage, Horseshoe Cavern), Elder	Gibian et al. (1988); AMS (KS.96021, KS.96025, KS.96031, KS.96033, KS.96035-36, KS.102761-62)
Family Dalodesmidae						
Undetermined dalodesmids	RM CC	N	Tp		Devil's Coach House, Hennings (entrance chamber), Serpentine, Mammoth (Sand Passage, Horseshoe Cavern)	Gibian et al. (1988); material collected by Smith, Wheeler, Gibian, Eberhard, in AMS (KS.96009, KS.96022-23, KS.96026-27, KS.96029, KS.96032, KS.96034, KS.96038, KS.106995)
CLASS ARACHNIDA						
Order Araneae						
Family Cycloctenidae						
Cycloctenus abyssinus Urquhart, 1890	MG	N	Tp	Described by Urquhart (1890) from the Jenolan Caves (females). Male described by Rainbow (1893) - not located in AMS collection	Paradox, Mammoth, Hennings (bat guano or wandering over rocks, often in entrance chamber)	Gray (1973); Gibian et al. (1988); material collected by Smith, Holland, Eberhard, Marx and Wheeler in AMS (KS.10222, KS.18274, KS.21855, KS.23495, KS.35009)
Family Desidae						

Badumna socialis (Rainbow, 1905)	Typ	N	Tp	Originally described by Rainbow (1905) as *Amaurobius socialis*; eventually transferred to *Badumna* Gray (1983)	Grand Arch	Types in AMS (KS.6422, KS.6423)
Forsterina sp.	MG	N	Tp		Arch, Serpentine (flood debris)	Gibian et al. (1988); material collected by Smith and Gray in AMS (KS.17834, KS.19041)
Toxopsoides sp.	MG HS	N	Ac		Mammoth entrance chamber	Single specimen collected by Marx in AMS (KS.10223)
Family Dictynidae						
Undetermined				Referred to in Gibian et al. (1988) as "*Callevophthalmus*" group	Devil's Coach House (flood debris)	Gibian et al. (1988); specimen could not be traced
Family Gradungulidae						
Kaiya terama Gray, 1987	MG	N	Tp	First recorded as *Gradungula* sp.n. (Gray 1973), later described (Forster, Platnick and Gray 1987) from material collected in rotting log in forest at Jenolan, and other forest locations in NSW	Paradox, Mammoth, Hennings (twilight zone, tree root chamber)	Gray (1973); Gibian et al. (1988); material collected by Gibian and Eberhard AMS (KS.17844, KS.17846, KS.37485)
Family Lamponidae						
Lampona cylindrata (Koch, 1866)	MG	N	Ac		Grand Arch	Specimens collected by Wood in AMS (KS.6441)
Family Linyphiidae						
Laetesia weburdi (Urquhart, 1890)	MG	N	Tp	Originally described as *Linyphia weburdi* by Urquhart in 1890 from "a cave in NSW", it was later transferred to *Bathyphantes* by Rainbow (1911). Van Helsdingen (1972) transfers the species to *Laetesia*	Chifley, Devil's Coach House, Serpentine (flood debris), Orient; also other NSW caves	Gray (1973); Gibian et al. (1988); Thurgate et al. (2001a); specimens collected by Gray, Smith, Wheeler, Greenslade, Eberhard, Gibian, H. Smith and Musser in AMS (KS.5076, KS.17825, KS.18428, KS.19020, KS.19040, KS.19042, KS.35013, KS.120145)
Ostearius melanopygius (O. P. Cambridge, 1879)		I/C	Ac?			Gibian et al. (1988); not located: most AMS linyphiid material is currently unavailable
n. gen. et n.sp.	MG	N	Tb	Male and juvenile	Imperial, River (moist active shawl)	Gray (1973); Gibian et al. (1988); Thurgate

						et al. (2001a); AMS (KS.115960)
Family Lycosidae						
Lycosa sp.		N?	Ac	Juvenile only	Bow Cave (Tullgren funnel extraction of leaf litter)	Specimen collected by Smith, Wheeler and Gibian AMS (KS.32229)
Family Micropholcommatidae						
Micropholcomma longissimum (Butler, 1932)	GM	N	Ac	Single male; if correctly identified, is probably not Tp; Rix and Harvey (2010) report similar undescribed species from NSW	Imperial (mud bank)	Specimen collected by Smith and Wheeler in AMS (KS.32232)
Micropholcomma sp.	GM	N	Tp?	Male, females and juveniles	Chifley (small irregular webs on stalagmites), Serpentine	Gibian et al. (1988); material collected by Gray and Greenslade in AMS (KS.5075, KS.9969, KS.18429, KS.19043, KS.21854, KS.21853)
Rayforstia sp.	MR	N	Tp?		Mammoth Cave (Horseshoe Cavern) (flood debris, Tullgren funnel)	Single specimen collected by Wheeler, Smith and Gibian in AMS (KS.19030)
Textricella sp.	MR	N	Tp?	Juveniles only	Devil's Coach House (leaf litter berlesate)	Specimens collected by Smith and Wheeler in AMS (KS.19036)
Family Mimetidae						
Australomimetus maculosus (Rainbow, 1904)	Typ	N	Ac	*Mimetus maculosus* was described by Rainbow (1904) from material labelled as Jenolan Caves, collected by J. Wiburd. It was transferred to *Australomimetus* by Heimer (1986) and redescribed by Harms and Harvey (2009)	Imperial (mud bank), Binoomea Cut	Types AMS (KS.5821). Later specimens listed here not identified to species: Gray (1973); Gray one juvenile (KS.17832); Gray, H Smith and Musser one female (KS.120146)
Family Mysmenidae						
Undetermined	MG	N	Ac		Lucas (small web off track)	Gibian et al. (1988), Smith and Wheeler collected a male now in AMS (KS.19046)
Family Orsolobidae						
Tasmanoonops sp.	MG	N	Ac	Females only	Elder (under stone near scattered webs in drip zone below tree roots), Hennings (on pool in intermittent sump area)	Gibian et al. (1988). Material collected by Smith and Wheeler in AMS (KS.18272, KS.19022)
Family Sparassidae						

Heteropoda sp.	HS	N	Ac		Binoomea Cut	Gray, H. Smith and Musser collected female (KS.120153)
Family Stiphidiidae						
Stiphidion facetum Simon, 1902	MG	N	Tp		Mammoth, Arch, McKeowns Hole. Common cave entrance spider but also surface habitats. Also known from caves at Wombeyan, Bungonia, Colong, Yarrangabilly, Wee Jasper, Mole Creek	Gray (1973); Gibian et al. (1988); Eberhard (1993); 3 specimens collected by Smith, Gray and Gibian in AMS (KS.17833, KS.17847, KS.32231)
Family Tetragnathidae						
Orsinome sp.	MG	?	Ac		Bow (in or near webs about 10 m from entrance above litter)	Gibian et al. (1988); specimen collected by Smith in AMS (KS.19045)
Family Theridiidae						
'Achaearanea' sp.	MG		Ac	Undetermined male, females and juveniles; 2 spp, fully pigmented and most likely accidental	Arch, Lucas (web next to track), Elder	Gibian et al. (1988); Eberhard (1993); Specimens collected by Gibian and Gray in AMS (KS.17835, KS.19023, KS.21862)
'Achaearanea' propera (Keyserling, 1890)	HS	N	Ac		Binoomea Cut	Gray, H Smith and Musser collected female (KS.120150)
Cryptachaea gigantipes (Keyserling, 1890)	HS	N	Tp	Previously listed as *Achaearanea veruculata* but species moved to *Cryptachaea* in 2008; however all located specimens have been re-identified as *C. gigantipes* (Keyserling, 1890)	Devil's Coach House (leaf litter berlesate), Chifley (entrance passage)	Gibian et al. (1988); specimens collected by Smith and Wheeler and Gray in AMS (KS.17828, KS.19037-38)
Enoplognatha sp.		N?	Ac?	Doubtful record		Gibian et al. (1988); specimen not traced, may have been re-examined and included with *Icona* sp. or undetermined Theridiidae
Icona n. sp.	HL	N	Tp	Referred to genus *Steatoda* in Gray (1973); subsequently listed under *Icona* (H.W. Levi pers. com. to MG) as sp. 1 and sp. 2 (in Eberhard and Spate 1995, Gibian et al. 1988); likely to represent one variable species	Devil's Coach House, Imperial, Wiburds Lake, Mammoth ("scatty webs over mud or leaf litter")	Gibian et al. (1988); Thurgate et al. (2001a); specimens collected by Smith, Wheeler, Gray, Gibian, Eberhard, Marx; all in AMS (KS.10224, KS.17831, KS.17842, KS.17845, KS.17848, KS.17849, KS.19019, KS.19024-28, KS.19031, KS.19039, KS.32230, KS.35010-12)

Gen.undet. n. sp.?	MG	N	Tb	Listed under *Icona* sp 3 (in Eberhard and Spate 1995, Gibian et al. 1988); very small, fully depigmented, eyeless; known only from single immature male	Hennings (on pool in intermittent sump area)	Gibian et al. (1988); specimen collected by Gray in AMS (KS.18273)
Undetermined		N?	Tp?	Male, females, juveniles	Mammoth (Sand Passage and Horseshoe Cavern) (leaf litter)	Gibian et al. (1988); specimens collected by Gray in AMS (KS.102763, KS.102764)
Family Theridiosomatidae						
Baalzebub sp.	MG	N	Tp	Females and juveniles. Referred to in Gray (1973) as Theridisomatid gen. nov. sp. nov.	Chifley, Elder, Paradox, Hennings, Serpentine, Casteret; usually areas with light breezes; common cave frequenting genus but also found in sheltered surface localities	Gibian et al. (1988); material collected by Gray, Holland, Smith, Gibian, Eberhard, Renwick, Wheeler in AMS (KS.10444, KS.17827, KS.17841, KS.18275, KS.19021, KS.19044, KS.19047, KS.21856, KS.35008, KS.73233)
Family Uloboridae						
Philoponella pantherina (Keyserling, 1890)	MG	?	Tp?		Chifley, Lucas, Grand Arch	Gray (1973); Gibian et al. (1988); specimens collected by Gray and Gibian in AMS (KS.10227, KS.17826, KS.17836, KS.21861)
Order Opiliones						
Family Triaenonychidae						
Holonuncia cavernicola Forster, 1955	GH MG	N	Tp	Described by Forster (1955b) from material collected at Jenolan Caves. Hamilton-Smith (1967) also listed Yarrangabilly, Wyanbene and Wombeyan as locations for species. Hunt (1992) examines additional material from Jenolan and redescribes the species (and the genus for which *H. cavernicola* is the type species)	Chifley, Imperial, Devil's Coach House, Hennings, Cerberus, McKeowns Hole, a Southern Limestone cave, Temple of Baal, Paradox and several epigean specimens from the Jenolan area; tentatively also a specimen from Tuglow Caves. Pigmentation and eye mound size varies between cave and surface populations	Hunt (1992); Forster (1955b), types in AMS (KS.6912, KS.6914); Gibian et al. (1988) other material collected by Hunt, Gray, Clark, Gibian, Eberhard, Smith, Wheeler, Dew, Guides and "Speleo Club" in AMS (KS.5077, KS.17829, KS.19033, KS.19048, KS.19050, KS.21402-04, KS.21857, KS.23216, KS.35027)
Family Neopilionidae						
Megalopsalis sp.	GH MG	N	Ac	Listed as *Spinicrus* by Gibian et al. (1988); genus is now considered to	Mammoth	Gibian et al. (1988) specimens collected by Pickering and Gibian in AMS (KS.19032,

				be part of *Megalopsalis*		KS.97658)
Acarina						
Order Mesostigmata						
Family Ascidae						
Proctolaelaps holmi Halliday, 2001	BH	N	Tp	Described from material collected by E. Holm at Jenolan	Lucas (bat guano)	Halliday (2001); 10♀♀; types in ANIC
Proctolaelaps pygmaeus (Müller, 1859)	BH	I/C	Tp?	Cosmopolitan species described from a cave in Germany	Lucas (bat guano)	Halliday (2001); 4♀♀ ANIC
Family Digamasellidae						
Dendrolaelaps adelaideae Womersley, 1954	BH	N	Ac		Devil's Coach House (overflow passage) (litter), Serpentine (litter), Paradox (guano)	Halliday (2001); 4♀♀ 2 DN; ANIC
Family Laelapidae						
Stratiolaelaps scimitus (Womersley, 1956)	BH	N	Tp?	Originally identified in Halliday (2001) as *Stratiolaeleps miles* (Berlese, 1892) which was thought to be the same as *S. scimitus*; they are now known to be different species (Halliday in litt. 2013)	Lucas (guano); soil dwelling predatory mite	Halliday (2001); 11♀♀ 4DN 2PN (laboratory reared progeny); ANIC
Several species of *Gaeolaelaps* Evans and Till, 1966	BH			This family very difficult taxonomically so further identification of these species still required (Halliday in litt. 2013)		Halliday (in litt. 2013); ANIC
Family Macrochelidae						
Geholaspis mandibularis (Berlese, 1904)	BH	I/C	Ac		Devil's Coach House (overflow passage), Serpentine, Bow, Mammoth (Horseshoe Cavern, Sand Passage) (litter); previously only recorded from Europe where it is widespread and abundant	Halliday (2001); 25 ♀♀ 14DN 8PN; ANIC
Macrocheles tenuirostris Krantz and Filipponi, 1964	BH	N	Tp		Paradox (guano); subterranean species found in caves and animal burrows in SE Australia	Halliday (2001); 1♀; ANIC
Family Ologamasidae						

Antennolaelaps testudo Lee, 1970	BH	N	Ac		Bow; known from Queensland (moss and leaf litter)	Halliday (2001); 1♀; ANIC
Athiasella caverna Halliday, 2001	BH	N	Tp	Described from material collected by Eberhard as well as Gibian, Smith and Wheeler	Devil's Coach House (overflow passage), Serpentine, Bow (litter), also surface localities at Jenolan	Halliday (2001); 8♀♀; types in ANIC
Geogamasus fornix Halliday, 2001	BH	N	Tp	Described from material collected by Gibian, Smith and Wheeler	Bow (litter)	Halliday (2001); 2♀♀; types in ANIC
Family Pachylaelapidae						
Pachydellus hades Halliday, 2001	BH	I/C	Ac	Described as *Pachylaelaps hades* by Halliday (2001) from material collected by Smith and Wheeler and subsequently transferred to *Pachydellus* (Mašan 2007). Later (Halliday and Mašan 2008) found to be a species common in south-eastern Europe but not previously described due to its similarity with other species. It is therefore probably introduced into Australia	Devil's Coach House (overflow passage) (litter)	Halliday (2001); 3♀♀; types in ANIC
Pachylaelaps humeralis Berlese, 1910	BH	I/C	Ac		Devil's Coach House (overflow passage), Mammoth (Horseshoe Cavern); Bow (litter)	Halliday (2001); 31♀♀ 1 DN; ANIC
Family Parasitidae						
Pergamasus quisquillarum (Canestrini and Canestrini, 1882)	BH	I/C	Ac		Mammoth (Horseshoe Cavern), Devil's Coach House (overflow passage), Bow (litter) as well as surface localities at Jenolan. Widespread in Europe, occurring in decomposing organic matter including leaf litter	Halliday (2001); 23♀♀ 3♂♂ 3DN; ANIC
Family Veigaiidae						
Veigaia pusilla (Berlese, 1916)	BH	I/C	Ac		Devil's Coach House (overflow passage) (litter), Mammoth (Horseshoe Cavern and Sand Passage) (litter), Serpentine (litter), Bow (litter). Known in Europe and North America from soil and dead leaves	Halliday (2001); 24♀♀ 2DN; ANIC

Veigaia planicola (Berlese, 1892)	BH	I/C	Ac	Identified as *Veigaia serrata* Willman, 1935 in Halliday (2001) which has recently been shown to be a synonym of *Veigaia planicola*; very common European species (Halliday in litt. 2013)	Devil's Coach House, Mammoth (Horseshoe Cavern and Sand Passage), Serpentine, Bow (litter)	Halliday (2001); 20♀♀ 12DN; ANIC
Infraorder Uropodina						
Family Trachytidae						
Acroseius tuberculatus (Womersley, 1961)	BH	N	Ac		Bow; common in leaf litter in NSW forests	(Halliday in litt. 2013); ANIC
Apionoseius n.sp.	BH	N	Tp		Abundant in Mammoth (Horseshoe Cavern), Devil's Coach House, Bow, Paradox; also present in other caves in NSW	(Halliday in litt. 2013); ANIC
Polyaspinus tasmanicus Bloszyk and Halliday, 2000	BH	N	Tp		Paradox; described from forest litter in Tasmania; also present in Deua Caves	(Halliday in litt. 2013); ANIC
Family Uropodidae						
n. gen. et n.sp.	BH	N	Tp?		Mammoth (Horseshoe Cavern) (flood debris)	(Halliday in litt. 2013); ANIC
Family Urodinychidae						
Castriidinychus n. sp.	BH	N	Tp?		Serpentine, Mammoth (Horseshoe Cavern), Paradox, Devil's Coach House (guano, flood debris). Genus described for three species found in leaf litter	(Halliday in litt. 2013); ANIC
Uroobovella coprophila (Womersley, 1960)	BH	N	Tp		Present in many cave systems, very abundant in guano in Jenolan and Wee Jasper	(Halliday in litt. 2013); ANIC
Family Polyaspididae						
Uroseius n.sp.	BH	N	Tp		Paradox (guano), Bow; also occurs in guano at Deua Caves and Wee Jasper	(Halliday in litt. 2013); ANIC
Family Dinychidae						
Dinychus greensladeae Bloszyk and Halliday, 1995	BH	N	Ac		Described from forest litter in Tasmania, now found to be abundant in all Jenolan	(Halliday in litt. 2013); ANIC

					flood debris samples	
Order Trombidiformes suborder Prostigmata						
Family Rhagidiidae						
Undetermined	BH	?	?		Found in low numbers in various caves at Jenolan; predatory mites	(Halliday in litt. 2013); ANIC
Family Erythraeidae						
Undetermined	BH	?	?		Found in low numbers in various caves at Jenolan; predatory mites	(Halliday in litt. 2013); ANIC
Family Pygmephoridae						
Undetermined	BH	?	?		Found in low numbers in various caves at Jenolan; fungivorous mites	(Halliday in litt. 2013); ANIC
Order Sarcoptiformes						
Undetermined Oribatida	BH		Tp		Present in most samples, sometimes abundant	(Halliday in litt. 2013); ANIC
Order Ixodida						
Family Ixodidae						
Bothriocroton undatum (Fabricius, 1775)		N	Ac	Originally described as *Acarus undatus* (Fabricius, 1775), later included under *Aponomma* and finally transferred to *Bothriocroton*	Paradox (Tullgren funnel samples of bat guano); a parasite of reptiles	Specimen collected from guano by Smith and Holland in AMS (KS.21858)
Order Pseudoscorpiones						
Family Chthoniidae						
Austrochthonius sp.	MH	N	Ac?		Devil’s Coach House (leaf litter, berlesate)	Gibian et al. (1988); material collected by Smith and Wheeler in AMS (KS.19034-35)
Sathrochthonius tuena Chamberlin, 1962	MG MB	N	Tp	Described by Chamberlin (1962) from material labelled "unnamed cave, ‘probably in the Blue Mountains near Sydney’". Beier (1967) confirms species present at Jenolan	Southern Limestone; Paradox (Tullgren funnel); also known from Wombeyan Caves	Beier (1967), Gibian et al. (1988); material collected by Holland, Smith, Gibian, Wheeler, Dew in AMS (KS.21859-60, KS.32228, KS.88165-66); ♂ holotype (JC-2014.02001, ♀ allotype (JC-2014.0202) in AMNH
Family Pseudotyrannochthoniidae						

Pseudotyrannochthonius jonesi (Chamberlin, 1962)	MG MH	N	Tb	Originally described as *Tubbichthonius jonesi* Chamberlin, 1962 from material labelled "cave in Australia, ‘probably in Blue Mountains near Sydney’". Transferred by Beier (1966) to *Pseudotyrannochthonius*. Redescribed Harms and Harvey (2013)	Imperial, Chevalier extension	Chamberlin (1962), Gibian et al. (1988); Harms and Harvey (2013); material collected by Gray and "Speleo club" in AMS (KS.5279, KS.17267, KS.17830, KS.21863); ♀ holotype (JC-2014.01001) in AMNH
PHYLUM MOLLUSCA						
Undetermined Gastropoda					Hennings, Serpentine, Mammoth, Wiburds Lake	Gibian et al. (1988); whereabouts unknown possibly AMS
Family Camaenidae						
Pommerhelix depressa (Hedley, 1901)	CA	N	Tp	Described from Jenolan Caves as *Thersites gulosa depressa*, later referred to as *Meridolum depressum* and included in *Pommerhelix* by Clark (2009)	Casteret	Dew (1963); AMS (C.325073)
Family Charopidae						
Elsothera sericatula (Pfeiffer, 1849)	JS	N	Ac	Listed in Dew (1963) as *Strongesta* sp. but only specimen in AMS collected by Dew in Southern Limestone has since been identified as *Elsothera sericatula* (Pfeiffer, 1849)	Cave in Southern Limestone	Dew (1963); AMS (C.354880)
Family Glacidorbidae						
Glacidorbis hedleyi Iredale, 1943	WP	N	Ac		Imperial resurgence	AMS (C.361944)
SUBPHYLUM CRUSTACEA						
Order Cyclopoida						
Undetermined					Imperial river (netted)	Gibian et al. (1988); material collected by Smith and Wheeler in AMS (P.38508)
Family Cyclopidae						
Macrocyclops albidus	TK	I/C	Ac		Mammoth (muddy pools left after Lower	Eberhard (1993); Thurgate et al. (2001b);

(Jurine, 1820)					River flood); widely distributed larvivorous species	material collected by Eberhard in AMS (P.65478, P.65478.001)
Tropocyclops prasinus (Fischer, 1860)	TK	I/C	Ac		Lucas; widely distributed species	Eberhard (1993); Thurgate et al. (2001b); material collected by Eberhard in AMS (P.65479, P.65479.001)
Order Amphipoda						
Family Eusiridae						
Pseudomoera fontana (Sayce, 1902)	JB	N	Ac?	Originally described as *Atyloides fontana* from stream at Woods Point (Vic); moved to *Pseudomoera* by Barnard and Karaman (1982)	Northern Streamsink, Imperial resurgence; SE Australian species inhabiting freshwater streams	Eberhard (1993); material collected by Eberhard in AMS (P.82630-31)
Family Neoniphargidae						
Neocrypta simoni Bradbury and Williams, 1997	JB WW	N	Sb	Described by Bradbury and Williams (1997) from Paradox Cave	Paradox	Eberhard (1993); Thurgate et al. (2001b); holotype and allotype collected by Eberhard in AMS (P.51368-69)
Undetermined					Imperial river	Gibian et al. (1988); Eberhard (1993); Thurgate et al. (2001b); 5 specimens netted by Smith, Gibian and Wheeler in AMS (P.38506)
Order Anaspidacea						
Undetermined	PS	N			Spider (flood pool); River (Pool of Reflections)	Eberhard (1993); Thurgate et al. (2001b); material collected by Eberhard and Thurgate in AMS (P.45752, P.57897)
Family Psammaspididae						
n. gen. et n.sp	PS	N	Sb		Spider (flood pool), Imperial and Jubilee (river and flood pools)	Eberhard (1993); Thurgate et al. (2001b); material collected by Eberhard in AMS (P.43374, P.45764-65)
Order Isopoda						
Large pigmented eyed oniscid slater			Ac		Elder	Gibian et al. (1988); specimen not traced
Family Phreatoicidae						
Crenoicus sp.	GW	N	Sp?		Imperial resurgence, Paradox	Eberhard (1993); Thurgate et al. (2001b); material collected by Eberhard in AMS

						(P.52680-81)
Family Styloniscidae						
Styloniscus sp.	AG	N	Tp?		Mammoth (Cold Hole) (gravel, mud)	Gibian et al. (1988); Eberhard (1993); Thurgate et al. (2001b); material collected by Smith in AMS (P.38507)
PHYLUM ANNELIDA						
Subclass Oligochaeta						
Undetermined terrestrial and aquatic worms		?	?		Devil's Coach House, Imperial river, Mammoth, Serpentine, Cerberus, River	Gibian et al. (1988); Eberhard (1993); Eberhard and Spate (1995); location of specimens unknown
PHYLUM NEMATODA						
Undetermined terrestrial and aquatic nematodes?		?	?		Devil's Coach House, Imperial river, Mammoth, Serpentine, Cerberus, River	Gibian et al. (1988); Eberhard (1993); location of specimens unknown
PHYLUM PLATYHELMINTHES						
Undetermined flatworms of both Paludicola and Terricola		?	?	One flatworm possibly troglobitic (Eberhard and Spate, 1995)		Dew (1963); Eberhard (1993); Eberhard and Spate (1995); Thurgate et al. (2001a); Moulds (in litt. 2013); location of specimens probably AMS

Jenolan Show Caves: Origin of Cave and Feature Names

KATH BELLAMY[1], CRAIG BARNES[2]

[1]226 Rankin Street, Bathurst, NSW 2795, Australia, dbellamy@tpg.com.au
[2]The School of Chemistry, F11, The University of Sydney, NSW 2006, Australia, cbarnes6@bigpond.com

Bellamy, K. and Barnes, C. (2014). Jenolan show caves: origin of cave and feature names. *Proceedings of the Linnean Society of New South Wales* **136**, 69-75.

The Jenolan Caves Historical and Preservation Society researchers and surveyors worked together to place cave and feature names on maps being produced by the Jenolan Caves Survey Project. Their sources for these names were guidebooks, newspaper articles, tourist publications, postcards, and photographs. Valuable contributions also came from the oral history supplied by past and current guiding staff. From 1838 to the present day, guides have striven to acquaint visitors with the "exotic" cave environment, resulting in a tradition of giving features familiar names. To the informed, names of caves and formations can take on a hieroglyphic character that can guide you through the history of the caves. Being aware of the feature names can give a glimpse of the discoverers, prompt interest in the adventures of early visitors and even recognise the work involved in making the caves accessible. The result is that over a thousand names have been found that link historically and culturally the discoverers, management and visitors.

Manuscript received 26 August 2013, accepted for publication 19 February 2014.

KEYWORDS: cave lighting, cave names, Fish River Cave, Jenolan Cave.

In 2005, as part of the Jenolan Caves Survey Project, the authors started to work on names for the maps. The Jenolan Show Caves are made up of "caves", sections of a system that have been given specific names to facilitate them as cave tours (Figure 1). The naming project immediately expanded as some cave and feature names provided an historical and cultural record of the Jenolan Show Caves. The result is an important record of the tradition of naming at Jenolan from the discovery of the caves to the present day.

The early years

The first recorded descriptive names commenced with the discovery of the arches in 1838 (Ralston 1989). Samuel Cook (1889) suggested that an arch known as the Devils Coach House was so named for reasons that had led to similar names for numerous Devils Pinches and Peaks for surface features around the world. Captain Cook had given the name Devils Basin to a harbour because of its gloomy appearance, being surrounded by savage rocks. For a brief period, the Devils Coach House was renamed Easter Cave, although the name never became popular.

The cave system has been known by various names: McKeon's Caves in 1856, Binda Caves in 1867, Fish River Caves in 1879, and finally on 19th August 1884 the name Jenolan Caves was approved (Havard 1933).

By the 1860s names had been established for the New Cave (Ralston 1989). Visitors began their tour to this cave by hiking through the bush to Wallaby Hole, entering the cave through the Sole of the Boot to reach the Cathedral. They had to negotiate The Slide by sitting on a bag and descending further into the cave. In the Exhibition Cave they climbed over rocks, lunched on Picnic Rock and drank water from the Hidden River. In Lurline Cave those familiar with William Wallace's opera Lurline, first performed in 1860, could see "…the coral bowers and cells to which Rudolph was transported" (Cook 1889). In an area of the Bone Cave called the Irish Corner there was an interesting formation known as the Potato Patch, and further along Bone Cave were Snowball Cave and Crystal Fountain. Returning to Irish Corner, visitors were astonished to find they had to ascend a wire ladder to return to Cathedral and thence the cave entrance. Although this route is not used today, many of these names are still in use on the Lucas tours.

Some names became enshrined with the advent of guidebooks; "English visitors see in this stalagmite the features of Lord Salisbury" (Trickett 1905).

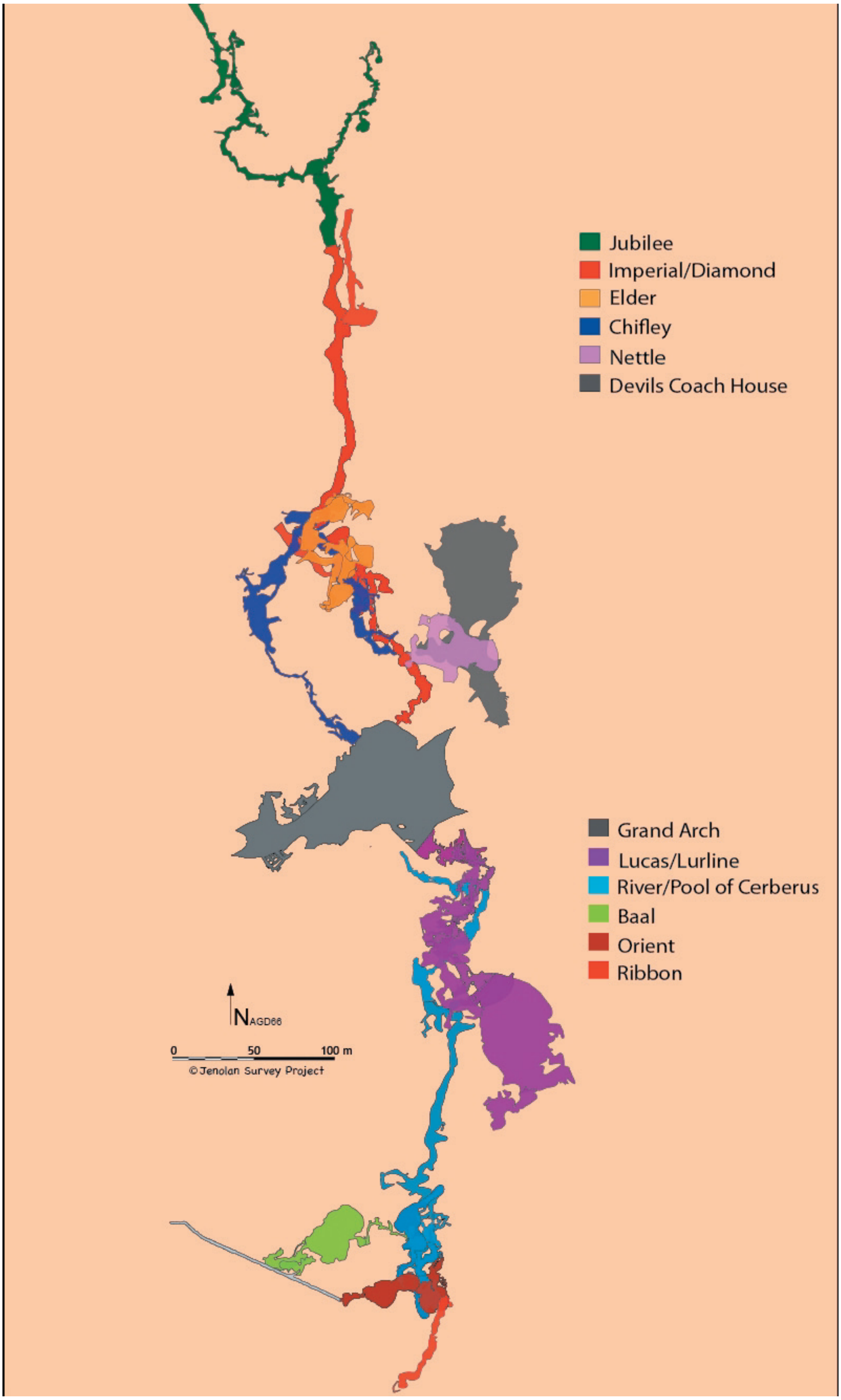


Figure 1. Jenolan Show Caves

Figure 2. The Old Curiosity Shop.

According to the 1924 Orient guidebook, visitors "... one and all will recognise uncanny imitations..." and decorations seem "...veiled in a film of suggestion where more is meant than meets the eye and depends to a certain extent upon the imagination" (Havard 1924). Figure 2 shows the Old Curiosity Shop where such a process has resulted in 13 named features amongst the mass of helictites. The names for the features in this figure can be found in Figure 3.

At present the Orient (Figure 3) contains 134 named features, by far the most of any cave at Jenolan. Many of the features have been renamed over time, with some features like the Dome of St Pauls renamed as many as 5 times (so far), to give a total of 206 names for the Orient alone. There are only 119 of the 206 names on Figure 3; it was not possible to fit any more on!

Names and name changes

The reasons for names and name changes for caves, parts of caves and features are multitude, and the following paragraphs outline just a few examples. The shapes that prompt a person to choose names are usually explained by culture, history and, sometimes, even profession. The chambers in the Orient (Figure 3) have names from that part of the world which is now known as the subcontinent.

The imagination of guides and tourists

From the very beginning, cave guides and tourists used names to describe formations, in part to make the strange more familiar. It is a tradition that has evolved and continues even to the present as new cave is discovered. For example, renamed by young visitors, the Unicorn's Horn has become ET's Finger and The Minaret has become The Ice Cream Cone. The cave divers have named a stalagmite as the Upside Down Ice Cream Cone. A medical person was probably responsible for describing the helictites in the Dragon's Throat in Baal as Diphtheria Symptoms.

The beautiful and small

There are many sparkling calcite crystal decorations at Jenolan, such as stalactites, stalagmites, flowstones and helictites, that have been named but some of the most intriguing formations are obscure. Old publications and photographs have enabled identification of these treasures. Among one mass of tangled helictites, named The Battlefield, is the minute Leaping Stag. The Diminutive Horse Head is one of the smallest examples of named features at Jenolan (Figure 4).

The ambience of the environment

George Rawson (1882) wrote of a visit to Fish River Caves that "...one is bought into a silent and reverent attitude…" hence it is no surprise that many names of religious significance were used. There is an Organ Loft and Pulpit in the Grand Archway, a Sanctuary in Nettle, a Cathedral and Bishop in Lucas, Twelve Apostles in Orient (Figure 5), with Imperial and Chifley both having a Vestry. Biblical names include Elijah's Retreat, Tower of Babel and Lots Wife

Historical events

Historical events have also played a part, particularly in renaming features. The Terraces in Exhibition Chamber became the Pink and White Terraces in remembrance of those in New Zealand destroyed by the 1886 eruption of Mount Tarawera (Cook 1889). Mafeking was besieged during the Boer War for 217 days, from October 1899 to May 1900. The relief of Mafeking by the British from the Boer

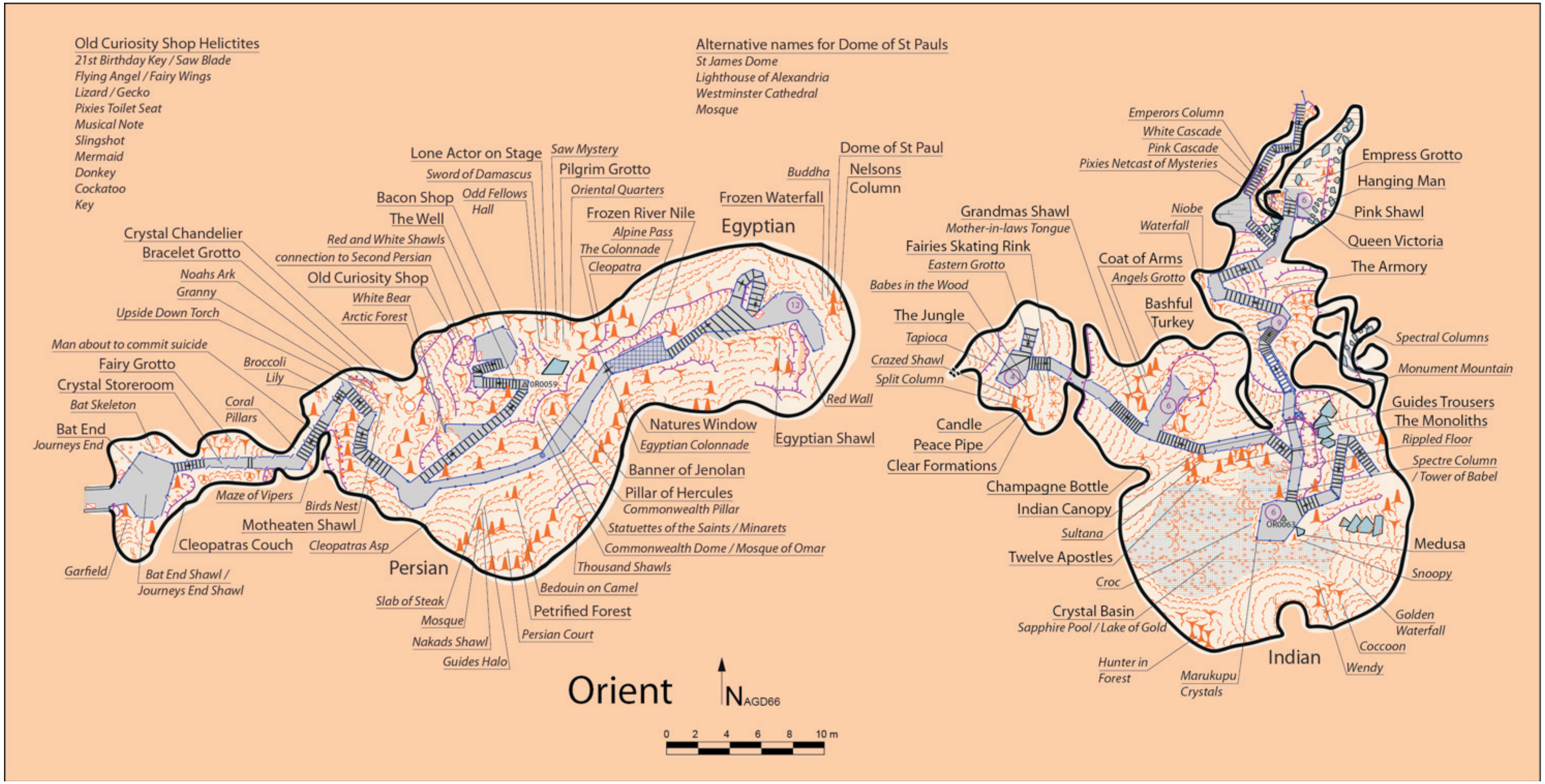


Figure 3. The Orient Map.

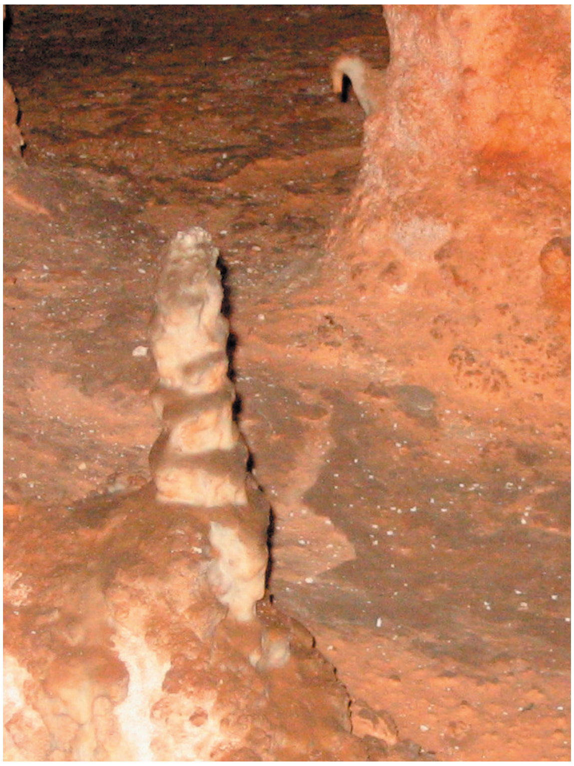


Figure 4. Diminutive Horse Head.

Figure 5. The Twelve Apostles.

coincided with the discovery of a high level passage in the Exhibition Chamber, hence its name and the names of some features in it (Figure 6).

Currently, there is a proposal to commemorate the Queen Elizabeth II Jubilee with a named dome and arch in Jubilee and Imperial respectively.

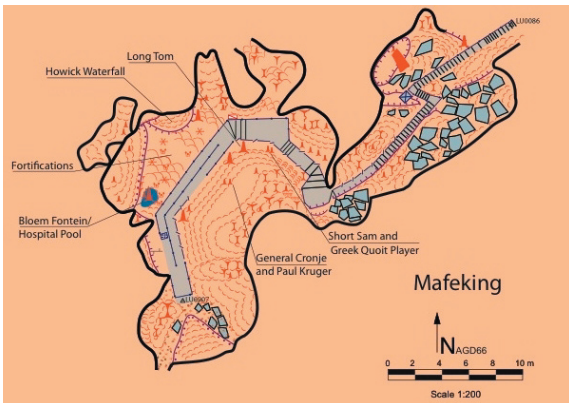


Figure 6. Map of Mafeking.

Honouring Australian dignitaries

In 1878 the New Cave was named Lucas after John Lucas, M.L.A; "In consequence of the great interest I displayed, and by the publication of my paper, which first drew the attention of the public to them, the Surveyor-General and other high officials made an official visit, and named the largest cavern The Lucas Cave" (Rawlinson 1976). One formation was named Judge Windeyer's Couch "…because it is said that the learned judge sat on it when he visited the caves" (Cook 1889). In 1952, the Left Branch of Imperial was renamed Chifley Cave in honour of J.B. (Ben) Chifley, who represented in the Federal Parliament the region that included Jenolan. The name change attracted some criticism; "The gesture, however well intentioned, will not give much pleasure to Mr Chifley's admirers, for the sake of the memory of a highly regarded man, I hope some more tactful Chief Secretary changes the ludicrous name of Chifley Cave back to what it was before" (Anon. 1952).

Cave incidents

Jeremiah Wilson, exploring Jubilee in 1893, described the dreadful experience of having his candle go out and believing he had no matches. Fortunately he found some in his pocket, but he ensured the event was not forgotten by naming the place where he was at the time Wilson's Despair. In Imperial, Ridleys Short Cut was named after "...a visitor who stepped back to allow a lady to pass and fell through (to a cave below)..." (Leeder 1994). The guides describe the incident as a "...rambling visitor who strayed from the fold, put a foot in the wrong place, and descended fifty five feet without the benefit of the rope. He landed on a coil of netting and bounced off" (Ralston 1989).

The influence of lighting

Different lighting can influence what can be

Figure 7. Queen Victoria.

recognised in the caves. Scenes lit by flickering candles, and at times augmented by magnesium lamps, delighted early visitors. However, the Stooping Lady could "...be seen only by candle light, the magnesium flare being too penetrating for this particular effect" (Foster 1890). Harry Potter's Scar was visible in the Exhibition Chamber until the lighting system was recently upgraded. The new lighting did however result in a perfect representation of a Terracotta Warrior appearing in shadow on the wall over the River Styx in Lucas.

After ladies

In Lucas, Queen Victoria is unmistakable as she looks out over the Royal Chamber (Figure 7).
Other ladies have figured in naming Jenolan features, at times being substituted as their prominence wanes. Queen Esther still has a chamber, Margarita Cracknell, Selina Webb and Lucinda Wilson have small caves, Katie Webb and Edie have their bowers, while Josephine, Ethel and Minnie each still merit grottos. Helena Hart cave was initially renamed in favour of Lady Cecilia Carrington after her visit to the caves, but this chamber is now called Madonna Cave. Matildas Retreat, however, has become the more mundane Marble Grotto. The provenance of these names occasionally causes some dispute too. A grotto attributed to Nellie Webb was challenged by a visitor in May 1976 who stated the grotto "…was named in honour of Nellie Carruthers…" (McIver 1976) (Figure 8).

Conclusion

As part of the Jenolan Show Caves Survey, the naming project has and will continue to assist in providing accurate information on names and locations, but it is an evolution. This is no better reflected than in the words of a visitor who, in September 1911, wrote on a Jenolan postcard "It is wonderful how many shapes and images are suggested to your imagination and I could have added hundreds more…" (Anon. 1911). This discussion of the names of Jenolan features and their sources has been illustrated with only a few selected examples; it could have been many more as the Excel spread sheets for the Survey now contain more than a thousand names. The Jenolan Show Caves can therefore be thought of as the "Caves of a Thousand Names".

ACKNOWLEDGEMENTS

The authors acknowledge the valuable contributions from the Jenolan Caves Reserve Trust, Jenolan Caves Historical and Preservation Society, the Jenolan Cave Guides and the many caver helpers, Jenolan Caves Survey Project for use of the maps, and Al Warild for drafting figures. Photos: C. Barnes (Figures 5, 7), J. Lim (Figure 2), R. Whyte (Figure 4).

REFERENCES

Anonymous (1911). Jenolan postcard in Binoomea No.141. Jenolan Caves Historical and Preservation Society

Anonymous (1952). 'Candid Comment', Sunday Herald 6th April 1952, Sydney NSW.

Cook, S. (1889). Jenolan Caves: An Excursion in Australian Wonderland, Eyre and Spottiswoode, London.

Foster, J.J. (1890). 'The Jenolan Caves', (Charles Potter Government Printer, Sydney - facsimile edition 2011, Jenolan Caves Historical and Preservation Society).

Havard, W.L, (1924). 'The Orient Cave'. (A. J. Kent Government Printer, New South Wales - facsimile edition 2011, Jenolan Caves Historical and Preservation Society).

Havard, W.L. (1933). 'The Romance of Jenolan Caves'. (Artarmon Press, Sydney - limited facsimile edition, NSW Department of Leisure, Sport and Tourism).

Leeder, P.M. (1994). Personal letter to Jenolan (archived by Jenolan Caves Historical and Preservation Society).

McIver, F. (1976). Personal statement to Jenolan archived by Jenolan Caves Historical and Preservation Society.

Ralston, B. (1989). 'Jenolan: The Golden Ages of Caving'. (Three Sisters Productions Pty. Ltd. Australia).

Rawlinson, N. (1976). 'John Lucas: Conservationist or Vandal' (Occasional paper for 8 May 1976 meeting of Jenolan Caves Historical and Preservation Society - facsimile edition 2010, Jenolan Caves Historical and Preservation Society).

Rawson, G.H. (1882?). 'Guide to and Description of the Fish River Caves'. (original handwritten manuscript, transcribed and illustrated 2013, Jenolan Caves Historical and Preservation Society).

Trickett, O. (1905). 'The Jenolan Caves, New South Wales', 2nd edition. (William Applegate Gullick, Government Printer Sydney).

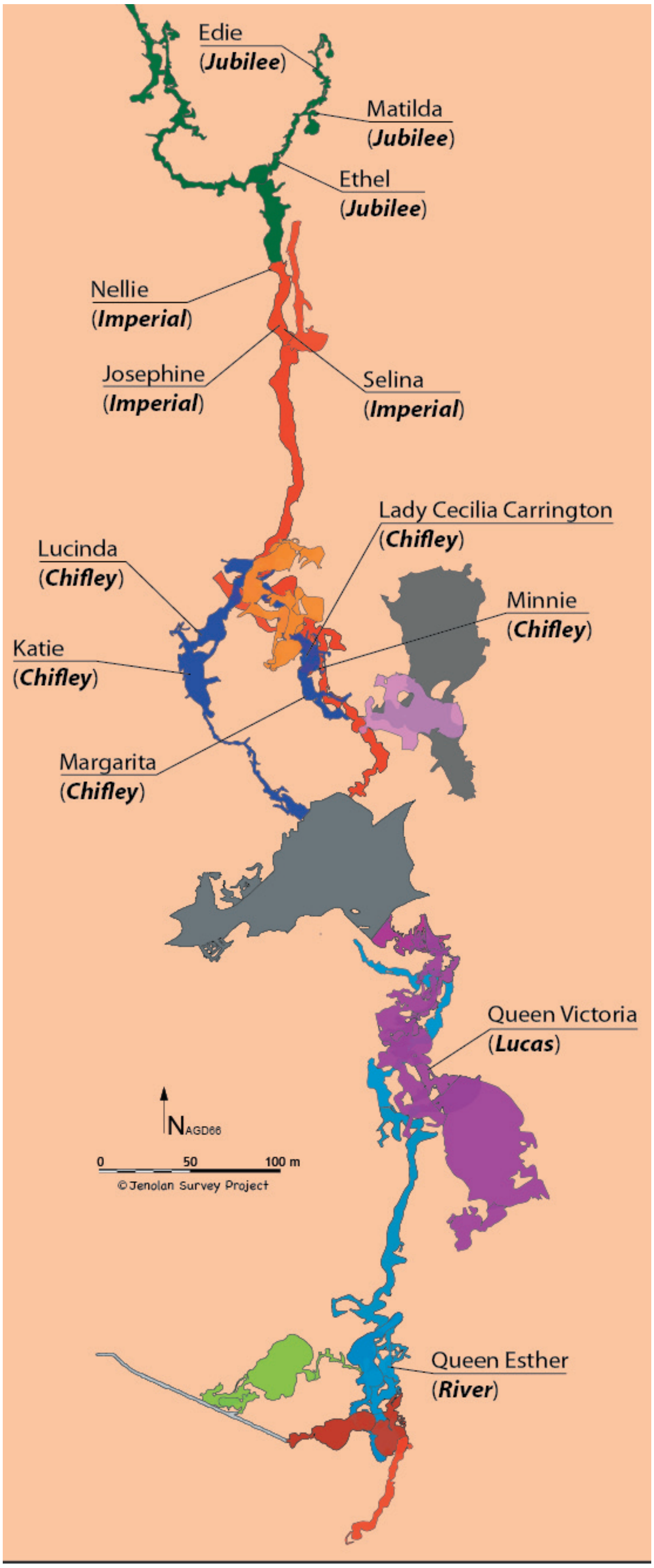


Figure 8. Location of features named for ladies.

Understanding the Origin and Evolution of Jenolan Caves: The Next Steps

R. Armstrong L. Osborne

Faculty of Education and Social Work, A35, The University of Sydney, NSW 2006
armstrong.osborne@sydney.edu.au

Osborne, R.A.L. (2014). Understanding the origin and evolution of Jenolan Caves: the next steps. *Proceedings of the Linnean Society of New South Wales* 136, 77-97.

The dating of cave and surficial sediments by Osborne et al. (2006) indicated that some sections of Jenolan Caves, particularly the large chambers, formed in the Early Carboniferous before deposition of sediments dated at 340 Ma. The dating also identified younger mass-flow sediments, dated at 303Ma and secondary fine illite, dated at 258 Ma and 240 Ma indicating burial of the caves under the Sydney Basin. These dates meant that a new chronology for cave development at Jenolan is required to supersede that of Osborne (1996b). Construction of this chronology raises new questions: Did the paragenetic conduits form before deposition or after stripping of the Sydney Basin? Caymanites (marine carbonate turbidite palaeokarst) appear to be older than 340 Ma, but does this make palaeogeographic sense? The Early Carboniferous dates give us a beginning for the history of the present caves at Jenolan, but much of the story is missing. Many obvious features in the caves have not been studied. Present knowledge of the developmental history, palaeokarst and sediment stratigraphy, morphology and mineralogy of tourist caves at Jenolan Caves is insufficient to support sound conservation, management, development and interpretation. The next step in understanding Jenolan Caves is a structured program of dating, geological, mineralogical and geomorphic studies.

Manuscript received 17 July 2013, accepted for publication 11 December 2013

KEYWORDS: cave sediments, dating, Jenolan Caves, palaeokarst, speleogenesis

INTRODUCTION

Despite the popularity of Jenolan Caves, there was very little study and very little was written about the origin and evolution of the caves prior to the publication of my synthesis (Osborne, 1999b). Sussmilch and Stone (1915) speculated on the age of the caves while Taylor (1923, 1958) attempted to correlate cave development with that of the Blue Mountains landscape using a fluvial model of cave development. In the numerous editions of his guidebooks Dunlop (1979) noted the role of solution, cracks and the three streams passing through the limestone in cave development. Beginning in 1983 I started a new study of Jenolan Caves, at first concentrating on palaeokarst and the geological record of cave development.

During the 1990s it became clear that while the palaeokarst made sense, the morphology of the caves themselves made little sense, particularly if they were conventional stream caves as had been generally accepted. After visits to Slovenia and Hungary in 1997, I realized that much of what we see at Jenolan is quite unlike the text-book stream caves of Slovenia, but the large dome-shaped chambers such as the Temple of Baal have similarities with features seen in the hydrothermal caves of Budapest. Looking at the caves in a new light I saw both bottom up and paragenetic features, which resulted in my first attempt at putting the story of cave development at Jenolan together (Osborne, 1999b).

Assumptions and definitions

In this paper I make certain assumptions about the origin and evolution of Jenolan Caves and use some terms in particular ways. Firstly, my basic premise is that Jenolan is a multiphase / multi-process cave system, which means that:

1. Caves have formed several times in the 400 Ma history of the Limestone.
2. Some old caves are filled with lithified sediment and are now intersected by younger caves. I restrict the use of the term *palaeokarst* to these sediments and the features they fill.
3. Some caves contain very old sediment contained within the same cave walls that delimit the open cavities that it is possible for humans to enter today. I call these deposits *relict* sediments. I do not use the term palaeokarst to apply either to these sediments or to the cavities they fill even though they may the hundreds of millions of years old.
4. There are no simple answers to the questions "How old are the caves?" and "How did the caves form?" as different sections of the accessible and palaeokarst caves formed at different times and by different processes.

Secondly, following Bella and Bosák (2012), I have abandoned the use of the terms hypogene and hydrothermal except where there is direct evidence that hot water or water with a deep-sourced aggressive agent is responsible for speleogenesis. In cases where there is morphological evidence that a cave has been excavated by rising water of unknown composition I use the term *per-ascensum.*

METHODS

Morphology

Caves are underground landforms, so just like surface landforms their gross morphology (seen by visual observation, in plans and in long and cross-sections) and their macro-morphology (seen in the rock forms in the caves called speleogens) should provide evidence for their mode of formation. In the case of Jenolan the pattern of cave development is strongly influenced by the shape and geological structure of the limestone mass with passages north of the Grand Archway following the general NNW-SSE strike of bedding and cleavage and south of the Grand Archway ("1" in Figure 1A) having a more N-S orientation following a change in strike (Figure 1A).

In long-section (Figure 2) it can be seen that while most of the cave development is horizontal, there are specific zones of vertical cave development spaced at apparently regular intervals along the length of the cave. Osborne (1999a) recognised that fluvial cave cross-sections in most textbooks showed sections of caves in horizontally bedded limestone (Figure 3A) and that cave cross-sections in almost vertically-dipping limestone like Jenolan would be different (Figure 3B) and that paragenetic conduits in vertically-dipping limestone would have a distinctive cross-section (Figure 3C).

Three types of large solution cavities at Jenolan can be identified on the basis of their gross morphology; *per-ascensum* cupolas such as those in the Mud Tunnels ("1" in Figure 1B, Figure 4A), paragenetic conduits, such as that north of the Pool of Reflections in River Cave ("2" in Figure 1B, Figure 4B) and fluvial streamways such as the Flitch of Bacon ("2" in Figure 1A, Figure 4C).

Morphostratigraphy

In caves like Jenolan where there have been several distinct phases of cave development it is possible to observe crosscutting relationships between one cavity type and another. Recognising these relationships can be a difficult and confusing exercise, but should allow the relative ages of different groups of cavities to be determined.

Sedimentology and Stratigraphy

Cave sediments can only be deposited after a cave has formed and surface-derived sediments can only enter a cave when an open pathway to the surface exists. The age of the oldest sediment in a cave gives the *minimum* age for the cave. The age of the bedrock is the maximum age of any cave.

Figure 1 (NEXT PAGE)

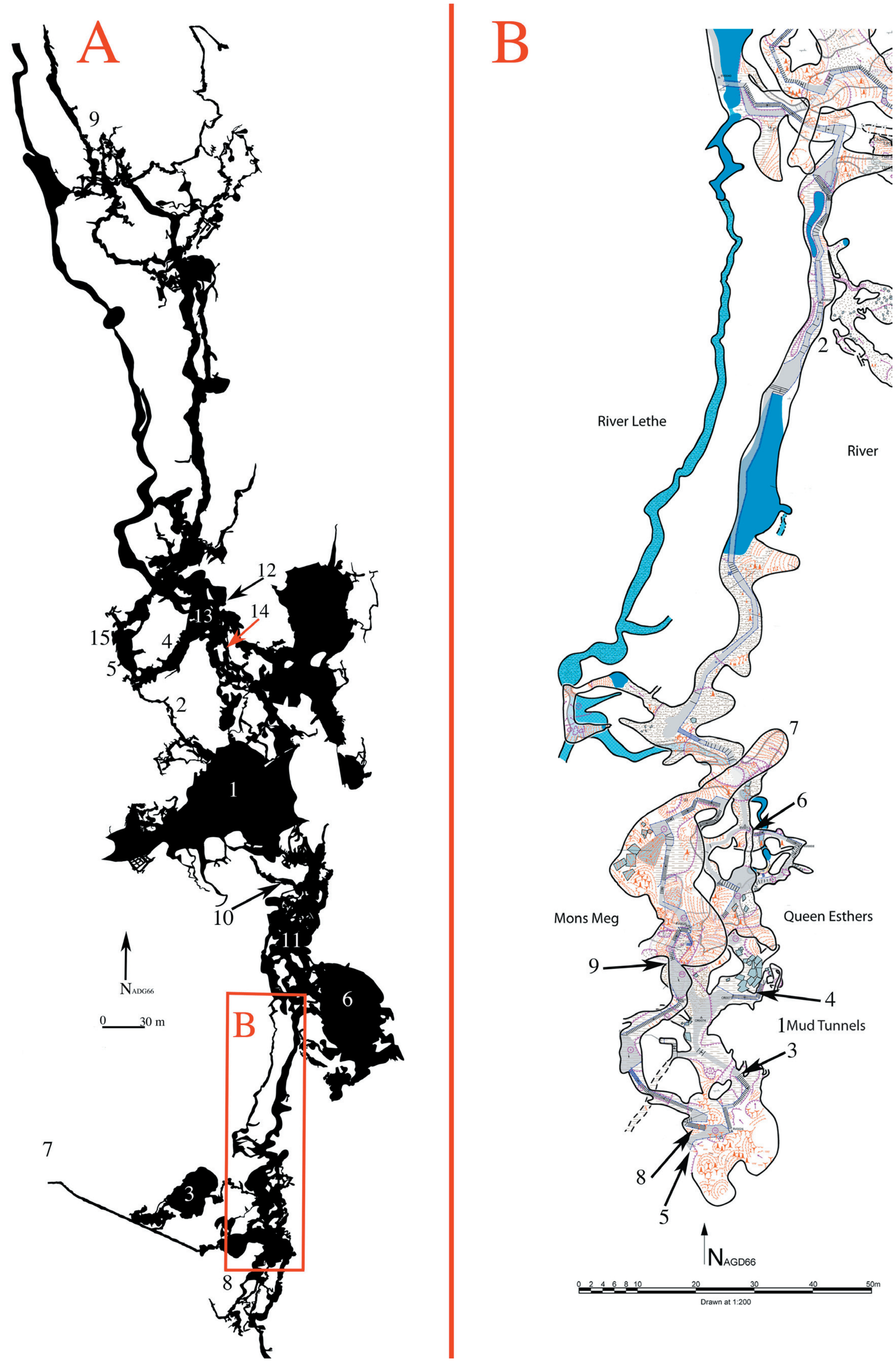
A: - Plan silhouette of the Jenolan Show Caves courtesy of Alan Warild, Jenolan Survey Project. (1) Grand Archway; (2) Flitch of Bacon; (3) Temple of Baal;(4) Wilkinson Branch; (5) Katie's Bower, Chifley Cave; (6) Exhibition Chamber, Lucas Cave; (7) Drain adjacent to Binoomea Cut; (8) Ribbon Cave; (9) Jubilee Cave; (10) Pool of Cerberus Cave;

(11) Cathedral, Lucas Cave; (12) Bone Box, Imperial Cave; (13) Imperial Streamway;

(14) Raft deposit in Imperial Cave (15) The Mystery, Chifley Cave.

B: - Detail plan of River Cave area, omitting Temple of Baal, Orient Cave and related cavities, courtesy Alan Warild, Jenolan Survey Project. (1) Mud Tunnels; (2) North of Pool of Reflections; (3) Olympia Stairs; (4) Orient Stairs; (5) South of Olympia;

(6) T Junction; (7) Northern extension of Mons Meg Loop; (8) The Ladder; (9) Mossy Rock.


A
9
12
13
14
15
4
5
2
1
10
11
6
N ADG66
0 30 m
B
7
3
8
B
River Lethe
River
2
7
6
Mons Meg
Queen Esthers
9
4
1 Mud Tunnels
3
8
5
N AGD66
0 2 4 6 8 10 20 30 40 50m
Drawn at 1:200

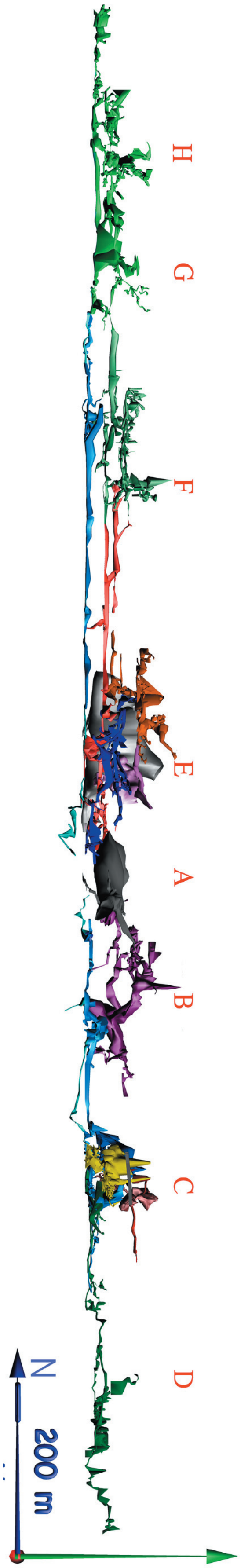


Figure 2, Long Section, looking east, of the Jenolan Show Caves courtesy of Alan Warild, Jenolan Survey Project. Note regularly spaced high points B-H mostly cupola swarms, separated by zones of generally horizontal development A = Grand Archway, B = Cathedral, Lucas Cave, C = Baal-Orient System.

The grainsize and texture of cave sediments and the sedimentary structures in them are good indicators of the environment in a cave at their time of deposition. Sand, small rounded pebbles, ripples and imbricated cobbles are good indicators of fluvial conditions. Mud, finely laminated and graded-bedded layers and crystal raft deposits are indicative of a lacustrine environment while mixtures of cobbles, gravel and mud, without sand are indicative of mass flow deposits.

Palaeokarst features and deposits are evidence for the existence of caves in the past. Features with bedding or other geopetal structures oriented to the present horizontal must have formed after the last folding event. Cave sediments and palaeokarst deposits are difficult to date and can have very complex stratigraphy (Osborne, 1984). This can lead to the situation where even when an event is dated, it can be of little help in understanding the age relationship between major events assumed to be younger or older.

Correlation

Ideally, it should be possible to correlate both cave sediments and cave morphology with the known geological and geomorphic history of the strata and landscape in which a cave has developed. For instance, incision events in the surface landscape should correlate with incision and watertable lowering in the caves. Erosion and deposition at the surface, should, if there is a surface connection, correlate with deposition in the caves. Major events in regional geological history such as folding, granitic intrusion and burial should also leave their mark in the caves. In eastern Australia, however, correlation between the caves and geological and geomorphic history has proved to be neither simple nor uncontroversial (Osborne, 2005, 2010). In the case of Jenolan, the more we know, the more difficult some of the correlation seems to become.

THE INITIAL SYNTHESIS

In my 1999 Presidential Address to the Linnean Society of NSW I presented the elements of a synthesis and a framework chronology for the origin of Jenolan Caves. This recognized ten phases of cave development; five phases represented by ancient caves and palaeokarst deposits filling them, and five phases identified by the morphostratigraphy of and the sediments found in the presently open caves themselves, Table 1, below.

This chronology was largely based on observations made in the southern show caves, which proved to be more easily interpreted that those to the

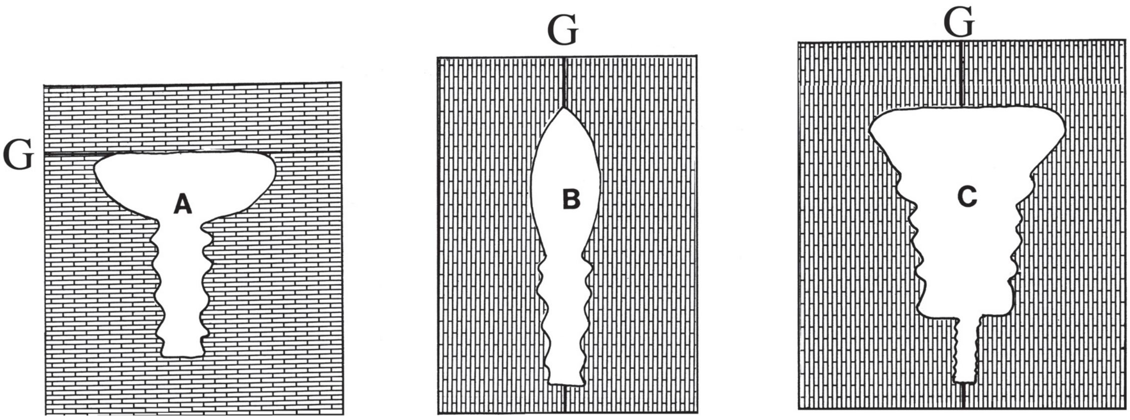


Figure 3, Passage cross-sections after Figure 17 of Osborne (1999a). (A) Textbook section of fluvial cave, upper part of profile phreatic, developed below horizontal guiding joint or bed "G"; lower part vadose canyon; (B) Cavity with similar origin to that in A, but developed along vertical guiding joint or bed "G". Note that vadose canyon is unchanged from "A"; (C) Cross-section of a paragenetic conduit developed in vertically dipping limestone modelled after cross-section of passage at "2" in Figure 1B.

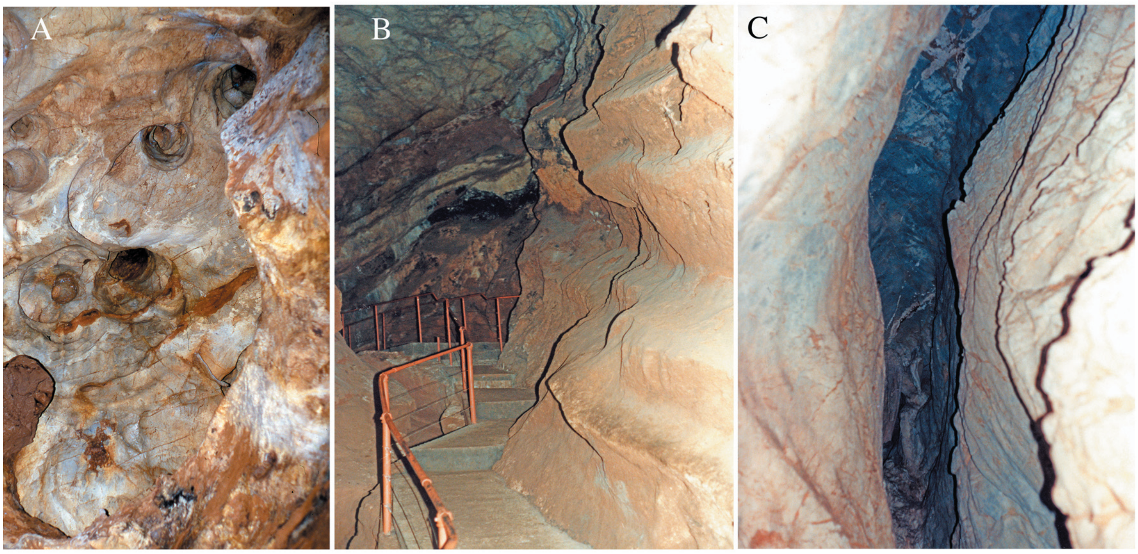


Figure 4, The three main cavity morphotypes of Jenolan Caves. (A) Per-ascensum, ceiling cupolas in the Mud Tunnels, River Cave, "1" in Figure 1B; (B) Paragenetic, paragenetic conduit north of the Pool of Reflections, River Cave, "2" in Figure 1B, looking north. Note rising and falling notches in eastern wall; (C) Fluvial, meandering vadose canyon, The Flitch of Bacon, Chifley Cave, "2" in Figure 1A. View looking up to cave ceiling.

north of the Grand Archway. As no absolute dates had been determined for either the clearly ancient material or for the unconsolidated sediments in the caves, the chronology was based entirely on stratigraphic and morphostratigraphic considerations and an attempt to fit the cave chronology in with regional geological and geomorphological history.

On these grounds I suggested that the palaeokarst might extend back in age to the Early Carboniferous Kanimblan Orogeny and that some cave filling, such as the caymanites, might be Latest Carboniferous in age, filling Carboniferous caves. Based on my previous work (Osborne, 1995), I suggested that the gravels on the surface at Jenolan and filling high-level caves such as Dreamtime Cave were most likely to be Permian in age. I recognized that the oldest phase of development of the currently open caves was *per-ascensum* development of the large cupolas such as the Temple of Baal ("3" in Figure 1A). I thought that this "phase 6" of cave development post-dated

Table 1. After Table 1 of Osborne (1999b)
A Framework Chronology for Jenolan Caves

Geological Era/Period	Phase	Event/Process	Feature	Example
Present	10	Stability	Low Mg Calcite Speleothems	Orient Cave
			Continued Weathering	Ribbon Cave
			Mg Rich Minerals	Ribbon Cave
Quaternary	9	Meteoric Speleogenesis 5 Exhumation	Nick Point Sediment Cliffs	The Ladder, River Cave
			Breakdown	Exhibition Chamber, Lucas Cave
A number of Cainozoic Phases	8	Meteoric Speleogenesis 4 Paragenesis	Conduits	The Slide, Lucas Cave
			Loops	Mons Meg, River Cave
? Tertiary	7	Meteoric Speleogenesis 3	Invasion Caves	Baal-River Passage
? Late Cretaceous	6A	Hydrothermal Speleogenesis 2 Hydrothermal Fills & Alteration	Crystal-lined Cavities	Mud Tunnels, River Cave
			Dolomitic crystal	Pool of Cerberus Cave
			Altered Algal Mats	Ribbon Cave
			Altered Palaeokarst	Olympia Steps, Ribbon Cave
			Non-Detrital Clay	River Lethe, River Cave
? Late Cretaceous	6	Hydrothermal Speleogenesis 2 Excavation	Cupolas	Persian Chamber, Orient Cave
			Halls	Jenolan Underground River
			Tubes	Ribbon Cave
Permian	5	Cave Fill & Landscape Burial	Fluvial Sediments	Dreamtime Cave
Permian	4	Meteoric Speleogenesis 2	Large Caves	Dreamtime Cave
? Early Permian	3	Hydrothermal Speleogenesis 1	Crystal-lined Cavities	Lucas Cave Entrance
? Latest Carboniferous	2	Marine Transgression and filling	Caymanites	Olympia Steps, Ribbon Cave
? Late Carboniferous	1	Meteoric Speleogenesis 1	Phreatic Caves	Olympia Steps, Ribbon Cave

deposition and partial removal of the Sydney Basin, suggesting that it was likely to be Cretaceous in age, resulting from hydrothermal activity related to the opening of the Tasman Sea and the uplift of the Eastern Highlands.

Just two years later, in March 2001, Horst Zwingmann produced the first K-Ar clay dates from Jenolan, and the whole world changed. Among the first dates to emerge was the Devonian date (389 Ma) for the sheared blue-grey clay from the Wilkinson Branch (“4” in Figure 1A). This made sense as a deformed palaeokarst deposit, correlated with the volcaniclastics, which disconformably overlie the limestone to the east, filling early caves.

The group of dates clustered around 340 Ma were, however, a great surprise and puzzle. There were no recorded Early Carboniferous strata within 180 km of Jenolan Caves, the nearest being in the New England Fold Belt (Figure 5), and it had never been suspected that palaeokarst, cave sediments or strata exposed or sitting on the surface in the Lachlan Fold Belt could be of this age. The real surprise from the K-Ar dating was that no Permian material other than overgrowth crystals were found in the caves and that surface

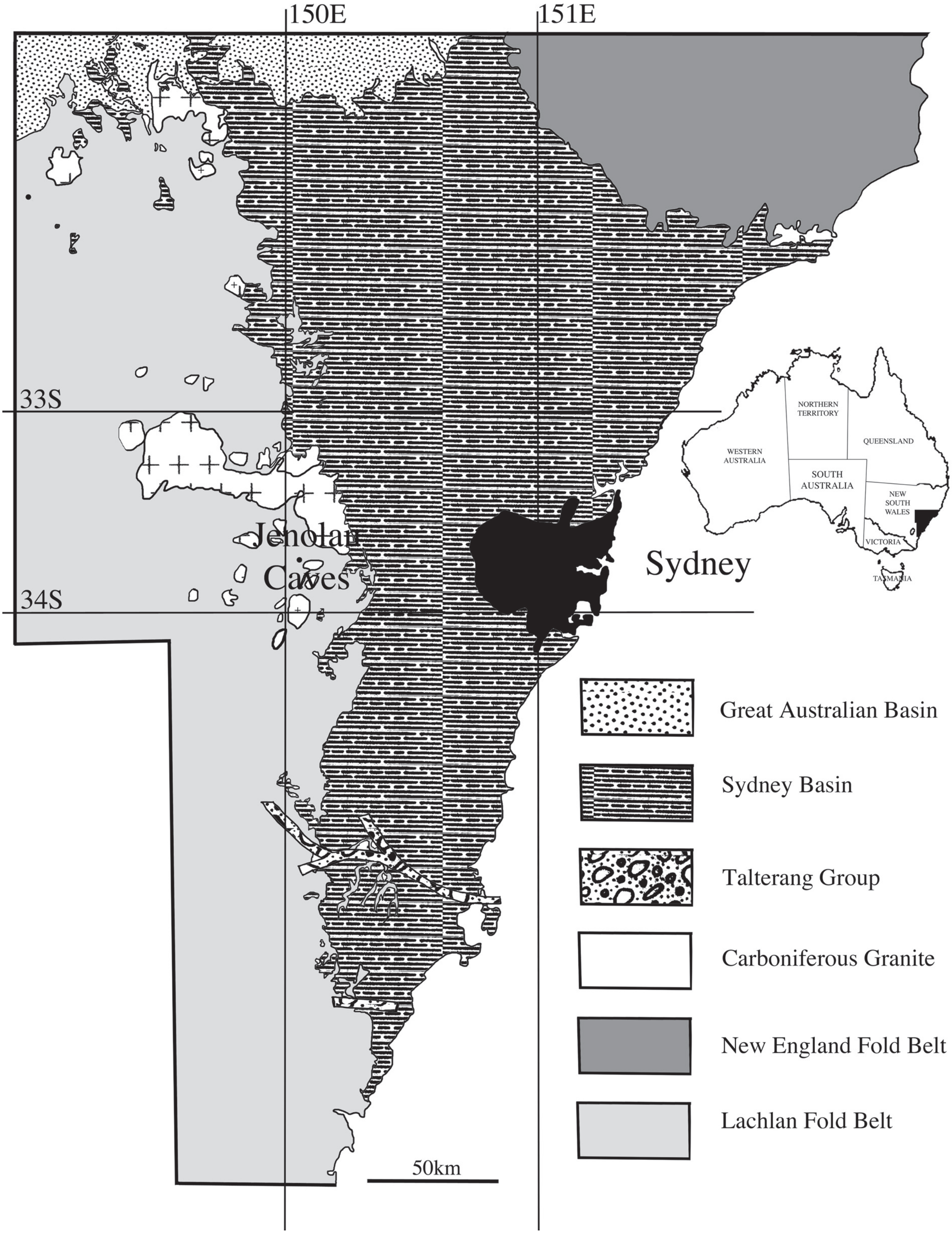


Figure 5, Regional geological setting showing location of Jenolan relative to Carboniferous strata.

deposits long thought to Permian, and represented on geological maps as Permian, such as those in the cutting on the Kanangra Wall Road at Mount Whiteley turned out to be Early Carboniferous.

A CURRENT SYNTHESIS

If we use the K-Ar dating of Osborne et al. (2006), recent observations in the caves and developments in thinking about landscape development in and near the Blue Mountains (e.g. van der Beek et al., 2001) to modify the Osborne (1999b) chronology we end up with Table 2 below.

Problems with the current synthesis

The lack of dating of events younger than the filling of cupolas by mass-flow deposits, except for the indication of burial under the Sydney Basin, makes the present synthesis quite limited. While there is good morphological evidence that cupola development and filling was followed by a major phase of paragenetic development there is no evidence yet as to whether this event pre-dated or post-dated deposition of the Sydney Basin, so I have represented this event twice in Table 2, below.

Present knowledge does not allow correlation between the cave record and the deposition of the Sydney Basin, one of the major events in the regional geological history. I, and many others, expected that due to the proximity of the caves to the edge of the Sydney Basin that basal Sydney Basin sediments would be found in the caves. It is possible that we do see the sediments in the form of the 303 Ma mass-flow deposits in the Temple of Baal.

WHERE NEXT?

Geological problems outside the caves

Studies in caves are frequently impacted by deficiencies in the basic knowledge of the geological and geomorphic environment in which the caves are located. There are several problems at Jenolan. While the structure and composition of the limestone is well known at a gross scale, more detailed structural, stratigraphic and sedimentological studies would help in understanding the factors influencing cave development.

Dating some key features of the local geology would also contribute to understanding the geological background to cave development. It has been generally assumed that the volcaniclastic rock overlying the limestone is similar in age to the Devonian Bindook Volcanic Complex, but this has never been confirmed by dating the volcanics at Jenolan. Similarly, a range of interpretations have been made about the age and origin of the andesite located directly to the west of the limestone near Caves House. These have ranged from an Ordovician or Silurian submarine lava flow to a Jurassic intrusion. Dating this rock would be of great assistance.

To the southwest the sequence at Jenolan is intruded by the Kanangra Granite and to the east by the un-named granite into which Hellgate Gorge is incised, both considered to be related to the Bathurst Batholith. Pogson and Watkins (1998) stated that the Kanangra Granite is likely to be middle Carboniferous (325-330 Ma) in age based on general dating of the Bathurst Batholith. They give the total age range for emplacement of the Batholith as being between 340 and 312 Ma. The dates for the emplacement of the Bathurst Granite overlap with those of the dated clays given by Osborne et al. (2006) making it likely the volcaniclastic source material for the clays came from volcanism related to the emplacement of the granite. As with the emplacement of the caymanites, this presents a palaeogeographic problem. How could the volcaniclastic debris enter the caves when at that time they should have been covered by kilometres thick of rock into which the granites intruded? Dating of the Kanangra Granite and un-named granite may help resolve this problem.

General problems in the caves

1. Underground cave/geology relationships

Apart from some honours thesis work by McClean (1983) and Allan (1986) and some small scale localized work by David Colchester and me, there has been practically no mapping of either the bedrock and/or of the karst geology in the caves. One factor preventing this was a lack of cave maps of suitable quality and resolution onto which field observations could be plotted. The recent completion of the work of the Jenolan Survey Project means that high resolution plans and sections are now available for the whole of the show cave system.

Mapping the bedrock and karst geology of the caves will make explicit relationships between cave development bedrock lithology and geological structures in the bedrock. It will also show the distribution of palaeokarst features in the bedrock, sediments filling the caves and the relationship between speleothems, mineral deposits and bedrock substrate. Unlike conventional cave maps, this type of mapping will indicate were the cave wall is composed of bedrock and where it is sediment, indicating the outlines of sediment-filled cavities.

Table 2. A Revised Jenolan Chronology

Relative	Ma	CAVE EVENT	CAVE EXAMPLES	BEDROCK/SURFACE
Tertiary-Recent		Continuing fluvial action and removal of old fills Breakdown	Queens Canopy Exhibition Chamber	Present surface streams
Early Tertiary		Active Streamways Generation 6 Caves	Imperial Streamway Lethe	Erosion 6 Extra Uplift of Blue Mts. Inner valley?
		Invasion meteoric caves Generation 5 Caves	Baal-River Tunnel	Stripping of Sydney Basin
				Erosion 5
Mid Cretaceous	100?			Uplift of E Highlands
		Lacustrine & Calcite Raft Deposits	Imperial	
		? Paragenesis Generation 4 Caves	Mons Meg, Pool of Reflections, Slide	
Permian-Mid Triassic	258-240	Secondary Illite Growth	Selina & Baal	Sydney Basin Cover
Latest Carb - Triassic				Sydney Basin Deposition
L Carb-Permian		? Paragenesis Generation 4 Caves	Mons Meg, Pool of Reflections, Slide	
Late Carboniferous	303	Mass-flow sediments with brown matrix	Baal, Orient, Imperial	Erosion 4
	340-312			Post-Tectonic Granites
Mid Carboniferous	320-327	Mass-Flow sediments with yellow matrix		Erosion 3, Kanangra Rd & Old School Diamictite
E Carboniferous	340	White & Yellow Clay	Baal, Orient, River	Volcanism
E Carboniferous		Per Ascensum 1 Generation 3 Caves	Baal, Orient, Pool of Cerberus	Erosion 3
E Carboniferous	>340	Crystal vughs	River, Imperial	
E Carboniferous	>340	Caymanites fill Generation 2 Caves	River, Grand Arch DCH	? Marine Transgression
		Generation 2 Caves		
			? Crackle Breccias	
E Carboniferous				Kanimblan Folding
Late Devonian		Unlikely to be found at Jenolan		Lambie Group
		Unlikely to be found at Jenolan		Erosion 2
		Unlikely to be found at Jenolan		Tabberabberan Folding
Late Early Devonian				Volcanics overlying the Jenolan Caves Limestone
Devonian	389	Blue clay palaeokarst	Wilkinson Branch	
	>389	Generation 1 Caves		Erosion 1
Latest Silurian				Jenolan Caves Limestone

While it is easy to see the benefits of such an undertaking for cave management, interpretation and science this project would require a considerable amount of time and would require fieldwork by experienced workers with eyes for carbonate geology, structural geology, palaeokarst, cave sediments, speleothem and cave minerals, hopefully working in the field together, along with significant funds allocated for lab work in petrology, structural geology, x-ray mineralogy, sedimentology etc.

2. Age and origin of the crackle breccias

Crackle breccias consist of bedrock fragments in a crystalline matrix. They are usually grain-supported and often have the appearance of adjacent blocks that have been pushed apart by the emplacement of the matrix, and fit together like pieces of a jigsaw puzzle.

There are two large exposures of crackle breccia in the Jenolan Show Caves, both difficult to access and sample. One forms the ceiling of Katie's Bower in the Chifley Cave ("5" in Figure 1A) while the other is exposed in the cave wall and ceiling at the bottom of the Slide in Lucas Cave at its junction with Exhibition Chamber ("6" in Figure 1A). The Katie's Bower exposure (Figure 6A) shows evidence of rotated blocks while the Lucas Cave exposure (Figure 6B) shows large angular blocks. Crackle breccias are also found at Wombeyan Caves (Osborne, 2004) and Bungonia Caves.

There are conflicting views about the origin of this type of breccia. Polish economic geologists have attributed the origin of these structures in dolomite to solution-collapse following the removal of underlying limestone (Sass-Gustkiewicz, 1974) while American petroleum geologists (Loucks, 2007) have attributed them to the collapse of cave systems due to burial by an overwhelming mass of overburden. The latter explanation seems most likely in eastern Australia.

While the Limestone was probably not covered by a great thickness of Sydney Basin sediments, by the end of the Devonian it was probably buried by a significant thickness of mid-Devonian volcaniclastics and siliceous late Devonian Lambie Group sediments. While at present there is no direct evidence for the age of these breccias, it seems likely that they are of significant, possibly Devonian, age.

3. Age of the caymanites

Unconformable caymanites (marine carbonate turbidite palaeokarst, Jones, 1992) are exposed in NSW in caves and in surface outcrop at Jenolan, Bungonia and Borenore and in caves at Colong and Wellington. While stratigraphic relationships suggest they predate the Early Carboniferous clays at Jenolan, they contain no datable macrofossils and attempts to date them using microfossils have proved unsuccessful as none were recovered. Palaeomagnetic dating has been attempted with little success except to indicate that they most likely predate the Sydney Basin.

Caymanite deposits are common at Jenolan in the show caves, in the open arches, in the wild caves and in surface exposure. One of the most important exposures is at Olympia Steps in the Mud Tunnels section of River Cave ("3" in Figure 1B, Figure 6C). Here an incomplete section more than 5 m thick is exposed with a clearly defined unconformable upper boundary, representing the palaeo-cave ceiling (Figure 6D). The caymanite deposits include a range of lithologies including beds of coarse crinoidal grainstone (Figure 6E), graded-bedded sequences (Figure 6F) and fine, cryptocrystalline mudstones.

The caymanites appear to represent an Early Carboniferous marine transgression over parts of the Lachlan Fold Belt, which is not recorded in the conventional stratigraphic record. It is very difficult to conceive an Early Carboniferous palaeogeography that would allow marine water and sediment to enter caves in the limestone at this time. The palaeogeography of Late Carboniferous to Early Permian times, however, is much more conducive to such an event. So I (Osborne, 1999b) concluded that the caymanites were likely to be Late Carboniferous to Early Permian (Table 1). The problem is that crosscutting relationships observed in the caves by Osborne et al. (2006) and other examples seen since all suggest that the caymanite is older than the dated Early Carboniferous clays. Field evidence also suggests that the caymanite is older that the crystal filled vughs, which are also older than the dated Early Carboniferous clays. Osborne (2007) discussed the palaeogeographic problems arising from the emplacement and survival of Early Carboniferous sediments at Jenolan as part of the general problem of explaining why ancient caves should survive at all and suggested differential vertical movements of fault blocks as a possible solution.

A new attempt at palaeomagnetic dating of the Jenolan and other caymanites in New South Wales and further studies of their stable isotope geochemistry is planned and may help to resolve this problem. Finding datable fossils or microfossils in the caymanites would be the best outcome, but that seems unlikely.

4. Effect of granite emplacement on the caves

While I have put a lot of thought into the palaeogeographic implications of emplacement and later un-roofing of the Carboniferous post-tectonic granites for the survival of Early Carboniferous caves at Jenolan, it was not until Dr Percival raised the issue of "How did the granites affect the caves?" in his presentation at the Jenolan Symposium that I thought about whether I had seen any evidence that the caves were affected by the emplacement of the granites.

Given that the boundary of the un-named granite into which Hellgate Gorge is incised is 2 km east from Jenolan Caves, and that the emplacement of this granite was likely to have occurred between 325-330 Ma, one might expect to see an impact on caves older than 340 Ma and on the 340 Ma sediments in these old caves. The emplacement of granites is

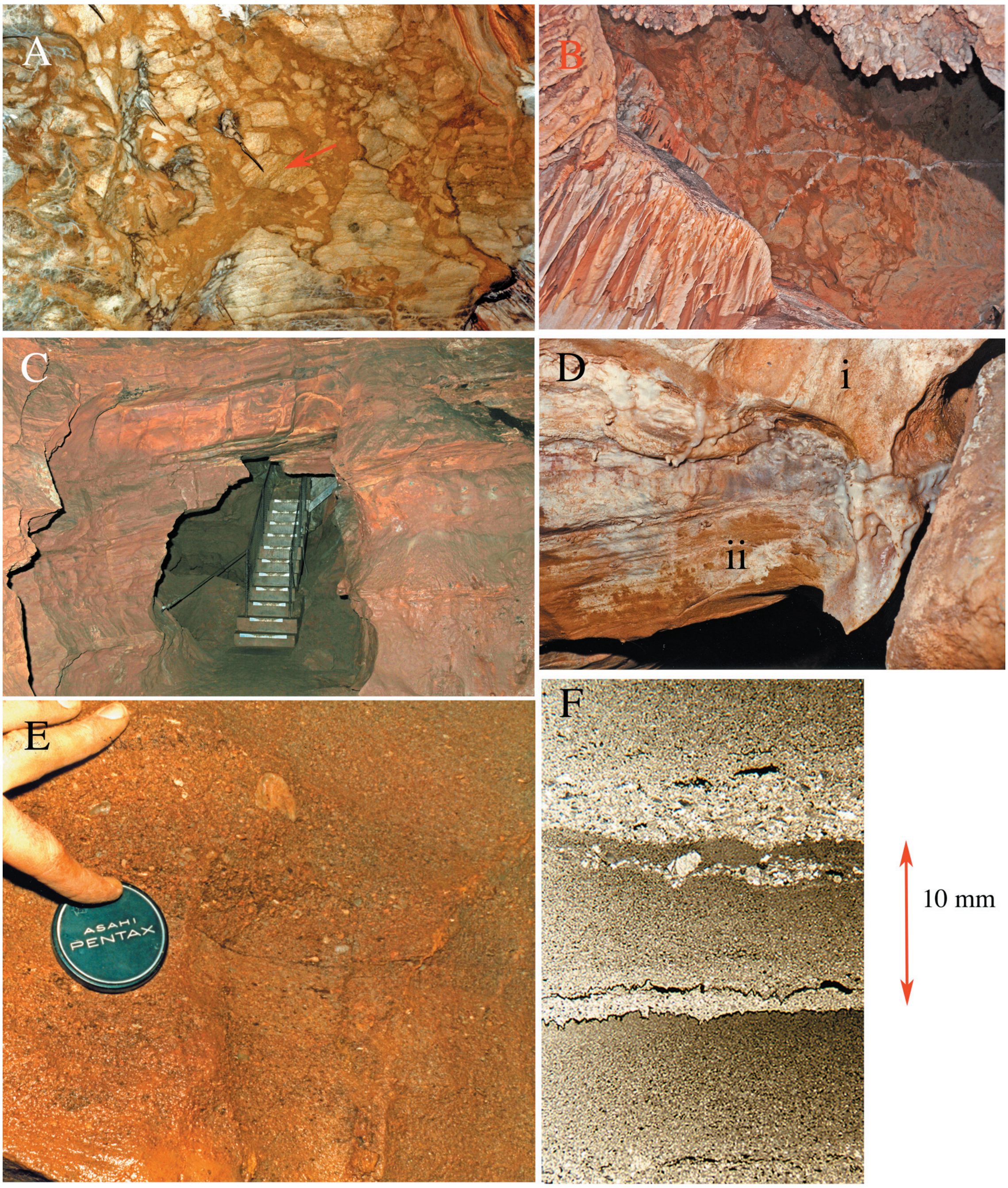


Figure 6, Crackle breccia and caymanite. (A) Crackle breccia in Katie's Bower ceiling, note rotated block in centre of image indicated by red arrow; (B) Crackle breccia exposed a western wall and ceiling near junction of The Slide with Exhibition Chamber. Image courtesy Ted Matthews; (C) Olympia Stairs caymanite exposure, looking south at "3" in Figure 1B; (D) Upper boundary of caymanite deposit representing ceiling of filled palaeocave in the Mud Tunnels near Orient Stairs ("4" in Figure 1B) i = dipping Jenolan Caves Limestone bedrock, ii = sub-horizontally dipping caymanite; (E) Exposure of coarse crinoidal grainstone facies caymanite in Barrelong Cave, Lens cap 55mm; (F) Thin section of laminated and graded-bedded caymanite from Olympia Stairs deposit.

usually accompanied by significant heating of the surrounding country rock, resulting in contact metamorphism. In the case of the 340 Ma illite-bearing clays one might expect this to result in the growth of fine-grained spiky illite crystals during the peak phase of granite emplacement between 325-330 Ma. We do find secondary spiky illite crystals on clays from the Temple of Baal and on clays filling a crystal vugh in Imperial Cave, but these give dates between 258-240 Ma, more likely to be related to burial under the Sydney Basin than to the emplacement of the granites.

Heating by batholiths often leads to hydrothermal mineralization, and close to large bodies of limestone could lead to hydrothermal cave formation and/or the formation of crystal veins and vughs. Once again all the available evidence suggests that the large *per-ascensum* cupolas and the crystal vughs, both of which could be hydrothermal in origin, are older than the emplacement of the granite.

While the 12 km distance from the Kanangra Granite might rule out any great impact from it, one might expect an effect from the nearby un-named granite in which Hellgate Gorge is incised. One possible explanation for the apparent lack of impact by granite emplacement on the caves could be that the un-named granite is significantly older than 325-330 Ma. If the un-named granite was emplaced before 340 Ma, its emplacement could have been responsible for both hypogene cave and crystal vugh development without having any impact on the dated clays. This idea could and should be tested by dating the un-named granite.

A more radical possibility is that the rock mass containing Jenolan Caves was not in its present position relative to the granites at the time of their emplacement, but was "shuffled" into its present place by fault movements after the emplacement of the granites but before the deposition of the Sydney Basin. This is not completely impossible as there is some evidence that the western boundary of the limestone is faulted and House (1988) suggested movement of the major north-south trending fault to the east of the limestone post-dated emplacement of the un-named granite. The relationship between the caves and the granites remains a puzzle and work and thought needs to be applied to solving this problem.

5. Age of gravels and mass-flow deposits

Dating by Osborne et al. (2006) gave two different ages for the polymictic, matrix supported, cobbly gravels at Jenolan Caves; approximately 320-327 Ma for deposits on the Kanangra Walls Road (Figure 7A) and at the old school and 303 Ma for the deposit that appears to have once filled much of the Temple of Baal (Figure 7B).

Without the benefit of dating, Osborne (1995), recognised that there were two distinct groups of cemented gravels at Jenolan; polymictic gravels with pyrite such as those in Dreamtime Cave (Figure 7C) and polymictic gravels without pyrite. It was suggested that those with pyrite in their cement were not Cainozoic in age and were most likely latest Carboniferous to earliest Permian in age. None of these gravels have yet been dated and their relationship with either group of dated Carboniferous mass-flow deposits at Jenolan or with other undated gravels is not at all clear.

It is very likely that some gravel deposits result from the re-working of older deposits. Some deposits now on the surface may not be surficial deposits at all, but deposits filling unroofed caves, such as the gravel deposit on top of the Grand Archway (Figure 7D). A great deal of fieldwork in very steep country, as well as in the caves, is required if any progress in understanding the age and relationships of the gravels is to be made.

6. Dolomite and ankerite

The Jenolan Caves Limestone is very pure and in bulk contains very little magnesium. The caves, however, contain significant isolated occurrences of aragonite speleothems, often associated with deposits of magnesium-bearing minerals such as hydromagnesite and huntite and at one locality dolomite is actively being deposited.

Ankerite veins protrude from the cave walls in close proximity to aragonite deposits in Ribbon Cave ("8" in Figure 1A), Jubilee Cave ("9" in Figure 1A) and in the Mud Tunnels. Figure 8A shows protruding ankerite veins at the southern end of Ribbon Cave associate with a brown fill or alteration zone that has yet to be sampled or investigated in detail. Also growing from an apparently dolomitic substrate in Ribbon Cave is a spectacular aragonite speleothem mass called the Lyrebirds Nest (Figure 8B) with spiral vermiform aragonite helictites tipped with growing cauliflower-shaped masses of moist huntite with a texture like cream cheese.

Some of the most impressive and extensive aragonite speleothems occur in Pool of Cerberus Cave ("10" in Figure 1A) associated with ferruginous mud and soggy yellow weathered dolomitic limestone. One section of the cave path has been cut through some of the substrate to reveal yellow dolostone with angular ferruginous fragments (Figure 8C). Some of the aragonite speleothems in Pool of Cerberus Cave and their rusty clay substrate are shown in Figure 8D.

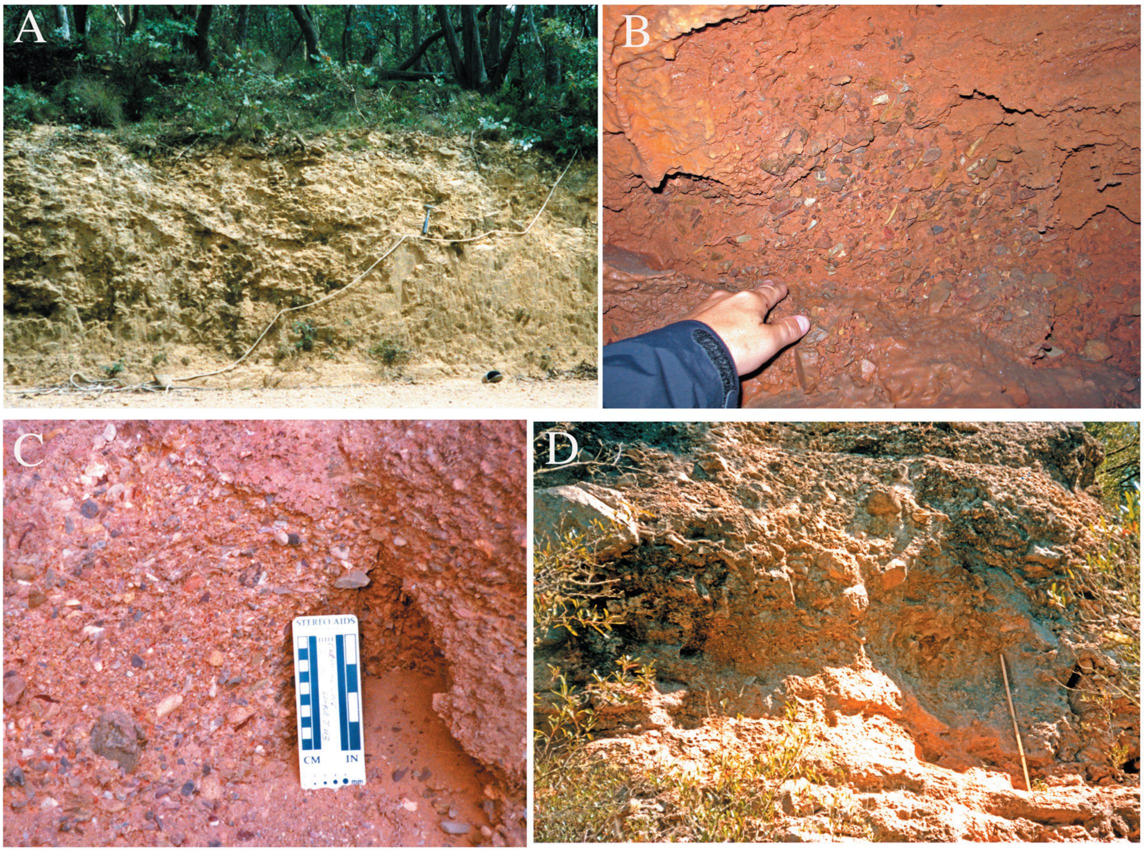


Figure 7, Gravel deposits. (A) Kanangra Road, tape marks unconformity at base of gravel deposit; (B) Mass-flow deposit in western side of the Temple of Baal, Image courtesy Bojan Otoničar; (C) Cemented gravel in Dreamtime Cave; (D) Gravel deposit, possible unroofed cave in saddle above the Grand Archway.

The scattered deposits of aragonite and magnesium minerals appear to be closely related to ankerite veins and irregular dolomitic bodies in the limestone. Some of the caymanite deposits are dolomitized and it appears that a single bed towards the top of the limestone sequence has been extensively dolomitized. Weathered dolomitic/ankeritic net veins can be observed in surface limestone outcrops. One example is the veins exposed in the bank of the drain running in front of the entrance to Binoomea Cut (“7” in Figure 1A, Figure 8E).

Contact Cave, located high on the eastern side of McKeown Creek valley, is named because it was thought to have formed at the boundary between the Limestone and the overlying Devonian volcanics. The cave is close to, but not on the boundary and the rock forming the eastern wall of the cave and much of the ceiling is not composed of volcaniclastics but of rusty yellow weathering dolomitic limestone. Complex aragonite anthodites, with dolomite crystals forming at their tips, grow from the weathering dolomite substrate (Figure 8F).

Rowling (2004) described aragonite deposits in several caves at Jenolan and suggested a relationship with magnesium, strontium and sulfate ions, all of which could be sourced from pyritic dolomite and ankerite. Ross Pogson, David Colchester and I have made some investigation of the ankerite and dolomite veins and outcrops in the caves, but much more needs to be done and funding is required for chemical and isotopic analyses.

7. “Yellow stuff”

Visitors and cave guides often inquire and sometimes argue about the nature of striking yellow coloured deposits partially filling or intersected by the caves. These occur throughout the caves, but are mostly noticed in the southern show caves. Now that new maps are available it would be useful from both a scientific and an interpretation point of view to map and identify these deposits. Where these deposits have been investigated the “yellow stuff” turns out to encompass a range of materials with a similar colour and often a gooey texture. These include 340 Ma

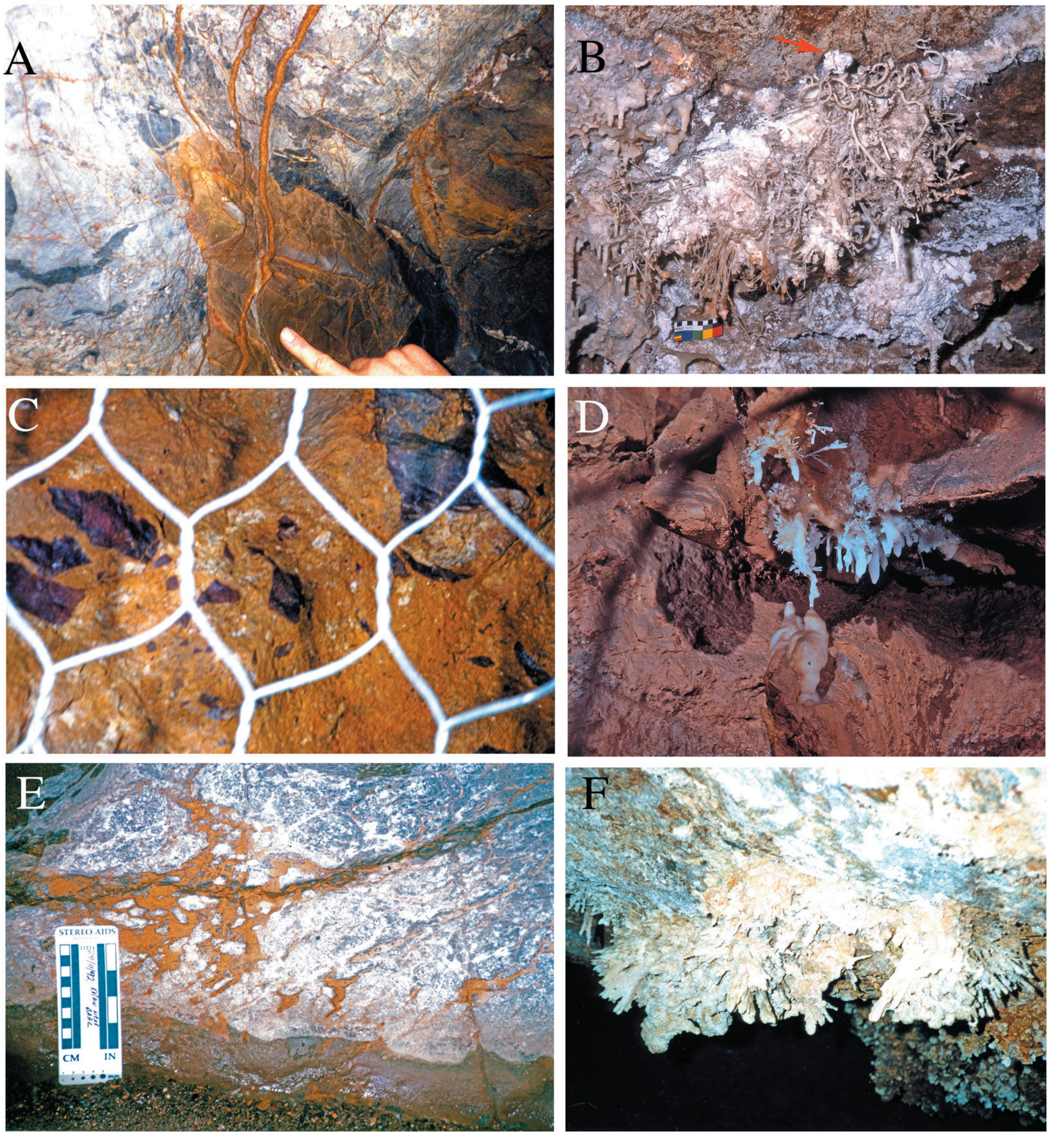


Figure 8, Dolomite and ankerite. (A) Protruding orange ankerite veins and undetermined brown material on wall of Ribbon Cave ("8" in Figure 1A); (B) The Lyrebird, Ribbon Cave, a complex aragonite speleothem mass with soft cauliflower-like deposits of huntite (indicated by red arrow) growing on the tips of vermiform helictites. Black squares on scale 10mm; (C) Tan dolomitic mass with ferruginous clasts intersected in excavated ceiling of Pool of Cerberus Cave ("10" in Figure 1A) adjacent to significant deposit of aragonite speleothems; (D) Aragonite stalactites growing from ferruginous mud with curved laminations (possibly weathered dolomite) in close proximity to "C"; (E) Dolomitic net veins in limestone bedrock exposed in side of drain adjacent to entrance to Binoomea Cut ("7" in Figure 1A); (F) Aragonite speleothems (anthodites) with dolomite crystals being actively deposited at their tips, Contact Cave.

clays, weathered ankerite veins, altered algal mats and dolomitized diagenetic infill sediments with bedrock fossils.

Figure 9 shows some examples of "yellow stuff" from the southern show caves. Figure 9A is one of several crumbly sandy pendants that hang from the ceiling of Pool of Cerberus Cave. This material is clayey sand with no carbonate content and contains small double-terminated quartz crystals, so it could be Early Carboniferous volcaniclastic sediment. Figure 9B is either a limestone boulder or a bedrock projection from the cave wall exposed in the side of a cutting in an old tourist path south of Olympia ("5" in Figure 1B). The rock has a thin coating of yellow

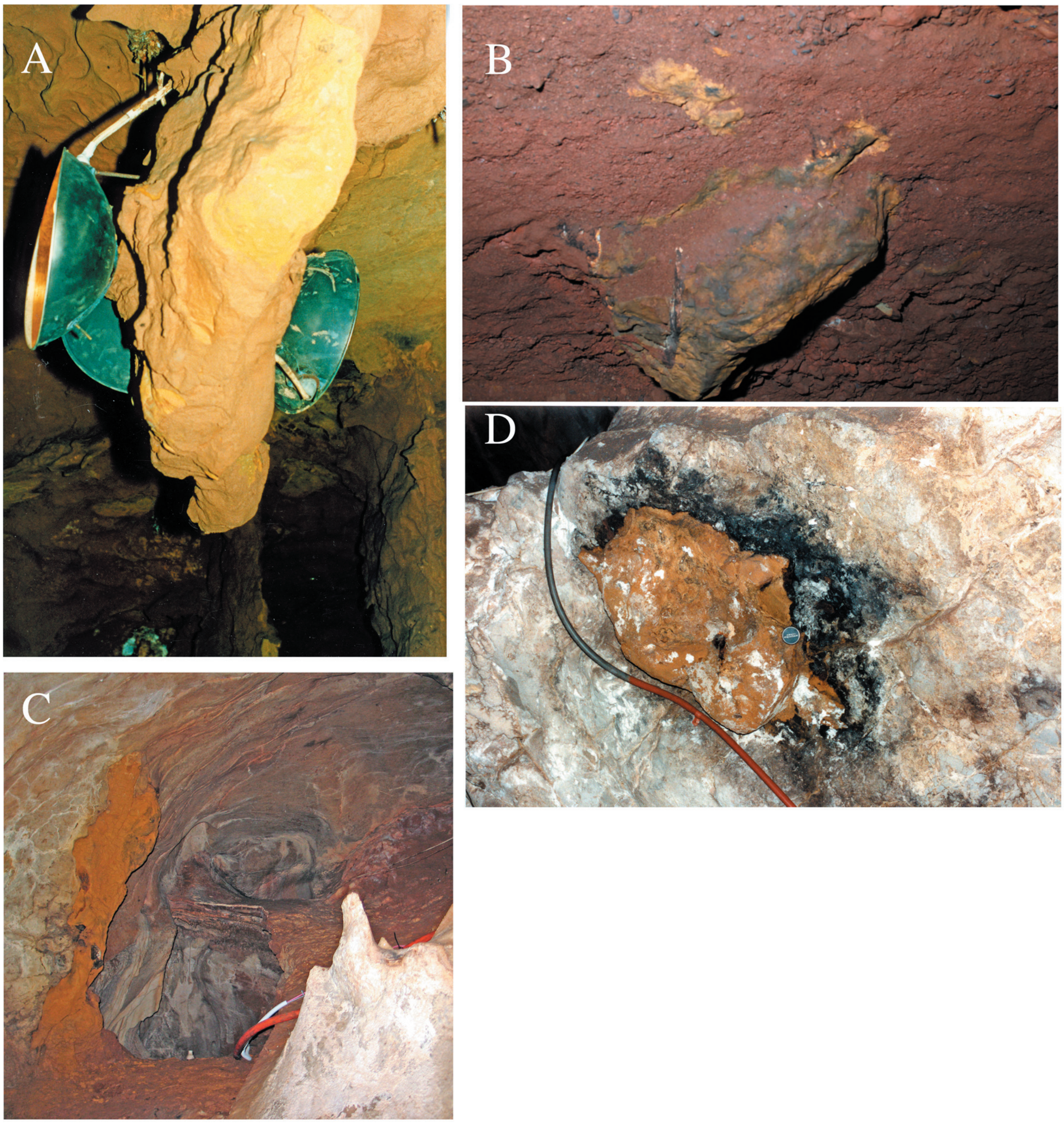


Figure 9, Yellow stuff. (A) Ceiling pendant of siliceous "yellow stuff" with old light fittings attached in Pool of Cerberus Cave; (B) Undetermined yellow coating on exhumed boulder or cave wall in cutting of old tourist path south of Olympia ("5" in Figure 1B); (C) Dated Early Carboniferous volcaniclastic sediment (orange) at T-junction in River Cave ("6" in Figure 1B) Image courtesy Bojan Otoničar; (D) Leisegang-banded ironstone with quartz grains, separated from bedrock by manganiferous reaction rim on wall of the Cathedral, Lucas Cave ("11 in Figure 1A).

paste, which has yet to be analysed. Figure 9C shows a bright orange remnant of dated Early Carboniferous clay located at the "T" junction in River Cave ("6" in Figure 1B). Figure 9D shows a yellow ferruginous remnant, consisting of a small number of quartz grains in a ferruginous matrix, separated from the bedrock by a layer (? reaction rim) of manganiferous paste on the wall of the Cathedral, Lucas Cave ("11" in Figure 1A). The origin and previous extent of this deposit is unknown.

While in most cases the yellow colouring is likely to be ferruginous, Ian Cooper pers. comm. (2013) has reported observing native sulfur in both River and Jubilee Caves, however this has yet to be confirmed by sampling and analysis. Now that good maps are available, a collaborative effort between cave guides, marking localities of “yellow stuff” on maps and researchers sampling and characterising the material is possible and could result in both better interpretation and enhanced scientific understanding.

Southern show caves

The most important step in understanding the history of the southern show caves is dating the paragenetic sediments. These deposits are of two types, sequences in wall niches and thick deposits either filling passages or protected by flowstone caps. The later type appear to be remnants of sediment that probably once filled the whole length of these conduits, exposed at the present erosion head.

Wall niche deposits are easily observed on the niches in the walls of River Cave north of the Pool of Reflections (“2” in Figure 1B, Figure 10A). Sections exposing sediments at erosion heads also occur in River Cave. Sections are exposed at either end of the Mons Meg paragenetic loop. An 8-metre section of fine laminated mud (Figure 10B) fills what appears to be the ancient northern route of River Cave before its down-dip migration to the west (“7” in Figure 1B) while a section more than 6-metres high is exposed at the Ladder at the southern end of the Mons Meg Loop (“8” in Fig 1B, Figure 10C). Another 8-metre section is exposed at the northern end of the Mud Tunnels near Mossy Rock (“9” in Figure 1B, Figure 10D).

Northern show caves

Much of my work has focused on the southern show caves as it is easier to study the cupolas and observe morphostratigraphic relationships between features produced by different phases of cave development there. I had assumed, falsely as it has turned out, that the northern show caves were essentially stacked levels of former underground streamways, filled with fluvial sediment, representing a series of underground captures of McKeown Creek (Osborne, 1999b).

What I have since realised about the northern show caves is the difference in morphology between the cavities along which the main tourist paths run in Imperial Cave, Jubilee Cave and most of Chifley Cave and the morphology of the cavity at river level in the Imperial Streamway.

Near the main tourist paths the cave walls are white and smooth. Scallops are rare and there is little sign of sand (Figure 11A). Cave morphology is suggestive of excavation by paragenetic rather than fluvial processes. Below, in the streamway, the walls and projections from the ceiling appear to be made of fresh limestone and are covered with many small scallops, indicating fast-flowing water (Figure 11B). In addition to the scallops, the rock surface is rough due to the presence of small sharp pieces of insoluble material projecting from the rock surface indicating that the water in the stream is unable to dissolve small pieces of chert and silicified fossils in the limestone. There is clean sand with ripples in the streambed and there are some overbank deposits of mud formed during flood events. The active processes we see today in the Imperial Streamway are clearly not the key to the past as seen in the higher-level passages.

Recent casual observations have shown that while there are relatively uncommon deposits of fluvial sand and gravel, the principal sediment types in the northern show caves are crystal rafts (Figure 12A), muds (Figure 12B) and poorly-sorted mass-flow deposits (Figure 12C), indicative of lacustrine or paragenetic conditions rather than fluvial.

While significant progress has been made in unravelling the developmental history of the southern show caves, there has been less progress in the north and much remains to be done. There is a least one PhD project in sorting out the sediments and morphology in the northern show caves.

TAKING THE NEXT STEPS

Despite their ease of access the Jenolan Show Caves are among the most complex and confusing caves to study and understand. There are, however very good reasons not just to persist with research at Jenolan but to expand it. These include the scientific significance of the caves, the significance of the caves for interpretation and education, the significance of the science for the conservation, management and sustainable development of the caves, and their natural heritage significance, which I believe could be demonstrated to be at a level appropriate for nomination to the World Heritage List.

Scientific significance

Jenolan Caves are among the world’s oldest and most complex limestone caves containing unconsolidated sediments dating back to the Early Carboniferous and preserving records of past events not found elsewhere. The caves are important in illustrating the effects of multiple phases of different cave forming mechanisms, *per-ascensum,* paragenetic, fluvial and breakdown being overprinted within a small body of limestone.

The caves are also important for their great diversity of mineral species and for the particular

Figure 10, Paragenetic Sediments. (A) Mud deposits on niches in eastern wall of River Cave, north of Pool of Reflections ("2" in Figure 1B) wall approx. 6 m high; (B) North extension of Mons Meg section 8 m + ("7" in Figure 1B); (C) Section at Ladder 6 m+ ("8" in Figure 1B); (D) Section at Mossy Rock 8 m thick below flowstone ("9" in Figure 1B)

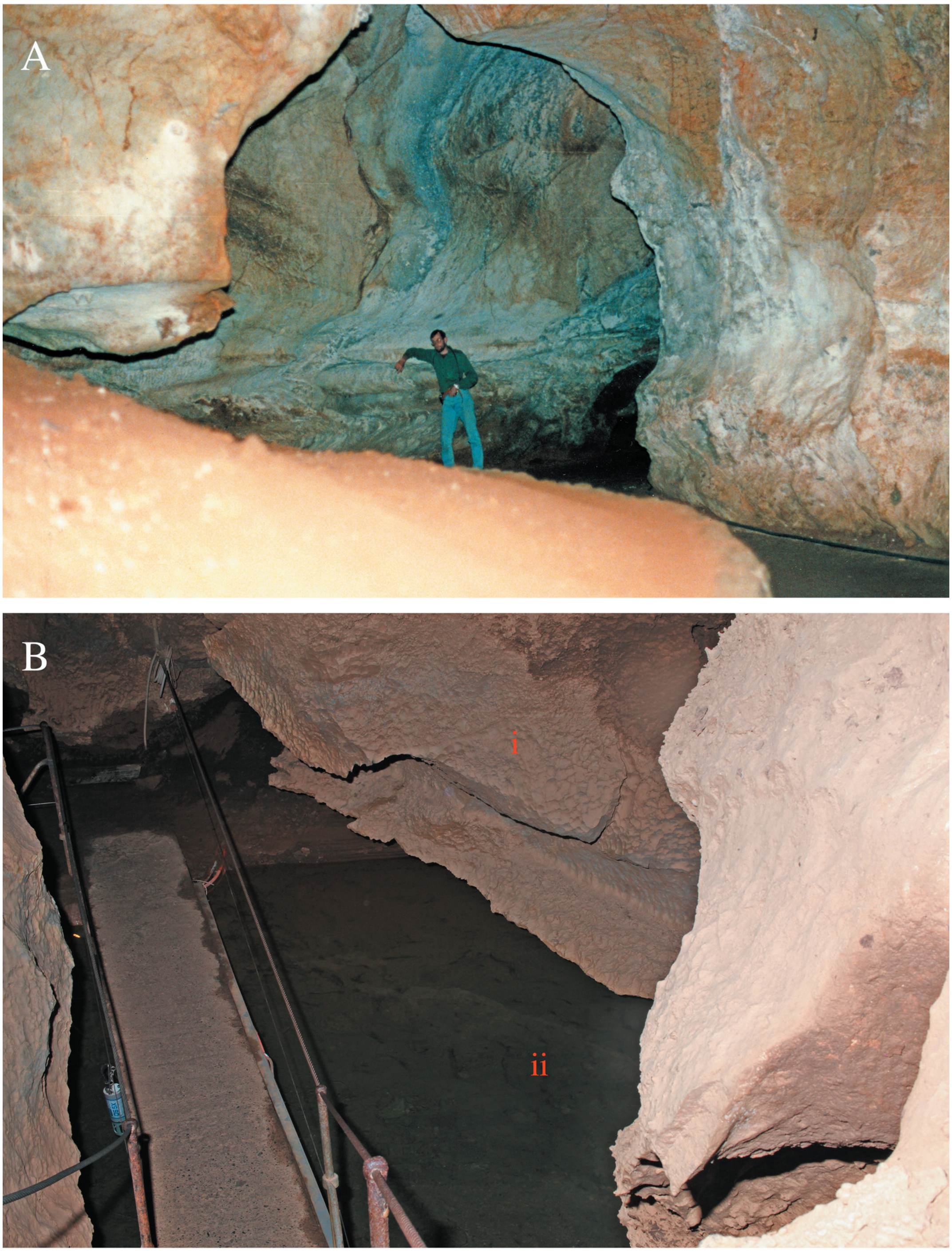


Figure 11, Morphology of cave at tourist path level compared with that at stream level in Northern Show Caves. (A) Imperial Cave tourist path, looking north, north of the Bone Box ("12" in Figure 1A). Note relatively smooth walls and lack of scallops; (B) Looking down to the Imperial Streamway ("13" in Figure 1A) note scallops on ceiling at "i" and ripples in sand in streambed at "ii".

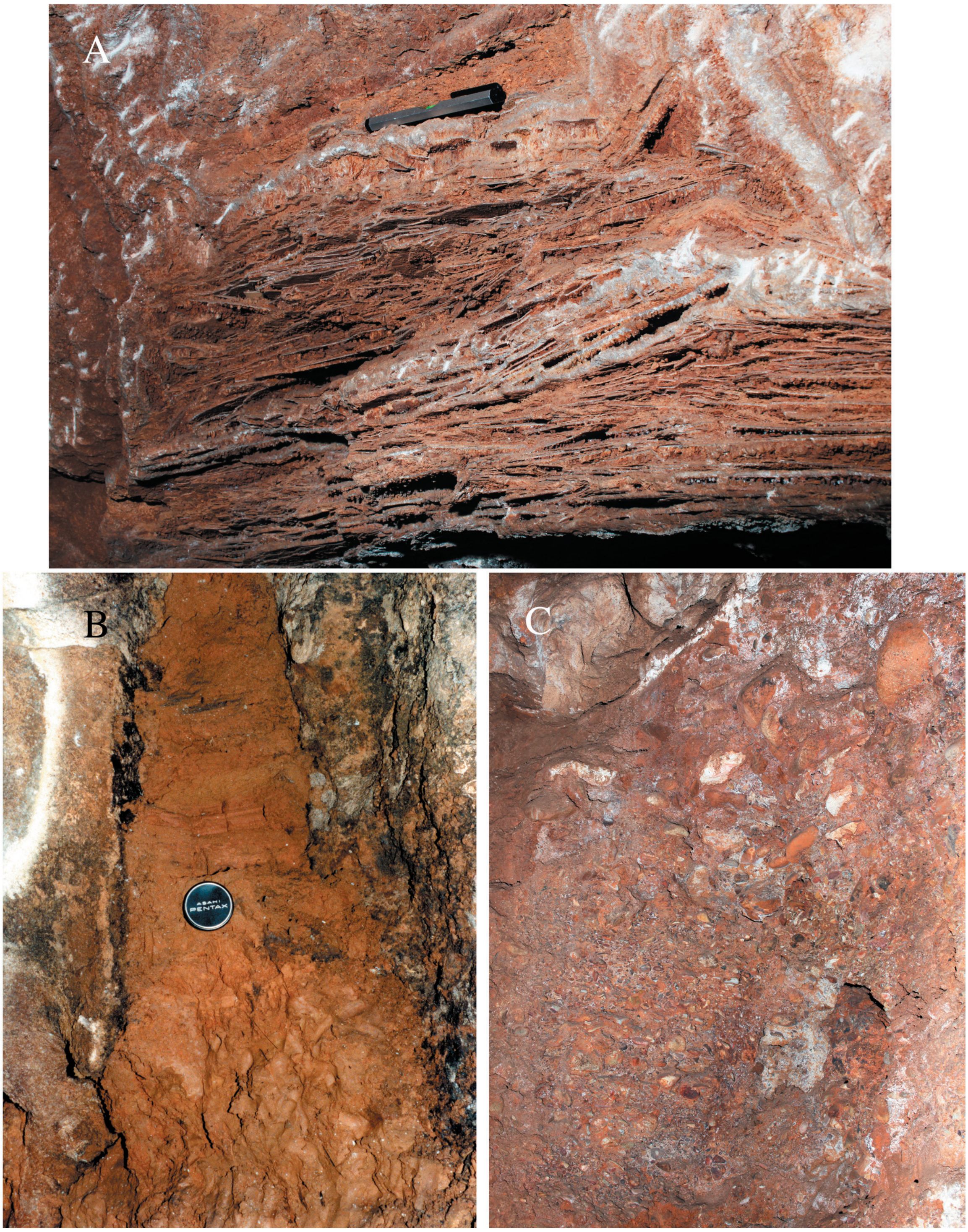


Figure 12, Sediments in Northern Show Caves. (A)Calcite raft deposit in eastern wall of excavated tourist path in Imperial Cave ("14" in Figure 1A). Pocket spirit level is 80 mm long; (B) Laminated mud deposit near the mystery, Katie's Bower, Chifley Cave ("15" in Figure 1A). Lens cap 55 mm; (C) Mass flow deposit of cobbles and gravel in a mud matrix exposed in cutting of path to the Imperial Streamway ("13" in Figure 1A).

expression of some forms of speleothem (see Pogson et al. this volume).

Significance for interpretation and education

As Australia's most visited show caves, with some 240,000 cave visits annually, Jenolan Caves are an important site for scientific and environmental interpretation to the public, particularly for the interpretation of Earth sciences. Of these visits, 11,700 annually are by primary and secondary students, making it one of the State's most important school excursion venues.

Good interpretation requires a good story, derived from rigorous theory, synthesis and a strong factual base. For the caves at Jenolan we have a beginning in the Early Carboniferous and an end in the present cave environment; we know some of the events in between, but not their sequence. Theory and synthesis are now beginning to emerge, but as illustrated in the case of "yellow stuff" many obvious features of the caves have not yet received serious scientific attention and cannot be properly interpreted to the public.

Significance for conservation, management and sustainable development

In order to properly conserve, manage and develop a natural heritage site it is essential to know what is there and if it is highly significant, rare, fragile or vulnerable. Inventory studies did not exist when Jenolan Caves were first developed for tourist use in the late 19th and early 20th centuries, so our lack of good data to inform conservation, management, development and interpretation is partly historical, but like most major show caves world-wide there has never been an inventory study of the show caves at Jenolan. Without an inventory study, monitoring of caves is deficient (Osborne, 2002) so an inventory study should be undertaken before any major changes in cave management occur.

The work of Osborne et al. (2006), and the continuing research proposed here has a focus on unconsolidated sediments and less attractive mineral deposits: materials that often receive less care and regard during cave maintenance and when development is proposed. Remnant sediment masses, such as those near the Pool of Reflections could easily be destroyed by over zealous use of high-pressure water cleaning, while the first dated Early Carboniferous clay locality was formerly used as a source of material to repair drain pipes.

These ancient materials have, however proved to be essential for understanding the history of cave development and are records of past events not previously known to science. The present risk at Jenolan as in most other show caves is that something of great significance might be harmed or destroyed simply because it is un-recognised and un-recorded.

World Heritage significance

While Jenolan Caves are within the Greater Blue Mountains World Heritage Area (GBMWHA), neither Jenolan Caves, nor any of the other landscape and geological features of the GBMWHA were among the reasons for listing. There are many cave and karst areas now included on the World Heritage List so adding more would present a challenge. However, there has been interest over many years in the possibility of including Jenolan as part of an Eastern Australian Impounded Karsts nomination or in making a case to have the values at Jenolan Caves included in the existing GBMWHA listing.

World Heritage listing requires places to be of "outstanding universal value" and for non-living natural places a detailed comparison of significance with places having similar values internationally is required. It is difficult to find caves internationally with which to compare Jenolan, but I think there are some caves in central Europe with which this may be possible. A detailed understanding, listing and evaluation of the values, and an inventory study would be required. Any action on World Heritage listing is a considerable undertaking and successful nominations internationally always require the mobilization of government and academic scientific resources.

CONCLUSIONS

There are clear steps to be taken to further our understanding of the origin and evolution of Jenolan Caves. Taking these steps is not only of scientific importance, but will greatly enhance the conservation, management and interpretation of Australia's most significant tourist cave system and is also essential for progress towards World Heritage listing of Jenolan Caves. The next steps require an application of cave science at a scale not previously seen in Australia. Are we up to the challenge?

ACKNOWLEDGEMENTS

This paper is an expanded version of a paper presented at *The Science of Jenolan Caves Symposium* held at Jenolan Caves on May 23-24, 2013. For the author, 2013 marks thirty years of research into the geology, geomorphology and mineralogy of Jenolan Caves. The ideas and some of the images presented here have emerged from this extended period of looking, puzzling, looking again and just sometimes seeing the light. Firstly I must acknowledge David Branagan who wrote the magic piece of paper that gained permission for my first research trip to Jenolan in 1983, supervised my PhD, and always thought the caves were old, but as it turned out not old enough.

Many Jenolan people have assisted with fieldwork, paperwork, accommodation, and shared their valuable local knowledge and insights with me. I must particularly thank Ernst Holland, Nigel Scanlan, Andy Lawrence, the late John Callagan, Andrew Fletcher, Stephen Riley, Stephen Meehan, Ted Mathews and Dan Cove in this regard. It is impossible to undertake research in show caves without the cooperation and support of the cave guides and I must thank guides past and particularly guides present for their welcome, assistance and cooperation.

Understanding of Jenolan Caves has been greatly enhanced by collaboration with mineralogy colleagues from the Australian Museum: Ross Pogson and David Colchester and revolutionized by collaboration with dating colleagues from the CSIRO: Horst Zwingmann and Phil Schmidt.

The compilation of this paper has been greatly assisted by the supply of maps and sections by Al Warild, Jenolan Survey Project, and the capture of a missing image by Ted Matthews. My family Penney and Michael have endured and survived my research and with her great eye for detail Penney has read and corrected the drafts of this paper.

REFERENCES

Allan, T.L. (1986). Geology of Jenolan Caves Reserve. BSc Hons thesis, University of Sydney, Sydney.

Bella, P and Bosák, P. (2012). Speleogenesis along deep regional faults by ascending waters: case studies from Slovakia and Czech Republic. *Acta carsologica* **41**, 169-192.

Dunlop, B.T. (1979). 'Jenolan Caves, 11th Edition'. (New South Wales Department of Tourism: Sydney).

House, M. J. (1988). The geology of an area centred on Bulls Creek, Northeast of Jenolan Caves N.S.W. BSc Hons thesis, University of Sydney, Sydney.

Jones, B. (1992). Void-filling deposits in karst terrains of isolated oceanic islands: a case study from Tertiary carbonates of the Cayman Islands. *Sedimentology* 39, 857-876.

Loucks, R.G. (2007). A review of coalesced, collapsed-paleocave systems and associated suprastratal deformation. *Acta carsologica* **36**, 121-132.

McClean, S.M. (1983). Geology and cave formation, Jenolan Caves, N.S.W. B.App.Sc. thesis, N.S.W. Institute of Technology, Sydney.

Osborne, R.A.L. (1984). Lateral facies changes, unconformities, and stratigraphic reversals: Their significance for cave sediment stratigraphy. *Cave Science: Transactions of the British Cave Research Association* **11**, 175-184.

Osborne, R.A.L. (1995). Evidence for two phases of Late Palaeozoic karstification, cave development and sediment filling in southeastern Australia. *Cave and Karst Science* 22, 39-44.

Osborne, R.A.L. (1999a). The inception horizon hypothesis in vertical to steeply-dipping limestone: applications in New South Wales, Australia. *Cave and Karst Science* 26, 5-12.

Osborne, R.A.L. (1999b). The origin of Jenolan Caves: Elements of a new synthesis and framework chronology. *Proceedings of the Linnean Society of New South Wales* 121, 1-26.

Osborne, R.A.L. (2002). Significance and monitoring. *Acta carsologica* 31, 21-33.

Osborne, R.A.L. (2004). Tales from Marble Halls: The geology and geomorphology of Wombeyan Caves. In 'Caves and Karst of Wombeyan' (Ed R. Ellis) pp. 55-71. (Sydney Speleological Society: Sydney).

Osborne, R.A.L. (2005). Dating ancient caves and related palaeokarst. *Acta carsologica* 34, 51-72.

Osborne, R.A.L, (2007). The world's oldest caves: - how did they survive and what can they tell us? *Acta carsologica* 36, 133-142.

Osborne, R.A.L. (2010). Rethinking eastern Australian caves. In 'Australian landscapes'. (Eds P. Bishop and B. Pillans) pp 289-308. Geological Society of London Special Publication 346.

Osborne, R.A.L., Zwingmann, H., Pogson, R. E. and Colchester, D. M. (2006). Carboniferous Clay Deposits from Jenolan Caves, New South Wales, Australia. *Australian Journal of Earth Sciences* 53, 377-405.

Pogson, D. J. and Watkins, J. J. (1998). 'Bathurst 1:250 000 Geological Sheet SI/55-8: Explanatory Notes'. (Geological Survey of New South Wales: Sydney).

Rowling, J. (2004). Studies on aragonite and its occurrence in caves, including New South Wales caves. *Journal and Proceedings of the Royal Society of New South Wales* 137, 123-149.

Sass-Gustkiewicz, M. (1974). Collapse breccias in the ore-bearing dolomite of the Olkusz mine (Crakow-Silesian ore district). *Roczink Polskiego Towarzystwa Geologicznego* 44, 217-226.

Sussmilch, C.A. and Stone, W.G. (1915). Geology of the Jenolan Caves district. *Journal and Proceedings of the Royal Society of New South Wales* 49, 332-348.

Taylor, G. (1923). The Blue (Mountain) Plateau. In 'Pan-Pacific Science Congress, Australia 1923, Guide-book to the Excursion to the Blue Mountains, Jenolan Caves and Lithgow' (Alfred James Kent, Government Printer: Sydney)

Taylor, G. (1958). 'Sydneyside scenery and how it came about'. (Angus and Robertson: Sydney).

van der Beek, P., Pulford, A. and Braun, J. (2001). Cenozoic Landscape Development in the Blue Mountains (SE Australia): Lithological and Tectonic Controls on Rifted Margin Morphology. *The Journal of Geology* 109, 35–56.

Geology and Geomorphology of Jenolan Caves and the Surrounding Region

David F. Branagan[1], John Pickett[2] and Ian G. Percival[3]

[1]Honorary Associate, School of Geosciences, University of Sydney, NSW 2006 (dbranaga@usyd.edu.au);
[2]Honorary Associate, Geological Survey of NSW, WB Clarke Geoscience Centre, Londonderry NSW 2753
(picketj@bigpond.net.au);
[3]Geological Survey of NSW, WB Clarke Geoscience Centre, Londonderry NSW 2753
(ian.percival@trade.nsw.gov.au)

Branagan, D.F., Pickett, J.W. and Percival, I.G. (2014). Geology and Geomorphology of Jenolan Caves and the Surrounding Region. *Proceedings of the Linnean Society of New South Wales* 136, 99-130.

Detailed mapping by university students and staff since the 1980s has significantly elucidated previously poorly known stratigraphic and structural relationships in the Jenolan Caves region. Apart from andesite of ?Ordovician age, rocks west of the caves probably correlate with the lower Silurian Campbells Group. That succession is faulted against the Silurian (mid Wenlockian) Jenolan Caves Limestone, in which caves developed during several episodes from the late Palaeozoic. Immediately east of Jenolan Caves, siliciclastic sedimentary and volcaniclastic rocks with interbedded silicic lavas constitute the newly defined Inspiration Point Formation, correlated with the upper Silurian to Lower Devonian Mount Fairy Group. Several prominent marker units are recognised, including limestone previously correlated with the main Jenolan limestone belt. Extensive strike-slip and thrust faulting disrupts the sequence, but in general the entire Silurian succession youngs to the east, so that beds apparently steeply-dipping westerly are actually overturned. Further east, Upper Devonian Lambie Group siliciclastics unconformably overlie the Inspiration Point Formation and both are overlain unconformably by lower Permian conglomeratic facies. Carboniferous intrusions include the Hellgate Granite with associated felsite dykes. The regional geomorphology probably evolved from late Carboniferous–early Permian time, with ‘steps’ in the deep valleys indicating episodic periods of valley formation, possibly including Permian glaciation.

Manuscript received 16 October 2013, accepted for publication 23 April 2014.

KEYWORDS: Carboniferous, Devonian, geomorphology, Jenolan Caves, palaeontology, Permian, Silurian, speleogenesis, stratigraphy

INTRODUCTION

Jenolan Caves, located 182 km west of Sydney by road (Fig. 1), are Australia’s best known and most spectacular limestone caves. Early geological studies concentrated on the narrow belt of limestone and mapping of the cave system it encloses, whereas more recent scientific research has emphasized the speleogenesis of the caves and their antiquity. In comparison, the regional geology surrounding the Jenolan karst area has been relatively neglected, largely due to its rugged terrain and structural complexity. Thus the geological context in which Jenolan Caves formed, that is so crucial to an understanding of how the cave system evolved, has taken a long time to unravel, and indeed still requires

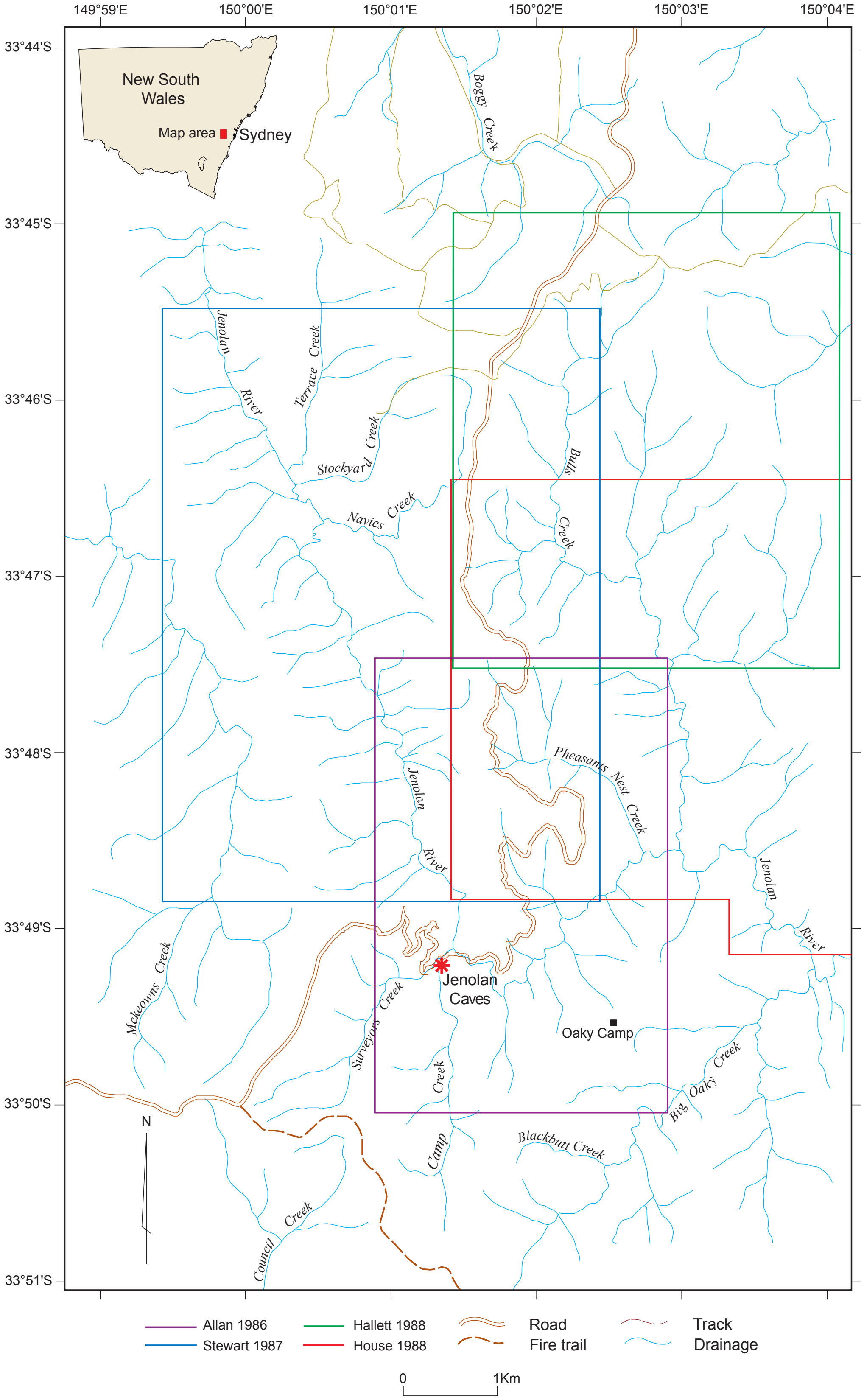


Fig. 1. The Jenolan Caves region, showing the main access road and natural drainage pattern; inset map shows location within the state of New South Wales. Also plotted are the outlines of student thesis maps reproduced as Fig. 5 (Allan 1986, in purple), Fig. 6 (Stewart 1987, in blue), Fig. 7 (Hallett 1988, in green) and Fig. 8 (House 1988, in red).

further study. Geological mapping by students and staff (mainly at the University of Sydney) over the past thirty years, notably during the 1980s, has greatly improved knowledge of rock types, their distribution and relationships in the vicinity of Jenolan, but this work has remained largely inaccessible in unpublished theses and field compilations. The results presented here are primarily based on detailed field mapping (at a scale of 1:10,000) and accompanying reports by Allan (1986), Stewart (1987), Hallett (1988) and House (1988) (Figs 1, 5, 6, 7, 8), supplemented with mapping over the same period by D.F. Branagan and K.J. Mills (all of the University of Sydney), with additional thesis mapping by Doughty (1994). Unpublished studies by Stanley (1925), Chand (1963), Pratt (1965), McClean (1983), and E. Holland (former Jenolan Manager) have also been taken into consideration. Other geological investigations of the area remain unpublished, although in preparation of this paper we have had the benefit of discussion with various workers (particularly Ian Cooper) who have mapped the Jenolan Caves Limestone and nearby strata in considerable detail.

PREVIOUS WORK

The earliest geological observations of a scientific nature on the Jenolan Caves area were made by staff of the Geological Survey of New South Wales (Fig. 2), including Wilkinson (1884) and Young (1884) (vide Havard 1933). Fossils in the limestone attracted the attention of Government Palaeontologist Robert Etheridge Jr (1892) who described a pentameride brachiopod and first assigned a late Silurian age to these rocks. Initial usage of the name ‘Jenolan Cave Limestone’ can be attributed to Etheridge (1894) but the terminology was not formalized for another 77 years.

T.W.E. David (1894) (Fig. 2) concurred with the late Silurian age of the limestone, also assigning that age to the strata to the east that he later described (David 1897a) as consisting of “several hundred feet of dark indurated shales, greenish-grey argillites, reddish-purple shale and coarse volcanic conglomerates with large lumps of *Favosites*, *Heliolites*, etc.”. David (1897b) further postulated that “the felsite dykes east of the limestone had assimilated much lime in their passage through the limestone”, and suggested that the conglomerates exposed on the Jenolan road 6 miles (9.7 km) from the caves were Upper Devonian. Extrapolating from his work on similar rocks at Tamworth of Devonian age, David surmised that the cherty radiolarian-bearing rocks cropping out west of the limestone belt at Jenolan were younger than the limestone, for which he indicated a westerly dip, and that their cherty nature was the result of contact metamorphism by intruding dykes. Consequently he revised his opinion of the age of the “Cave Limestone” to Early or Middle Devonian, younger than the limestones at Yass. However, David and Pittman (1899), in a further examination of the radiolarian-bearing cherty sediments, expressed uncertainty as to whether the limestone was Silurian or Devonian.

Curran (1899) (Fig. 2) discussed some aspects of the Jenolan geology, placing the eastern succession of sedimentary rocks in the Silurian, intruded by diorites, quartz- and felspar- porphyries, and included a photo of one of the cuttings on the road down to the caves.

The matter rested there until Morrison (1912), carrying out a reconnaissance trip to complete the proposed Geological Map of New South Wales (published 1914), placed the limestone in the Silurian, together with the adjacent rocks including ‘slates, radiolarian cherts, claystones … and contemporary lavas’, and assigned a post-Devonian age to the intrusive porphyries and felsite dykes observed by David. Morrison (Fig. 2) noted the unconformable nature of the junction between the Devonian sandstones and quartzites [Lambian rocks] and the ‘Upper Marine’ Permian beds, and the occasional occurrence of the younger strata abutting the Devonian rocks, but several hundred feet below the Devonian outcrops.

Süssmilch and Stone (1915), following brief statements by Süssmilch (1911, 1913), presented the results of a study of the caves region undertaken over a number of years. Their paper remained the standard explanation of the geology until at least the 1960s**.** The study by Süssmilch and Stone (Fig. 2), based on the outcrops along the Mount Victoria road (almost to Inspiration Point), and the first few bends (Two Mile Hill) of the Tarana road, the Six-Foot track and the Jenolan River, recognised the essential lithological variations. They dismissed David’s contention that the cherts occurring west of the limestone were formed by contact metamorphism and determined that they did not dip conformably with the limestone, but were probably brought into contact by overthrusting. Süssmilch and Stone (1915) suggested that the cherts (‘Jenolan radiolarian cherts’) and associated dark claystones were of Ordovician age. They recognised the ‘Cave limestone’ and the geographically distinct (but then vaguely located) east-dipping ‘eastern limestone’, which appeared to be unfossiliferous, believing that the separated limestones belonged to a single ‘bed’ on opposite sides of a large anticline.

Fig. 2. A selection of geologists who have made significant contributions (discussed in the text) to the investigation or mapping of the Jenolan Caves region, spanning more than a century from 1884 to 1988. The final four photographs are those of students from the University of Sydney whose B.Sc. (Honours) thesis maps were used in the compilation of this paper. Some of the historic photographs are sourced from Johns (1976) and Middleton (1991); others are from the image library of the NSW Department of Resources and Energy. Top row (L to R): C.S. Wilkinson (NSW Geological Surveyor-in-charge 1875-1891), T.W.E. David (University of Sydney), E.F. Pittman (NSW Government Geologist 1891-1916), Rev. J.M. Curran. Middle row, left image: officers of the NSW Department of Mines c.1893 (clockwise from top left L.F. Harper*, R. Etheridge Jr (Palaeontologist), O. Trickett (Inspector of Caves), M. Morrison (Assistant Geological Surveyor); right image: C.A. Süssmilch (seated) and W.G. Stone, both of the Department of Geology, Mineralogy and Mining, Sydney Technical College; Bottom row (L to R): J.E. Carne (NSW Government Geologist 1916-1920), G.A.V. Stanley (graduate of the University of Sydney 1925), T. Allan (B.Sc. Hons 1986, S.U.), W. Stewart (B.Sc. Hons 1987, S.U.), M. Hallett (B.Sc. Hons 1988, S.U.), M. House (B.Sc. Hons 1988, S.U.). *note that L.F. Harper was engaged on geological investigations in areas other than Jenolan Caves.

Süssmilch and Stone grouped all the variably-coloured, thin-bedded, highly-jointed rocks, east of the 'Cave limestone', as Silurian slates underlying the limestone. The unit identified by them as a rhyolite-porphyry, cropping out close to the Grand Arch, was an important marker for their structural interpretation of an anticline, as it was located again west of the eastern limestone. Other igneous bodies were identified as intrusive. These included the andesite occurring west of the 'Cave limestone', and quartz porphyrites and felsites to the east.

The stratigraphic order set down by Süssmilch and Stone (1915), in addition to their interpretation of the geomorphic history, subsequently became entrenched in the literature of Jenolan. Influenced by Andrews' (1911) concept of the Kosciusko Uplift, said to have occurred at the end of the Pliocene, they thought that the age of formation of the cave system could only be less than 500,000 years.

The regional geological interpretation of Süssmilch and Stone (1915) was accepted by Carne and Jones (1919), who outlined more accurately the outcrop of the limestone, showing it extending for some distance both north and south of the tourist caves. Of particular interest on their map is the marking of two pods of limestone approximately 400 m westerly of the almost continuous main belt at its northernmost extent, close to McKeowns Creek, suggesting a possible offsetting by faulting**.** However, mapping of these bodies was clearly affected by the inadequate base maps available to these earlier workers, as more recent mapping shows that despite poor outcrop, the limestone does in fact swing westerly away from the creek, by flexure, and encloses these two pods. Carne and Jones also located the eastern limestone more accurately than was shown on earlier maps (e.g. Süssmilch and Stone 1915).

Süssmilch (1923) expanded a little on his previous work, with a revised cross-section, and provided a geological history beginning with a deep-sea environment in which the radiolarian cherts were deposited, shallowing to a warm sea in which the eastern sediments were deposited, followed by clear, shallow seas in which lime-secreting organisms built up a mass of limestone (but not a reefal body). The succession was thought to have been folded at the close of the Devonian or during the early Carboniferous.

G.A.V. Stanley (Fig. 2) carried out considerable mapping for an Honours thesis at the University of Sydney in 1925, but this work was never published, so the results were ignored for many years. He thought the western succession was probably Devonian with a gradational boundary against the limestone. Though pointing out the considerable differences between the main and eastern limestones, Stanley still regarded them as stratigraphically equivalent, interpreting the eastern body as closer to the sediment source, while the main body he surmised to be of reefal origin. He thus accepted the large anticlinal structure suggested by Süssmilch and Stone (1915), but believed it was complicated by cross faults and strike -slip faulting. Stanley regarded all the igneous bodies east of the main limestone as sills. Perhaps Stanley's major achievement was the preparation of the first, surprisingly accurate, contour map of the Jenolan region, using compass and tape, Abney level and aneroid.

Geological interpretation of the Jenolan region remained untouched for the next 40 years, until a new round of university student studies took place in the mid-1960s, with work by Chand (1963), Gulson (1963) and Pratt (1965). However, stratigraphic relationships and actual geological ages remained uncertain and there was certainly some confusion introduced by the incorrect assignment of bedding to structures in the limestone and other units. Chand's 1963 work, extending a considerable distance east from the limestone belt beyond Black Range, was the most painstaking, including the collection of nearly 900 rock specimens from widespread documented localities.

Branagan and Packham (1967) were the first to recognise the overturning of the sequence east of the limestone belt, and Packham (1969) revised the stratigraphic relations, with the western units being oldest, followed by the limestone and the younger eastern beds.

Pickett (1969, 1970, 1981, 1982) provided much of the modern palaeontological data available on the limestone. His early reports identified macrofossils submitted by C. Mitchell and L. Chalker who remapped the limestone (Chalker 1971). Additional fossils, predominantly corals, stromatoporoids and algae, were identified for that paper by J. Byrnes. The age of the Jenolan Caves Limestone was given as Ludlovian (late Silurian). Conodonts diagnostic of Silurian biostratigraphic zones, however, proved elusive, despite 20 samples being processed from throughout the extent of the western limestone belt (Pickett 1981). Talent et al. (1975, 2003:198), citing unpublished work by P.D. Molloy, mentioned the presence of conodonts referable to the *Ozarkodina crispa* Zone (of latest Ludlow age: Strusz 2007) from the upper well-bedded part of the main limestone belt. Unfortunately these specimens were not illustrated. Strata underlying the Jenolan Caves Limestone were assigned to 'equivalents of the Campbells Formation' (now Group) of late Silurian (Ludlow) age by Talent et al. (1975: fig. 1, column 23).

Lishmund et al. (1986) presented a generalized map of the limestone occurrences in the vicinity of Jenolan and the immediately surrounding geology, modified from mapping by Chand (1963), Gulson (1963), Pratt (1965) and Chalker (1971). Lishmund et al. (1986) also thought that the sedimentary rocks west of (underlying) the main limestone belt might be Silurian, based on lithological similarity to potential regional equivalents, notably the Kildrummie Formation.

Subsequent detailed mapping by Allan (1986), Stewart (1987), Hallett (1988) and House (1988), which has remained largely unpublished till now (Figs 5-8), forms the basis of our current understanding of the geology of the Jenolan region, and is fully discussed below. Osborne and Branagan (1985) indicated a likely karstification age at least as old as Permian for the development of the caves, and subsequently (Osborne and Branagan 1988) included a brief description of the Jenolan karst in an overall review of karst in New South Wales. Detailed studies of the Jenolan Caves Limestone, concentrating on its karstification history, have been published by Osborne (1991, 1993, 1994, 1995, 1999), Osborne et al. (2006) and Cooper (1990, 1993). For a project directed to developing tourism at Jenolan, Branagan (in Hunt 1994) compiled a geological map based largely on the detailed Honours thesis mapping undertaken between 1986 and 1988 mentioned above. Branagan et al. (1996) summarized the results from this mapping together with that of Doughty (1994).

Apart from the maps by Süssmilch and Stone (1915), Carne and Jones (1919), Chalker (1971) and Lishmund et al. (1986), other generalised maps of the boundary of the limestone to have been published include those of Trickett (1925), Shannon (1976), and Kelly and Knight (1993), the latter which also shows adjacent geology, based on unpublished thesis mapping by Allan and Stewart. Osborne (1999) in illustrating the limestone belt used mapping by Shannon (in Welch 1976), but attributed it to Welch.

STRATIGRAPHY

Despite the rather formidable topography, some excellent road and creek exposures can be measured in the Jenolan area, providing the key to much of the understanding of the stratigraphy presented in this paper (Figs 3, 4). The road exposures were the basis of the mapping by Süssmilch and Stone (1915), although some sections of the roads have since been relocated. Allan (1986) mapped the Inspiration Point road section in great detail, providing the basis for our revised interpretation of the rock succession east of the Jenolan Caves Limestone. In Figures 5-8 depicting the detailed geology as mapped by Allan (1986), Stewart (1987), Hallett (1988) and House (1988), we retain the informal stratigraphic nomenclature of their studies, but on the compilation map (Fig. 4) the formal stratigraphic terminology as described below is employed. It should be noted that there are some differences apparent between the compilation map (Fig. 4) and those of the student theses (Figs 5, 6, 7 and 8). These differences are due to additional field observations by Branagan and K.J. Mills and consequent reinterpretation. The main stratigraphic sections presented (Figs 5-8) are Five Mile Hill to Jenolan Caves, Navies Creek, Bulls Creek (with Pheasants Nest Creek), and the Jenolan-Kanangra Road (Two Mile Hill section). These sections reveal unequivocally that this stratigraphic sequence is overturned (with but few exceptions) — the succession younging to the east. Numerous strike (and thrust) faults in the area separate the rocks into distinct lithostratigraphic and structural domains but because of the paucity of fossils so far found, the relative age of these domains cannot be stated with certainty. However, reinterpretation of the scant palaeontological evidence provides the basis for revised correlations of rock units west and east of the main limestone belt, as well as reassessment of the age of the Jenolan Caves Limestone.

A. Lower Palaeozoic rocks west of the main Jenolan Caves Limestone belt

As indicated above, these rocks, with a few exceptions, have generally been regarded as older than the limestone and probably of Ordovician (or alternatively Silurian) age. Pratt (1965) informally referred to these beds as the ‘Oberon Hill Chert’, including the andesitic volcanic unit exposed behind Caves House (and in the Lower Car Park), which he thought belonged within the ‘Jaunter Tuff’ of Shiels (1959). Pratt noted closely-spaced concentric folds within the chert sequence. Doughty (1994) followed Pratt (1965) to some extent, informally naming the succession of shales, siltstones, sandstones, cherts and andesite, west of and underlying the limestone in the vicinity of Jenolan, as the ‘Oberon Hill Formation’. Doughty commented on the general lack of chert where he examined the unit as the basis for the modification of the name, and gave its minimum thickness as between 1200 and 1500 m. The succession continues north from the tourist area, beyond Dillons Creek (the first main stream northerly from the Jenolan-Oberon Hill road, draining from Oberon Hill and joining McKeowns Creek opposite South Mammoth Bluff),

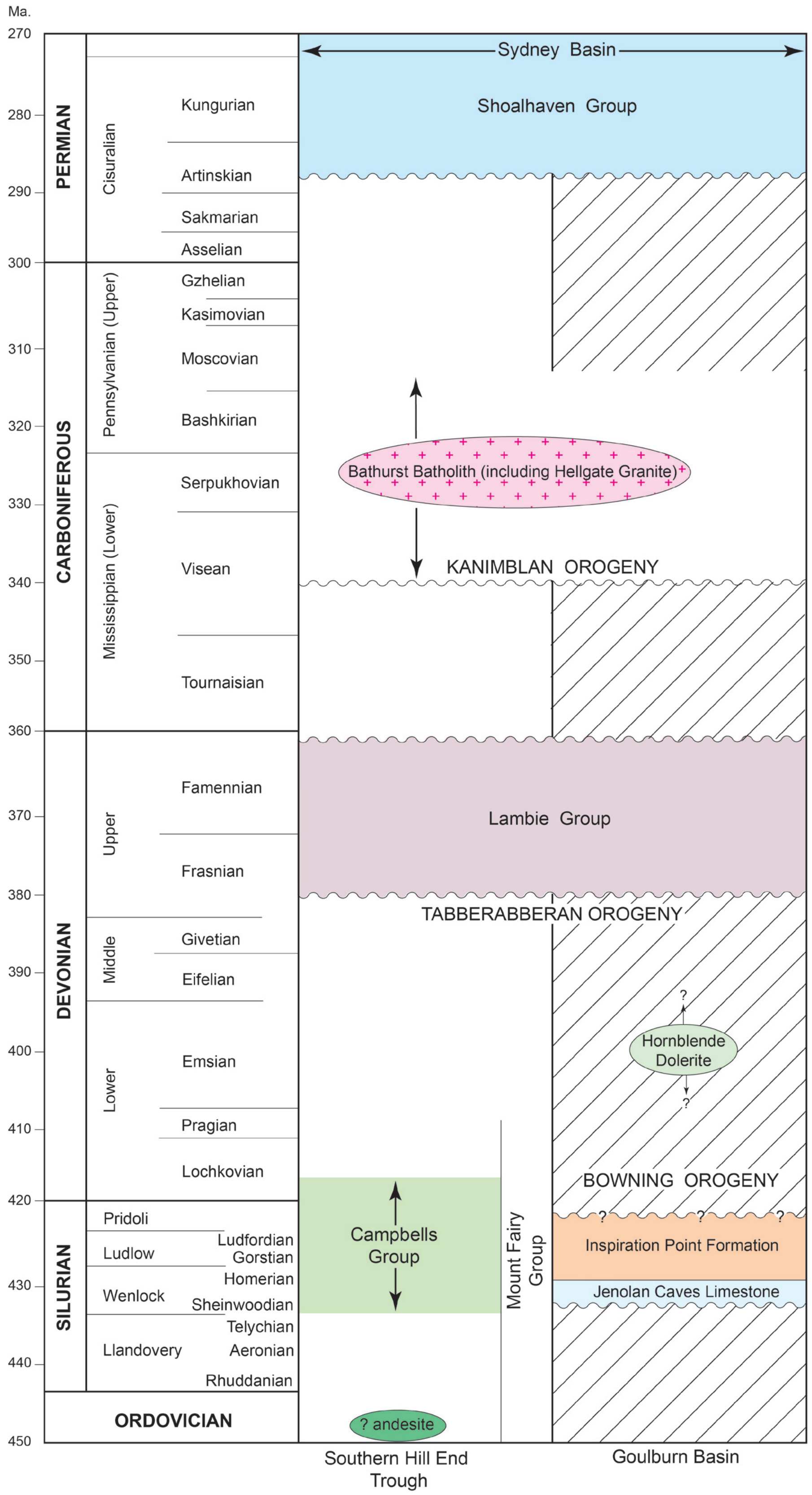


Fig. 3. Palaeozoic stratigraphy and intrusion history of the Jenolan Caves region; cross-hatched areas represent intervals of non-deposition and/or erosion (see text for discussion). Timescale from Gradstein et al. (2012).

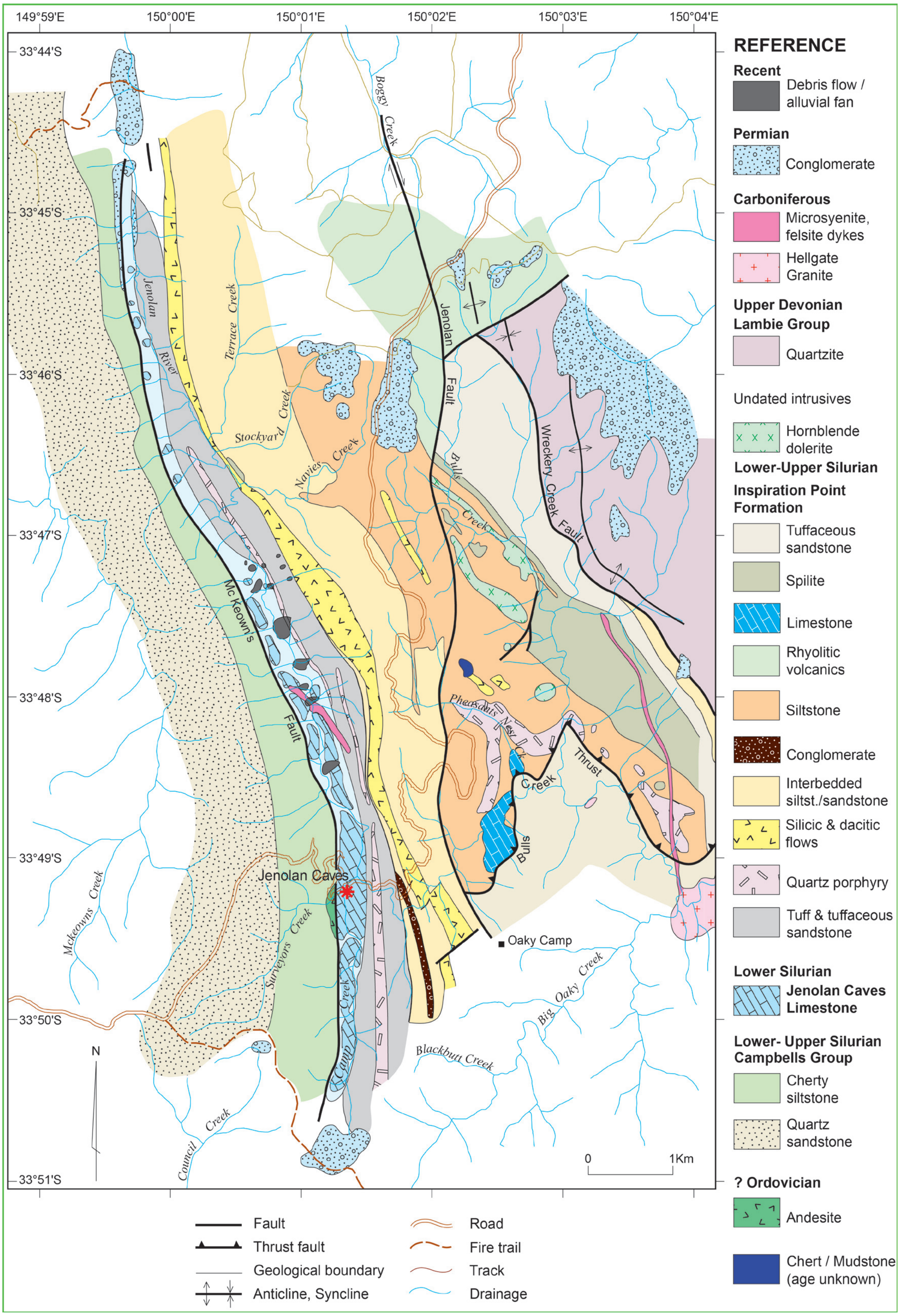


Fig. 4. Geological map of the Jenolan Caves region, compiled by D.F. Branagan and K.J. Mills, based on B.Sc. Honours thesis mapping especially as shown in Figs 5-8, and personal observations. Note that there are minor inconsistencies between this map (which shows the formal stratigraphic nomenclature adopted in this paper) and those of the students.

where Stewart (1987) mapped a sequence more than 500 m thick that he informally named the ‘Western Jenolan Beds’**.**

1. ?Ordovician andesite

The andesite (informally referred to as ‘Caves House andesite’ on some maps), which has puzzled all observers since the area was first examined, abuts the Jenolan Caves Limestone over a short distance in the vicinity of Caves House (Fig. 5). Chemical analysis by Stone (in Süssmilch and Stone 1915) showed it was originally of basaltic-andesitic composition. Two rock types are present: a fine-grained augite-andesite, and a porphyritic augite-andesite which occurs as inclusions within the fine-grained rock. Chalker (1971) suggested that the andesite represented an intrusive body, although it has more generally been interpreted as a flow, apparently conformable with the limestone. However, it is probable that the andesite unit has been brought into position by faulting along McKeowns Fault and that its stratigraphic position is, therefore, uncertain. Doughty (1994) noted that close to Caves House, the Jenolan Caves Limestone contains clasts of andesite, indicating an unconformable or disconformable relationship with the andesite body. Presence of an unconformity is supported by the observation that in the eastern Lachlan Fold Belt, andesitic rocks are characteristic of the Ordovician, rather than the Silurian. Accordingly, the andesite is most likely of Ordovician age, making it the oldest rock unit exposed in the Jenolan region.

2. Campbells Group equivalents (Lower Silurian)

The ‘Western Jenolan Beds’ of Stewart (1987) consist of two broad units, an older quartz-rich sandstone unit, and a younger ‘cherty’ sequence (Fig. 6). The sandstone unit includes fine and medium-grained sandstones, with very minor slates, and a thin tuffaceous layer (possibly more than one). The unit is dark to light grey with a distinctive blocky outcrop, and occupies the ridge tops. In thin-section it is seen to be composed mainly of rounded, strained grains of quartz, with 5 to 10% of lithic fragments, and about 1% of mica fragments, and about the same volume of matrix, composed of white mica, calcite, sphene, chlorite and epidote. Iron oxide cement is present, usually only about 1%, but in exceptional cases it may make up about 20% of the rock, imparting a dark colour to some hand specimens. The tuffaceous layer is mainly composed of weathered felspar. This sandstone unit continues west of the mapped area and its thickness exceeds 450 m.

There is a distinct, but not sharply delineated, lithological change to the overlying finer-grained sequence. This sequence, about 500 m thick, is made up of wide bands of thinly-bedded radiolarian-rich black siltstones, interbedded with slates and minor beds of quartz sandstone. The siltstone bands contain tight slump folds, show graded bedding, small-scale erosional features, and flame structures, which indicate an easterly facing. In thin section the siltstone consists mainly of a dark chlorite and quartz matrix, with larger spheroids of microcrystalline quartz. These are casts of radiolaria, often visible to the naked eye, but they are generally poorly preserved and cannot be readily identified. Occasional specimens display a relict internal structure, and some bear short robust spines.

Although evidence is slight in the immediate vicinity of Jenolan, exposures to the north (in McKeowns Valley) show that these ‘Western Jenolan Beds’ have a faulted, and probably unconformable, contact with the overlying limestone succession. Süssmilch and Stone (1915) recognized an overthrust fault, subsequently mapped by Stewart (1987) as a high-angle reverse fault (the McKeowns Fault, interpreted as a near-vertical thrust defined by a thin layer of fractured rock) that separates this succession from the Jenolan Caves Limestone. This fault is noted also on the western end of the detailed section measured by Stewart (1987) along Navies Creek (Fig. 6).

On the western side of McKeowns Valley there is a 90 m wide zone of brecciation, consisting mainly of cherty clasts (Fig. 6). Neither the displacement nor the amount of strata missing can be determined, but there appears to be no angular discordance between the two units. However, in view of the apparent lack of chert in the succession as it is mapped south to Jenolan and beyond, it may be that this fault runs slightly obliquely to the general strike of the beds and cuts out the cherts. The width of the fault zone certainly suggests that the effect of the fault could be quite significant.

The ‘Western Jenolan Beds’ have previously been assigned an Ordovician age by some authors (e.g. Stewart 1987), although Pratt (1965) thought they might range into the early Silurian. Packham (1969) suggested that they could be correlated with the Rockley Volcanics, cropping out to the west. Other authors (Chalker 1971; Talent et al. 1975; Lishmund et al. 1986) have regarded the rocks underlying the main limestone belt to be of Silurian age.

Recent mapping by the Geological Survey of NSW suggests that much of the Rockley Volcanic Belt should now be regarded as Silurian, with reported evidence of Ordovician ages (e.g. Fowler and Iwata 1995) from this tract to the west of Jenolan being

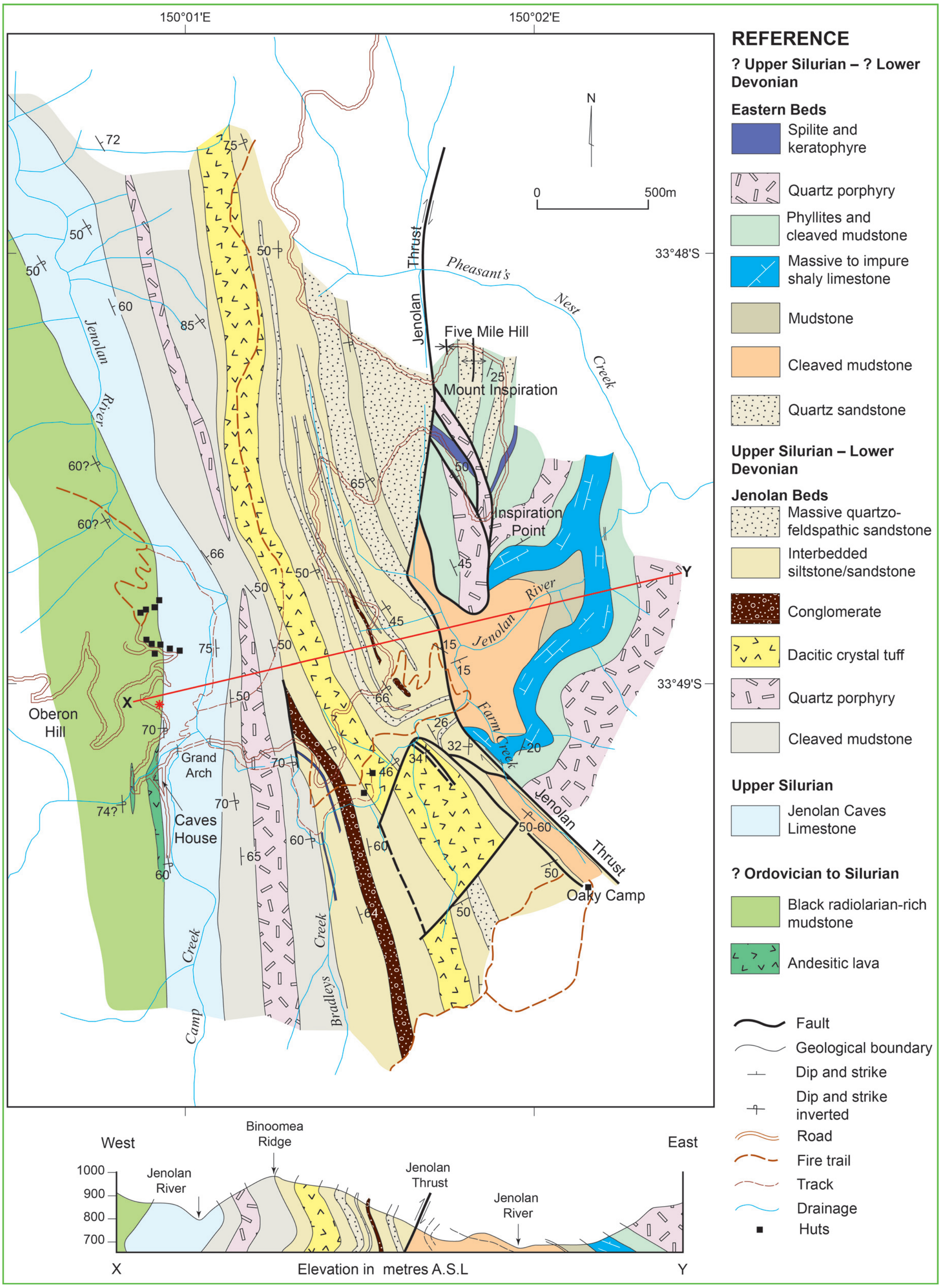


Fig. 5. Geological Map and cross section, modified from Allan (1986). Note that stratigraphic names utilized in the Legend (except for Jenolan Caves Limestone) are informal.

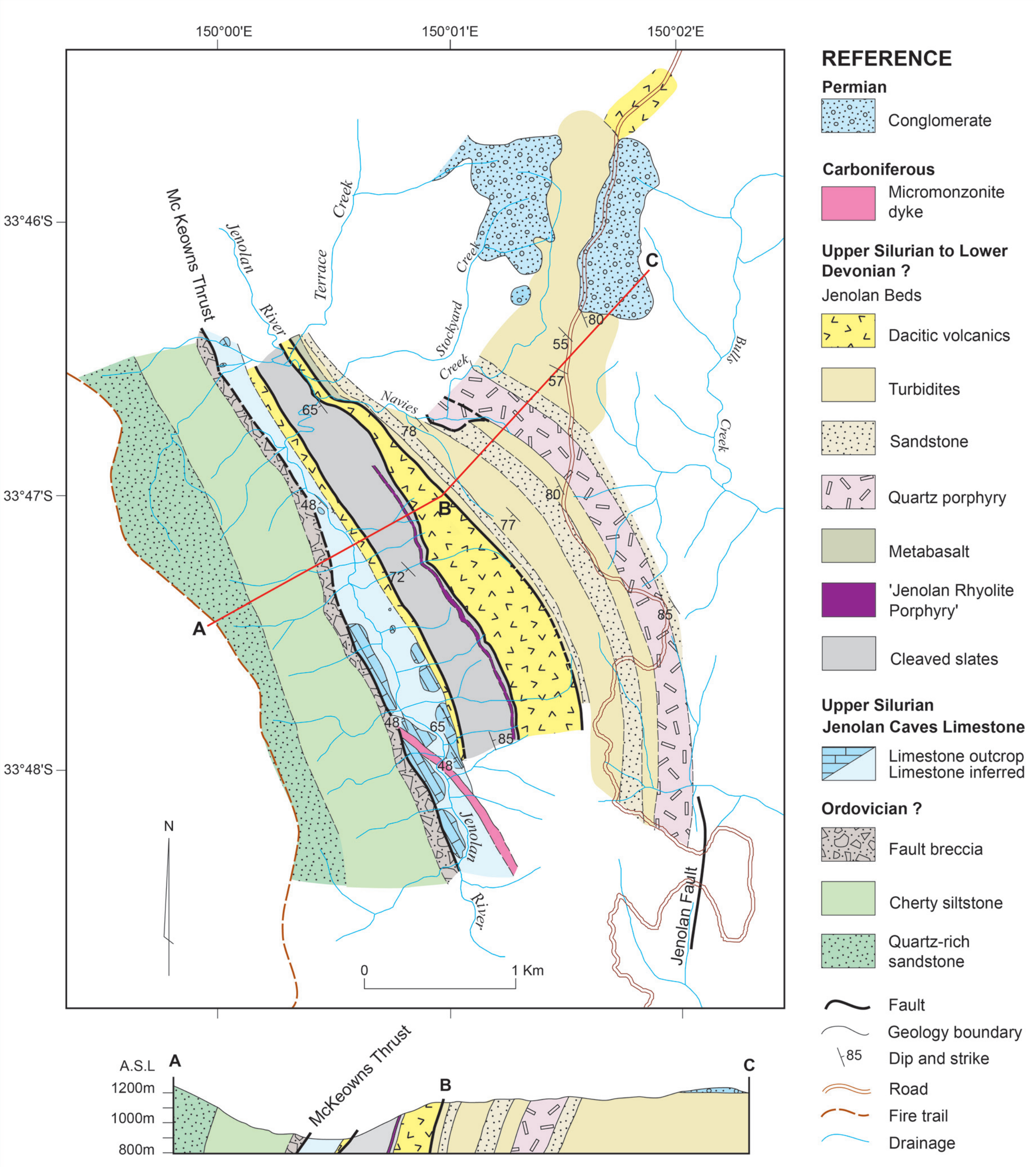


Fig. 6. Geological Map and cross sections, modified from Stewart (1987). Note that stratigraphic names utilized in the Legend (except for Jenolan Caves Limestone) are informal.

reinterpreted as derived from allochthonous blocks redeposited in the Silurian (C.D. Quinn, pers. comm. 2011). If so, this challenges the widely-held view that the rocks west of the main limestone belt are necessarily Ordovician in age, particularly in view of the lack of fossil evidence.

Ordovician quartz-rich sandstones and cherts of the Abercrombie Formation are extensively distributed in the northern half of the Taralga 1:100,000 mapsheet to the SW of the Jenolan area (Thomas and Pogson 2012). These homogeneous sandstones are described as quartz arenites, with sublitharenites at the base of the succession. Flame structures, flute marks and load casts are present in some sandstone beds, and the cherts frequently contain relict radiolaria (seen as amorphous silica blebs). The presence of tuffaceous layers in the 'Western Jenolan Beds' is atypical of the Ordovician Abercrombie Formation. Therefore, it is thought more likely that the 'Western Jenolan Beds' correlate with the lower Silurian to Lower Devonian Campbells Group. This does not, however, explain the age of the 'Caves House andesite' which remains an enigma.

If, as surmised by Lishmund et al. (1986), the strata west of the Jenolan Caves Limestone are lithological equivalents of the Kildrummie Formation (now included in the Campbells Group), this may provide an age constraint on the overlying rocks to the east. Conodont assemblages reported by de Deckker (1976) led him to conclude a late Ludlovian age (upper *crispus* to lower *steinhornensis* Zones) for the upper Kildrummie Formation. Simpson (1995) reinterpreted the specimens that de Deckker referred to *"Spathognathodus" crispus* as Pa elements of *Kockelella ranuliformis*, and thus suggested an age no younger than basal *siluricus* Zone for the upper part of the Formation. This age determination was influenced by co-occurrence of other conodonts from the Kildrummie Formation referred by de Deckker (1976) to *Diadelognathus primus* and *Distomodus curvatus*. As recognised by Simpson (1995), these clearly represent elements of the apparatus of *Coryssognathus dubius*, which ranges as high in the Yass succession as the Hume Limestone, from which Link and Druce (1972) recorded the zonal species *Polygnathoides siluricus*. However, *Kockelella ranuliformis* first appears locally in the *amorphognathoides* Zone that spans the Llandovery–Wenlock boundary, and typically occurs in the eponymous *ranuliformis* conodont biozone of lower to mid-Sheinwoodian age (early Wenlock). Its local upper limit was placed by Bischoff (1986) within the *K. amsdeni* to *K. variabilis* zones (late Sheinwoodian to mid-Homerian, or about mid-Wenlockian). Thus it is likely that the age of the upper Kildrummie Formation is no younger than mid Wenlock. Correlation of the rocks immediately west of the Jenolan Caves Limestone with the Kildrummie Formation therefore implies that they are equivalent to the lower Silurian portion of the Campbells Group.

B. Jenolan Caves Limestone

Prior to the present paper, the Jenolan Caves Limestone (Chalker 1971) was the only formally named stratigraphic formation in the karst conservation area. This unit is dominantly a light to dark grey bioclastic limestone, sometimes bedded, sometimes massive, but it contains occasional mudstone lenses and minor dolomite, and there is some evidence of brecciation in places. The limestone outcrop extends in a north-south linear belt for some 11 km. At the northern end it is covered by younger rocks and alluvium, but has become noticeably thinner, while at the southern end it appears to have been cut off by faulting. The succession shows some variations in lithology as mapped by Osborne (1991) in the Binoomea cut. Doughty (1994) suggested there are four facies in the 'southern' limestone, including (1) thin-bedded limestone and calcareous mudstone (at the basal and top boundaries), essentially lenticular and occasionally dolomitic); (2) massive recrystallised limestone with thin mudstone partings, forming the bulk of the Jenolan Caves Limestone; (3) massive, discontinuous limestone composed of fossil fragments; and (4) calcareous mudstone with minor siltstone partings, which is intercalated with the other three facies.

Doughty indicated a thickness of 350 m for the limestone in the vicinity of Caves House, with a considerably reduced section of 50 m in the south, and noted that sudden reductions in thickness are due to faulting which has usually removed the lower section of the limestone. Just north of Dillons Creek, the limestone is a maximum of 285 m thick and it thins to 75 m in the vicinity of Navies Creek. Here it passes conformably upwards into limy shale about 5 m thick, which in turn passes into cleaved slate, a few metres thick, indicating continuous deposition, but with a change in environment (and source). Alternatively, cessation of massive carbonate production and replacement by fine-grained mud-rich clastics may have been caused by relatively rapid subsidence of the carbonate platform below optimal water depths. We regard these strata as the uppermost preserved beds of the Jenolan Caves Limestone.

Cross-bedding and graded bedding can be found in the limestone at one locality behind Caves House. The cross-bedding has an eroded top, indicating an easterly facing. This is supported by the overlying graded bedding unit, which fines to the east.

Outcrops are variable, and particularly at the northern end of the limestone belt it becomes difficult to map the edge of the limestone accurately. In fact although karst features, such as dolines, have been used to map the western edge of the limestone, it seems likely that the presence of large quantities of water along the boundary may have caused dissolution (or at least erosion and subsequent collapse) of the adjacent "shales", so the boundary of supposed limestone may not be as accurate as one would wish. The limestone dip is generally easterly, but close to vertical, although it is often difficult to observe or measure. The limestone shows considerable topographic variation, which is in part the result of facies variability, but also may be due to faulting, as indicated by Shannon (1976).

In places the limestone is abundantly fossiliferous, as seen at the entrance to the Binoomea Cut where disarticulated pentameride brachiopod valves are

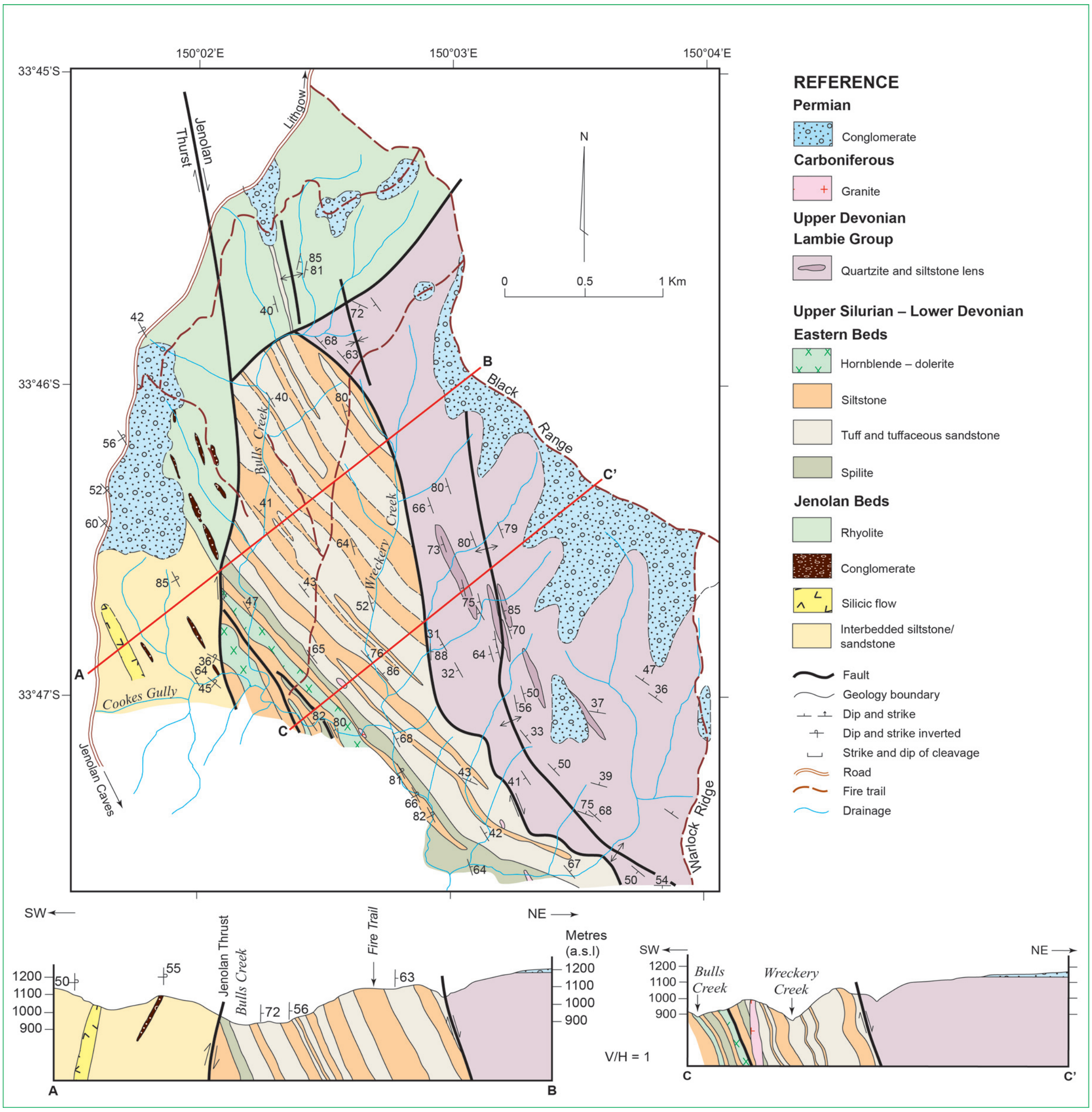


Fig. 7. Geological Map and cross section, modified from Hallett (1988). Note that stratigraphic names utilized in the Legend are informal.

crowded in layers, perhaps representing storm deposits. Elsewhere, corals (*Favosites*, *Heliolites*, *Tryplasma*, *Phaulactis*) and stromatoporoids (*Actinostroma*, *Clathrodictyon*) occur sporadically, previously regarded as indicative of a general Ludlovian (late Silurian) age (Chalker 1971; Pickett 1981, 1982). Unfortunately, age-diagnostic conodonts are rare in the limestone. The material identified by Pickett (1981) includes Pa elements of *Kockelella ranuliformis* (Walliser, 1964), illustrated in Fig. 9. As discussed earlier, this species appears to have a much longer range in Australia than elsewhere; nonetheless, the youngest possible age is no younger than mid-Homerian (mid-Wenlockian). This is the same species which provides the best age control on the Kildrummie Formation, so the conodont assemblages do not permit a differentiation in age between the two units. Previously the most significant biostratigraphic information derived from unpublished work carried out in the early 1970s by P.D. Molloy, subsequently reported by Talent et al. (1975:64) and Talent et al. (2003:198), that indicated the presence of conodont assemblages of *Ozarkodina crispa* Zone age (latest Ludlow) in the uppermost beds of the Jenolan Caves Limestone. Regrettably, this material remains unpublished. Endeavours to locate Molloy's samples

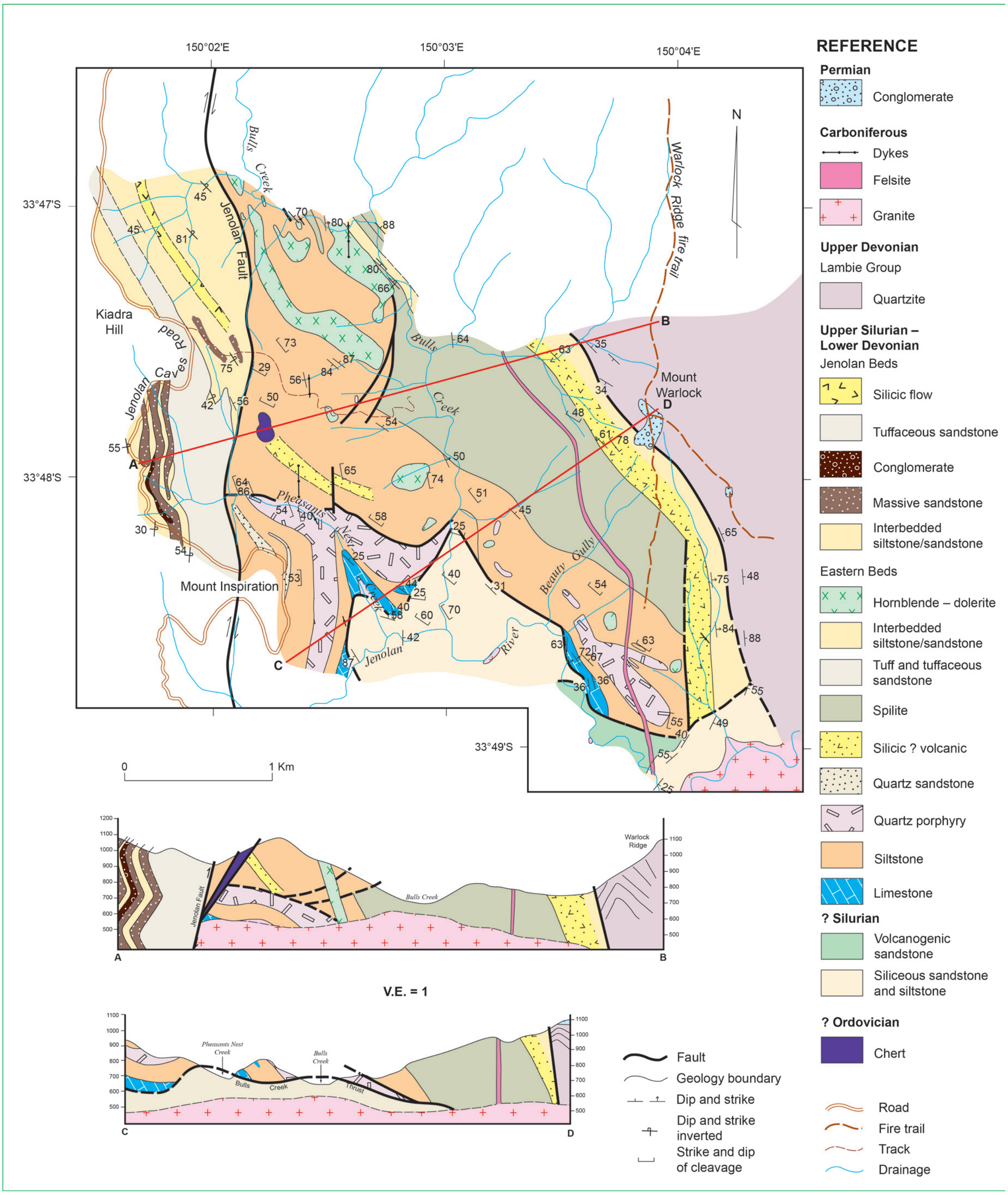


Fig. 8. Geological Map and cross sections, modified from House (1988). Note that stratigraphic names utilized in the Legend are informal.

proved fruitless, so they must be regarded as lost. The age suggested by Pickett's samples conflicts with Molloy's result, but since the latter can no longer be checked, these should be disregarded. There appears to be no basis at all for the assumption of a Pridoli age for the Jenolan Caves Limestone, as claimed by Scheibner and Basden (1998:478-479).

Halysitid corals have never been reported from the Jenolan Caves Limestone, in marked contrast to the Kildrummie Formation from which de Deckker (1976:68) listed at least four species of halysitids. Based on their absence, a comparison with the Yass section thus implies an age at least equivalent to that of the Hattons Corner Group (specifically the

Silverdale Formation) which lacks halysitids. Further support for this correlation comes from faunas of the 1050 m thick Molong Limestone, from which Pickett (2003) reported conodonts of the *ploeckensis* and *siluricus* Zones, the boundary between these zones lying 120 m stratigraphically above the last halysitids in the section. These last halysitids are accompanied by the rugosan *Palaeophyllum oakdalense* Strusz, typical of the "Dripstone Fauna" of Strusz and Munson (1997), to which they assigned an age range of late Sheinwoodian to earliest Gorstian (i.e. mid-Wenlockian to basal Ludlovian), approximately *ranuliformis* to earliest *crassa* Zones. This accords with the likely age for the Kildrummie Formation deduced from conodonts (see preceding discussion), and indicates that although the Jenolan Caves Limestone is most probably younger, the difference in age is slight.

In summary, taking the small conodont assemblages as the most reliable indicators, but considering the absence of halysitids, an age for the Jenolan Caves Limestone near the top of the Australian range of *K. ranuliformis* is most probable; that is, mid-Homerian (mid-Wenlockian).

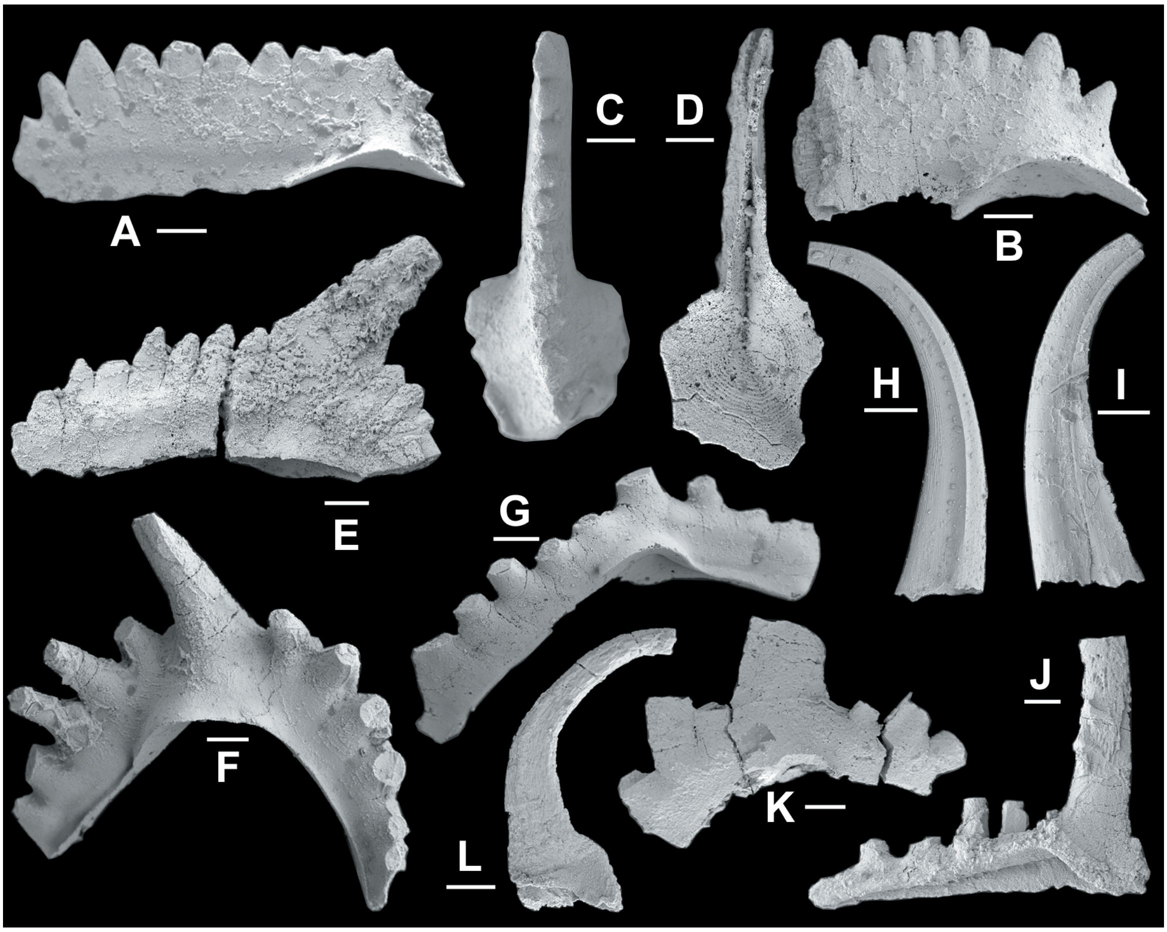


Fig. 9. Scanning Electron Microscope images of conodonts from the Jenolan Caves Limestone (A-J) and limestone within the Inspiration Point Formation (K, L). A, C from GSNSW conodont sample C697; B, D-J from GSNSW conodont sample C683 (for locations see Pickett 1981). Scale bars in all cases represent 100 microns. A-D, *Kockelella ranuliformis* (Walliser, 1964). A, Pa element in lateral view, MMMC4411; B, Pa element in lateral view, MMMC4412; C, Pa element in aboral view, MMMC4413; D, Pa element in oral view (note concentric growth lines around basal cavity), MMMC4414; E, *Ozarkodina* sp., Pb element in lateral view, MMMC4415. F, G, J, *Oulodus* sp. F, Sb element in inner lateral view, MMMC4416; G, Pb element in inner? lateral view, MMMC4417; J, M element in inner lateral view, MMMC4418. H-I, *Panderodus unicostatus*. H, element in outer lateral view (unfurrowed side), MMMC4419; I, element in outer lateral view (furrowed side), MMMC4420. K, specimen identified as the form-species *Ozarkodina ziegleri tenuiramea* Walliser, 1964 by House (1988), MMMC4421; L, unknown coniform element in lateral view, MMMC4422.

C. Lower Palaeozoic rocks east of the main Jenolan Caves Limestone belt

The succession east of the Jenolan Caves Limestone is complicated by faulting (Fig. 4). The general stratigraphy (shales, lavas, and graded-bedded sandstones) determined by Süssmilch and Stone (1915) for rocks lying between the Jenolan Caves Limestone and the Jenolan Fault – previously referred to as the 'Jenolan Beds' by Allan (1986), following Gulson (1963) and Chand (1963) – has remained largely unchanged to the present, except that the igneous units (felsic to intermediate types) were variously interpreted as intrusives, while other geologists regarded them as extrusives. Equivalent rocks east of the generally north-south trending Jenolan Fault were informally termed the 'Eastern Beds' by Allan (1986) (Fig. 5). These two lithostratigraphic divisions were adopted by Hallett (1988) (Fig. 7) and House (1988) (Fig. 8). Based on mapping in the vicinity of Wombeyan Caves, 55 km S of Jenolan, Simpson (1986) suggested correlation of this succession with the Bindook Volcanic Complex (now Bindook Group). The Bindook Group is a variable association of volcanic, volcaniclastic, clastic and carbonate rocks of Early Devonian age, united by their silicic volcanic affinities, in particular the presence of dacite. Outcrop of this association is known to extend north as far as Yerranderie, 35 km SE of Jenolan (Simpson et al. 1997). However, new fossil finds reported here support a late Silurian age for limestone interbedded with the steeply-dipping strata overlying the Jenolan Caves Limestone. Accordingly, we formally define a new stratigraphic unit, the Inspiration Point Formation, that is characterized by felsic volcanics and associated sedimentary rocks, and correlate it with the lower to middle part of the Mount Fairy Group, which is exposed in a NNE-trending belt (the Goulburn Basin) on the eastern side of the Goulburn 1:250,000 sheet (Thomas et al., in Thomas and Pogson 2012).

Inspiration Point Formation (nov.)

Derivation of name:from Inspiration Point, the eastern extremity of a prominent hairpin bend of the Jenolan Caves Road below Mount Inspiration (Fig. 5).

Synonymy: the formation includes rocks informally designated as the 'Jenolan Beds', the 'Eastern Beds', the 'Northern Beds', and the 'Eastern Limestone'.

Constituent units: no formal members are proposed, but the formation includes several prominent marker beds, including limestone, conglomerate, quartz porphyry, and dacite.

Distribution: the formation extends from the eastern margin of the Jenolan Caves Limestone to at least the Black Range (eastern extent of the area mapped in detail) (Fig. 4).

Geomorphic expression and outcrop: forms rugged topography intersected by deep valleys; outcrop is most accessible in creek beds and road cuttings.

Type area: due to the structural complexity, steep and rugged topography, and heavily vegetated slopes, it is not practicable to nominate a type section. However, a type area can be designated north of Jenolan Caves, bounded by the eastern margin of the main limestone belt in McKeowns Valley and proceeding eastwards across Binoomea Ridge to the main Jenolan Caves access road (with good sections along this road particularly between the Five Mile Hill in the Mount Inspiration area and the Grand Arch at the Caves), thence extending generally east from the main road to Mount Warlock, and further north in the valley of Bulls Creek.

Boundary relationships: the Inspiration Point Formation is interpreted as conformably overlying the Jenolan Caves Limestone, despite the sporadic absence of a felsic volcanic unit at the base of the formation (probably faulted out) that allows purple and grey cleaved mudstone slightly higher in the succession to abut directly the Jenolan Caves Limestone east of the Grand Arch.

Thickness: a total thickness in excess of 3220 m is estimated for the former 'Jenolan Beds', comprising (from oldest to youngest) felsic volcanics to 30 m thick; 350 m of purple and grey cleaved mudstone; a prominent quartz porphyry with maximum thickness about 150 m; an unspecified thickness of siliceous mudstones interbedded with felspathic siltstones and sandstones and containing a prominent conglomerate bed 60 m thick; altered dacitic crystal tuff of 350 m maximum thickness; a turbidite succession about 200 m thick in total; quartz-felspathic sandstone up to 145 m thick; turbidites about 85 m thick; a distinctive crystal-rich tuffaceous sandstone about 200 m thick; a further succession of turbidites about 1400 m thick; and culminating in a series of massive volcanic rocks with occasional conglomeratic lenses, more than 350 m in total.

Lithological variation: In the vicinity of Navies Creek, grey slate at the top of the Jenolan Caves Limestone is overlain by a band of felsic volcanics up to 30 m thick forming the basal unit of the Inspiration Point Formation. The volcanics disappear in the south, about 400 m north of Dillons Creek. Outcrop is patchy, but the unit probably sits directly on the limestone south of Navies Creek. Lateral variation in texture is rapid and common, and a lack of continuity is not unexpected in such a unit, which consists of fine ash, volcanic breccia with lapilli-sized fragments and several flows of quartz porphyry and banded dacite. The volcanic band is bounded on the east by a shear zone, which may account partly for the lack of continuity. Displacement on the fault, however, seems to be restricted to the north, so that to the south an apparently conformable contact probably exists between the felsic volcanics and the overlying unit, which consists of purple and grey cleaved slaty mudstone 350 m thick. This is the unit which appears to abut directly against the limestone just east of the Grand Arch. When weathered it becomes quite red. This unit contains numerous shear zones, but they seem to occur only within possible bedding planes, although bedding is rarely seen. In thin section this mudstone consists of fine quartz grains in a matrix of white mica, plagioclase and finer quartz. Doughty (1994) indicated that a few thin beds of interbedded volcanoclastic sandstones are present south of the Grand Arch.

Occurring within the slaty mudstone is the prominent quartz porphyry named ‘Jenolan Rhyolite Porphyry’ by Süssmilch and Stone (1915), equivalent to the ‘Binoomea Quartz Porphyry’ of Doughty (1994), which is easily identified just to the east of the Blue Pool. The porphyry occurs as two separate bodies north from the tourist area, on about the same stratigraphic horizon, but the more northerly body approaches closely to the eastern boundary of the mudstone and continues north with noticeable thinning until about 500 m south of Navies Creek. South from the tourist area, Doughty (1994) mapped the porphyry as widespread around Green Ribbon Hill, possibly as the result of folding (which apparently has affected the limestone: Allan 1986), although Doughty suggested that there are separate porphyry masses in this area. The southern extent of the porphyry is obscured under the Permian beds of Mount Whitely. In hand specimen the porphyry is white with green patches and contains large, fragmental phenocrysts of quartz and felspar in an aphanitic groundmass, formerly of fine glassy ash, now altered to chlorite, albite, calcite, prehnite and sphene. The quartz crystals average about 3 mm, and make up some 10-20% of the rock. The felspar crystals (dominantly orthoclase), which comprise about 15%, are altered, dull white and usually smaller than the quartz phenocrysts. Biotite is visible occasionally in hand-specimen. Evidence of flow banding, pumice fragments (Fig. 10) and absence of contact metamorphism indicates that the porphyry is a primary pyroclastic rock (i.e. not reworked). Its maximum thickness is about 150 m.

The purple and grey mudstone succession is followed by slightly coarser siliceous mudstones with interbedded fine felspathic siltstones and sandstones. The siltstones consist of interlocking mats of fine white mica and biotite with occasional very fine (< 0.1 mm) quartz grains. There is a dominance of grain growth sub-parallel to bedding, probably reflecting an original fissility. A prominent conglomerate bed (60 m thick) within this package contains clasts of limestone, spilite and mudstone ranging in size from boulders to pebbles; cobbles and pebbles being dominant. The matrix is relatively coarse sand, composed of altered plagioclase (andesine) felspar, calcite and spilite interspersed with finer grained calcite, quartz, chlorite and white mica. South of the Jenolan River the mudstone and siltstone units appear to be conformable, but the conglomerate bed swings northwesterly when crossing the Five Mile Hill Road and runs directly into the purple-grey mudstone unit. Allan (1986) attributed this swing to faulting, and showed a fault of limited extent, striking N-S, to explain the phenomenon, but the trend of the nearby dacitic tuff (see below) shows a similar bend and suggests that there might be a disconformable boundary between the mudstones and the siltstones. There is little or no evidence of an extensive continuous fault along this boundary.

The sedimentary succession is interrupted by a prominent dacitic unit, referred to by Allan (1986) as an altered crystal tuff, but to the north interpreted by Stewart (1987) as a flow. Its nature is concealed by alteration. The unit crops out well as a distinctive resistant band, weathering along joints and breaking into large blocks. It varies in thickness from about 70 m in the vicinity of Navies Creek to 350 m two kilometres to the south east. It is 120 m thick in the Five Mile Hill road cutting, east of the Grand Arch, and more than 300 m thick south of the Jenolan River. These variations are probably largely stratigraphic, although Stewart (1987) indicated that there is evidence, in the form of brecciation of the dacite and some sheared slates in a few places, that the eastern boundary of the dacite may be faulted. The rock has a characteristic pink-green groundmass, mottled with dark green and light yellow-green patches, making it readily identifiable in the field. The main primary minerals are large grains of plagioclase, smaller grains of quartz and finer quartz within the groundmass, which also contains K-felspar. Chlorite patches probably represent altered biotite. Granophyric and micrographic textures suggest a flow rather than a

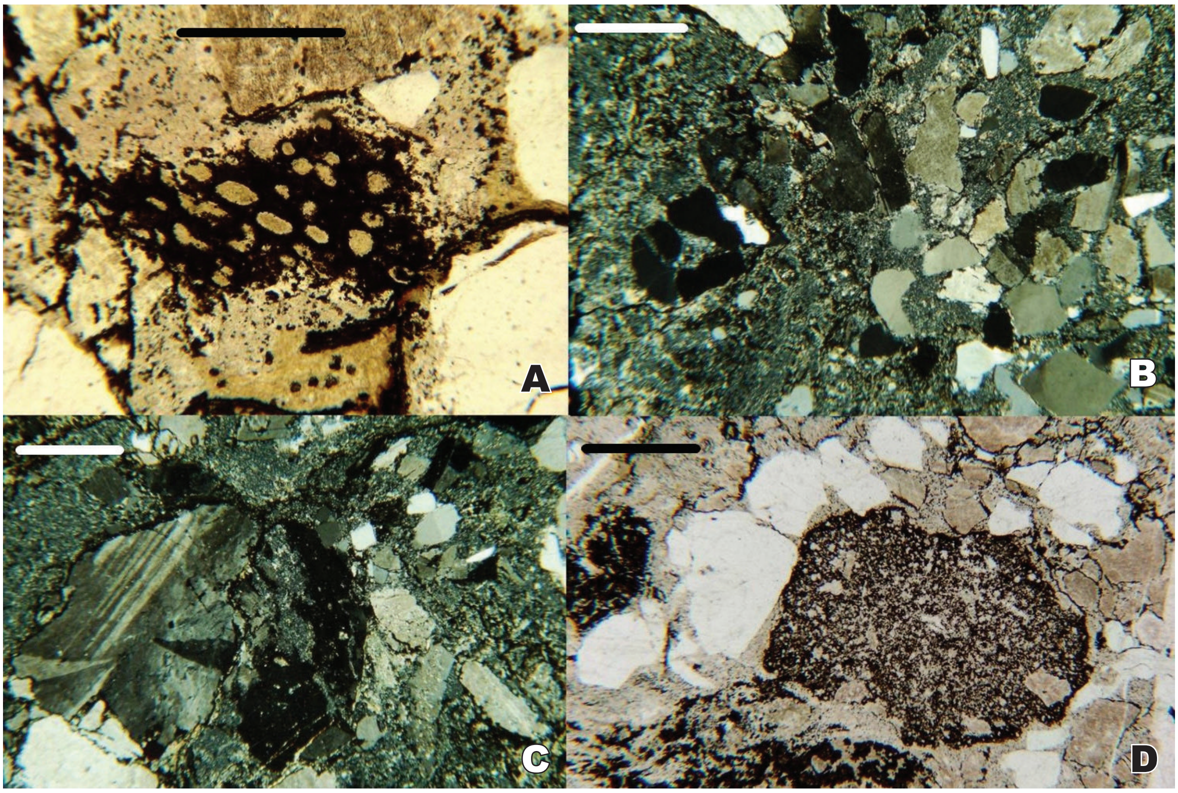


Fig. 10. Photomicrographs of thin sections of quartz porphyry (GSNSW T88825) from outcrop just east of the Blue Pool at Jenolan Caves (identified as 'Jenolan Rhyolite Porphyry' by Süssmilch and Stone 1915), showing the pyroclastic origin of this rock. A, with large pumice fragment in centre of field of view; B, showing rounded volcanic quartz grains; C, with large plagioclase crystal on left side of field of view, exhibiting twinning; D, with rounded volcanic rock fragment (dark grey speckled appearance) in centre of field of view. Scale bar for A = 0.5 mm, for B, C, D = 1.0 mm.

pyroclastic origin. Alteration minerals, in addition to chlorite, include epidote, albite, prehnite, pumpellyite, calcite and white mica.

North of Navies Creek, and separated from the dacite on the east by just a few metres of turbidites, a thin layer of metabasalt crops out. It is a dark green rock consisting of generally aligned, altered plagioclase and clinopyroxene, partly replaced by actinolite. Other metamorphic minerals — chlorite, epidote, albite, prehnite, calcite and sphene — are present.

The siltstone overlying the dacitic unit grades up into medium-coarse grained quartz-felspathic sandstones, with bed thicknesses varying from 5 to 50 m, often grading up from conglomeratic bases. These pass easterly into well-bedded siltstones and sandstones typical of turbidite successions, which are about 200 m thick in total. Most of the sandstones have volcanogenic sources and are composed of rounded quartz grains (25%), altered plagioclase felspar (up to 45%), lithic fragments (5-15%) and matrix. The siltstones in this succession consist dominantly of quartz, both as fragments and in the matrix.

The turbidites east of, and overlying, the dacite are overlain in turn by quartz-felspathic sandstone which is up to 145 m thick. It is coarse-grained, pink and green, making it easily recognised. The southern end of its outcrop, southwest of Mount Inspiration, is cut off by the Jenolan Fault (see later). A succession of turbidites about 85 m thick follows conformably. Then follows a distinctive crystal-rich tuffaceous sandstone about 200 m thick. This is a dark grey, fine to coarse-grained inequigranular rock, consisting of sub-angular grains of quartz, up to 5 mm across, and euhedral altered white felspar (both plagioclases and alkali types) up to 2 mm long, in a finer dark cryptocrystalline groundmass, made up of quartz, ?albite and chlorite. There has possibly been some re-working, so the unit is called a crystal-rich tuffaceous sandstone rather than a crystal tuff. However, Stewart (1987) suggested there is evidence that the unit grades upwards from tuff into a quartz-felspar porphyry flow.

A further succession of turbidites follows, about 1400 m thick, exposed along both the Jenolan Road and in the various branches of Cookes Gully (Fig. 7). It contains several mappable lenses of conglomerate. The turbidites are interrupted, about 250 m above the base, by what House (1988) and Hallett (1988) referred to as a silicic flow. This rock is light grey to pale yellow in hand specimen, aphanitic, marked by black spots up to 2 mm across, and with numerous fine pyrite grains. It was apparently originally a fine-grained dacitic flow with phenocrysts of plagioclase, mica and amphibole set in a fine glassy groundmass, which devitrified to give fine quartz and albite. Later low-grade regional metamorphism produced calcite and chlorite.

The youngest unit of the 'Jenolan Beds' is exposed along the Jenolan Road, where it has a thickness of rather more than 350 m. The boundary with the underlying turbidites is obscured by Permian conglomerates, but it is probably conformable. This uppermost unit is a series of massive, poorly-layered volcanic rocks with occasional conglomeratic lenses. The volcanic rocks range from siliceous rhyolitic flows, sometimes with orbicular accretions, overlain by a series of pink and green quartz-felspar agglomerates.

A series of similar volcanic rocks, referred to by Hallett (1988) as his 'Northern Beds', occurs east of the Jenolan Fault along the Jenolan Road, and extends along the Black Range Road. The 'Northern Beds' are separated from the 'Eastern Beds' by a northeast trending fault, extending from the Jenolan Fault and continuing at least 1.5 km to beyond the Black Range Road (Fig. 7).

The stratigraphy of the area east of the Jenolan Fault (previously referred to as the 'Eastern Beds') is more complicated than to the west. This is the result of faulting and the effects of contact metamorphism, superimposed on regional metamorphism. In addition the difficulties of access have made the interpretation of the geology very challenging.

The oldest unit in this area is a small circular exposure of buff white, intricately folded, laminated chert, and associated fine-grained silicic sandstone, found on a hillside 300 m north of Pheasants Nest Creek. It may represent an allochthonous 'window' of material and appears similar to lithologies in the Campbells Group west of Jenolan. Possibly associated with the chert is a 15 m thick bed of silicic tuff which crops out nearby.

Volcanogenic sandstone, overlain by siliceous buff-grey fine sandstone fining upwards into siltstone over several cycles, occurs along the valley of the Jenolan River and the lower reaches of Bulls Creek, and probably represents the next oldest strata in the area. The sandstone forms thick massive layers with good outcrop, but exposure of the siltstone is relatively poor. These beds are of undetermined thickness and bedding is rarely readily identifiable, but there is some evidence of younging to the east. The sequence is cut off to the north by the shallow-dipping Bulls Creek Thrust. This thrust has emplaced a structurally overlying succession of limestone, siltstone, spilite and tuffaceous sandstone which is exposed in Pheasants Nest Creek, the upper reaches of Bulls Creek and Beauty Gully (Fig. 8). All these "upper" (?younger) beds have a distinct north-west trend, which distinguishes them from the trend in the 'Northern Beds' (Hallett 1988), and in most of the 'Jenolan Beds', although the trend of the last named does range from north-south to northwest-southeast.

A second belt of limestone, interrupted by complicated folding and faulting, crops out about 2 km east of the main belt (Fig. 4). It extends below Mount Inspiration on both sides of the Jenolan River, and forms outcrops on Pheasants Nest Creek and again on the north side of the Jenolan River south of Beauty Gully. House (1988) mapped this 'Eastern Limestone' in the form of a continuous body some 40 m thick (Fig. 8), rather than a series of isolated pods as depicted by Carne and Jones (1919) and Chalker (1971). However, on the south side of the Jenolan River, upstream from the junction with Pheasants Nest Creek, the limestone tends to occur in the form of large lenses that grade vertically and laterally into shaly sediments, as shown by Allan (1986) (Fig. 5). The well-bedded shaly lower portion comprises interbedded calcareous shales and massive limestone layers ranging from 5 to 30 cm thick. Up sequence the ratio of shale to limestone decreases and it passes into a massive limestone, occasionally developing small caves. Macrofossils are generally not obvious in the limestone due to its pervasive sheared appearance. House (1988) reported tabulate corals, brachiopods, crinoid stems and gastropods from one outcrop, and extracted from acid-insoluble residues three conodont elements, one identified as the form species *Ozarkodina ziegleri tenuiramea* Walliser, 1964. However, reexamination of this specimen (Fig. 9K) suggests that it is too incomplete, with missing denticles, to be so precisely identified. Recent fieldwork by Pickett and others, investigating exposures of this limestone south of the Jenolan River between Farm Creek and Pheasants Nest Creek, led to recognition of the tabulate coral *Propora*, a rugose coral identified as *Pycnostylus* (catalogued in the Geological Survey of NSW Palaeontological Collection as MMF45233) and large pentamerid brachiopods similar to *Conchidium*, all indicating an age no younger than late Silurian.

The limestone passes upwards gradationally into siltstone, about 50 m thick, with rare thin lenses of quartz sandstone, the siltstone being succeeded by a thick yellow-green to grey quartz porphyry up to 130 m thick, exposed in Pheasants Nest and Bulls Creeks, and forming large pods to the east, below Warlock Ridge. Both siltstone and limestone clasts have been found within this unit. It appears to have an erosional boundary with the underlying siltstone, but its upper (northeastern) boundary is irregular and might be faulted. A further thick siltstone with well-developed cleavage, in reality a phyllitic succession, up to 360 m thick, ranging from purple-brown to grey and grey-green, follows. It contains a prominent lens of silicic ?tuff. Towards the top of the siltstone succession there are several lensoidal intrusions of hornblende dolerite (see below). Thin layers of spilite are also present.

The siltstone unit is followed by a very thick spilite (ranging from 500 m in the south to 900 m in the north), which to the northwest is intercalated with tuffaceous sandstones and siltstones. The thickness may possibly be exaggerated by repetition through faulting. The spilite is a dark green-grey rock of varying grainsize, depending on the degree of recrystallisation, which alternates between vesicular and massive types, with evidence of auto-brecciation and pillows (up to 50 cm across) towards the top of the unit.

North of, and ?faulted in places against the spilites, is a thick sequence of massive grey coarse-grained tuffaceous sandstones interbedded with laminated siltstones. Some of the sandstone units are probably scarcely reworked tuffs, containing occasional clasts of siltstone and limestone. This sequence occurs in a number of fining-up cycles, each 30 to 100 m thick. Hallett (1988) indicated a total thickness in excess of 1200 m.

While thickness of each of the units varies greatly, the stratigraphic succession remains consistent. The succession is cut off by a north-north-west trending fault, bringing it against Upper Devonian Lambie Group rocks.

Age and correlation: Internal evidence of age of the Inspiration Point Formation is meagre, being restricted to the occurrence of *Propora* sp. and pentamerid brachiopods. A constraint on the maximum age of the Inspiration Point Formation is provided by the underlying Jenolan Caves Limestone, of mid-Wenlockian age. The Inspiration Point Formation conformably overlies the Jenolan Caves Limestone and includes limestone that contains sparse fossils no younger than late Silurian. Hence an age range of latest Wenlockian or Ludlovian, possibly extending to the Pridolian, is most likely for the Inspiration Point Formation, correlating it with the lower to middle part of the Mount Fairy Group described from the Goulburn 1:250,000 map area SW of Jenolan. The Mount Fairy Group in the Goulburn Basin ranges in age from mid-Wenlock (early Silurian) to mid-Lochkovian (Early Devonian). Thomas et al. (in Thomas and Pogson 2012) describe the lower to mid portion of the Mount Fairy Group as comprising clastic sedimentary rocks (including siltstone, mudstone and fine-grained sandstone) and limestone lenses near the base, interfingering with mainly felsic volcanics, consisting of rhyolite, rhyodacite, dacite and andesite lavas and volcaniclastic rocks. Graptolitic black shales, and in other areas a succession of thick, regionally extensive, fine- to very coarse-grained, quartzose to lithic–quartz sandstone of turbiditic origin, interbedded with siltstone and mudstone, overlies the lower portion of the group. The upper portion of the Mount Fairy Group overlying the turbidite sequence is characterised by a thick succession of felsic to intermediate lavas and volcaniclastic sedimentary rocks with minor basaltic lavas. Thus there are considerable lithological similarities with the Inspiration Point Formation.

D. Intrusive hornblende dolerite

The hornblende dolerite (mentioned above) is a dark green, medium-grained holocrystalline rock, the essential minerals consisting of dark green hornblendes and white felspars with minor and smaller green minerals which are probably epidotes. The felspars (mainly albite) are up to 4 mm long, and form an interlocking mass with coarse amphiboles (to 5 mm), which makes up more than 50% of the rock. Because the amphiboles are primary, the term ‘hornblende dolerite’ is preferred to other names, such as amphibolite, which has the connotation of a regionally metamorphosed rock. Using comparisons with mafic rocks described by Joplin (1931, 1933, 1935, 1944) at Hartley, Macara (1964) suggested that similar occurrences on the Kanangra Road were associated with granite of Carboniferous age. However, the occasional foliation which occurs in the rocks here described, and even folding of individual grains, indicates that these rocks are considerably older, most probably pre-dating the Middle Devonian Tabberabberan Orogeny (Fig. 3).

E. Lambie Group

Sedimentary strata assigned to the Upper Devonian Lambie Group are medium to fine-grained white-buff, well-bedded quartzites, quartz-rich sandstones and siltstones (phyllites). Conglomerates, which are typical of the basal Lambie Group in the eastern Lachlan Fold Belt, are missing in the Jenolan area, and have possibly been faulted out. Lambie Group rocks have not been overturned but are folded more broadly than the older units to the west, except where the beds have been deformed adjacent to the boundary fault, where they crop out in tight plunging inclined folds. These rocks have been described by Hallett (1988) and House (1988). While they would not be seen by the casual visitor to Jenolan, they occupy a significant place in the regional history of erosion and karstification. Chand (1963) mapped these beds extending well beyond Black Range, and indicated the position of several fold axes of broad folds. Hallett (1988) also mapped the more westerly of these fold axes (Fig. 7), and noted the presence of brachiopod fossils in the more phyllitic bands; these indicate that the Lambie Group in the Jenolan region was deposited in a marine environment.

F. Carboniferous Intrusive Rocks

The major intrusion in the area, here named the Hellgate Granite, crops out on the Jenolan River about 3 km downstream from the Caves Reserve (Fig. 4), and is equivalent in age (early to mid Carboniferous) to the multiphase Bathurst Batholith (Fig. 3). The edge of this intrusion was mapped by Chand (1963), who regarded it as an offshoot of the Hartley Granite (Joplin 1931, 1933, 1935), and by House (1988) (Fig. 8). Two phases can be recognized – a red granite and a white marginal granite. The red granite making up the main part of the body is a fine to coarse (up to 8 mm) inequigranular, wholly crystalline rock. Pink–brown coarse grains of quartz constitute more than 40% of the rock, pink felspars consist of 35% plagioclase and K–felspar 22%, with white mica making up 4%. The plagioclase is frequently altered. The white granite is a medium–grained equigranular, wholly crystalline rock with quartz (to 4 mm) comprising 35%, plagioclase (29%), K-felspar (25%), white mica (up to 5 mm) (10%) and garnet (1%).

The contact with the country rock is sharp and the granite roof, which is irregular, is often marked by a 5–10 cm thick layer of coarse pegmatitic material. A few smaller outcrops separate from the main body occur upstream on the river.

In the south–eastern and topographically lower portion of the mapped area, the Hellgate Granite has caused noticeable contact metamorphism within the 'Eastern Beds' and the Lambie Group. The effects of the contact metamorphism appear to be more dependent on the depth of the granite below, than the lateral distance from any granite exposure. A contact aureole approximately 400 m wide has been mapped (House 1988). In the inner 100 m an assemblage characteristic of the hornblende hornfels facies occurs. The outer 300–350 m of the aureole contains an assemblage characteristic of the albite–epidote hornfels facies.

A felsite dyke averaging about 10 m thick, first mapped by Chand (1963), runs northerly as an offshoot from the granite, cropping out continuously for more than 2 km to Warlock Creek, cutting obliquely across the beds it intrudes. It is a pink–brown flesh–coloured, equigranular fine–grained, wholly crystalline rock, composed almost entirely of pink felspars (alkali felspar 60%, plagioclase 30%, accessories 10%), indicating a syenitic composition. Hallett (1988) identified it as a syenite/monzonite where it crops out at Warlock Creek. Several dykes identified as micromonzonites were also mapped by Hallett (Fig. 7). Another micromonzonite dyke, weathered orange and dipping steeply SW, was mapped by Stewart (1987) cutting NW across his 'Jenolan Beds' and the Jenolan Caves Limestone, north of Dillons Creek (Fig. 6), and cut off by the McKeowns Fault, thus antedating it [?post Carboniferous]. It is 50 m thick, mainly granular, but has some porphyritic phases, and contains equal proportions of K–felspar and plagioclase and about 5% of quartz and minor groundmass.

G. Permian rocks

Conglomerates (with distinctive white quartz pebbles) and sandstones, regarded as outliers of the Shoalhaven Group (possibly equivalent to the Megalong Conglomerate) of the Sydney Basin, crop out sporadically. They occur mainly on ridge tops on an old erosion surface, forming a plateau which can be recognised extending far north to Mudgee and beyond (Branagan and Packham 2000). In the vicinity of Jenolan these sedimentary rocks occur particularly along the Kanangra Road. However, there are patches at various levels, sometimes lying directly (unconformably) on the Jenolan Caves Limestone, and very likely occurring also as cave fill in some places (Osborne and Branagan 1985).

METAMORPHISM AND MINERALIZATION

Rocks of the Jenolan region are characterized by low-grade regional metamorphism, mostly within the greenschist facies range. In the pelites and tuffs of the Inspiration Point Formation the regional pattern is within the biotite zone in the upper greenschist facies. Regional metamorphism has caused albitisation of original basalts and andesites, producing spilites. North of Jenolan, within the Inspiration Point Formation, the sedimentary rocks occasionally fall within the pumpellyite–prehnite facies, chlorite being associated with green biotite, but a chlorite–epidote–calcite–pumpellyite association is more common in these strata. Actinolite occurs in a few instances in doleritic rocks.

In the higher (topographically) country NW towards the Jenolan Fault, contact metamorphic effects diminish away from the granite intrusion at Hellgate Gorge, but can still be recognized as an overprinting on the earlier regional metamorphism. Occasional retrograde metamorphism, marked by the occurrence of laumontite, occurs within fractures and veins in the spilites, and is probably attributable to circulation of hydrothermal fluids. Minor mineralization (pyrite, chalcopyrite and arsenopyrite), occurring pervasively and in narrow veins, is possibly related to the metamorphism.

Copper mineralisation (bornite, malachite and azurite) associated with the spilites occurs in several places in the Inspiration Point Formation. A little bornite ore was extracted from a 20 m long adit early in the 20th century (Carne 1908), and shallow pits have been dug in malachite mineralisation in a 2 m wide shear zone, where the malachite occurs in thin veins throughout the rock and on cleavage surfaces.

STRUCTURE AND TECTONICS

The Silurian succession at Jenolan has been structurally complicated (thus obscuring stratigraphic relationships) by the effects of deformation during three significant tectonic episodes: the earliest Devonian Bowning Orogeny, the mid-Devonian Tabberabberan Orogeny, and the early Carboniferous Kanimblan Orogeny. The present attitude of the Jenolan Caves Limestone and the Inspiration Point Formation represents the combined effect of all three of these orogenies. Upper Devonian Lambie Group strata were affected only by the latter folding episode. Permian strata are gently-dipping rocks, which post-date the major folding and faulting. Folding of the lower Palaeozoic succession is complex, with several styles recognisable, restricted to different domains that are separated by faults (most apparent, but some interpreted). Within the newly-defined Inspiration Point Formation (including Allan's 'Jenolan Beds') and the Jenolan Caves Limestone, Allan (1986) mapped a series of large scale, open and fairly symmetrical, near-recumbent folds (wave lengths of the order of 400 m), the fold axes plunging northerly, on which smaller-scale parasitic folds (wave length of less than 40 m) are superimposed. To the east there are large-scale anticlinal structures, gently plunging north-easterly, on which are developed (at outcrop scale) both asymmetrical kink folding and fairly tight symmetrical folds. In some areas both cleavage and bedding can be clearly seen to be folded. Allan (1986), Hallett (1988) and House (1988) deal in considerable detail with the complexities of folding in the region.

Thrusts, or steeply-dipping reverse faults, dipping both east and west, are probably extensive. North-south striking vertical faults, probably in part strike-slip, are also common. The major (and some minor) faults mapped or interpreted are shown on Fig.4. Several of the faults are of regional significance, in particular the fault bordering (or close to) the Jenolan Caves Limestone on the west (Stewart's McKeowns Fault), and the Jenolan Fault striking generally north-south just west of Mount Inspiration.

The Jenolan Fault separates the two lithostratigraphic and structural domains previously informally termed the 'Jenolan Beds' and the 'Eastern Beds'. Its outcrop pattern indicates that it is consistently close to vertical. Although Allan (1986) believed this was a high-angle thrust fault, House (1988) presented evidence that it was more likely a dextral strike-slip fault with some normal component of displacement. The evidence is of two types: shallowing and bending of cleavage in the 'Eastern Beds', and drag of bedding in the 'Jenolan Beds', as the fault is approached. There is also the indirect evidence of differences in metamorphic grade, the 'Jenolan Beds' having a noticeable lower grade, siltstones west of the fault giving way to phyllites on the east. House (1988) also suggested that the fault post-dates the Jenolan granite intrusion (Hellgate Granite herein), as the contact metamorphism evident in the 'Eastern Beds' in Pheasant Creek adjacent to the fault is missing from the 'Jenolan Beds'.

Evidence for the low angle Bulls Creek Thrust of House (Figs 4, 8) is given by the sharp low-angle boundary separating probably older siliceous sandstone and siltstone from outcrops of the limestone and nearby quartz porphyry within the Inspiration Point Formation. This boundary is marked by shearing of the beds, brecciation of quartz blocks, and considerable slickensiding. The evidence suggests thrusting from the southeast with the folding plunging shallowly to the north.

Shannon (1976) showed five faults cutting across the limestone belt in McKeowns Valley. The three southern ones, two south of and one north of Dillon's Creek are parallel, trending NNE, with the southern sides displaced easterly a small distance. The two more northerly faults, north and south of Hennings Creek, trend SSE. However, all five appear to have little regional significance as no displacement has been recognized in the adjacent beds, either on the west or the east. These faults were reproduced on the geological map in Kelly and Knight (1993).

GEOMORPHOLOGY

Jenolan Caves is situated at an altitude of 790 m in the deeply-incised east-trending valley of the Jenolan River. The sides of the valley are marked by several prominent benches in the landscape. Although partly caused by lithological variations these benches are almost certainly old erosion surfaces (Kiernan 1988, Osborne 1987), suggestive of valley-in-valley formation, indicating episodic uplifts following long periods of stability and slow down-cutting.

The Jenolan River valley is located at the southern edge of a slightly undulating plateau, named the Jenolan Plateau by Craft (1928), which is a partly-exhumed, gently-domed surface of Late Palaeozoic age revealed by the partial removal of a thin cover of Permian glacial and fluvio-glacial and (possibly) Triassic rocks (Branagan 1983). Craft (1928) gave considerable latitude to the definition of the plateau, writing that it "extends vertically from 3700 feet (1125 m) to 4400 feet (1338 m) above sea level (the highest point is Mount Bindo, 1359 m), with an average elevation slightly greater than 4000 feet (1216 m)". The surface is generally fairly even, and extends at the higher level westerly to Oberon. This high level continues extensively south and southwest (as the Boyd Plateau) from Jenolan, but northeast it is less extensive, the surface here with elevation above 900 m consisting of Warlock Ridge, the narrow easterly trending Black Range ridge, and further north Mini Mini Range, with Gibraltar Rocks (1070 m) at its easterly culmination.

The Caves area is drained by the Jenolan River, which commences in McKeowns Valley on the west side of the Jenolan Caves Limestone, flowing southerly and controlled by the strike of the limestone and associated beds, then continuing underground through the limestone belt before emerging on the east side of the Grand Arch. Then it flows easterly, possibly structurally controlled by recumbent folding plunging towards the south and north (Kiernan 1988), through Hellgate Gorge, then north-easterly to join the Cox River at a 'concordant' junction, indicating perhaps that the Jenolan River is a long-established part of the Cox River system. Taylor (1958:145), possibly following Süssmilch (1911:40), suggested that water from McKeowns Valley flowed through the caves system, at five different levels at different times in its history, marking possibly five separate phases of erosion (down-cutting) in the formation of the Jenolan Valley. While the uppermost reach of the Jenolan River (McKeowns Valley) has a course largely controlled by the structural trend of the Jenolan Caves Limestone, its swing across the limestone and consequent eastern flow are oblique to the geological 'grain', and may represent superposition of an old course on an uplifted surface.

The eastern slope of the Jenolan valley is drained by the south-flowing Bulls Creek (the main tributary, nearly 8 km long, of the Jenolan River), which heads several km east from the north end of Binoomea Ridge. The lower reaches of this stream contain some alluvial terraces where flow is intermittent, and the valley floor is relatively wide (House 1988).

The region east of Jenolan has been lowered by the action of the long-established Cox River and its numerous small tributaries. The Cox River has a complex pattern, beginning in a shallow, broad valley in the vicinity of Blackmans Flat (near Lidsdale), in Permian rocks, then cutting deeply (structurally controlled) through Late Devonian quartzites west of Mount Walker (near Marrangaroo), flowing south of Wallerawang in deeply-weathered rock (part of the Bathurst-Hartley granite intrusion), now flooded by construction of the Lyell Dam (Howes and Forster 1997). From near Lawson's Sugarloaf, about 4 km upstream from the junction of the Cox and the River Lett, the main stream of the Cox River follows a meandering course in a fairly broad valley for about 38 km, dropping steadily over a distance of about 19 km from an altitude of about 760 m near the Old Bowenfels-Rydal Road to 600 m five km north of the Cox River Rd-Lowther Road. It subsequently proceeds another 19 km through an increasingly narrow valley, decreasing to 510 m west of Megalong; then over only 7 km, dropping to 304 m (near Pinnacle Ridge on the east and Gibraltar Rocks on the west), then to 150 m. The level of the Cox River then declines very slowly over more than 30 km to well beyond its junction with the Kowmung River.

We disagree with Craft (1928) who believed that the older Palaeozoic rocks were less resistant to erosion than the adjacent beds of the Sydney Basin Permian-Triassic succession, and that they were worn down relatively more rapidly. To explain the present relationship between the higher Jenolan Plateau and the Sydney Basin landscape, Craft suggested that the Jenolan Plateau surface had been uplifted with 'greater recent elevation than the remainder of the surrounding country'. However, there seems little reason to explain the history of local landscape development thus. Our field observations indicate that the Sydney Basin sedimentation was restricted essentially to the region presently covered by these rocks. The present highest point on the Sydney Basin occurs a short distance east of Cullen Bullen, at approximately 1280 m, whereas the Jenolan Plateau has numerous points well above this elevation, as mentioned previously. North from the Jenolan Plateau, Permian and Triassic sedimentation of the Sydney Basin is restricted in the Portland-Cullen Bullen-Ben Bullen region by resistant ridges of Devonian and Silurian rocks, and nearer to Jenolan, Sydney Basin sedimentation is similarly restricted by Late Devonian quartz-rich rocks at Mount Lambie to the west.

Scott and Pain (2006), based on work of the BMR Palaeogeographical Group (1993), indicated that the Jenolan Plateau is part of a much larger late Palaeozoic erosion surface covering a wide area of mid-western New South Wales and much of the Lachlan Fold Belt region south in Victoria (see also Blewett 2012:259, fig. 5.5). Examples of this ancient landscape can be clearly seen east of Mudgee, near Ben Bullen, and at the western edge of the Capertee Valley where the surface on which the sediments of the Sydney Basin began to be deposited is clearly dipping easterly, tilted by late Carboniferous movement. The existence of this old erosion surface accords with the now generally accepted idea, based on considerable evidence, that much of Australia's landscape is old and that modification has been slow (Young 1983, Bishop 1985, Gale 1992, Twidale and Campbell 1993). However, contradictory evidence based on apatite fission-track thermo-chronology (Blewett 2012:261, fig. 5.23) suggests considerable denudation (up to 4 km) over vast areas of Australia, including much of the supposed long-exposed landscape. These contradictions provide a major problem which, at present, shows little sign of resolution.

The Bathurst- Hartley-Jenolan Granite problem

An important event in the geological history of the region was the post-orogenic intrusion of the Kanimblan age Bathurst-Hartley granite body and associated smaller intrusions, such as that cropping out on the Jenolan River east of the caves (Hellgate Gorge). While the granite intrusions took place after the folding of the early-mid Palaeozoic Lachlan Fold Belt rocks, there is little evidence of the depth at which the intrusion was emplaced. Timing of the unroofing of this body is a key element in the understanding of the geomorphological history of the region, particularly given the suggestion by Osborne et al. (2006) that some cave sediments are of early Carboniferous age, and that the Jenolan region must have been essentially uncovered during the Carboniferous.

Vallance (1969) discussed the geology of the Bathurst (and associated) intrusions, dealing with its petrological variations and notably those mapped by Joplin at Hartley (Joplin, 1931, 1933, 1935, 1944), and suggested that the cover at the eastern end of the main igneous body was 'not more than 1500 m'. According to Vallance (1969) the granite had not been deeply eroded, although Howes and Forster (1997) indicate that weathering at the Lyell damsite was greater than expected.

Assuming this interpretation of cover thickness is correct, erosion of the material capping the Bathurst granite must have been very rapid, assuming that it took place essentially during Carboniferous to earliest Permian time. This leads directly into another important question: where were these considerable quantities of eroded sediments redeposited? Süssmilch (1911:38) pointed out that a cutting south of Lowther consisted of Permian conglomerate containing 'large water-worn boulders of quartzite and granite imbedded in a matrix of granite detritus (arkose), the whole resting upon an eroded granite surface'. Süssmilch recognised the conglomerate as belonging to what is now called the Shoalhaven Group, the basal Permian unit of the Sydney Basin succession. We now accept this unit as being, at least in part, of glacial or fluvio-glacial in origin, a matter that was not considered by the earlier workers. So erosion, possibly with some reworking, had clearly unroofed much of the granite by early Permian time, involving removal of possibly 1500 m of cover over an interval of some 50 million years. However, there is little record of the deposition of Carboniferous sediments adjacent to the zone of suggested erosion. The nearest evidence of late Carboniferous-earliest Permian deposition is found at the south-western edge of the Sydney Basin, where Herbert (1980) delineated a fluvioglacial drainage pattern (Talaterang Group – see also Tye et al. 1996) and a northerly 'tributary', the Burrawang Conglomerate, largely buried beneath younger Sydney Basin sedimentary rocks, and whose north-western extent is uncertain.

Modification of the Jenolan landscape clearly continued though Permian and Mesozoic time, with eroded material contributing to the formation of the Sydney Basin, although most evidence indicates that the bulk of that sedimentation came from the north and south. There is little evidence of an easterly-flowing drainage pattern which contributed to such erosion and consequent deposition. The relatively recent modifications of the Jenolan region in the Cenozoic are the result of differing surface weathering with the development of a variable regolith, and erosion, mainly by the Cox River and its tributaries (draining south and then east), and the Fish River and its tributaries on the west, draining northerly and then west and northwest in the Macquarie system.

While much of the above discussion is speculative, it seems appropriate to draw attention to these questions, which have not been previously addressed, but which impinge on our understanding of landscape evolution in the region.

Minor landscape-forming events and features

The Jenolan Fault has significant topographic expression between Mount Inspiration and the northern end of Pheasants Nest Creek, controlling saddle development. Further north it has little effect on topography, probably the result of relatively recent exhumation from beneath Permian conglomerates.

Scree slopes, slumps and rockslides are common throughout the region, but particularly in the eastern area. The surface below Mount Inspiration has prominent scarps with toes of slumps, consisting of jumbled masses of blocks and boulders, which cover the bedrock. House (1988) recorded a recent slump which included a much greater proportion of fine-grained material, and which clearly moved as a fluid.

Block streams with blocky, angular fragments (ranging up to two m in maximum dimension) of altered mafic volcanics and hornblende-bearing dolerites that occur on the steeper slopes (up to 45°) of gullies flanking Bulls Creek have been noted particularly by Hallett (1988). The streams are narrow, less than 20 m wide, and about 200 m long. In the northwestern part of the area, Stewart (1987) identified a series of block streams on eastern ridges high above the river and not reaching it, whereas debris flows and outwash fans were mapped at river level along the Jenolan River (McKeowns Valley), south of Navies Creek, the majority coming from the eastern side of the valley (Fig. 4).

Consolidated gravels occur at various levels. While some of these deposits are clearly related to relatively recent changes in the presently established streams, others, including some resting at high points on the Jenolan Caves Limestone, may represent events as far back as the Permian (Osborne and Branagan 1985). Consequently there is a considerable variability in outcrop, and accessibility to the ‘solid’ rock. The upper reaches of the tributary streams of the Jenolan River generally show considerable outcrop, but the lower reaches do not. Hill slopes are quite variable, depending in part on the rock type, the more resistant silica-rich units naturally being better exposed, but siltstones often show surprisingly extensive outcrops. In places the region is thickly vegetated, creeks are very steep, often with waterfalls, and talus often obscures outcrops, but there are some exceptions, as noted by Hallett (1988), who suggested that some rather smooth creek valley cross-sections indicated the preservation of Permian valleys, possibly developed through glacial or fluvioglacial processes.

GEOLOGICAL EVOLUTION AND HISTORY OF KARSTIFICATION

The Jenolan story can only be understood in relation to the history of the much wider picture of the Lachlan Fold Belt. In general terms we are looking at an area that was the focus of the deposition of sediments in a gradually shallowing (and stabilising) marine environment from Silurian to ?Early Devonian times, followed by another period of subsidence and shallowing (largely shallow marine to terrestrial) in Late Devonian time. Volcanic activity was a continuing factor. Intrusion of granite followed with some strong earth movements, and the region underwent erosion until early to mid-Permian time when the region was subjected to glacial or peri-glacial conditions, and sediments were deposited at the edge of a shallow sea that deepened to the east.

Until the 1980s the age of karstification at Jenolan and most other eastern Australian karst was quite dogmatically stated as Quaternary, or at the oldest, Pleistocene, post-dating the so-called Kosciusko Uplift in Pliocene time. This is the heritage of E.C. Andrews (1911). Ideas on the age of formation of karst have been very strongly influenced by Andrews’s Kosciusko Uplift hypothesis, which became the revealed truth or dogma of Australian geomorphologists until the 1970s. Andrews brought the idea of very recent uplift, peneplanation and erosional activity back to Australia after a visit to America in 1908, where he was strongly influenced by G.K. Gilbert and W.M. Davis. To some extent these ideas of recent activity were also held by J.N. Jennings, the result of his European experience, and his influence among Australian speleologists here was considerable during the 1960s-80s. It is probable that Jennings was modifying these ideas before his untimely death in 1984.

Karstification may have occurred during three main periods: Middle Devonian, late Carboniferous-early Permian and post Triassic. While modifications to the cave system have occurred since Tertiary times, the major karstification probably occurred earlier. The difficulties of terrain and outcrop mean that many problems remain to be elucidated in this challenging area.

The development of karst in eastern Australia has been a specific study of Armstrong Osborne, and his findings are set out in a number of papers published over the past twenty years (Osborne 1987, 1991, 1993, 1994, 1995, 1999; Osborne and Branagan 1985, 1988; Osborne et al. 2006). They are especially summarised in Osborne (1999) and Osborne et al. (2006), in which the complexity of the story is pointed out, with evidence for exhumation of McKeowns Valley post-Permian, and the presence also of Cenozoic bone-bearing gravels and a variety of surface and underground drainage paths of various ages (see also Kelly 1988). As Osborne (1984) showed, and reiterated (Osborne 1999:14) the Jenolan Caves 'are not the product of a single recent event during which a single process operated, but, rather, are the product of a number of different events, during which a variety of processes operated'. These events took place over a geologically significant period of time.

Constraints on age of cave development

Evidence that karst development has been proceeding since Carboniferous or even Early Devonian time was proposed by Osborne et al. (2006), who obtained K-Ar isotopic ages on illites from cave deposits from a range of localities at Jenolan, the oldest being late Emsian (Early Devonian), with no fewer than nine results providing early Carboniferous isotopic ages in the range 357 – 335 Ma, and a further three falling into the later Carboniferous (325 – 313 Ma). A single sample yielded a late Permian age (258.7 Ma). These results must be viewed within the context of the overall geological history of the area, and it is here that we observe certain areas of conflict which we outline below. For rapid reference, an extract of Osborne's data is provided in Table 1, with dates revised according to the latest geological time scale (Gradstein et al. 2012).

Tectonic constraints.

The Silurian succession at Jenolan has been affected by three significant tectonic episodes: the earliest Devonian Bowning Orogeny, the mid-Devonian Tabberabberan Orogeny, and the early Carboniferous Kanimblan Orogeny. The present attitude of the Jenolan Caves Limestone and its associated sediments represents the combined effect of all three of these orogenies.

The Kanimblan Orogeny, the last tectonic episode within the Lachlan Fold Belt, concluded with the intrusion of the Bathurst Batholith. Timing of both these events has been the subject of recent study, with ages for various phases of the Batholith interpreted to range between 340 Ma and 312 Ma (Pogson and Watkins 1998). Intrusions forming part of the Batholith crop out less than 2 km from Jenolan; the emplacement of these coarse granitic bodies implies a depth of cover of the order of 1.5 km (Vallance 1969).

The duration of movements related to the Kanimblan Orogeny appears to have been remarkably brief. Glen (2013:337 and fig. 3) indicated an age of 340 Ma with no stated range; it was likely confined to a brief interval in the earliest Visean. It follows that any cave deposits still in original attitude must be no older than this. This means that it is improbable that any cave sediments of either Devonian or earliest Carboniferous age could be horizontal.

The isotopic ages quoted in Table 1 cluster around the Tournaisian and Visean, either coeval with the Kanimblan Orogeny or just before it. There is also significant overlap with the isotopic ages determined for phases of the Bathurst Batholith. As emplacement of coarse-grained granitic bodies requires substantial depth, we can only conclude that dates for cave deposit formation falling within this period have to be regarded with caution. Furthermore, the range of K-Ar isotopic ages on illites determined by Osborne et al. (2006) from individual samples was considerable. The two most extreme cases (JIC1, DCH4) covered intervals of 83.04 Ma (mid Visean to late Permian) and 55.42 Ma (latest Emsian to mid Visean).

Caymanite.

Cave deposits identified by Osborne et al. (2006:379) as caymanites, by analogy with marine deposits from Caribbean occurrences, occur notably in the Devils Coachhouse, apparently from the locality of their sample DCH4 for which ages ranging from late Early Devonian to the later early Carboniferous were determined. These horizontally to sub-horizontally bedded sediments include crinoid columnals that are certain indicators of marine conditions.

Marine sediments of this attitude necessarily post-date the Kanimblan Orogeny, for simple geometric reasons. Since no marine deposits of Carboniferous age are known from anywhere within the Lachlan Fold Belt, and in any case the succession now exposed in the Jenolan area was of the order of 1.5 km below the surface, the Carboniferous age suggested by dating from sample DCH4, is, to say the least, extremely unlikely, and it quite improbable that this sample could be as old as Early Devonian. The sole interval since the Carboniferous during which the Jenolan area was under marine conditions is the Permian, by which time the Bathurst Batholith had already been unroofed. This is evident in the area around Hartley and to the south, where basal Sydney Basin marine sediments referred to the Berry Formation directly and extensively overlie granites

Age	Sample	Location	Age (Ma)	Time-scale (Veevers 2000)	GTS 2012
Permian	JIC1	Imperial, Selina	258.7 ± 5.12	Permian (Late Ufimian)	Late Permian (Earliest Lopingian)
Carbo-niferous	JIC1	Imperial, Selina	313.58 ± 6.21	Carboniferous (Namurian - Bashkirian)	Mid Moscovian (middle Late Carboniferous)
	O1	Orient, Jungle	320.19 ± 6.34	Carboniferous (Namurian - Serpukhovian)	Bashkirian (early Late Carboniferous)
	BR6	Temple of Baal	325.81 ± 6.43	Carboniferous (Namurian - Serpukhovian)	Middle Serpukhovian (latest Early Carboniferous)
	JI74	River, Mud Tunnels	335.02 ± 6.62	Carboniferous (Visean - Arundian)	Mid Visean (mid Early Carboniferous)
	O1	Orient, Jungle	336.71 ± 6.66	Carboniferous (Visean - Arundian)	Mid Visean (mid Early Carboniferous)
	O1	Orient, Jungle	338.25 ± 6.7	Carboniferous (Visean - Arundian)	Mid Visean (mid Early Carboniferous)
	DCH4	Devils Coach House	339.45 ± 6.72	Carboniferous (Visean - Arundian)	Mid Visean (mid Early Carboniferous)
	JIC1	Imperial, Selina	341.74 ± 6.76	Carboniferous (Visean - Chadian)	Mid Visean (mid Early Carboniferous)
	JRV7	River Lethe	342.40 ± 6.77	Carboniferous (Visean - Chadian)	Mid Visean (mid Early Carboniferous)
	JRV9	River, Junction	342.50 ± 6.97	Carboniferous (Visean - Chadian)	Mid Visean (mid Early Carboniferous)
	DCH4	Devils Coach House	351.12 ± 6.99	Carboniferous (Tournaisian - Hastarian)	Mid Tournaisian (Early Carboniferous)
	JRV9	River, Junction	357.30 ± 7.06	Carboniferous (Tournaisian - Hastarian)	Near basal Tournaisian (earliest Carboniferous)
Devonian	W5	Wilkinson Branch	389.24 ± 6.58	Devonian (late Eifelian)	Upper Eifelian (mid Middle Devonian)
	JRV9	River, Junction	391.47 ± 7.75	Devonian (Early Eifelian)	Early Eifelian (early Middle Devonian)
	DCH4	Devils Coach House	394.87 ± 7.85	Devonian (Late Emsian)	Latest Emsian (Late Early Devonian)

Table 1. Data selected from Osborne et al. (2006) showing K-Ar isotopic age dates determined on illites separated from samples of clay and caymanite within Jenolan Caves; samples from identical sites are colour-coded. The ages determined in the original paper have been recalibrated to the latest international time scale (Gradstein et al. 2012).

of the Batholith (Bryan et al. 1966). Consequently a Permian age for the caymanites, equivalent to that of the Berry Formation, remains the most probable.

Mineralisation.

Osborne (1999) has put forward the attractive idea that cupolate caves result from preferential erosion of zones of sulphide-mineralised limestone. Such mineralisation requires a source, and a review of potential sources can provide significant data relevant to both timing and origin. Subjacent sources are suggested by the close proximity of components of the Bathurst Batholith, as noted above. To these can be added older sources, almost contemporaneous with the Jenolan Caves Limestone itself. The acid tuff, first noted by Süssmilch and Stone (1915) as “rhyolite porphyry”, includes pumiceous fragments (Fig. 10), indicating an eruptive origin and the relatively close proximity of acid volcanism. The numerous porphyries of probable Late Silurian age shown on Figures 3-6 offer a further potential source. Mineralization associated with the spilites generally includes copper, which would almost certainly result in staining of limestone in the caves. As this has not been observed, this latter source is discounted.

CONCLUSIONS

We have clarified the proliferation of informal stratigraphic names throughout the Jenolan area, confirming correlation of the majority of rocks west of the Jenolan Caves Limestone with the lower part of the lower Silurian to Lower Devonian Campbells Group. The age of the Jenolan Caves Limestone (equivalent to the basal Mount Fairy Group) is revised as mid-Wenlock. Conformably overlying the Jenolan Caves Limestone to the east is a newly-defined unit, the Inspiration Point Formation, characterized by felsic volcanics and associated sedimentary rocks that resemble the succession in the lower to mid Mount Fairy Group (Fig. 3). The Inspiration Point Formation includes limestone (previously referred to as the ‘Eastern limestone’) that contains rare corals and brachiopods of probable late Silurian age, thus separating these outcrops from the Jenolan Caves Limestone in both time and space.

With the exception of the younger units (Permian conglomerates) that post-date the Kanimblan Orogeny during the early Carboniferous and are essentially flat-lying, the other stratigraphic units (in particular, the steeply-dipping Jenolan Caves Limestone) become progressively younger to the east, as determined by bedding (often overturned).

Major faulting (e.g. McKeowans and Jenolan faults) in the region mainly trends N-S. The type of faulting is not always clear, but some strike-slip is implied, as well as possible thrusting (Bulls Creek Thrust). The faults separate the region into a number of structurally-controlled domains, and tend to obscure stratigraphic and depositional relationships in a succession that is (apart from the Jenolan Caves Limestone) generally devoid of fossil control. However, some marker beds are recognized in the Inspiration Point Formation, which assists in mapping and correlation across faulted boundaries.

The present geomorphology of the region probably evolved from late Carboniferous-early Permian time, and the general plateau surface, representing this feature, has been widely exhumed around Jenolan. “Steps” in the deep valleys indicate episodic periods of valley formation.

Cave formation may have occurred during at least three main periods (Middle Devonian, late Carboniferous-early Permian and post Triassic), but the evidence for Devonian and Carboniferous periods of karstification must be treated with caution. While modifications to the cave system have occurred since Tertiary times, the major karstification probably occurred much earlier.

ACKNOWLEDGEMENTS

DFB gratefully acknowledges use of detailed field mapping, associated laboratory studies and reports compiled by T.L. Allan (1986), W. Stewart (1987), M. Hallett (1988) and M. House (1988) (tragically killed November 1999 by an underground collapse at NorthParkes mine), (all of University of Sydney), and D. Doughty (1994) (UTS) in preparation of this paper. Access to these and other university theses consulted in the preparation of this paper was made possible by the cooperation of the School of Geosciences, University of Sydney, the School of BEES at UNSW, and the University of Technology, Sydney. We appreciate useful discussions with K.J. Mills, E. Holland, R.A.L. Osborne, and other members of the former Jenolan Scientific Committee (1986-1998). Armstrong Osborne and Harry Burkitt assisted JWP and IGP in sampling fossil localities in limestone of the Inspiration Point Formation that were crucial to determining the age of this unit. Yong Yi Zhen (Australian Museum) kindly undertook SEM photography of the conodonts and assisted with preparation of Fig. 9. Jane and Larry Barron provided helpful discussion of thin sections of the quartz porphyry east of the Jenolan Caves Limestone and the photographs comprising Fig. 10. Thesis maps and the regional geology compilation were redrawn for this paper by Cheryl Hormann (Geological Survey of NSW, Maitland). Bruce Welch provided editorial advice in relation to optimum resolution of the figures. We thank reviewers Ian Cooper and Dennis Pogson for their perceptive and helpful comments on the manuscript. Percival and Pickett publish with the approval of the Executive Director, Resources and Energy NSW.

REFERENCES

Allan, T.L. (1986). Stratigraphy and Structure of Palaeozoic Rocks in the Jenolan Caves Area, N.S.W. B.Sc. (Hons.) Thesis, University of Sydney (unpublished).

Andrews, E.C. (1911). Geographical Unity of Eastern Australia in Late and Post Tertiary Time, with applications to Biological Problems. *Journal and Proceedings of the Royal Society of New South Wales* **44**, 420-480.

Bischoff, G.C.O. (1986). Early and Middle Silurian conodonts from midwestern New South Wales. *Courier Forschungsinstitut Senckenberg* **89**, 1-337.

Bishop, P. (1985). Southeast Australian late Mesozoic and Cenozoic denudation rates: a test for late Tertiary increases in continental denudation. *Geology* **13**, 479-482.

Blewett, R.S. ed. (2012). ‘Shaping a Nation: a Geology of Australia’. (Geoscience Australia and ANU E-Press: Canberra).

Branagan, D.F. (1983). The Sydney Basin and its vanished sequence. *Journal of the Geological Society of Australia* **30**, 75-84.

Branagan, D.F., Holland, E. and Osborne, R.A.L. (1996). The Geology of the Jenolan Region. In E. Hamilton-Smith (ed.) *Abstracts of Papers, Karst Studies Seminar, Naracoorte, South Australia.* Regolith Mapping, Hamilton, Victoria, p. 17.

Branagan, D.F. and Packham, G.H. (1967). ‘Field Geology of New South Wales’. 1st edition. (Science Press, Sydney).

Branagan, D.F. and Packham, G.H. (2000). ‘Field Geology of New South Wales’. 3rd edition. (Department of Mineral Resources: Sydney).

Bryan, J.H., McElroy, C.T. and Rose, G. (1966). ‘Sydney 1:250,000 Geological Series, Explanatory Notes’. (Geological Survey of New South Wales: Sydney).

Bureau of Mineral Resources Palaeogeographic Group (1993). ‘Australia: Evolution of a continent’. (Bureau of Mineral Resources, Canberra).

Carne, J.E. (1908). ‘The Copper-Mining Industry and the Distribution of Copper Ores in New South Wales’. *Mineral Resources No. **6***. (NSW Department of Mines: Sydney).

Carne, J.E. and Jones, L.J. (1919). ‘The Limestone Deposits of New South Wales’. *Mineral Resources No**.** **25***. (NSW Department of Mines: Sydney).

Chalker, L. (1971). Limestone in the Jenolan Caves Area. *Records of the Geological Survey of New South Wales* **13(2)**, 53-60.

Chand, F. (1963). The geology of an area northeast of Jenolan River. B.Sc. (Hons) Thesis, University of NSW, Sydney (unpublished).

Cooper, I. (1990). Intrusive control of speleogenesis, Mammoth Cave, Jenolan. *SUSS Bulletin* **30(1)**, 21-24.

Cooper, I. (1993). Geology and speleogenesis, in caves of Serpentine Bluff. *SUSS Bulletin* **33(1)**, 28-30.

Craft, F.A. (1928). The Physiography of the Cox River Basin. *Proceedings of the Linnean Society of New South Wales* **53(3)**, 207-254.

Curran, J.E. (1899). ‘Geology of Sydney and the Blue Mountains’. 2nd edition. (Angus & Robertson: Sydney)**.**

David, T.W.E. (1894). President’s Address, including a Sketch of our present Knowledge of the Geological history of Australia, Tasmania, and New Zealand, from Archean Time down to the commencement of the Permo-Carboniferous Period. *Proceedings of the Linnean Society of New South Wales* **8(4)**, 540-607.

David, T.W.E. (1897a). Anniversary Address: Summary of our present knowledge of the structure and origin of the Blue Mountains of New South Wales. *Journal and Proceedings of the Royal Society of New South Wales* **30**, 33-69.

David, T.W.E. (1897b). The occurrence of radiolaria in Palaeozoic rocks in N.S.Wales. *Proceedings of the Linnean Society of New South Wales* **21(4)**, 553-570.

David, T.W.E. and Pittman, E F. (1899). On the Palaeozoic radiolarian rocks of N.S.W. *Quarterly Journal of the Geological Society of London* **55(1-4)**, 16-37.

De Decker, P. (1976). Late Silurian (late Ludlovian) conodonts from the Kildrummie Formation, south of Rockley, New South Wales. *Journal and Proceedings of the Royal Society of New South Wales* **109**, 59-69.

Doughty, D.G. (1994). The stratigraphy and structure of the southern Limestone Area, Jenolan Caves, N.S.W. B.Sc. Thesis, University of Technology, Sydney (unpublished).

Etheridge, R., Jr. (1892). The Pentameridae of New South Wales. *Records of the Geological Survey of New South Wales* **3(2)**, 49-60.

Etheridge, R., Jr. (l894). Appendix 6: Annual Report of the Palaeontologist for the Year 1893. In *Annual Report of the Department of Mines and Agriculture, New South Wales for 1893*.

Fowler, T.J. and Iwata, K. (1995). Darriwilian–Gisbornian conodonts from the Triangle Group, Triangle Creek area, New South Wales. *Australian Journal of Earth Sciences* **42**, 119-122.

Gale, S.J. (1992). Long-term landscape evolution in Australia. *Earth Surfaces Processes and Landforms* **17**, 323-343.

Glen, R.A. (2013). Refining accretionary orogen models for the Tasmanides of eastern Australia. *Australian Journal of Earth Sciences* **60**, 315-370.

Gradstein, F.M., Ogg, J.G., Schmitz, M. and Ogg, G. (2012). ‘The Geologic Time Scale 2012’. (Elsevier Science Ltd: Oxford).

Gulson, B.L. (1963). The geology of an area southeast of Jenolan Caves N.S W. B.App.Sc. Thesis, NSW Institute of Technology [now University of Technology], Sydney]. (unpublished).

Hallett, M.S.C. (1988). The Geology of Bulls Creek (North), Jenolan, N.S.W. B.Sc. (Hons.) Thesis, University of Sydney (unpublished).

Havard, L.W. (1933). The Romance of Jenolan Caves. *Journal of the Royal Australian Historical Society*. [Limited facsimile edition. Department of Leisure, Sport and Tourism, n.d.]

Herbert, C. (1980). 5. Southwestern Sydney Basin. In C. Herbert and R. Helby (eds) 'A Guide to the Sydney Basin'. *Geological Survey of New South Wales Bulletin* **26**. Department of Mineral Resources, New South Wales, 83 - 99.

House, M.J. (1988). The Geology of an Area centred on Bulls Creek, Northeast of Jenolan Caves, N.S.W. B.Sc. (Hons.) Thesis, University of Sydney (unpublished).

Howes, M.S. and Forster, I. (1997). Engineering Geology of Lyell Dam, Lithgow NSW. In 'Collected Case Studies in Engineering Geology, Hydrogeology and Environmental Geology. Third Series' (Ed. G. McNally) pp. 53-66. (Environmental, Engineering and Hydrology Specialist Group, Geological Society of Australia, Inc: Sydney).

Hunt, L., editor (1994). Jenolan Caves Reserve Future Development Study: Final Report for Jenolan Caves Reserve Trust. Colston, Budd, Hunt and Twiney Pty. Ltd, August 1994, 120 pp. (unpublished).

Johns, R.K. ed. (1976). 'History and Role of Government Geological Surveys in Australia'. 111 pp. (Government Printer of South Australia: Adelaide).

Joplin, G.A. (1931). Petrology of the Hartley District. i. The Plutonic and Associated Rocks. *Proceedings of the Linnean Society of New South Wales* **56**, 16-59.

Joplin, G.A. (1933). Petrology of the Hartley District. ii. The Metamorphosed Gabbros and Associated Hybrid and Contaminated Rocks. *Proceedings of the Linnean Society of New South Wales* **58**, 125-158.

Joplin, G.A. (1935). Petrology of the Hartley District. iii. The Contact Metamorphism of the Upper Devonian (Lambian) Series. *Proceedings of the Linnean Society of New South Wales* **60**, 16-50.

Joplin, G.A. (1944). Petrology of the Hartley District. v. Evidence of Hybridization in the Moyne Farm Intrusion. *Proceedings of the Linnean Society of New South Wales* **69**, 129-138.

Kelly, B.F. (1988). The hydrogeology of the Northern Limestone, Jenolan Caves and related land management issues. B.Sc. (Hons.) Thesis, University of NSW (unpublished).

Kelly, B.F. and Knight, M.J. (1993). Hydrogeology of McKeown's Valley, Jenolan Caves, New South Wales, Australia. In 'Collected Case Studies in Engineering, Hydrogeology & Environmental Geology, Second Series'. (Eds G. McNally, M. Knight and R. Smith) pp. 72-91. (Environmental, Engineering & Hydrogeology Specialist Group, Geological Society of Australia, Inc: Sydney).

Kiernan, K. (1988). The geomorphology of the Jenolan Caves area. *Helictite* **26(2)**, 6-21.

Link, A.G. and Druce, E.C. (1972). Ludlovian and Gedinnian conodont stratigraphy of the Yass Basin, New South Wales. *Bulletin of the Bureau of Mineral Resources, Geology & Geophysics* **134**, 1-136.

Lishmund, S.R., Dawood, A.D. and Langley, W.V. (1986). The Limestone Deposits of New South Wales. *Mineral Resources* **No. 25** (2nd edition). 373 pp. (Department of Mineral Resources: Sydney).

Macara, B. (1964). Petrology of the Budthingeroo Metadiabase, a mafic body in the area of Jenolan Caves. M.Sc. thesis, University of New South Wales, Sydney (unpublished).

McClean, S.M. (1983). Geology and cave formation, Jenolan Caves, N S.W. B.App.Sc. (geology) thesis, NSW Institute of Technology [now University of Technology], Sydney (unpublished).

Middleton, G.J. (1991). Oliver Trickett: Doyen of Australia's Cave Surveyors, 1847 – 1934. *Sydney Speleological Society Occasional Paper* No. **10** [published in association with Jenolan Caves Historical and Preservation Society], 156 pp.

Morrison, M. (1912). Notes on the geology of the country between Rydal and Jenolan Caves. *Annual Report, Department of Mines, New South Wales for 1911*, 189.

Osborne, R.A.L. (1984). Multiple karstification in the Lachlan Fold Belt in New South Wales: Reconnaissance evidence. *Journal and Proceedings of the Royal Society of New South Wales* **117**, 15-34.

Osborne, R.A.L. (1987). Multiple karstification: the geological history of karsts and caves in New South Wales, (including Case Study No. 3: Jenolan Caves). Ph.D. Thesis, University of Sydney (unpublished).

Osborne, R.A.L. (1991). Palaeokarst Deposits at Jenolan Caves, New South Wales. *Journal and Proceedings of the Royal Society of New South Wales* **123(3-4)**, 59-74.

Osborne, R.A.L. (1993). Geological Note: Cave formation by exhumation of Palaeozoic palaeokarst deposits at Jenolan Caves, New South Wales. *Australian Journal of Earth Sciences* **40**, 591-593**.**

Osborne, R.A.L. (1994). Caves, dolomite, pyrite, aragonite and gypsum: the karst legacy of the Sydney and Tasmania Basins. *Twenty-eighth Newcastle Symposium on Advances in the Study of the Sydney Basin*. University of Newcastle (NSW, Australia), Department of Geology Publication No. **606**, 322-344.

Osborne, R.A.L. (1995). Evidence for two phases of Late Palaeozoic karstification, cave development and sediment filling in south-eastern Australia. Cave and Karst Science 22(1), 39-44.

Osborne, R.A.L. (1999). Presidential Address for 1998-99. The Origin of Jenolan Caves: Elements of a New Synthesis and Framework Chronology. *Proceedings of the Linnean Society of New South Wales* **121**, 1-27.

Osborne, R.A.L. and Branagan, D.F. (1985). Permian palaeokarst at Billys Creek, New South Wales. *Journal and Proceedings of the Royal Society of New South Wales* **118**, 105-111.

Osborne, R.A.L. and Branagan, D.F. (1988). Karst Landscapes of New South Wales, Australia. *Earth Science Reviews* **25**, 467-80.

Osborne, R.A.L., Zwingmann, H., Pogson, R.E. and Colchester, D.M. (2006). Carboniferous clay deposits from Jenolan Caves, New South Wales: implications for timing of speleogenesis and regional geology. *Australian Journal of Earth Sciences* **53**, 377-405.

Packham, G.H. ed. (1969). The Geology of New South Wales. *Journal of the Geological Society of Australia* **16**, 1-654.

Pickett, J.W. (1969). Fossils from the Jenolan Caves Limestone. *Geological Survey of New South Wales Report* **GS1969/519**.

Pickett, J.W. (1970). Fossils from the Jenolan Caves area. *Geological Survey of New South Wales Report* **GS1970/117**.

Pickett, J.W. (1981). Conodonts and the age of the Jenolan Caves Limestone. *Geological Survey of New South Wales Report* **GS1981/305**.

Pickett, J.W. ed. (1982). The Silurian System in New South Wales. *Geological Survey of New South Wales Bulletin* **29**, 1-264.

Pickett, J.W. (2003). Corals and conodonts from the Molong Limestone (Late Silurian), New South Wales, Australia. [Abstract]. *Berichte des Institutes für Geologie und Paläontologie der Karl-Franzens-Universität Graz* **7**, 82.

Pogson, D.J. and Watkins, J.J. compilers (1998). *Bathurst 1:250 000 Geological Sheet SI/55-8: Explanatory Notes*. 430 pp. (Geological Survey of New South Wales: Sydney).

Pratt, R.T. (1965). Geology of the area between Jenolan Caves and Ginkin, N S.W. B.Sc. (Hons) thesis, University of New South Wales, Sydney (unpublished).

Scheibner, E. and Basden, H. ed. (1998). 'Geology of New South Wales – Synthesis. Volume 2 Geological Evolution. Geological Survey of New South Wales, Memoir Geology 13(2). (Department of Mineral Resources: Sydney).

Scott, K. and Pain, C.F. eds. (2008). 'Regolith Science'. (C.S.I.R.O. Publishing: Melbourne).

Shannon, C.H. (1976). Notes on Geology, Geomorphology & Hydrology. In B.R. Welch (ed.) *The Caves of Jenolan* **2**: The Northern Limestone. Sydney University Speleological Society, 5-9.

Shiels, O.J. (1959). Geology of the Tuglow River area. B.Sc (Hons) thesis, University of Sydney (unpublished).

Simpson, A.J. (1995). Silurian conodont biostratigraphy in Australia: a review and critique. *Courier Forschungsinstitut Senckenberg* **182**, 325-345.

Simpson, C. (1986). Volcanic-plutonic associations within the Bindook Volcanic Complex, Goodmans Ford – Bullio area, New South Wales. *Australian Journal of Earth Sciences* **33**, 475-489.

Simpson, C.J., Carr, P.F. and Jones, B.G. (1997). Evolution of the Early Devonian Bindook Volcanic Complex, Wollondilly Basin, Eastern Lachlan Fold Belt. *Australian Journal of Earth Sciences* **44**, 711-726.

Stanley, G.A.V. (1925). A preliminary account of the geology and petrology of the Jenolan Caves Reserve. B.Sc. (Hons) thesis, University of Sydney (unpublished).

Stewart, W. (1987). Geology of an area north of Jenolan Caves, N.S.W. B.Sc. (Hons) thesis, University of Sydney (unpublished).

Strusz, D.L. (2007). The Silurian timescale – an Australian perspective. *Memoirs of the Association of Australasian Palaeontologists* **34**, 157-171.

Strusz, D.L. and Munson, T.J. (1997). Coral assemblages in the Silurian of eastern Australia: a rugosan perspective. *Boletín de la Real Sociedad Española de Historia Natural, Sección Geológica* **92(1-4)**, 311-323.

Süssmilch, C.A. (1911). A Geologist's Notes on a Trip to the Jenolan Caves. *Technical Gazette of New South Wales* **1**, 37-42.

Süssmilch, C.A. (1913). 'Introduction to the geology of New South Wales.' (Angus and Robertson: Sydney).

Süssmilch, C.A. (1923). 'Geological notes on the trip to the Jenolan Caves. Guide-Book to the Excursion to Blue Mountains, Jenolan Caves, and Lithgow'. (Pan Pacific Congress: Sydney).

Süssmilch, C.A. and Stone, W.G. (1915). Geology of the Jenolan Caves District. *Journal and Proceedings of the Royal Society of New South Wales* **49**, 332-384.

Talent, J.A., Berry, W.B.N. and Boucot, A.J. (1975). Correlation of the Silurian rocks of Australia, New Zealand and New Guinea. *Geological Society of America Special Paper* **150**, 1-108.

Talent, J.A., Mawson, R. and Simpson, A. (2003). Silurian of Australia and New Guinea: Biostratigraphic correlations and palaeogeography. In E. Landing and M.E. Johnson, eds, Silurian Lands and Seas. *New York State Museum Bulletin* **493**, 181-219.

Taylor, T.G. (1958). 'Sydneyside Scenery'. (Angus & Robertson: Sydney), 241 pp.

Thomas, O.D. and Pogson, D.J. (compilers) (2012). Goulburn 1:250,000 Geological Sheet SI/55-12, 2nd edition, Explanatory Notes. Geological Survey of New South Wales, Maitland.

Trickett, O. (1925). The Jenolan Caves (map). Jenolan Caves Reserve Trust.

Twidale, C.R. and Campbell, E.M. (1993). 'Australian Landforms: Structure, Process and Time'. (Gleneagles Publishing: Adelaide).

Tye, S.C., Fielding, C.R. and Jones, B.G. (1996). Stratigraphy and sedimentology of the Permian Talaterang and Shoalhaven Groups in the southernmost Sydney Basin, New South Wales. *Australian Journal of Earth Sciences* **43**, 57-69.

Vallance, T.G. (1969). Plutonic and Metamorphic Rocks. In G.H. Packham (ed.), Southern and Central Highlands Fold Belt. *Journal of the Geological Society of Australia* **16(1)** 180-200.

Veevers, J.J. (2000). Time Scale. In J.J. Veevers (ed.), 'Billion-year Earth History of Australia and Neighbours in Gondwanaland', pp 3-5. (GEMOC Press: Sydney).

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

Welch, B.R. ed. (1976). 'The Caves of Jenolan 2: The Northern Limestone'. (Sydney University Speleological Society: Sydney).

Wilkinson, C.S. (1884). 'The Railway Guide of New South Wales' (Second Edition), pp 144-148. (New South Wales Government Printer: Sydney).

Young, L. (1884). Description of the Jenolan Caves. In Wilkinson, C.S. 'The Railway Guide of New South Wales' (Second Edition). (New South Wales Government Printer: Sydney).

Young, R.W. (1983). The tempo of Geomorphological change: Evidence from Southeastern Australia. *Journal of Geology* **91**, 221-230.

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

Helene A. Martin

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

Martin, H.A. (2014). A review of the Cenozoic palynostratigraphy of the River Valleys in Central and Western New South Wales. *Proceedings of the Linnean Society of New South Wales* **136**, 131-155.

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

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

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

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

Manuscript received 23 October 2013, accepted for publication 19 February 2014.

KEYWORDS: climatic change, environmental history, eustasy, Neogene, palynostratigraphy, river valleys, tectonics, western slopes of NSW.

INTRODUCTION

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

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

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

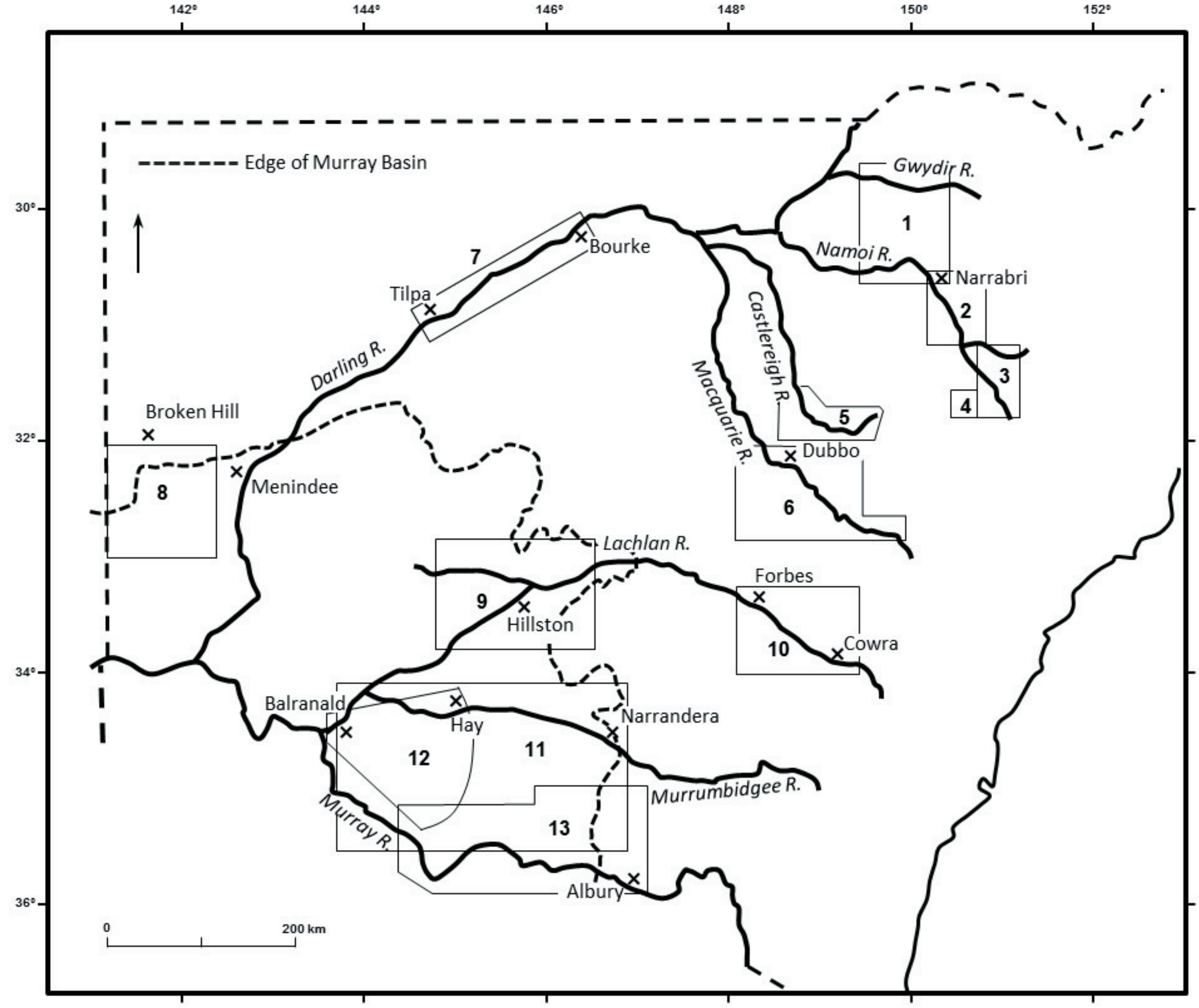


Figure 1. The stratigraphic palynology of the sediments has been studied in the areas as follows: 1. Namoi and Gwydir River Valleys (Martin, 1980). 2. Namoi River Valley, Baan Baa to Boggabri (Martin, 1994). 3. Mooki River Valley, (Martin, 1979). 4. Spring Ridge District (1981a). 5. Castlereagh River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

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

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

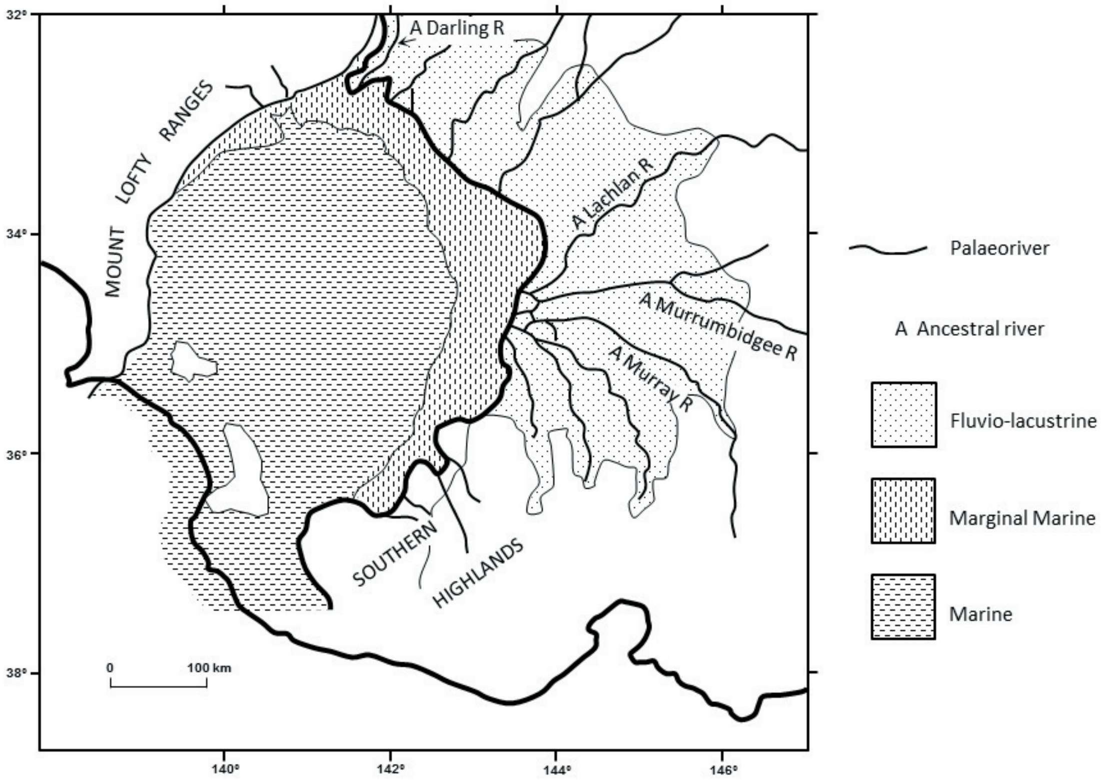


Figure 2. Early to mid Miocene paleogeography showing the marine incursion at its maximum extent in the mid Miocene and the ancestral rivers from the Western Slopes flowing into the Murray Basin. After Stephenson and Brown (1989).

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

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

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

METHODS

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

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

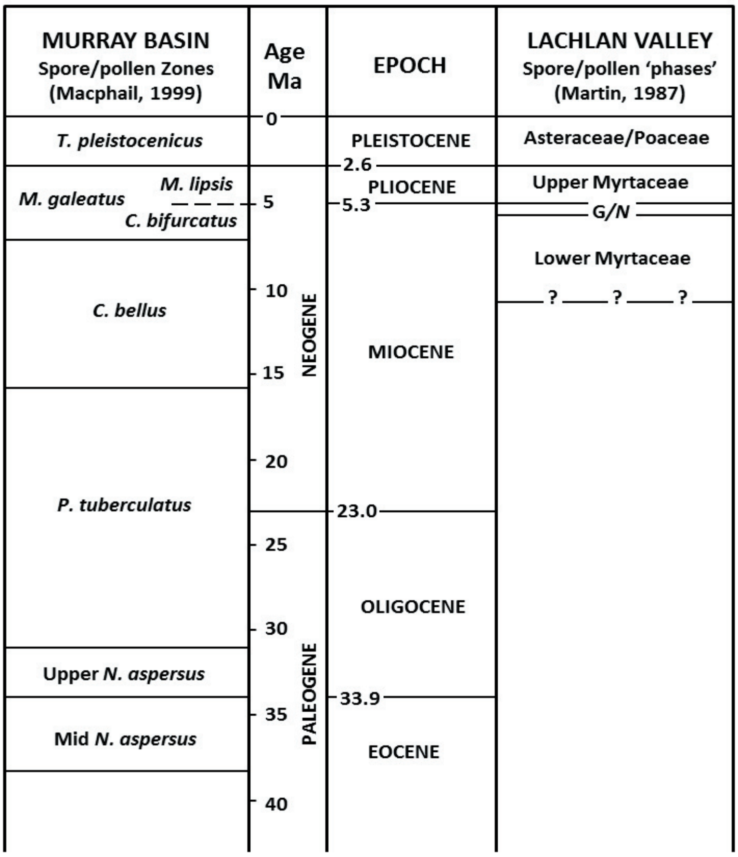


Figure 3. Summary of the palynological zones and the ages they indicate. G/N, Gymnosperm and/or Nothofagus phase. The time scale follows Ogg (2004) with the exception of the late Pliocene Pleistocene boundary that follows Ogg and Pillans (2008). Nomenclature follows Macphail (1999). See text.

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

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

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

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

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

1. The lower Myrtaceae phase of upper Miocene

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

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

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

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

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

The sequence of lower Mytaceae, *Nothofagus*,

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

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

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

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

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

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

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

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

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

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

THE PALYNOSTRATIGRAPHY OF THE RIVER VALLEYS

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

Lachlan River Valley

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

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

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

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

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

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

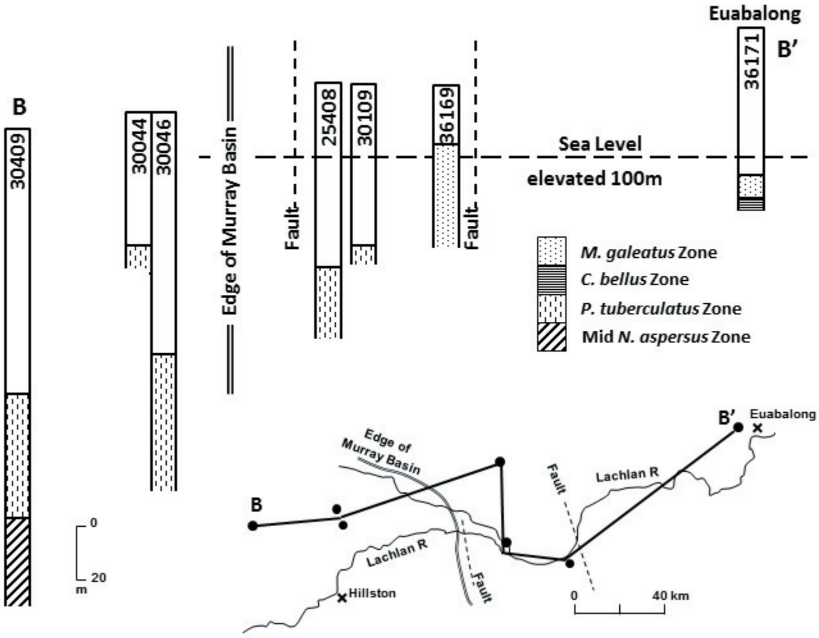


Figure 4. Palynology of the Lachlan River, the alluvial plain section (from Martin, 1987). For the ages the zones indicate, see Fig. 3.

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

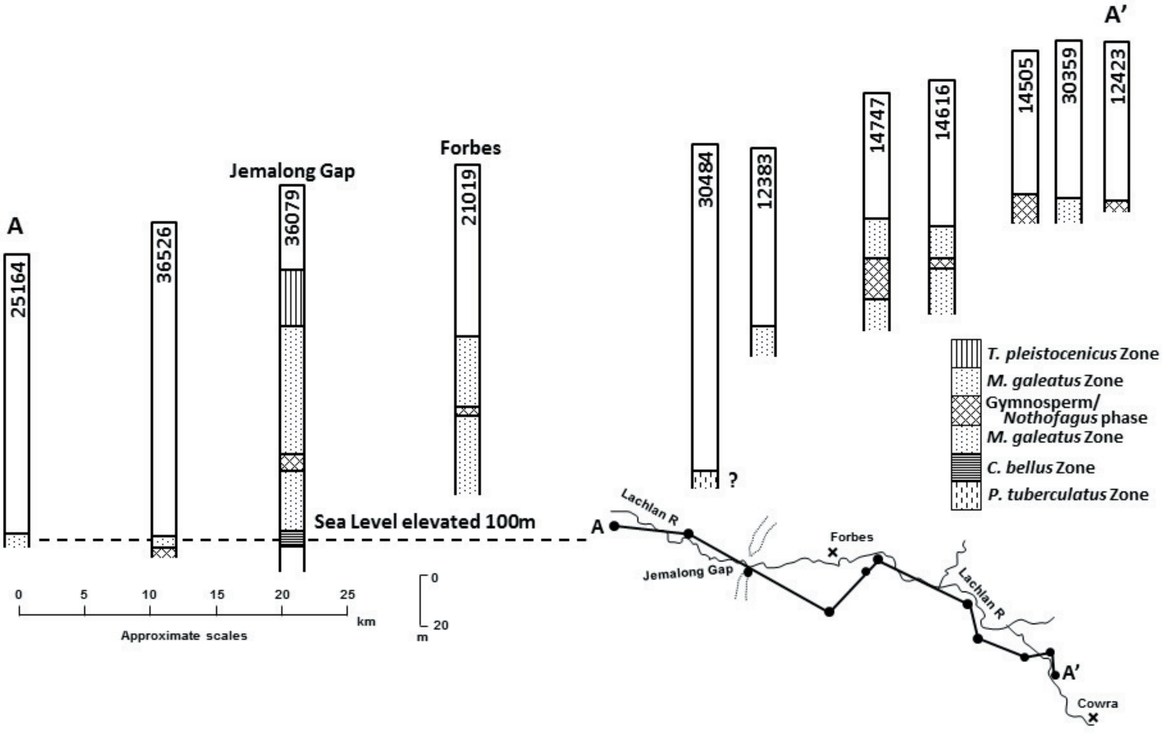


Figure 5. Palynology of the Lachlan River Valley, the upstream section (from Martin, 1987). For the ages the zones indicate, see Fig. 3.

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

The Pleistocene *T. pleistocenicus* Zone is not found in the valley, except for the Jemalong Gap bore where the uppermost polleniferous unit appears to be intermediate between the *M. galeatus* Zone and the *T. pleistocenicus* Zone. It occurs, however, in the tributaries of the Lachlan River (Martin, 1987).

The *T. bellus* and *M. galeatus* Zones are found further downstream of Jemalong Gap (Fig. 5). The sediments of the Murray Basin are much deeper and the Middle *N. asperus* Zone (upper Eocene) and *P. tuberculatus* Zone (lower Oligocene to lower Miocene) are found here.

Macquarie River

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

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

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

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

Namoi River Valley

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

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

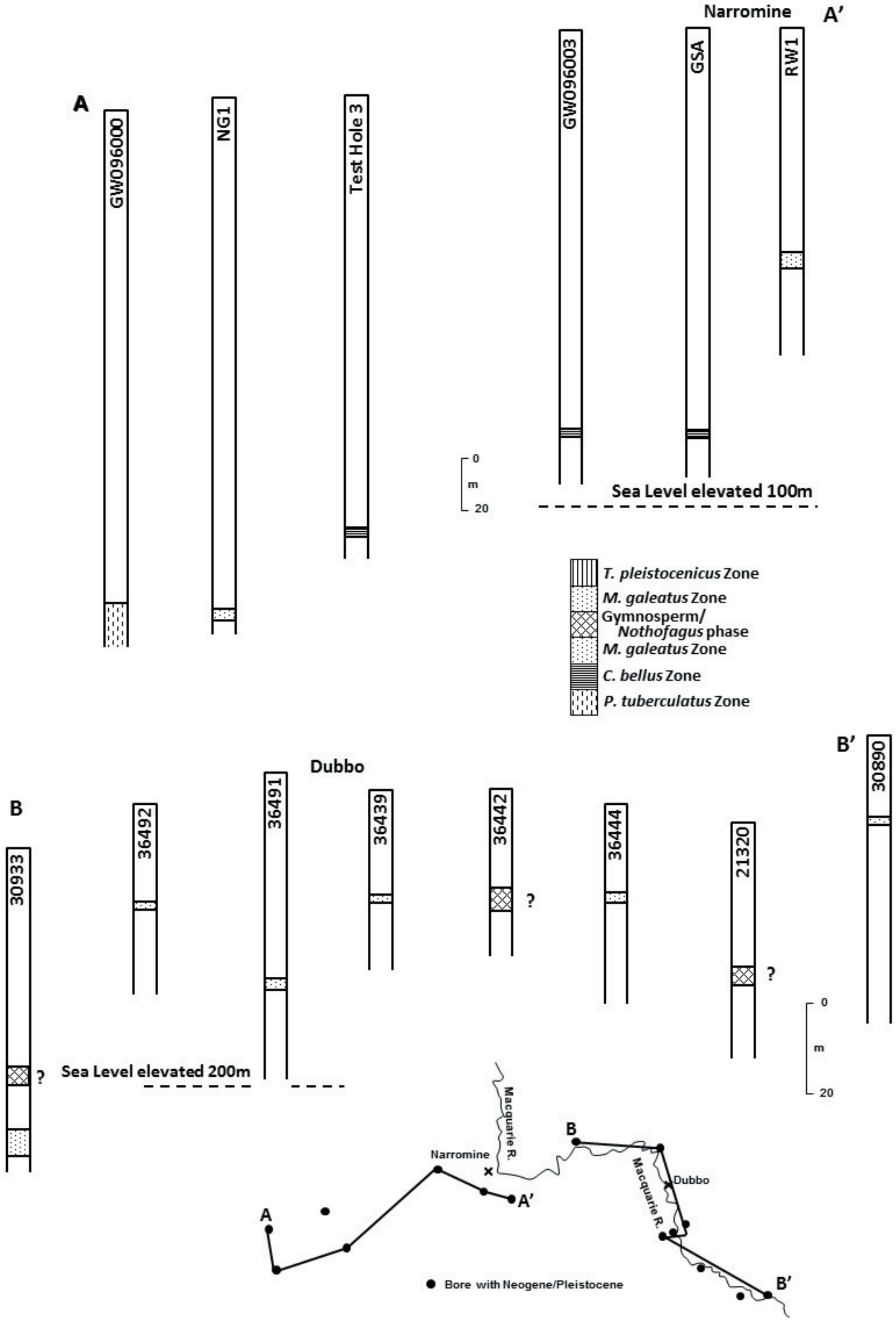


Figure 6. Palynology of the Macquarie River Valley (from Martin, 1999). Section A-A', the alluvial plain. Section, B-B', the river valley. For the ages the zones indicate, see Fig. 3.

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

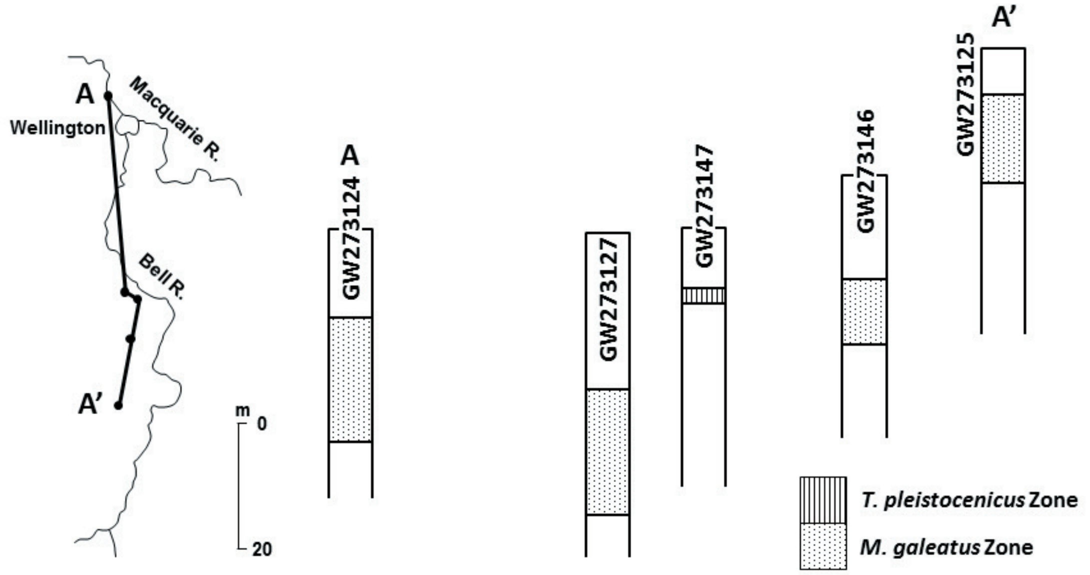


Figure 7. Palynology of the Bell River, a tributary of the Macquarie River (Martin, unpubl.).

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

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

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

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

Murray River Valley

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

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

The oldest sediments in the valley where the pre-

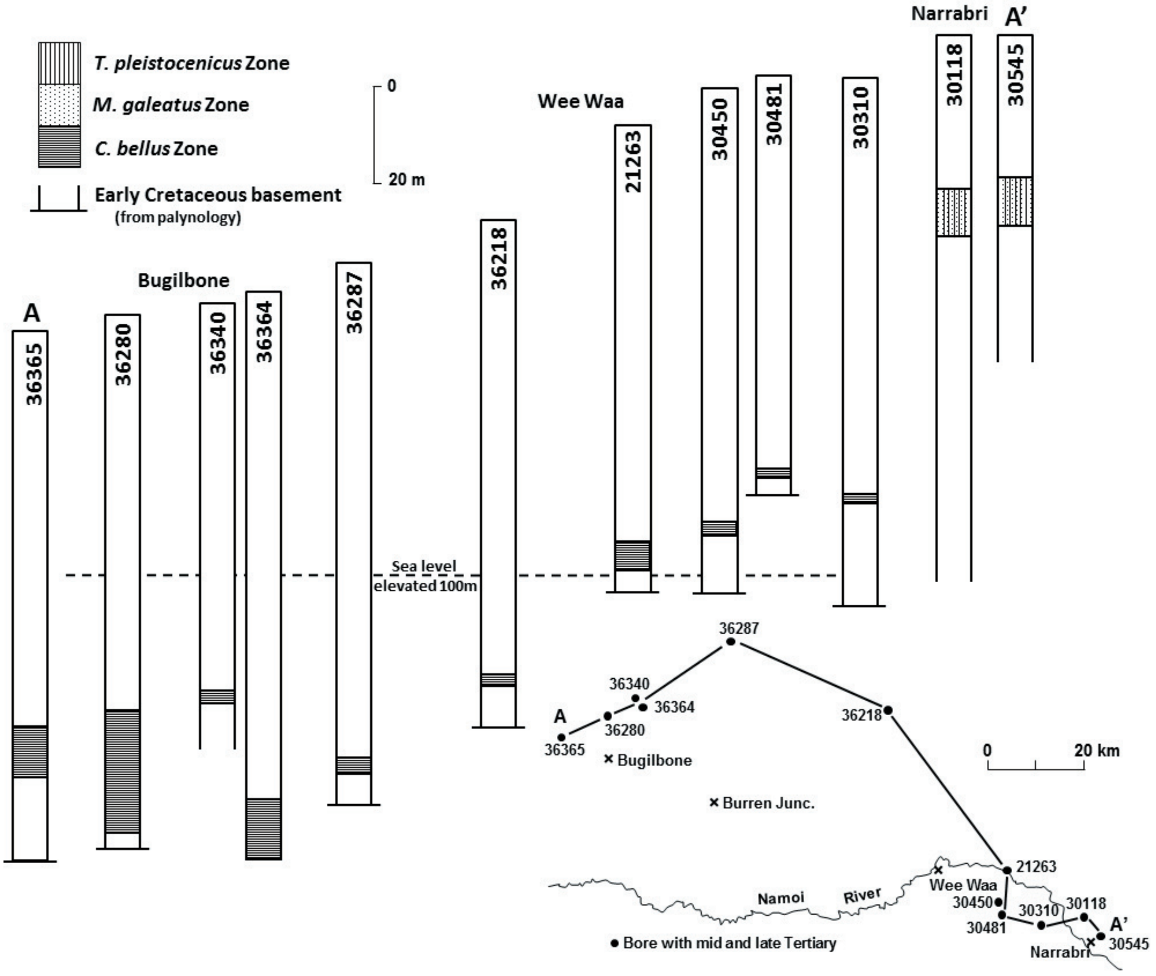


Figure 8. Palynology of the Namoi alluvial plain (from Martin, 1980). For the ages the zones indicate, see Fig. 3.

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

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

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

Murrumbidgee River Valley.

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

In a small section across the valley at Narrandera,

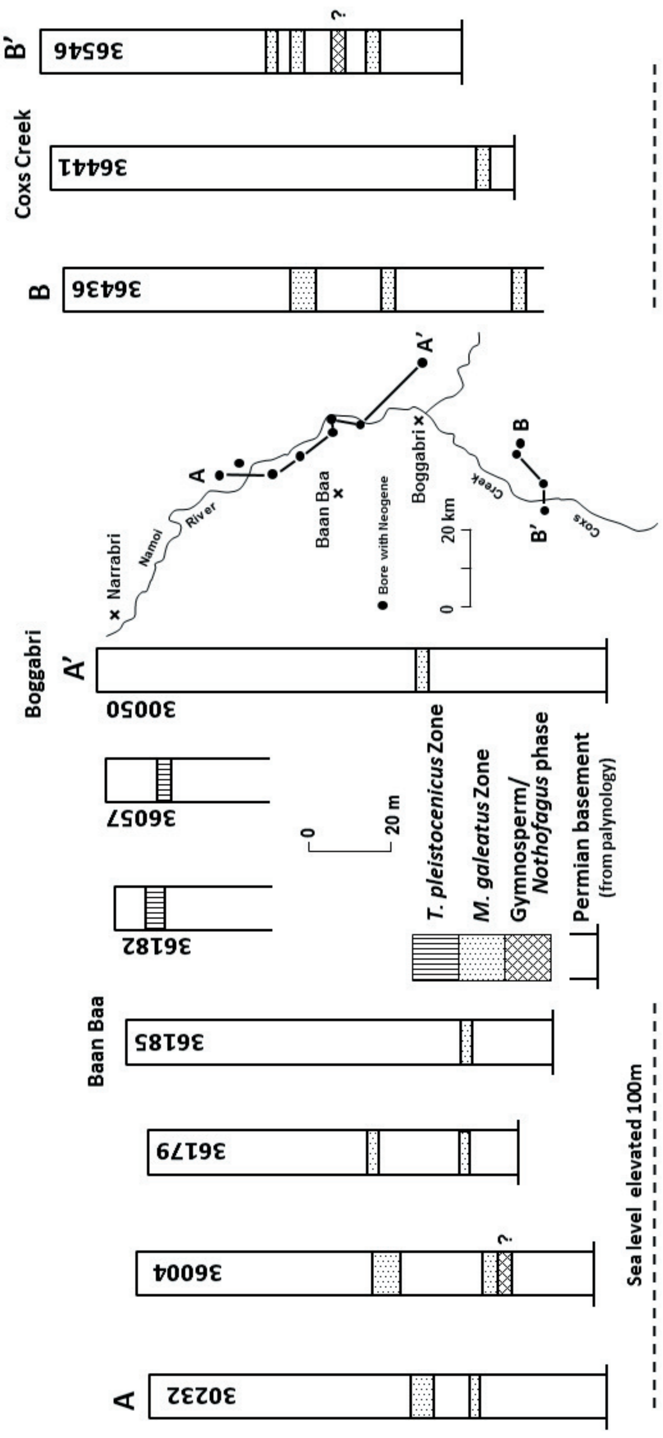


Figure 9. Palynology of the Namoi River Valley, Baan Baa to Boggabri and Coxs Creek (from Martin, 1994). For the ages the zones indicate, see Fig. 3.

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

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

Castlereagh River Valley

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

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

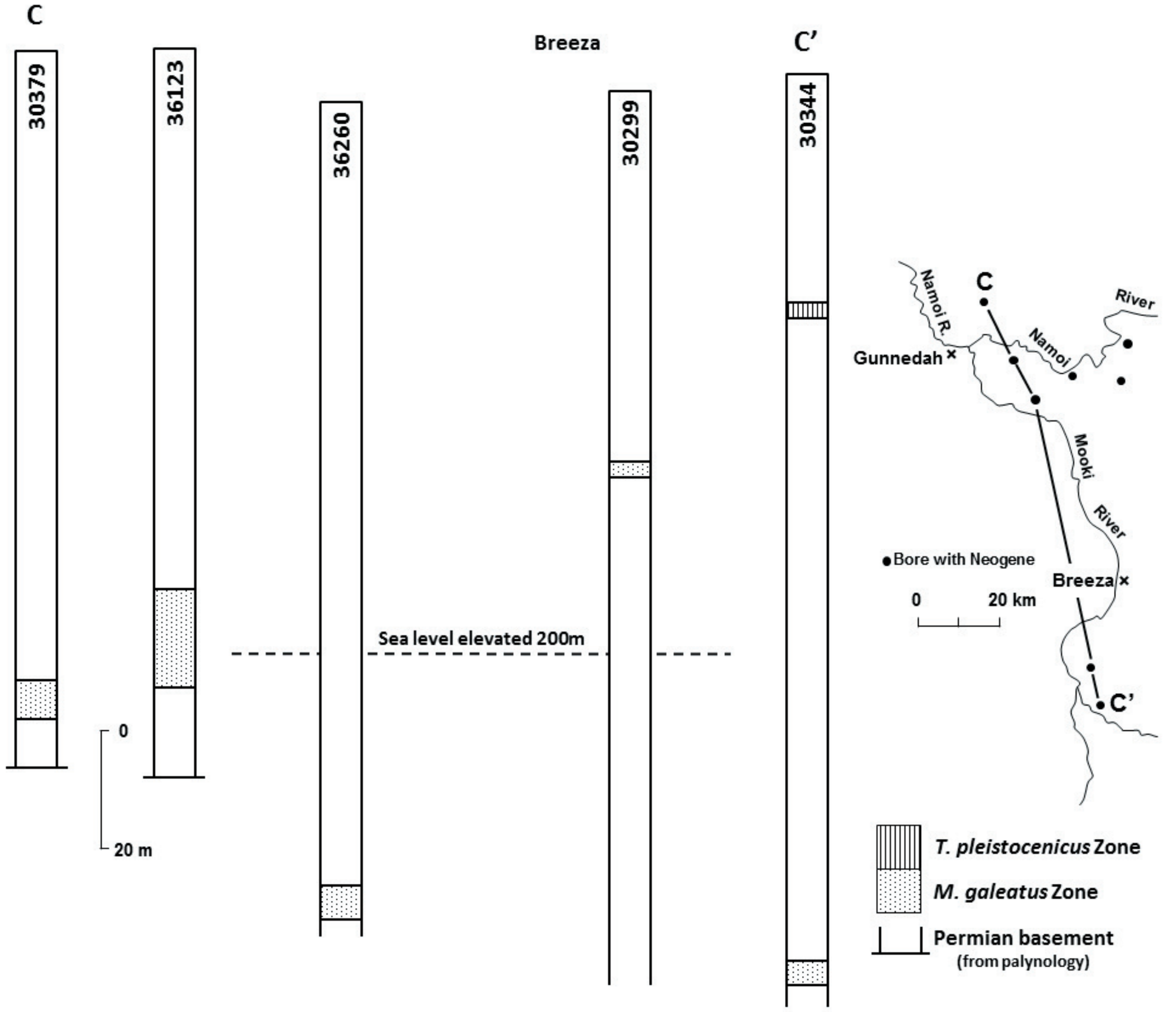


Figure 10. Palynology of the Mooki River Valley, tributary of the Namoi River (from Martin, 1979). For the ages the zones indicate, see Fig. 3.

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

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

Darling River

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

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

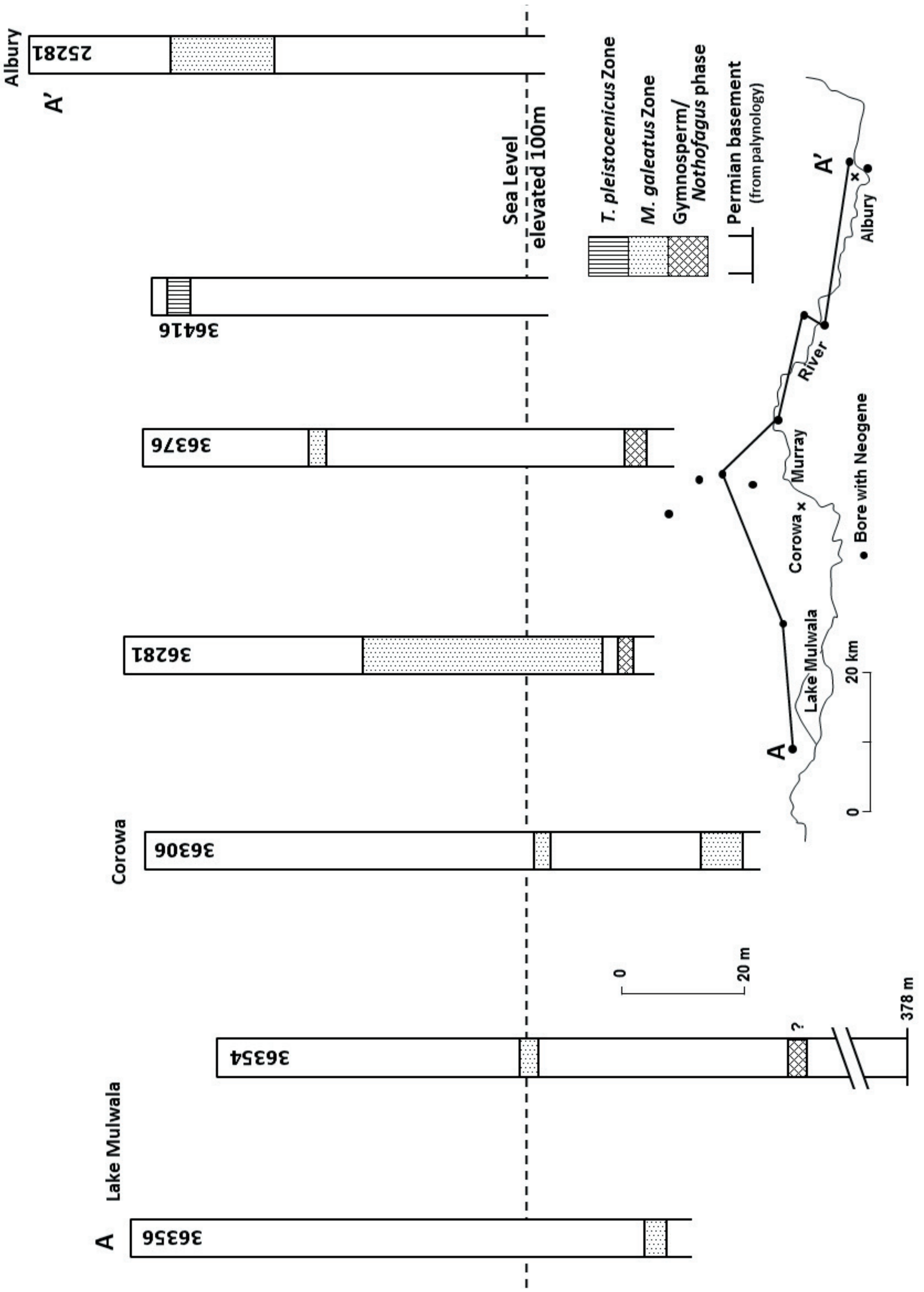


Figure 11. Palynology of the Murray River Valley (from Martin, 1995). For the ages the zones indicate, see Fig. 3

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

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

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

DISCUSSION

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

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

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

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

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

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

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

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

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

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

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

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

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

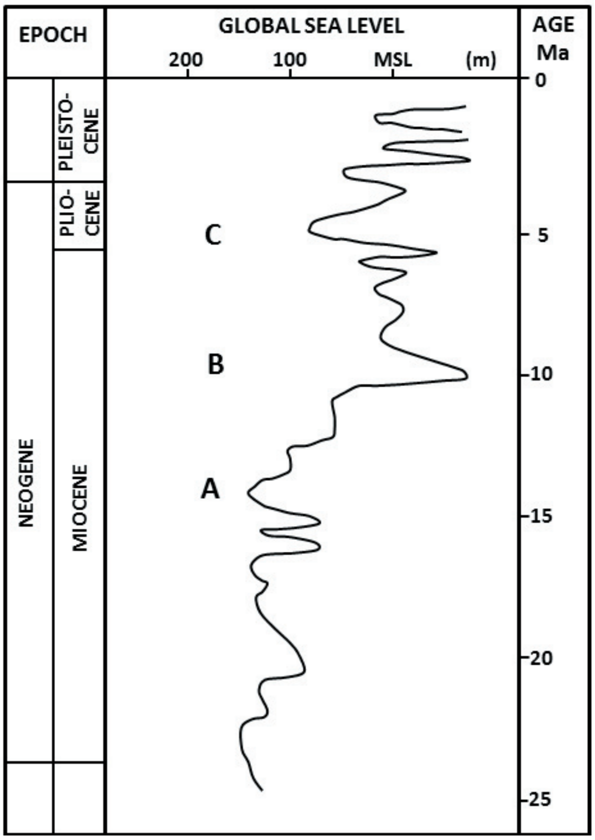


Figure 12. Global sea levels through the Neogene, from Haq et al. (1987). A, the first major drop in sea level ~14.7-13.9 Ma. B, the second major drop in sea level ~ 10.5 Ma (the time of the Mologa erosion/ non-deposition surface in the Murray Basin). C, the short-lived marine transgression/ regression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

(McLaren et al, 2011).

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

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

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

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

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

CONCLUSIONS

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

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

Tectonics in the Highlands and Western Slopes had a relatively minor and localised impact, probably only maintaining the elevation of the Highlands.
The palynofloras indicate an increasingly drier climate through the Neogene and into the Pleistocene, and change from a high-energy to a low energy erosion/deposition environment that would have influenced the nature of the sediments being deposited.

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

ACKNOWLEGEMENTS

I am indebted to the New South Wales Office of Water and its predecessors that have provided samples from bores and financial support. Hydrogeologists in the Office of Water have assisted with invaluable information and support, particularly Ms Ann Smithson of the Dubbo Office of Water. Dr Mike Macphail gave invaluable advice about palynostratigraphy. A/Prof Bryce Kelly critically commented on the manuscript. Mr Matthew Hunt prepared the diagrams.

REFERENCES

Barrett, C. (2012). Upper Namoi Groundwater Source – Status Report 2011. (NSW Department of Primary Industries Office of Water, Sydney).

Bishop, P. and Brown, R. (1992). Denudational isostatic rebound of intraplate highlands: the Lachlan River Valley, Australia. *Earth Surface Processes and Landforms* 17, 345-360.

Brown, C.M. (1989). Structural and stratigraphic framework of groundwater occurrence and surface discharge in the Murray Basin, southeastern Australia. *BMR Journal of Geology and Geophysics* 11, 127-146.

Brown, C.M. and Stephenson, A.E. (1991). Geology of the Murray Basin, Southeastern Australia. *Bureau of Mineral Resources, Geology and Geophysics Bulletin* 235. 1-430

Green, D., Petrovic, J., Moss, P., Burrell, M. (2011a). Water Resources and management overview: Lachlan catchment pp 1-28. (NSW Office of Water, Sydney).

Green, D., Petrovic, J., Moss, P., Burrell, M. (2011b). Water Resources and management overview: Macquarie-Bogan Catchment pp 1-29. (NSW Office of Water, Sydney).

Green, D., Petrovic, J., Moss, P., Burrell, M. (2011c). Water Resources and management overview: Namoi catchment pp 1-31. (NSW Office of Water, Sydney).

Green, D., Petrovic, J., Moss, P., Burrell, M. (2011d). Water Resources and management overview: Murrumbidgee catchment pp 1-29. (NSW Office of Water, Sydney).

Haq, B.U., Hardenbold, J. and Vail, P.R. (1987). Chronology of fluctuating sea levels since the Triassic. *Science* 235, 1156-1167.

Holdgate, G.M., Wallace, M.W., Gallagher, S.J., Wagstaff, B.E. and Moore, D. (2008). No mountains to snow on: major post-Eocene uplift of the East Victorian Highlands; evidence from Cenozoic deposits. *Australian Journal of Earth Sciences* 55, 211-234.

John, C.M., Karner, G.D., Browning, E., Leckie, M.R. Mateo, Z. et al. (2011). Timing and magnitude of Miocene eustasy derived from the mixed siliclastic-carbonate stratigraphic record of the northeastern Australian margin. *Earth and Planetary Science Letters* 304, 455-487.

Macphail, M.K. (1997). Late Neogene climates in Australia: fossil pollen and spore- based estimates in retrospect and prospect. *Australian Journal of Botany* 45, 425-464.

Macphail, M.K. (1999). Palynostratigraphy of the Murray Basin, inland southeastern Australia. *Palynology* 23, 197-240.

Macphail, M.K. (2004). Palynostratigraphic analysis of core and cutting samples from the Lower Balonne area, southern Queensland, Australia. *CRC LEME Open File Report* 167, 1-40.

Macphail, M.K. and Truswell, E.M. (1989). Palynostratigraphy of the central west Murray Basin. *BMR Journal of Australian Geology and Geophysics* 11, 301-331.

Macphail, M.K. and Truswell, E.M. (1993). Palynostratigraphy of the Bookpurnong Beds and related late Miocene-early Pliocene facies in the central west Murray Basin, part 2: spores and pollen. *AGSO Journal of Australian Geology and Geophysics* 14, 383-409.

Macphail, M.K., Kellett, J.R., Rexilius, J.P. and O'Rorke, M.E. (1993). The "Geera Clay equivalent": a regressive marine unit in the Renmark Group that sheds new light on the age of the Mologa weathering surface in the Murray Basin. *AGSO Journal of Geology and Geophysics* 14, 47-63.

Macumber, P.G. (1978). Evolution of the Murray River during the Tertiary period. Evidence from northern Victoria. *Proceedings of the Royal Society of Victoria* 90, 43-52.

Martin, H.A. (1969). The palynology of some Tertiary and later deposits in New South Wales. PhD thesis, University of New South Wales (unpubl.).

Martin, H.A. (1973a). The palynology of some Tertiary Pleistocene deposits, Lachlan River Valley, New South Wales. *Australian Journal of Botany Supplement* 6, 1-57.

Martin, H.A. (1973b). Upper Tertiary palynology in southern New South Wales. *Special Publications of the Geological Society of Australia* 4, 35-54.

Martin, H.A. (1977). The Tertiary stratigraphic palynology of the Murray Basin in New South Wales. I. The Hay-Balranald-Wakool Districts. *Journal and Proceedings of the Royal Society of New South Wales* 110, 41-47.

Martin, H.A. (1979). Stratigraphic palynology of the Mooki Valley, New South Wales. *Journal and Proceedings of the Royal Society of New South Wales* 112, 71-78.

Martin, H.A. (1980). Stratigraphic palynology from shallow bores in the Namoi River and Gwydir River Valleys, North-Central New South Wales. *Journal and Proceedings of the Royal Society of New South Wales* 113, 81-87.

Martin, H.A. (1981a). An Early Cretaceous age for subsurface Pillaga Sandstone in the Spring Ridge District, Mooki Valley. *Journal and Proceedings of the Royal Society of New South Wales* 114, 29-31.

Martin, H.A. (1981b). Stratigraphic palynology of the Castlereagh River Valley, New South Wales. *Journal and Proceedings of the Royal Society of New South Wales* 114, 77-84.

Martin, H.A. (1984a). The stratigraphic palynology of the Murray Basin in New South Wales. II. The Murrumbidgee area. *Journal and Proceedings of the Royal Society of New South Wales* 117, 35-44.

Martin, H.A. (1984b). The stratigraphic palynology on the Murray Basin in New South Wales. III. The Lachlan area. *Journal and Proceedings of the Royal Society of New South Wales* 117, 45-51.

Martin, H.A. (1987). Cainozoic history of the vegetation and climate of the Lachlan River region, New South Wales. *Proceedings of the Linnean Society of New South Wales* 109, 213-257.

Martin, H.A. (1988). Stratigraphic palynology of the Lake Menindee region, northwest Murray Basin, New South Wales. *Journal and Proceedings of the Royal Society of New South Wales* 121, 1- 9.

Martin, H.A. (1991). Tertiary stratigraphic palynology and palaeoclimate of the inland river systems in New South Wales. In *The Cainozoic in Australia: a re-appraisal of the evidence* (Eds M.A.J. Williams, P. De Deckker and A.P. Kershaw). *Special Publication of the Geological Society of Australia* 18, 181-194.

Martin, H.A. (1993). Middle Tertiary dinoflagellate and spore/pollen biostratigraphy and palaeoecology of the Mallee Cliffs bore, central Murray Basin. *Alcheringa* 17, 91-124.

Martin, H.A. (1994). The stratigraphic palynology of the Namoi River Valley, Baan Baa to Boggabri, northern New South Wales. *Proceedings of the Linnean Society of New South Wales* 114, 45-58.

Martin, H.A. (1995). The stratigraphic palynology of the Murray River Valley in New South Wales. *Proceedings of the Linnean Society of New South Wales* 115, 193-212.

Martin, H.A. (1997). The stratigraphic palynology of bores along the Darling River, downstream from Bourke, New South Wales. *Proceedings of the Linnean Society of New South Wales* 118, 51-67.

Martin, H.A. (1999). The stratigraphic palynology of the Macquarie River Valley, Central Western New South Wales. *Proceedings of the Linnean Society of New South Wales* 121, 113-127.

Martin, H.A. (2006). Cenozoic climatic change and the development of the arid vegetation in Australia. *Journal of Arid Environments* 66, 533-563.

Martin, H.A., Worral, L. and Chalson, J. (1987). The first occurrence of the Paleocene *Lygistepollenites balmei* Zone in the Eastern Highlands Region, New South Wales. *Australian Journal of Earth Sciences* 34, 357-365.

McLaren, S., Wallace, M.D., Gallagher, S.J., Miranda, J.A., Holdgate, G.R., et al. (2011). Palaeogeographic, climatic and tectonic change in southeastern Australia: late Neogene evolution of the Murray Basin. *Quaternary Science Reviews* 30, 1086-1111.

McMinn, A. (1981). A Miocene microflora from the Home Rule kaolin deposit. *Quarterly notes of the Geological Survey, New South Wales* 43, 1-4.

McMinn, A. (1989/a). Tertiary palynology of Glen innes DDH 107. *Geological Survey of New South Wales Department of Mineral Resources Unpublished Palynological Report* 1989/1,

McMinn, A. (1989/b). Tertiary palynology of a sample from Glen Innes DDH110. *Geological Survey of New South Wales Department of Mineral Resources Unpublished Palynological Report* 1989/5.

McMinn, A. (1989/c). Eocene palynology of Glen Innes DDH105. *Geological Survey of New South Wales Department of Mineral Resources Unpublished Palynological Report* 1989/11.

McMinn, A. (1989/d). Early Tertiary palynology of sediment from Rileys Sugarloaf, near Bowral. *Geological Survey of New South Wales Department of Mineral Resources Unpublished Palynological Report* 1989/12.

McMinn, A. (1989e). Tertiary palynology in the Inverell area. *Quarterly Notes of the Geological Survey, New South Wales* 76, 2-10.

Middlemis, H., Lawson, S., Ross, J., Merrick, N. (1987). Hydrology of the Lower Macquarie area, with emphasis on the shallow alluvial groundwater system, recent drilling and simple modelling results. *Department of Water Resources Technical Services Report* No.1, October 1987.

Nott, J.F. and Owen, J.A. (1992). An Oligocene palynoflora from the middle Shoalhaven catchment in the southeast Australian highlands. *Palaeogeography, Palaeoclimatology, Palaeoecology* 95, 135-151.

NSW Department of Primary Industries Office of Water (2013a). Upper Murray catchment. http://www.water.nsw.gov.au/ (Accessed June 2013).

NSW Department of Primary Industries Office of Water (2013b). Murray Riverina catchment. http://www.water.nsw.gov.au/ (Accessed June 2013).

NSW Department of Primary Industries Office of Water (2013c). Castlereagh catchment. http://www.water.nsw.gov.au/ (Accessed June 2013).

Ogg, J.G. (2004). Status and divisions of the International Geologic Time Scale. *Lethaia* 37, 183-199.

Ogg, J.G. and Pillans, B. (2008). Establishing Quaternary as a formal international Period/System. *Episodes* 31, 230-233.

Owen, J.A. (1975). Palynology of some Tertiary deposits in New South Wales. Ph.D thesis, Australian National University (unpubl.)

Partridge, A.D. (2006). Late Cretaceous-Cenozoic palynology zonations Gippsland Basin. *In*: Monteil, E. (coord.). Australian Mesozoic and Cenozoic Palynology Zonation - updated to the 2004 Geologic Time Scale. *Geoscience Australia* Record 2006/2.

Smithson, A. (2010). Upper Macquarie Alluvium – Groundwater Management Area 009, Groundwater Status Report 2010. (NSW Office of Water, Sydney).

Stephenson, A.E. (1986). Lake Bungunnia – a Plio-Pleistocene megalake in Southern Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 57, 137-156.

Stephenson, A.E. and Brown, C.M. (1989). The ancient Murray River System. *BMR Journal of Geology and Geophysics* 11, 387-395.

Stover, L.E. and Partridge, A.D. (1973). Tertiary and Late Cretaceous spores and pollen from the Gippsland Basin, Southeastern Australia. *Royal Society of Victoria Proceedings* 85, 237-286.

Taylor, G., Taylor, G.R., Bink, M., Foudoulis. C . et al. (1985). Pre-basaltic topography of the northern Monaro and its implications. *Australian Journal of Earth Sciences* 32, 65-71.

Taylor, G., Truswell, E.M., McQueen, K.G. and Brown, M.C. (1990). Early Tertiary palaeogeography, landform evolution and palaeoclimates of the Southern Monaro, N.S.W. Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 78, 109-134.

Tomkins, K.M. and Hesse, P.P. (2004). Evidence of Cenozoic uplift and climate change in the stratigraphy of the Macquarie River Valley, New South Wales. *Australian Journal of Earth Sciences* 51, 273-290.

Truswell, E.M. and Owen, J.A. (1988). Eocene pollen from Bungonia, New South Wales. In *Palynological and Palaeobotanical studies in honour of Basil E. Balme* (Eds P.A. Jell and G. Playford). *Association of Australasian Palaeontologists, Sydney Memoir* 5, 259-284.

Tulip, J.R., Taylor, G. and Truswell, E.M. (1982). Palynology of Tertiary Lake Bunyan, Cooma, New South Wales. *BMR Journal of Australian Geology and Geophysics* 7, 255-268.

Vandenberg, A.H.M. (2010). Paleogene basalts prove early uplift of Victoria's Uplands. *Australian Journal of Earth Sciences* 57, 291-315.

Van der Beek, P.A., Braun, J. and Lambeck, K. (1999). Post–Palaeozoic uplift history of southeastern Australia revisited: results from a process-based model of landscape evolution. *Australian Journal of Earth Sciences* 46, 157-172.

Veevers, J.J. (1991). Mid Cretaceous tectonic climax, Late Cretaceous recovery and Cainozoic relaxation in the Australian Region. In *The Cainozoic in Australia: a re-appraisal of the evidence* (Eds M.A.J. Williams, P. De Deckker and A.P. Kershaw). *Special Publication of the Geological Society of Australia* 18, 1-14.

Wallace, M.W., Dickson, J.A., Moore, D.H. and Sandiford, M. (2005). Late Neogene strandlines of southern Victoria: a unique record of eustasy and tectonics in southeastern Australia. *Australian Journal of Earth Sciences* 52, 279-297.

Webb, J.A., Finlayson, B.L., Fabel, D. and Ellaway. M. (1991). The geology of the Buchan Karst – implications for the landscape history of the Southeastern Highlands of Australia. In *The Cainozoic in Australia: a re-appraisal of the evidence* (Eds M.A.J. Williams, P. De Deckker and A.P. Kershaw) *Special Publication of the Geological Society of Australia* 18, 210-234.

Wellman, P. and McDougall, I. (1974). Potassium-argon ages in the Cainozoic rocks of New South Wales. *Journal of the Geological Society of Australia* 21, 247-274.

Williams, R.M., Merrick, N.P. and Ross, J. B. (1989). Natural and induced recharge in the lower Namoi Valley, New South Wales. In M. L. Sharma (Ed.) *Groundwater Recharge* pp 238-253 (A.A. Balkema, Rotterdam).

Williamson, W.H. (1986). Investigations of groundwater resources of the Lachlan Valley alluvium. Part 1.Cowra to Jemalong Weir. Water Resource Commission of NSW Hydrological Report 1986/12.

Wooley, D.R. (1978). Cainozoic sedimentation in the Murray Drainage Basin, New South Wales. *Proceedings of the Royal Society of Victoria*, 90, 61-65.

Young, R.W. and McDougall, I. (1985). The age, extent and geomorphological significance of the Sassafrass basalt, southeastern New South Wales. *Australian Journal of Earth Sciences* 32, 323-331.

Young, R.W., Young, A.R.M., Price, D.M. and Wray, R.A.L. (2002). Geomorphology of the Namoi alluvial plain, northwestern New South Wales. *Australian Journal of Earth Sciences* 49, 509-523.

Integrating History and Ecological Thinking: Royal National Park in Historical Perspective

DANIEL LUNNEY

Office of Environment and Heritage NSW, PO Box 1967, Hurstville NSW 2220, and School of Biological Sciences, University of Sydney, NSW 2006. Email address: dan.lunney@environment.nsw.gov.au.

Lunney, D. (2014). Integrating history and ecological thinking: Royal National Park in historical perspective. *Proceedings of the Linnean Society of New South Wales* **136**, 157-199.

This paper aims to develop an ecological history of Royal National Park. The socio-cultural context for the push to reserve such a large tract of land in perpetuity in 1879 includes the Park's early links to the Royal Zoological Society of NSW (formerly the Acclimatisation Society of NSW), in addition to a strong political movement advocating the reservation of open space in urban areas. A selection of maps of the Park situates it in a broader context. Previously unpublished data from 1879 to the present is evidence of increasing formal support for nature conservation and protected areas. Tim Flannery's contentious essay 'Beautiful Lies' (2003) is challenged on the issue of long-term fauna conservation in Australia's national parks. The paper concludes that using an ecological approach to interpreting historical data enables us to gain a clearer grasp of the reasons behind the changes to the Park's boundaries since 1879, the relationship between the Park and its fauna, and the challenges facing the Park as an urban park in the twenty-first century.

Manuscript received 22 August 2013, accepted for publication 23 April 2014.

KEYWORDS: acclimatisation movement, ecological history, environmental history, Royal National Park, Royal Zoological Society of NSW, Tim Flannery; urban park, Yellowstone National Park.

INTRODUCTION

Oliver Rackham is a scholar with an unusual bent. He is interested in ancient woodlands and has developed the area of woodland ecology as a branch of historical ecology, which he sees as both a science and a part of history (Rackham 2003: xviii). He points out that woodland ecology is a discipline that is still in its early stages of development. In the second edition of his striking book, *Ancient Woodland*, Rackham notes that new data have strengthened his conviction that ancient woods are all different, and that each has its own unique development. Given that Rackham (2003: 435) views Australia as a miniature planet and contends that its ecosystems work on different principles to the rest of the globe, one can quickly appreciate that, from a world perspective, Royal National Park is an international treasure richly deserving of its own ecological history. The Linnean Society symposium of 2011 was a major step toward achieving that goal, by examining the Park from a number of different interpretive positions (see e.g. Adam 2012; Attenbrow 2012; Schulz and Magarey 2012). This paper aims to further that endeavour by moving between history and ecology to arrive at a deeper understanding of the future challenges facing the park.

Ecological history is a rapidly growing field attracting considerable international attention. Drawing on existing fields such as environmental history (with which it is often synonymous) and historical geography, ecological history has been recognised as crucial to developing ecological restoration programs and conservation strategies (Foster 2000; Donlan and Martin 2004; Jackson and Hobbs 2009), in addition to deepening our understanding of the human impact on the natural environment (Flannery 1994). As an approach, ecological history seeks to integrate disparate disciplines, drawing not only from ecology and history, but also cultural studies (Goodall 2010; D'Arcy 2006) and archaeology (Hayashida 2005; Briggs et al. 2006), among other fields. Many works in the field adopt a grand-scale approach, examining ecological changes which have taken place over millennia in whole regions (e.g. Vermeij 1987; Flannery 2001; Grove and Rackham 2001). For more localised studies, however, a small-scale approach is equally valuable in capturing the ecological specificities and changes in a given area. Although recognising that the history of Royal National Park – both ecological and cultural – did not begin with its dedication in 1879, this paper focuses on the decades following its dedication, which have been underexamined in the context of ecological history. In her captivating book, *The Colony*, historian Grace Karskens identifies that by the 1820s, the pattern of farming and grazing lands in New South Wales followed the funnel shape of the plain's arable soils. As a result, the rough sandstone country that encircled the plain was avoided. These once-shunned areas, she remarks, became Sydney's four treasured National Parks: Royal, Blue Mountains, Ku-ring- gai and Sydney Harbour. In Karskens' view, "their ecologies became the default 'Sydney ecologies'" (2009: 21). The landscapes of the arable soils, such as on the Cumberland Plain, and the rich alluvial flats, met a different fate: they are Sydney's "lost landscapes" (2009: 21). As Karskens recognises, the chance survival of a handful of areas has come to retrospectively structure our understanding of Sydney's pre-settlement natural environment as a whole. That Karskens highlights what has been lost suggests an awareness of the fact that what we have left, and the knowledge that can be gleaned from it, is necessarily incomplete.

There are many fascinating aspects of the ecological history of Royal National Park. Among these aspects is the meaning of 'national park' and what it meant in Australia in 1879 when what is now known as Royal National Park came into existence. Another is the place of the Park in coastal NSW and the Sydney region from a biologist's perspective. What is its vegetation, its fauna, and how do we manage this national park ecologically? A third area of interest is the location of the Park in relation to its immediate surroundings, and the implications of its location for the management of this larger unit of land. As an urban park, it is particularly important in the context of building public support for conservation initiatives. Developing a pro-conservation consensus among urban populations is a key challenge facing conservation organisations more generally, and promises to reward protected areas if achieved (Trzyna 2003). The location of the Park also poses specific challenges for its managers. As Conner (2003) argues, public awareness of the benefits of protected areas is particularly important with regard to urban parks. As such, he contends, managers need to promote their parks' natural and cultural heritage values and provide information to potential beneficiaries with a view to developing broader support for conservation among urban constituencies (Conner 2003).

While National Parks are always about the present, they are also about a sense of the past and the future. Without an examination of their history we cannot fully comprehend their development; without an eye on their future, they will not survive. For those who lack a sense of history, national parks and protected areas are an impediment to growth, wasted land which should be converted into something more useful. This view is manifest in so many areas of debate, whether concerning the river red gums on the Murray, the southeast woodchipped forests, or grazing in the high country, that we should never rest on the assumption that we have permanently made the case for a national parks system that meets all the ecological criteria that one can find, including how the parks and reserve system will fare in an era of climate change. The shining example of Royal National Park helps sustain that case. We might rest comfortably with the assumption that no-one will turn Royal National Park into a new set of suburbs, but we are far from sure that the remaining remnants of Sydney's pre-European vegetation will not be cleared for some development dream, a growth centre, infrastructure project or just incremental expansion of existing suburbs. That is their likely fate, but it ought not to be. To help project an image of a future Sydney that keeps as much of its biological heritage as possible, we should continue to point to Royal National Park. In 1879, it was a great idea, by 1979, at its centenary, it was a brilliant idea, and by 2079, it will be seen as a solid gold investment. Indeed, as the Trustees concluded in their *Official Guide to the National Park of New South Wales*, "It is Time, and Time alone, that will prove the vast value of this magnificent dowry to the people of New South Wales" (Elwell 1893:64).

We can now turn to some of the details of Royal National Park that might capture the attention of a future ecological historian who has the time to follow up any ideas and convert a tentative paper to a solid piece of scholarship. I might add that it is essential to publish such efforts: I know of too much material that is unpublished, and that is a tragedy for those with more than just a passing interest in Royal National Park, or indeed any other element of our natural environment. The importance of research and education concerning the natural history of Royal National Park become apparent when listening to people who have spent much of their lives studying and working in and around the Park. By 2079, these experts will have died, and as an important part of the Park's history it is necessary that we record this community's contribution while they are still active (see Appendix 1). A central theme of this paper is to draw attention to the need to record the history of all our National Parks and Nature Reserves, and to place their history in an ecological context. It is a difficult and time-consuming task: it took some years for a group of us to record Nadgee Nature Reserve (Lunney et al. 2012), but these efforts will be invaluable in the coming decades.

'THE LUNGS OF THE CITY': A BRIEF HISTORY

The decision to reserve such a large tract of land merely 25 kilometres from the Sydney CBD must be contextualised within the increasing concerns for public health which preoccupied many of the educated elite of the nineteenth century. For an intellectual and political milieu that prized public hygiene, racial purity and vitality, Sydney's rapid population expansion presented critical problems for the future. The city's sanitation, overcrowding and pollution attracted growing criticism in the late 1870s, as a State Government enquiry into Sydney's health [1885-1877] blamed a high child mortality rate on inadequate procedures for sewage disposal. It was as a direct consequence of these concerns that urban reformer John Lucas addressed the Legislative Assembly on 19 February 1879:

"The health of the people should be one of the first objects of all good Governments, and to insure a healthy, and consequently a vigorous and intelligent community, it is necessary that all cities, towns, villages, and such other centres of populations, should possess parks and pleasure grounds as places of public recreation." (Anon., 1879a: 3)

Lucas proposed that a tract of land should be dedicated exclusively for the purpose of public recreation – literal "breathing room" – in all of Sydney's densely populated suburbs. In their reportage of Lucas' address, the *Sydney Morning Herald* clearly agreed. While noting that Sydney already had the Domain, "some small reserves" – such as Moore Park, dedicated in 1866 – and "a most noble harbour", it contended that these were insufficient: "With all those facilities for health we had a puny race of young people growing up in our midst". Lucas was especially preoccupied by the long-term effects of overcrowding and pollution on children, who lacked "sufficient fresh air to give them a healthy and vigorous constitution." As a result, he viewed the probable consequences of population expansion "with horror". In his view, the *Herald* reported, "unless provision were made for sanitary improvements, … the death rate would be ten times as much as it was in Sydney at the present time" (1879a: 3).

Despite the reservations of then Premier Henry Parkes, who concurred with the sentiment of Lucas' address but criticised its radical implications for land use policy, Lucas' resolution was unanimously passed in the Assembly the following month. His proposal sheds valuable light on one of the ways in which the natural environment was conceived at the time: as 'the city's lungs', the antithesis to the polluted urban centre of the modern age. Yet the reformers' preoccupation with population health was not the sole factor behind the dedication of Royal National Park in 1879. As Pettigrew and Lyons (1979) argue, one of the primary reasons for its reservation from sale was the need to provide land for the acclimatisation of foreign animals. The Parkes Government strongly approved of the aims of the Zoological Society of New South Wales (initially called the Acclimatisation Society), which formed a month after Lucas' address on 24 March 1879. The Society was committed to "the introduction and naturalisation of song-birds, and of animals suitable for game" (Anon. 1879b: 5). Two days after its first meeting, the *Sydney Morning Herald* reported that the Parkes Government, "in order to promote its objects, will set apart a large tract of land for the purpose of acclimatisation." It specified that "the proposed reserve is on the south side of Port Hacking, extending from the coast some five miles back, and is said to embrace about 80,000 acres" (Anon. 1879c: 5). On 29 March, the *Herald* described the area in greater detail and credited the idea to John Robertson, Vice-President of the Executive Council, "who has thought of the project for years" (Anon. 1879d: 3). 18,000 acres (7284ha) were formally dedicated on 26 April 1879. On the same day, eleven Trustees were appointed, including Lucas, Robertson, and the convenor of the Zoological Society, Walter Bradley.

That Lucas and Bradley were both appointed as Trustees points, to a certain extent, to the compatibility of their aims. Both men, and the groups they represented, viewed the natural environment within a utilitarian framework. Although today the effective cooperation of a zoological body and an urban development group is complicated by the former's conservation ethic, in the nineteenth century their objectives were far more complementary. Irrespective of their individual backgrounds as naturalists, urban reformers, and government officials, the first generation of Trustees shared an understanding of the National Park as a reserve which existed primarily for public use. Its central purpose was to provide a space for public recreation. Accordingly, the Trustees saw the 'beautification' and 'improvement' of the Park as high on their list of management priorities. Central to this was the key problem of accessibility. Over the Park's first decade, the Trustees devoted the majority of their funding and effort toward the provision of access routes (Fig. 1). For some tenderers, clearing areas of the Park proved too great a challenge. As one tenderer, John Crowley, writes to his contractor in 1882: "I beg to inform you that I am reluctantly compelled to decline proceeding with the clearing portion of the National Park […] I am not surprised at having been deceived in my estimate of the work as the undergrowth of gum and appletree […] are all suckers growing from stumps of saplings and large trees that have been burnt level with the natural surface of the ground" (State Records NSW, Container No: 9/2188). Despite such setbacks, the 1893 *Guide* boasts that, during the Trust's first five years, "thirty-two miles of roads were cleared, and a considerable length was formed and finished for traffic." With the growing popularity of the Park as a "recreation resort", road construction operations were extended. "From that day to this," the *Guide* continues, "the work of road formation has been continued, and in the main, satisfactorily completed". The result is a network of "thoroughfares, now spreading web-like over the park" (Elwell 1893: 12-13).

These operations were applauded by the public. Although part of the Park's allure was that it had "remained so long unknown, unvisited, and unappropriated" – indeed, a "terra incognita" – it was considered inevitable that it would be "subdued to the hands of man" (Anon. 1879e: 4). As the *Sydney Morning Herald* commented: "In the main it is as little known and has been as little visited as if it had been 1000 miles away. The time has come for this solitude to be disturbed." In the reporter's estimation, this was "simply the rescue from neglect of a beautiful piece of wild country, and bringing it forth for the enjoyment of man" (Anon. 1879e: 4). Tellingly, the enthusiastic public response to the decision to reserve the Park in March 1879 was strongly linked to the expectation

Fig. 1. Audley Road, National Park (Government Printing Office, 1888). Photograph courtesy of the National Library of Australia (Digital Collection; Call Number 'PIC/8476/13 LOC Album 1037').

that it would accelerate the planning for the long-awaited Illawarra railway line. With this means of transportation, the park would be "a sanctuary for the pale-faced Sydneyites, fleeing the pollution, physical, mental and social, of that densely packed city." [quoted in Pettigrew & Lyons (1979) but no source cited. M. Maack (2002) attributes quote to John Robertson; "NSW Confederation Conservation History", The Bushwalker, Vol. 28, No. 1 (August 2002), p. 3].

The 1887 Deed of Grant formalised the Trustees' responsibility to the public. It empowered the Trustees "to use and permit to be used the said lands as a National Park for the recreation of the inhabitants of the said colony" and specified the Park's legitimate uses. These included "ornamental plantations of lawns and gardens", "zoological gardens", an "artillery range" and the "exercise and encampment of military or naval forces" (N.S.W. 1891: 3). The rest and recreation of the public were high on the list of priorities (Fig. 2). In alignment with the broader utilitarian philosophy which underscored the management of the Park, the Deed clarifies that the Park's natural resources are subservient to public need. It continues:

"…it shall be lawful for the Trustees of the National Park to grant licenses to mine upon and under the said land for and to take away and dispose of, as the licensees may think fit, all coal, lime, stone, clay, brick, earth or other mineral (excepting gold or silver) that may be found in the said lands." (1891: 4)

In her work-in-progress, entitled *European history of Royal National Park revisited*, Judith Carrick examines the history of attempts to mine the Park in more depth than can be explored here (Carrick, in press: 18-20). For our purposes, it is illuminating to note that the dominant conception of the Park as a space for public use coexisted in relative harmony with a deep appreciation of its perceived beauty. There seems to have been little concern, for example, when the Park's tableland was extensively cleared in

Fig. 2. Unknown boy on banks of river, National Park (Charles Bayliss, ca. 1880-1900). Photograph courtesy of the National Library of Australia (Digital Collection; Call Number 'PIC/7985/164 LOC Album 100').

Fig. 3. Encampment Ground, Loftus Heights (Government Printing Office, 1888). Photograph courtesy of the National Library of Australia (Digital Collection; Call Number 'PIC/8476/11 LOC Album 1037').

1884 for use by the military (Fig. 3). That this was considered a routine matter of management and not environmental degradation points to the historical specificity of the naturalists' relationship to the fauna and flora which they studied with fervour. However, despite these disturbances the Park retains many of its biodiversity values (Adam 2012; Schulz & Ransom 2010; King 2013) and continues to meet contemporary criteria for designation as a National Park.

POINTS OF CONVERGENCE: THE ZOOLOGICAL SOCIETY OF NSW

To a twenty-first century ecologist, the attitudes and priorities of the nineteenth-century naturalists seem bizarre. Particularly incomprehensible is the Zoological Society's interest in the acclimatisation of foreign species at a time when native fauna and flora had not yet received comprehensive legislative protection. Indeed, the first statute enacted in NSW addressing the issue of fauna protection, the *Animals Protection Act* of 1879, listed as its primary purpose the "importation and breeding" of alien species. The protection of native fauna (the list of which includes no mammals) rated second – and only applied "during the breeding season" (N.S.W. 1879: 56).

This stipulation reflects the acclimatisation movement's selective approach to the issue of preservation more generally. It supported the protection of certain native fauna on the basis of its utility. As Pettigrew and Lyons (1979: 18) argue, its proponents believed that the contemporary rates of exploitation had to be regulated not for conservation purposes, but to ensure that there remained sufficient populations for future generations to exploit. Furthermore, although it was largely comprised of naturalists passionate about the natural environment, the acclimatisation movement was, from the vantage-point of the contemporary conservationist, quite arrogant: it believed it could 'improve' nature. Few saw anything problematic in this objective; on the contrary, many were drawn to it by a sense of boundless possibility. As the *Sydney Morning Herald* commented, "It is difficult to set limits to the attractiveness which this fortunate national reserve may be made to possess" (Anon. 1879e: 4).

This conception of the Park, and of the fauna and flora within its shifting boundaries, persisted well into the twentieth century. The *Official Guide* of 1914, for example, is redolent with references to 'beautification', and boasts of the successful introduction of multiple non-indigenous species, including trout and perch. Yet the *Guide* hints at an introduction which would prove a headache: that of deer at Gundamaian. By 1886, the Trustees had acquired seven fallow deer, some white angora goats, and five valuable red deer through donation. According to the 1893 *Guide*, they thrived and rapidly multiplied (Elwell 1893: 13). A special Deer Park was established to house the deer near the Port Hacking River (Fig. 4), and more deer were later purchased. Yet, as the *Guide* records, "for them nine-wired fences did not a prison make. […] these ruminants broke bounds, and are now roaming, fancy free, over the wide domain" (Elwell 1893: 54). As early as 1893, Carrick notes, there was a complaint about deer escaping and destroying a neighbouring garden. By 1912, the Trust refused an offer of more deer, and by 1923 the Trust was attempting to 'donate' them to other parks. The management of deer, particularly the Javan rusa, remains a most difficult issue to this day (Keith and Pellow 2005).

Gundamaian was also home to the Scientists' Cabin. According to Carrick, the Cabin was built in 1924 for the Zoological Society, although Allen Keast remembers that it "had formerly housed the timber

Fig. 4. Fountain cottage and the fountain at the Deer Park, Port Hacking River (Government Printing Office, 1888). Photograph courtesy of the National Library of Australia (Digital Collection; Call Number 'PIC/8476/4 LOC Album 1037').

workers" engaged in logging operations before the Society occupied it in the "late 1920s" (Keast 1995a: 28). It was in the vicinity of the sawmill by the Hacking River, just above the Upper Causeway. During its time there, the Society conducted valuable research into the native birds of the Park, particularly the bower-bird. The Society was granted sole use of the cabin, but was given notice to leave in 1935 because it could not agree to the new terms of the permissive occupancy. Carrick notes that records show that the Society was still there in 1941. Concerning the eviction of the Zoological Society, Keast bitterly recalls that "the end of the Cabin came ignominiously about 1944 when most members of the Society were absent at the war: it was pilfered bit-by-bit for seaside cottages on the adjacent Park beaches" (1995a: 29).

Another interesting point of convergence between the Park and the Zoological Society is the push within both for the addition of the prefix 'Royal' to their titles. As public recognition of their value grew, so did their stature. To the management of both the Park and the Society, the insertion of 'Royal' would suitably reflect their growing importance in the eyes of the public. By 1908, almost 30 years after its formation, the Society had risen in prominence to the extent that its President, Dr. T.P. Anderson-Stuart, sought permission to add the 'Royal' prefix to the name. A Royal Charter was duly granted in September 1908. On 10 February 1909, the Society changed its name to 'The Royal Zoological Society of New South Wales'. Three decades later, the Trustees of the National Park discussed renaming it to Royal National Park, while other parks (namely, Ku-ring-gai) would be National Parks. For the Park, it was the visit of Queen Elizabeth II in 1954 which would prove to be decisive: the Park was renamed in 1955.

The addition of 'Royal' can be interpreted as both a political and cultural statement. It is distinctively British, it carries certain class overtones, and it was a fashion statement which the Royal Easter Show, Royal Society for the Prevention of Cruelty to Animals (RSPCA) and the Royal Flying Doctor Service also reflect. Its connotations raise the question of exactly which sectors of colonial society were to benefit from the dedication of the National Park in 1879. It is indeed far from clear as to whether the National Park was dedicated for the poor of the inner suburbs for health and recreation, or for a more privileged group that could consider importing and releasing exotic species, the very ones we now call alien invasive species. One should read the press release and accompanying documents with a critical eye. For historians, there is some digging to do here, particularly concerning the meaning of 'national'. Carrick, for example, argues that the word 'national' denoted, in 1848, the inclusion of all individuals in a locality irrespective of denomination and social standing. In view of this, one could reasonably extrapolate that, in 1879, the National Park was dedicated for all inhabitants of the colony. At the very least, it was certainly understood this way: the *Sydney Morning Herald*, for example, makes few references to Sydneysiders when speaking of the Park's use, preferring inclusive language such as "the people of the whole colony" and "the people of this country" (Anon. 1879d: 3; Anon. 1879e: 4).

On a related note, it is difficult to discern whether John Robertson was inspired by a foreign model when he created Royal National Park – and if so, which one. There is certainly some merit to the claim that the isolated Yellowstone would be an odd model for a park located so close to the inner city (Pettigrew and Lyons 1979). It is more likely that if Robertson had a model, it was London's recently established common parks, located on the border of the metropolis, though this is in need of further research. In Carrick's view, the links between the American trajectory and developments in Australia are ambiguous and in need of more probing study. In my perspective, the debate over which national park was first in the world - Yellowstone in 1872, or our local candidate - is distracting. It is more productive to examine the claims to originality critically and within their political context, as Robin (2012) has done in an intelligent paper. The ecological ideas of the 1870s (not, of course, conceived in twenty-first century ecological terms), are equally interesting. Their echoes are still present in NSW, whether the current public debate centres on marine parks, mining under the parks (such as the coal seam gas proposals for the Pilliga forests in north-western NSW), or hunting on public lands.

MAPPING ROYAL NATIONAL PARK

We live in a tenure-bound society. Maps are a manifestation of our preoccupation with boundaries, and of our specific relationship to the natural environment, although they have a long history of use in navigation. They are today so commonplace that it is difficult to grasp their initial novelty. The early maps of Royal National Park were among the first in Australia of a natural area enclosed by a boundary for the sake of demarcating an area considered to be purely natural. Until these maps were designed, natural history in Australia did not have set boundaries within which the natural environment could be managed. The mapping of Royal National Park fundamentally challenged the dominant exploitative approach to the land as a place to be colonised, cleared, and farmed. It gave emphasis to an emergent perspective of the natural environment which was not primarily valued in commercial terms and which was beginning to recognise, by the late nineteenth century, that forests could not be exploited in an unregulated manner (Lunney & Moon 2012). That this was a public area owned and managed by the State in perpetuity remains one of the great landmarks in world nature conservation. Royal National Park initiated the integration of nature study with the management of natural areas. In so doing, it made an extensive part of New South Wales' pre-settlement environment accessible to a large number of people who otherwise may not have come into contact with some of the most beautiful specimens of Australian fauna and flora in their natural settings.

For these reasons, it is worth turning our attention to the maps of Royal National Park. Many observations can be gleaned from examining the maps in sequence and in context of the surrounding areas. In what follows, I examine a series of maps chronologically in order to draw out some of the factors which have contributed to the dedication of the Park, and to illustrate the changes in the Park's boundaries and management over time.

The earliest map of the area of relevance to this study is dated 1845, and depicts the "country southward of Sydney, shewing the Road lately opened through it to the Illawarra" (Fig. 5). Operationally speaking, this road came to define the Park's boundaries, prefiguring the western border of the Park. That there were no roads in this area prior to 1845 can be seen as evidence that the land was of little commercial value: in comparison to the arable soil of the Cumberland Plain, for example, the land which was later to comprise Royal National Park had not been opened up for grazing crops or farming estates. Consistent with this, the map shows a clear absence of landscape differentiation, with no references to ownership. Indeed, it resembles more an explorer's map than the careful result of a set of surveyor's decisions. As Surveyor-General, Thomas Mitchell (whose signature appears at the bottom of the map) would have well understood the importance of tenure boundaries as a reflection of political and administrative decisions regarding land use. The absence of tenure boundaries on this map points to the fact that, in 1845, there had been no decisions made on the potential use of this area of undifferentiated Australian bush. Instead, it had escaped 57 years of colonisation without being surveyed and considered for agricultural and commercial use. With Sydney growing in a pattern that fitted the arable lands, it was a chance of geography, soil fertility, and the ready access to more productive landscapes that allowed the future Park area to remain 'unused' (in a contemporary land use sense) until 1879. Consistent with this, in the earliest existing parish map of Wattamolla – undated, but appraised to have been constructed between 1835 and 1870 – the sentence "barren land destitute of timber" was inscribed across what we now know as Royal National Park (Fig. 6). This phrase remained in subsequent maps lithographed in the early 1870s (Figs. 7-8). This indicates that, for successive governments, this land had been surveyed and had no commercial value.

In contrast to the 1845 map, a map of the Park dated 1879 (Fig. 9) displays clear tenure boundaries in the typical block fashion, with the leaseholders' names printed neatly on their respective portions (a close-up of this part of the map is provided in Fig. 10). This map was found by Allan Fox "crumpled in the corner of a room" in Royal National Park in the late 1970s, when Fox was helping to assemble information for the celebration of the Park's centenary. Fox states he found it "in a pile of rubbish to be thrown out" (pers. comm, 2013). The land which it depicts is representative of the original boundary which became the area dedicated in 1879 in three parts: the first on the 26th of April, the second on the 6th of October, and the third on the 25th of November (NSW Government Gazette 1879b, 1879c, 1879d). The upper left-hand corner of the map states that it is a "tracing shewing National Park &c., County of Cumberland". Although the map does not provide the name of the surveyor, it resembles an official document, perhaps prepared in readiness for the Park's dedication that year. Given the pencil marks on the map, it has the appearance of a working map. Interestingly, the words "Reserve from sale pending selection of railway line" cover a large area on the Park's western boundary which would later be excised (see below). Most importantly, however, the tenure boundaries of this map provide us with a timeframe within which to assess the changing management of this area of land. They show us that, between 1845 and 1879, decisions were being made on its potential use. What in 1845 had no formal land use designation was beginning to be dissected in 1879 for other uses. In view of this, it becomes clear that had the decision not been made to dedicate the area as a National Park, the vast majority of this land would have been cut up into private holdings by the turn of the century.

The gazettal notice of 26 April 1879 states that 18,000 acres were dedicated and gives a detailed written description of the boundary (NSW Government Gazette 1879b). We have used contemporary GIS technology to draw the boundary according to this original description. The calculated area stands at

Fig. 5. 'Country southward of Sydney, shewing the road lately opened through it to the Illawarra'. Sydney: Thomas Mitchell, 1845. Map reproduced courtesy of the Mitchell Library, State Library of New South Wales. Call number 'Cb 84/18'.

Fig. 6. Wattamolla parish map. Circa 1835-1870. Map reproduced with permission of the NSW Lands and Property Information, Department of Finance and Services, Panorama Ave., Bathurst 2795.

19,541 acres (7908 ha) and forms the basis of a new map, shown in Fig. 11. According to the gazettal notice of 3 August 1880, the Park was expanded on this date by 19,000 acres (NSW Government Gazette 1880). Again following the gazettal description, we used GIS technology to calculate the total area to be 36,532 acres (14,784 ha) and the actual area is depicted in Fig. 11. This largely – though, as we will see, not completely – forms the basis of what is now known as Royal National Park. The addition in 1880 is in the eastern half and incorporates the land which is shown in Fig. 10. It appears that the allotments shown in Fig. 10 were mining leases (as indicated by the initials 'ML' in the corner of each portion), leading us to assume that either the terms of the lease had lapsed by 1880, or that the approval for mining had been withdrawn. The absorption of these allotments may thus shed light on the early Trustees' relationship to mining in the Park: as Mosley (2012:35) has suggested, John Robertson and his supporters may have gone to great lengths to protect the Park from this threat.

For our purposes, it is interesting to note that the Park was still being surveyed at this time at Robertson's request (State Records NSW, Container No: 9/2188). In June 1879 a representative of the Department of Lands, PT Adams, opined that "on survey considerable modification of the present boundaries will be found necessary", and argued that "natural

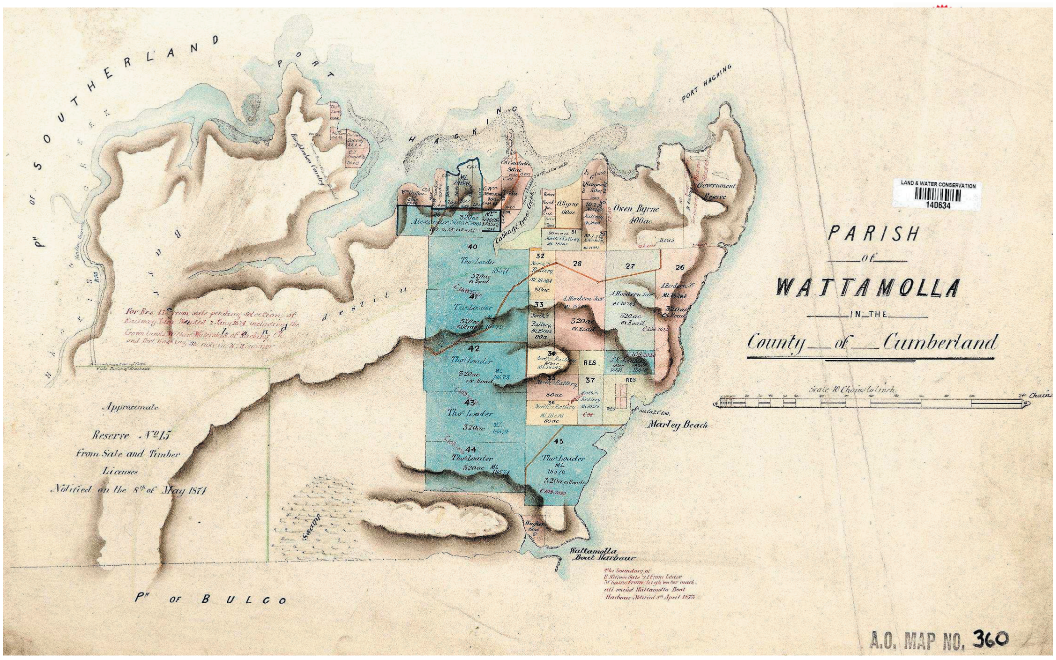


Fig. 7. 'Parish of Wattamolla in the County of Cumberland'. Circa 1873-1874. Map reproduced with permission of the NSW Lands and Property Information, Department of Finance and Services.

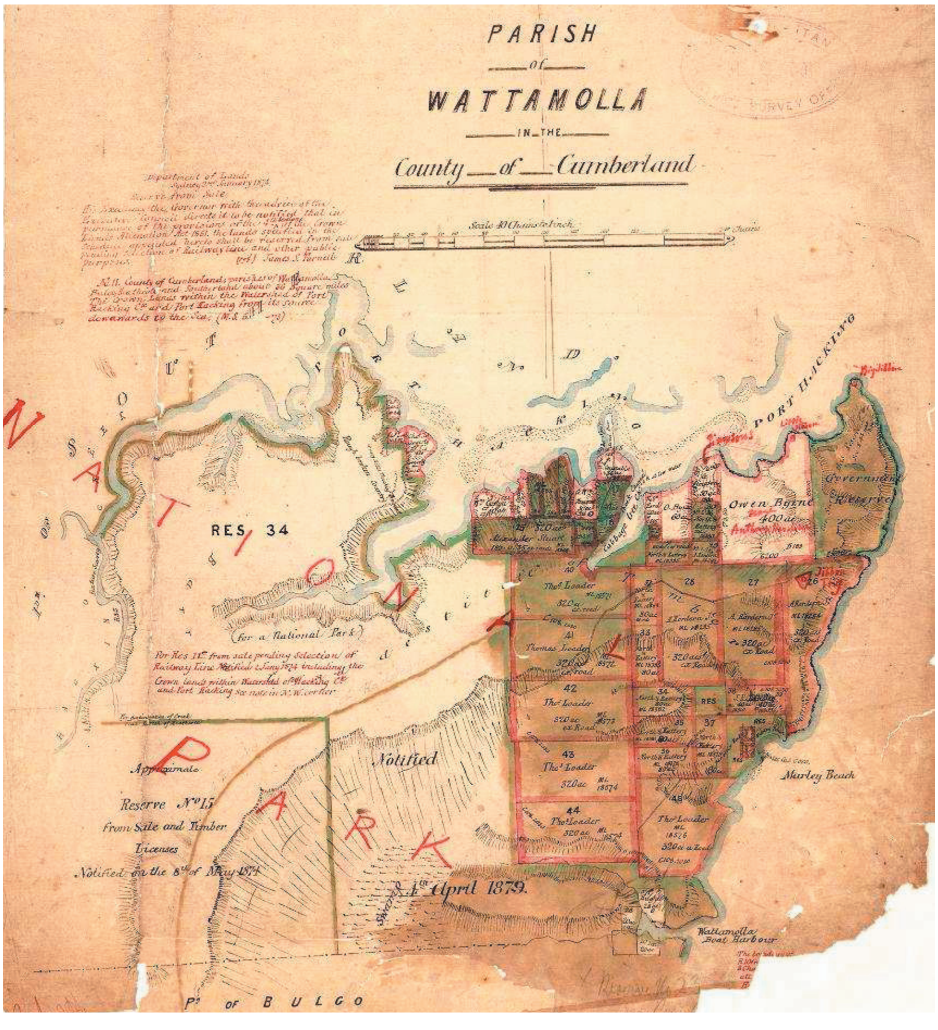


Fig. 8. 'Parish of Wattamolla in the County of Cumberland'. Circa 1880-1882. Map reproduced with permission of the NSW Lands and Property Information, Department of Finance and Services, Panorama Ave., Bathurst 2795.

Fig. 9. 'Tracing shewing National Park &c., County of Cumberland, New South Wales, 1879.' Unpublished map. Reproduced courtesy of Allan Fox.

Fig. 10. Tenure boundaries (detail), 1879. Image taken from Fig. 9. Unpublished map. Reproduced courtesy of Allan Fox.

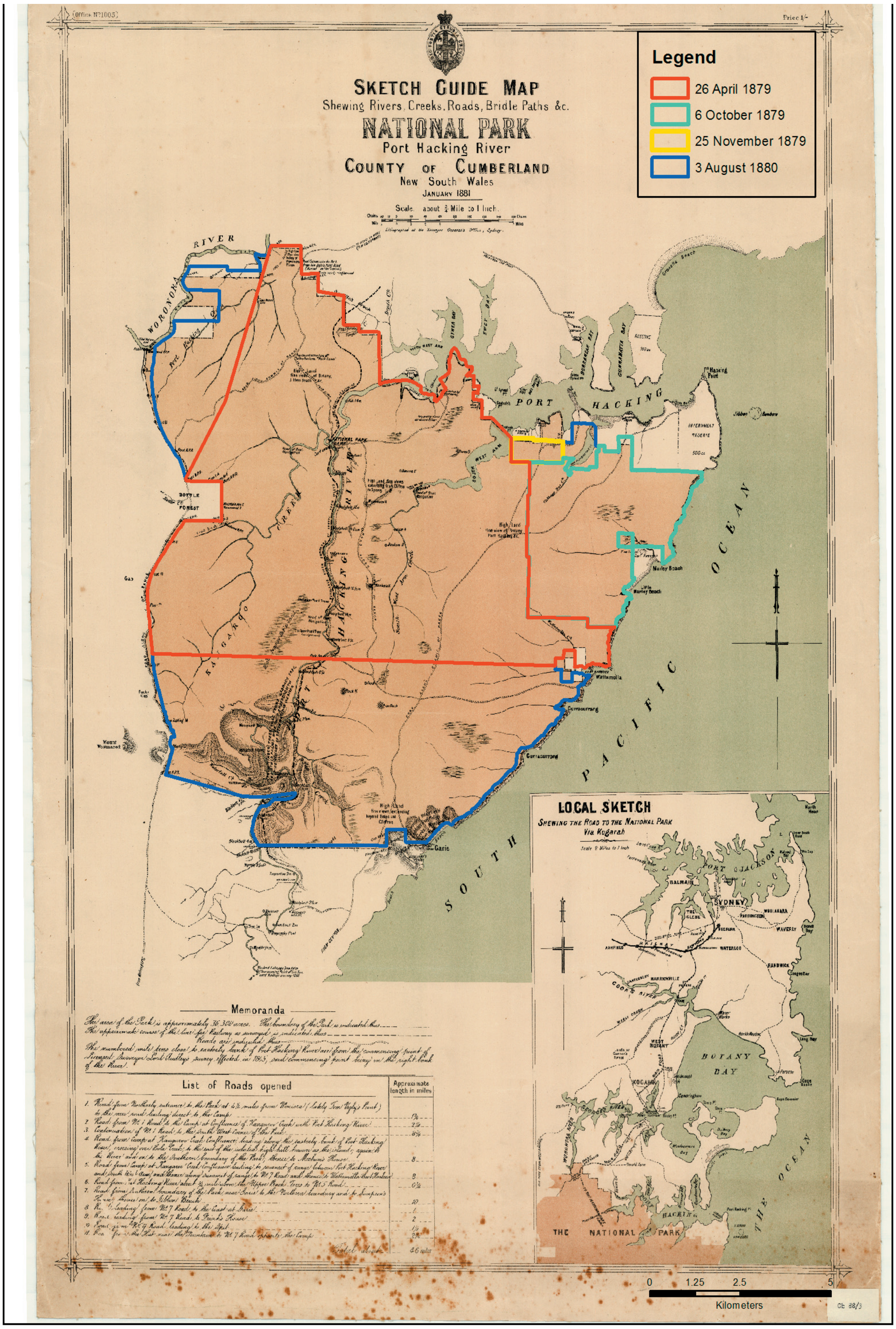


Fig. 11. Map showing incremental additions to Royal National Park from 26 April 1879 – 3 August 1880. This map uses the 1881 map in Fig. 12 as a base to show the boundaries of the successive increments over this period. The land bounded by the red line is the initial dedication of 26 April 1879. The green line shows the addition of 6 October 1879. The yellow line shows the addition of 25 November 1879. The land within the boundary of the Park which falls outside these lines was gazetted on 3 August 1880. This map was constructed using GIS to map the written descriptions in the gazettal notices of the four dates listed above. This approach allowed an accurate determination of the total area of each increment.

features should be substituted when the [sic] exist for arbitrary lines" (State Records NSW, Container No: 9/2188). In January 1881, a "sketch guide map shewing rivers, creeks, roads, bridle paths &c" in the newly dedicated National Park was lithographed at the Surveyor General's Office in Sydney (Fig. 12). When placed alongside the 1879 map, this map clearly illustrates the expanded boundary of the Park. In the 1881 map, the Park has absorbed the private holdings depicted in Fig. 7. Moreover, the information at the bottom of the map states that the "area of the park is approximately 36,000 acres" (Fig. 12). This is double the figure given in the Government Gazette for the Park's size in 1879, noted as "18,000 acres" (NSW Government Gazette, 1879a, 1879b). With a series of acquisitions (NSW Government Gazette 1880), the Park's southern boundary now roughly followed a line between Garie Beach and what later became Waterfall. Given that there existed no precedent for determining the boundaries of National Parks, it is understandable that the area doubled so early on, as competing uses of the land may have been resolved in the early years of the Park's administration. However, it is remarkable that this considerable expansion has largely gone unnoticed in the existing histories of the Park. These early changes to the Park's boundaries are worthy of a separate study, as deeper examination of how and why they occurred may shed light on the colonial administration's understanding of the Park in its earliest years. For our immediate purposes, however, it suffices to note that the fluidity of the Park's boundary in its early decades reflects the fluidity of the concept of a 'National Park' at this juncture. While we repeatedly cite 1879 as the pivotal year of dedication, it is in actuality only the first stage in the Park's history, and is representative not of a final boundary, but of an initial area set to greatly expand.

An official map dated 1897 (Fig. 13) provides us with another point of departure in examining the developmental history of the Park. Interestingly, this map appears to be identical to a map dated 1893 and published as part of the *Official Guide* (Elwell, 1893). The map clearly depicts the location of the Illawarra railway line in the area which was marked 'reserved from sale' in Fig. 9. Furthermore, the area west of the railway line is shown to remain within the Park's boundary. This was not to last long, however: as the politician and editor Andrew Garran presciently noted in 1886, "though it may remain a wild preserve, the railway will soon bring the long line of southern suburbs close up to its edge" (Garran 1974 [1886]: 98). The NSW Government Gazette of 26 August 1903 confirmed his prediction, declaring the intentions of the Governor, "with the advice of the Executive Council of [NSW]", to "wholly revoke the said dedications and grant in so far as they apply to or affect the said areas of 36 acres, 54 acres, 5 acres, 13 acres and 2 roods, 2 acres and 2 roods, and 2,950 acres of land described in the Schedule hereto" (NSW Government Gazette 1903: 6293-6294). A total of 3,060 acres was excised from the Park's western boundary. The Park's new boundary is shown in an official map produced in 1904 (Fig. 14). Interestingly, it appears that this map was a personal copy owned by the architect and conservationist Myles J. Dunphy, who was later to become known for his tireless efforts to protect key areas of the Blue Mountains. The 1904 map states that the area of the Park is now 33,719 acres – down from 36,320 in 1897. According to Carrick, the Park's Trustees agreed to a proposal made in 1895 by the Lands Department to withdraw this area, and received Jibbon Reserve (shown in Fig. 13 to be excluded from the Park) in exchange (Carrick, in press: 7). This is consistent with Carrick's contention that a "symbiotic relationship" existed between the Trustees and the Department of Railways "from the beginning" (Carrick, in press: 42), and is worthy of further research in a future study.

These maps illustrate considerable changes to the Park's boundaries in its early decades. Yet, although these changes are directly observable when represented visually, they are often discussed in the aggregate in existing literature. This has confused our understanding of the historical development of the Park. For the purposes of clarifying this development, a number of graphs and tables were prepared for this paper. Cathy Johnson of the Reserve Establishment and Land Information Section (OEH) prepared a spreadsheet tracking the 37 additions to Royal National Park over the period 1 October 1967 - 11 March 2005, increasing the park size from 14,851.94 ha on 1 October 1967 to its current size of 15,091.7173 ha (Table 1). Appendix 2 provides a crucial context for appreciating the information provided in Table 1. It shows the date of dedication, initial area, and area modifications of all of the National Parks and Nature Reserves in NSW prior to the *National Parks and Wildlife Act* 1967. While accessible, the information provided in this appendix is extremely difficult to locate and, to the author's knowledge, has not been reproduced. It is appended here as a benefit to scholars. While providing area information in two or more decimal places may seem too fastidious, precision is vital in view of the vulnerability of Australian parks and reserves more generally. There is the issue, however, of whether the surveys were sufficiently accurate to justify this many decimal places. As we have now established that, in 1879, the figure of 18,000 acres

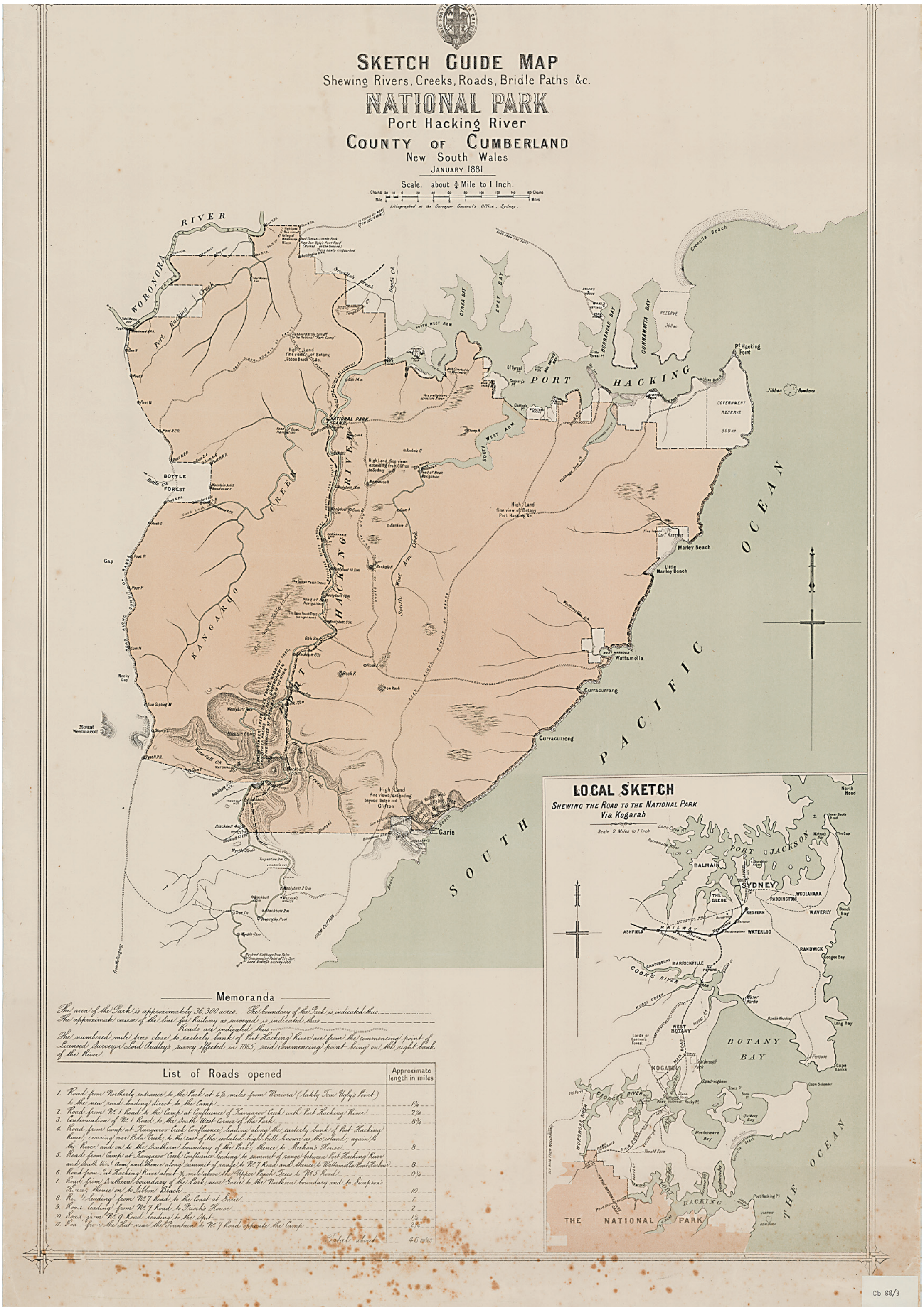


Fig. 12. 'Sketch Guide Map shewing Rivers, Creeks, Roads, Bridle Paths, &c. National Park. Port Hacking River, County of Cumberland, New South Wales.' Sydney, New South Wales: Surveyor General's Office, January 1881. Map reproduced courtesy of the Mitchell Library, State Library of New South Wales. Call number 'Z/Cb 88/3'.

Fig. 13. 'Plan of the National Park: shewing Railway Stations, Roads, &c.' Sydney, New South Wales: Department of Lands, 1897. Map reproduced courtesy of the Mitchell Library, State Library of New South Wales. Call number 'Z/M1 811.114/1897/1'.

was simply a close approximation, what is at issue now are the incremental additions and revocations to Royal National Park, as shown in Table 1 and Fig. 15. We can reasonably assume that, since 1967, any further changes were mapped with a higher level of accuracy and thereby provide interested parties with clear and precise information. Furthermore, in view of these standards, this paper adopts the current reporting level of accuracy.

From an historical viewpoint, the records do not begin at OEH, or the National Parks and Wildlife Service [NPWS], before October 1967 when the *National Parks and Wildlife Act 1967* was passed and the NPWS established. The *National Parks and Wildlife Act 1974* replaced the earlier Act, and is the current Act under which Royal, and indeed all the National Parks and Nature Reserves in NSW, are acquired and managed. Mike Prentice (also of the Reserve Establishment and Land Information Section) and Cathy Johnson kindly helped me to isolate the specific additions to and excisions from the Park. Their data were used to construct a series of maps, which illustrate the changing boundary of the Park from 1879-2011 (Figs 16a-h). As these maps are

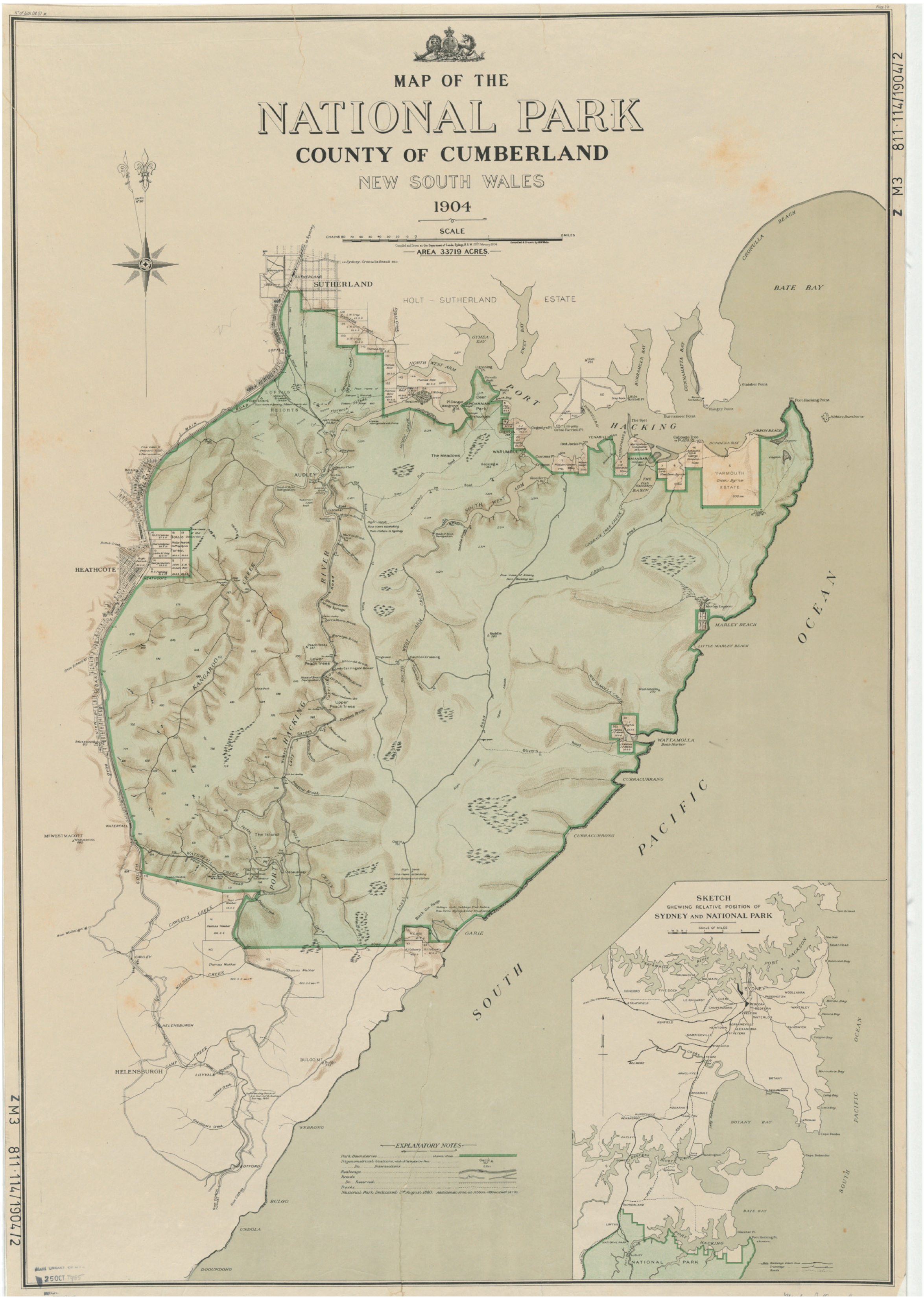


Fig. 14. 'Map of the National Park, County of Cumberland, New South Wales'. Sydney, New South Wales: Department of Lands, 1904. Map reproduced courtesy of the Mitchell Library, State Library of New South Wales. Call number 'Z/M3 811.114/1904/2'

Table 1. Additions to Royal National Park, 1 October 1967 – 11 March 2005. Credit: Cathy Johnson (Reserve Establishment and Land Information Section, OEH).

Legend	Date	Area (ha)
-	01-Oct-1967	14,851.94*
A-1	06-Dec-1968	19.24
-	13-Dec-1968	0.29
-	06-Jun-1969	0.13
-	05-Dec-1969	0.29
-	05-Dec-1969	0.51
A-7	08-May-1970	8.77
-	08-May-1970	0.14
A-9	24-Dec-1970	4.9852
-	24-Dec-1970	0.15
A-11	28-Jan-1972	3.98
A-12	04-Feb-1972	6.48
-	13-Oct-1972	0.18
A-14	28-Sep-1973	5.49
A-15	07-Dec-1973	2.73
-	31-May-1974	0.65
A-17	29-Nov-1974	5.82
A-18	19-Mar-1976	26.30
A-19	08-Oct-1976	6.48
A-20	17-Nov-1978	28.83
A-22	28-Dec-1979	47.60
A-23	23-Oct-1981	7.48
A-24	21-Jan-1983	2.13
-	18-Feb-1983	0.26
-	23-Dec-1983	0.59
-	06-Jun-1986	0.18
-	11-Sep-1987	0.17
A-30	26-Feb-1988	2.33
A-31	18-Mar-1988	3.28
A-32	03-Feb-1989	3.48
A-33	15-Dec-1989	45.00
A-34	25-Jul-1997	11.41
-	01-Dec-2000	0.42
A-36	11-Mar-2005	11.31

consistent in scale and visual presentation, they are provided as a supplement to the original maps, which can be difficult to compare.

Drawing upon all available data for all Parks and Nature Reserves in NSW, a detailed graphical presentation of the growth of the Parks and Reserves system from its inception in 1879 to the present (30 June 2012) is shown in Fig. 17. These graphs place the maps of Royal National Park in the historical context of growing support for the dedication of Parks and Reserves in NSW. The standard way of displaying the Parks and Reserves in NSW is in map form, meaning that unless one compares one map to another, the growth pattern is not easily discernible. Furthermore, unless one digs through the Gazette records, their growth in area is not apparent, especially when the growth in a given period is comprised of a series of modest increments. The regular mapping of the distribution of Parks and Reserves in NSW has missed the value of the pattern of numerical growth over time. These graphs were prepared specifically to overcome this deficiency in existing scholarship, and represent a new contribution to our understanding of the Parks and Reserves system in NSW. The data which were used to construct these graphs is provided in Appendix 3.

There are many points that can be made from the documents provided in this section. By examining the sequence and the dates, it is remarkable that such a large area was explicitly named as a National Park in 1879. There had been many small parks set aside in and around Sydney for recreation and health, but nothing near the size of Royal National Park at that time. It then becomes surprising that the area doubled in size so quickly: indeed, it has grown, with the additions of the adjacent Heathcote and Garawarra expanding the conservation estate. The growth of the Park in recent decades parallels the growth of the National Parks estate across NSW. Interpreting the earliest additions to the Park's boundary is complex, however: it is possible that they reflect growing support for the Park, and lobbying by special interest groups such as the Acclimatisation Society.

When a series of other maps are set next to these documents, further features emerge that help explain why the Park area remained Crown land in 1879. The maps in Benson and Howell (1990: 8) and Keast (1995b) depict the area as sandstone plateau country unsuitable for farming. Thus, it was a chance of geography that left the area intact for the 91 years since the European settlement of Sydney. However, it would not have been there in 1967 when the first National Parks and Wildlife Act came into force. Early timing was thus crucial in its dedication. The issue of timing, the importance of Crown lands, and the role of government attitudes have all been recognised as factors which determine the acquisition of national parks and nature reserves. This recognition largely grew out of the Fauna Protection Panel in the 1950 and 1960s and, after 1967, the NSW National Parks and Wildlife Service. Exactly which of these factors took precedence in the acquisition of National Parks in twentieth-century NSW was the subject of a debate

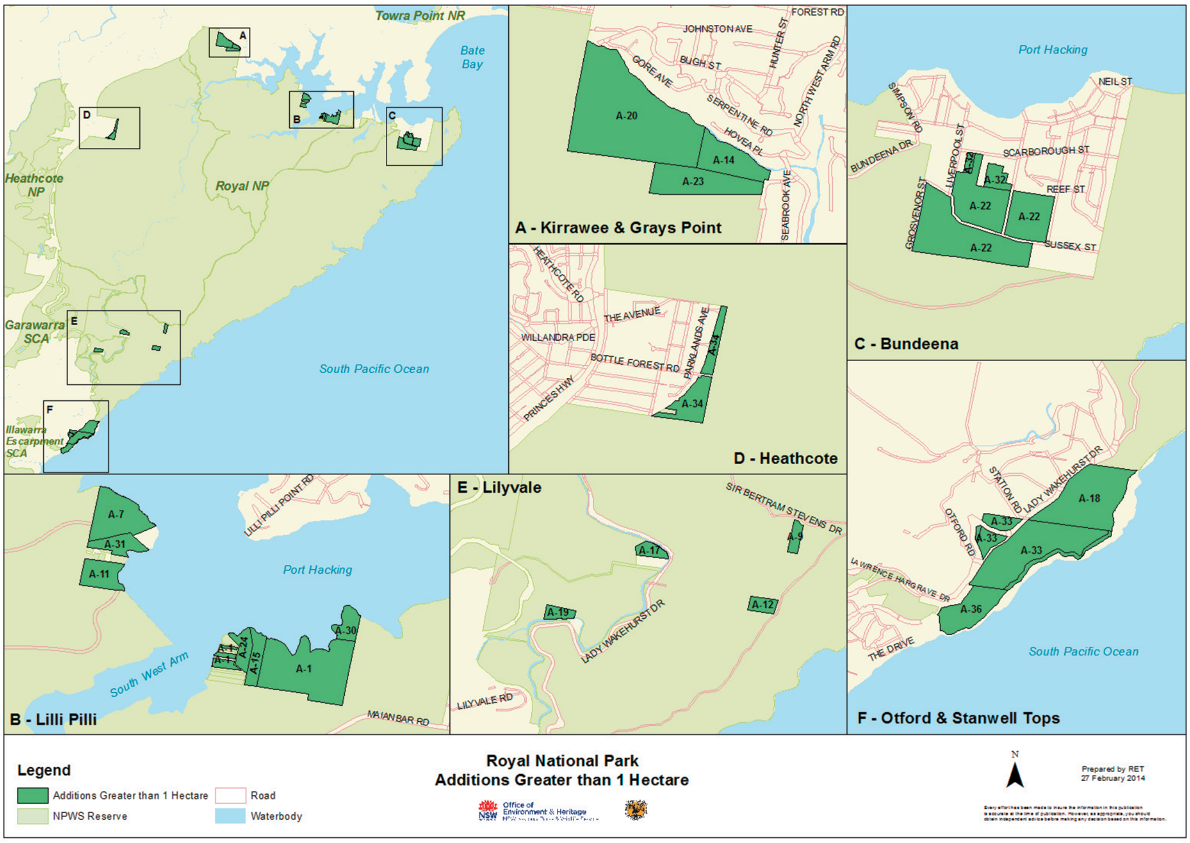


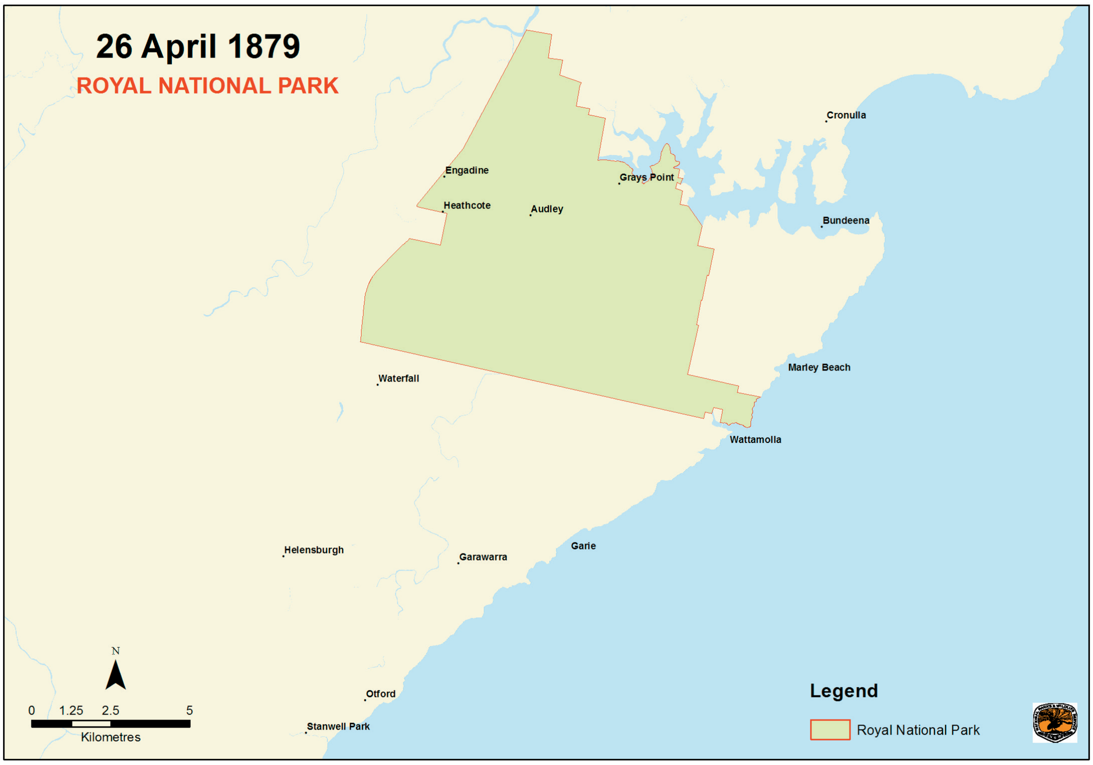
Fig. 15. Additions to Royal National Park greater than one hectare, 1967-2005. This map was produced by Cathy Johnson (Reserve Establishment and Land Information Section, OEH) specifically for this paper. For the data to which it refers, see Table 1.

in 1990 in the *Australian Zoologist* (McMichael 1990; Pressey 1990; Reed 1990; Specht 1990; Starling 1990; Whitehouse 1990a,b). For so many areas, the decades between World War II and the turn of the century held the last chance to dedicate large new parks and reserves, and it remains one of the feats of foresight and action that we have such a magnificent set of national parks and nature reserves in NSW.

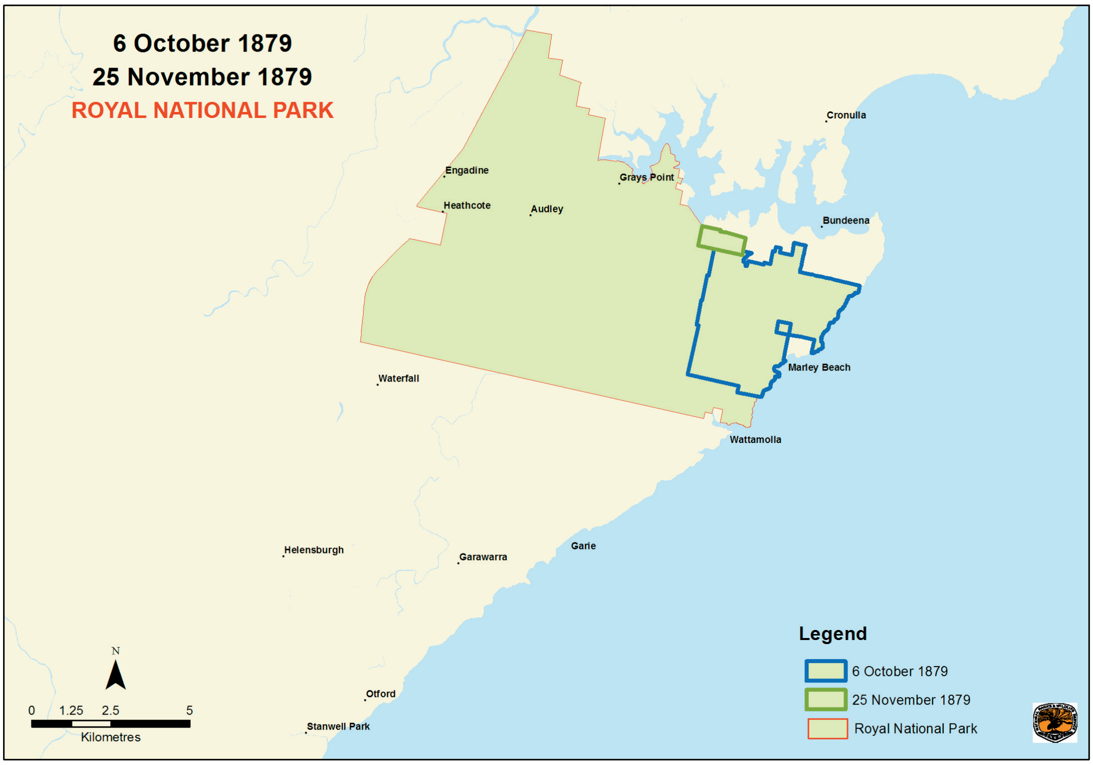
FAUNA AND HISTORY

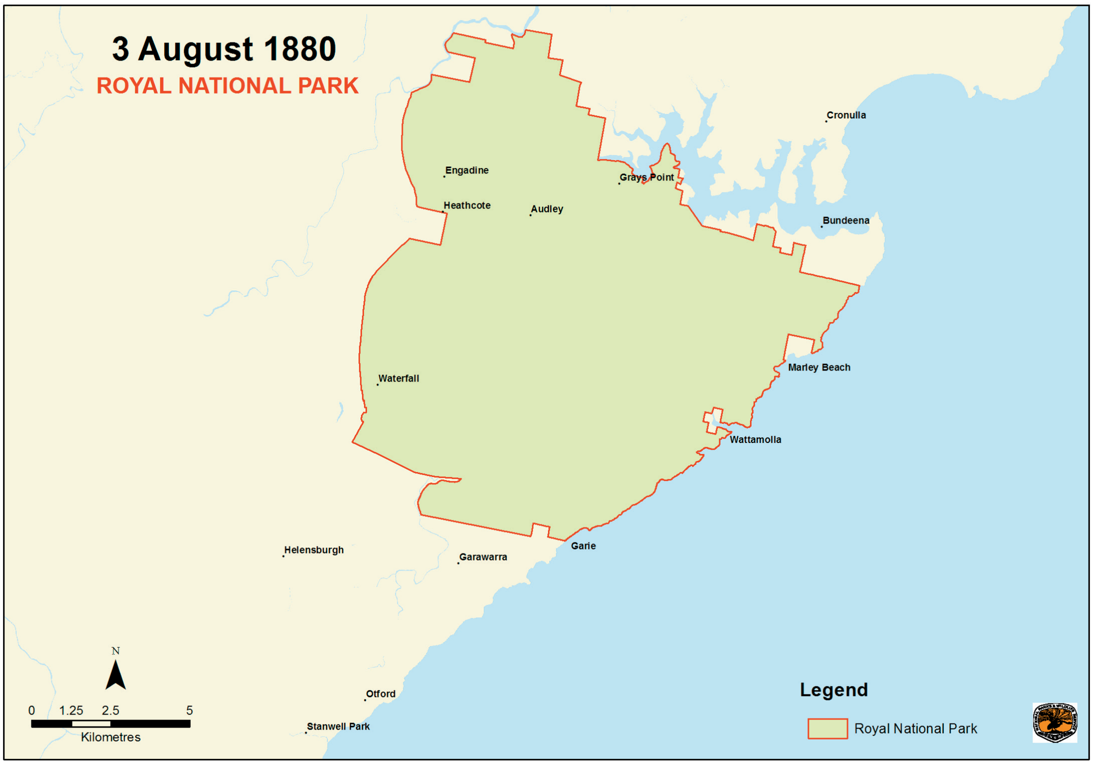
In the *Official Guide to the National Park of New South Wales (Elwell* 1893), the Trustees also comment on the history of Royal National Park in relation to its fauna. The Trustees credit themselves with making great strides in fauna conservation, as a direct consequence of preventative by-laws which prohibit

Figs 16a-h (next 4 pages). The changing outline of Royal National Park from 1879-2011. Comparing the maps allows us to discern a number of changes to the Park's boundaries over time: most significantly, a large excision from the Park in its north-west corner (indicated by colouring the excised land grey), and a steady expansion of the Park's area. The names of key places are provided for reference purposes. Fig. 16a shows the outline at 26 April 1879. Fig. 16b shows the outline on 6 October 1879, after an addition to the Park. Fig. 16c shows the Park's boundary in 1881. Fig. 16d shows the Park's boundary in 1904, with the grey area representing an excision from the Park's area since 1881. Fig. 16e shows the outline in 1967, when Royal became part of the NSW National Parks and Wildlife Service. It also shows the area of Heathcote National Park, which was dedicated in 1963. Fig. 16f shows the additions to Royal National Park between 1968-1979. Fig. 16g shows the additions to Royal between 1980-1999 and the location of both Heathcote National Park and Garrawarra State Conservation Area. Fig. 16h shows the current (at 30 June 2012) boundary of Royal National Park, which had been established by 2000. These maps were produced by Cathy Johnson (Reserve Establishment and Land Information Section, OEH) specifically for this paper.

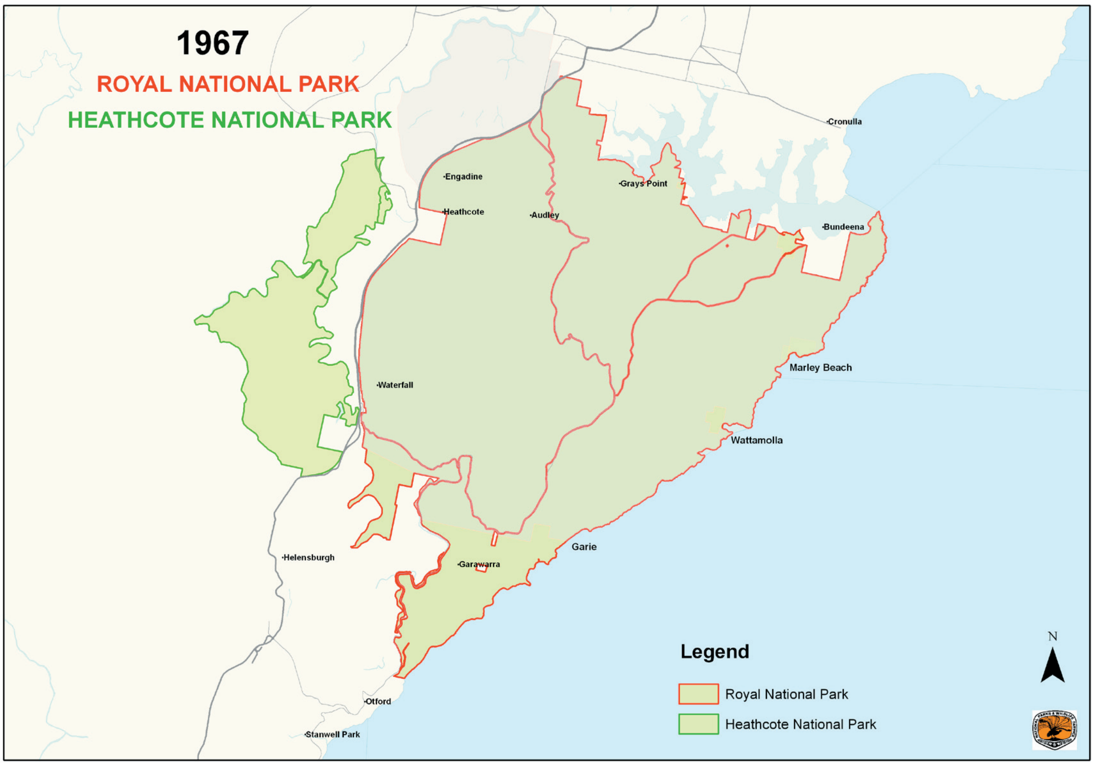


16 a above, 16 b below

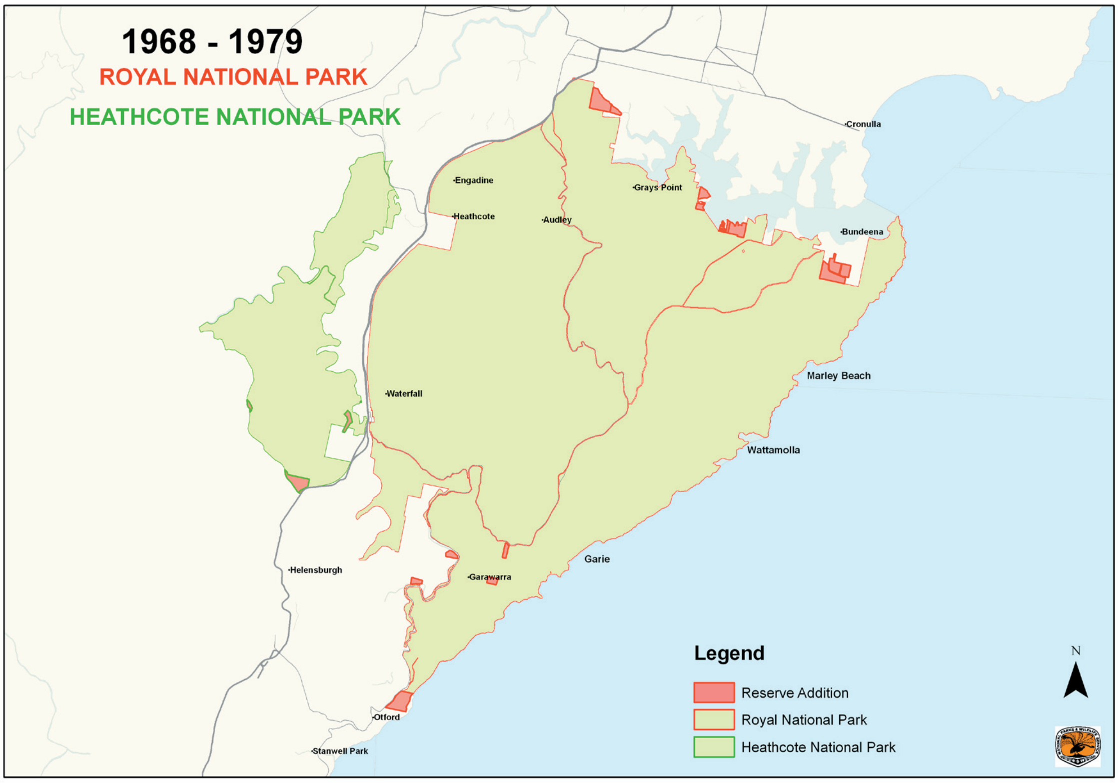


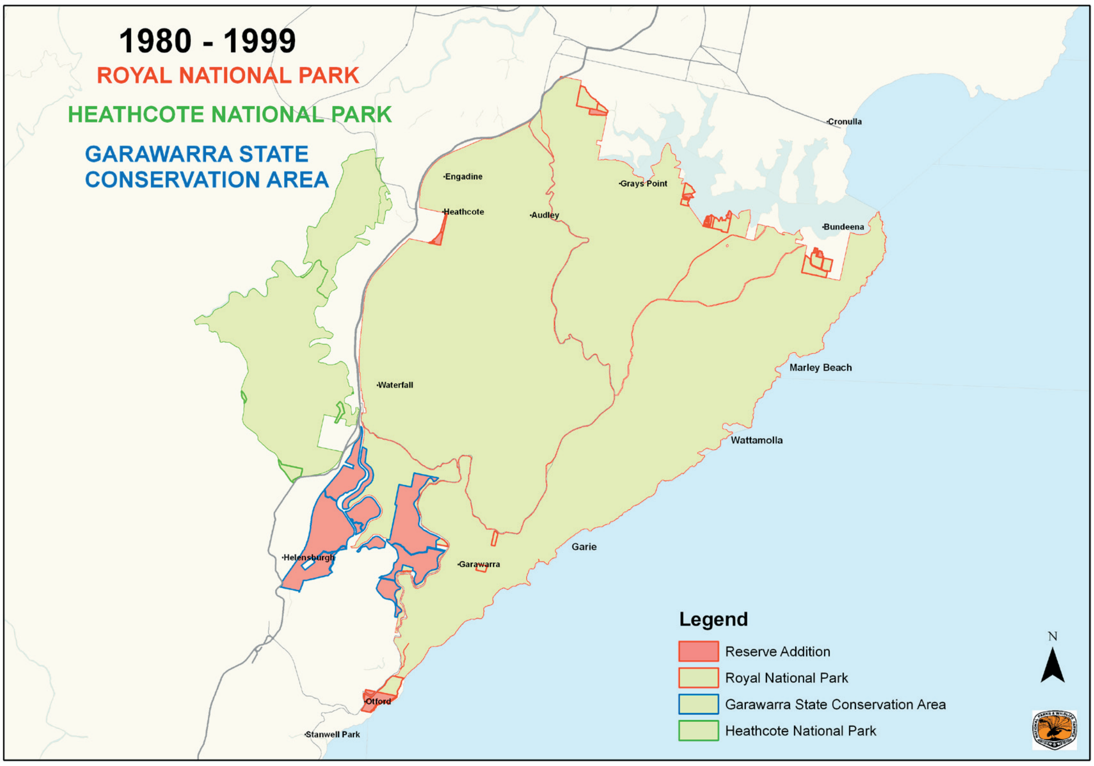


16 c above, 16 d below



16 e above, 16 f below





16 g above, 16 h below

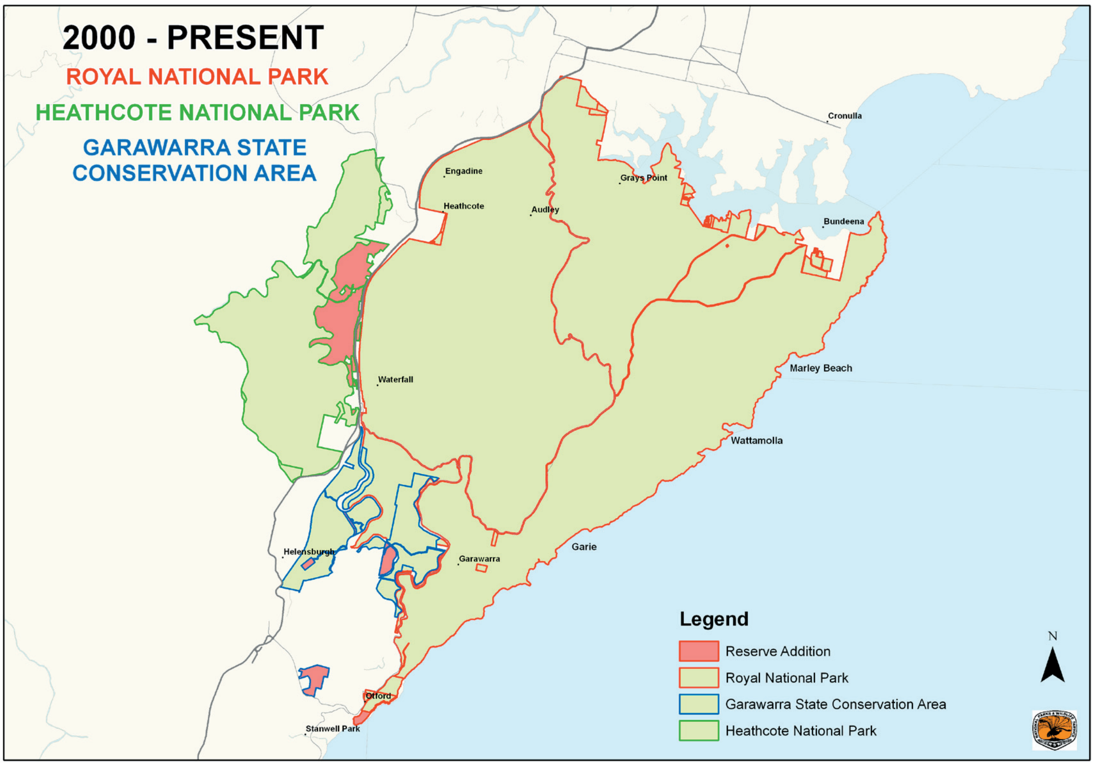
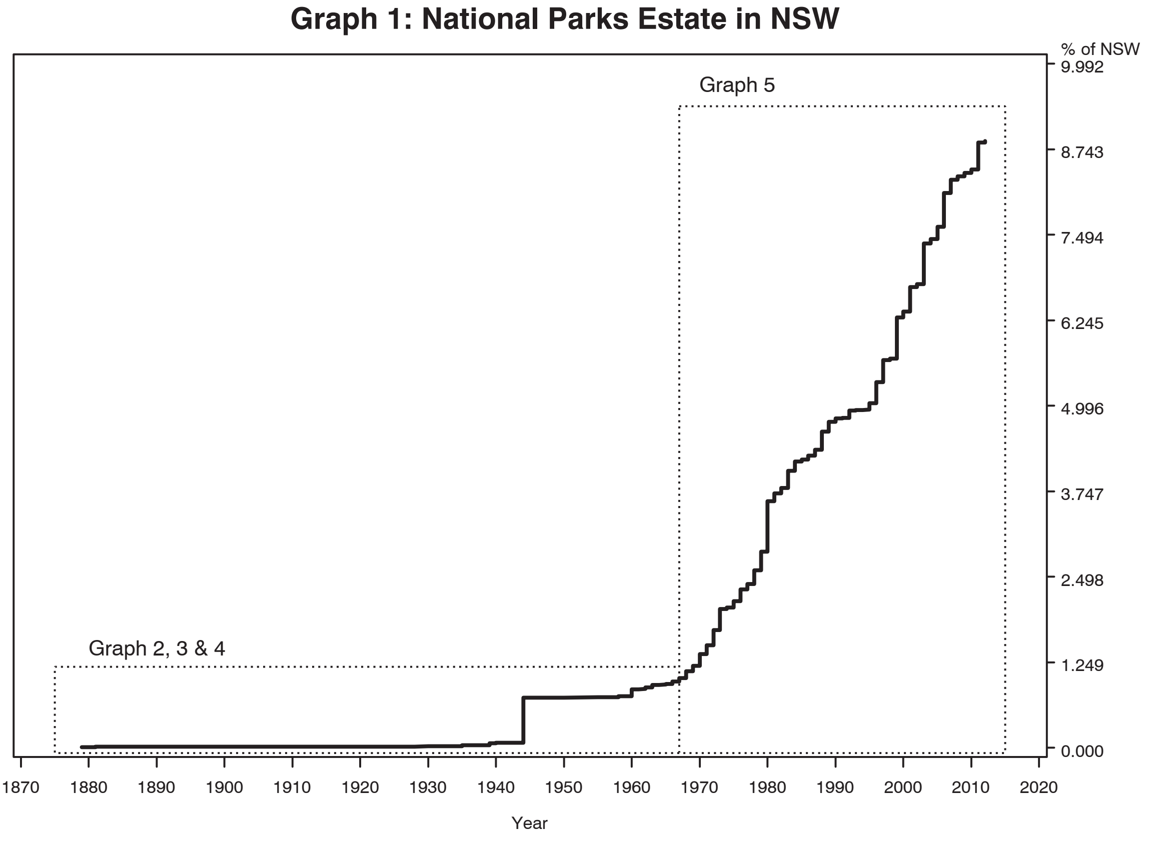
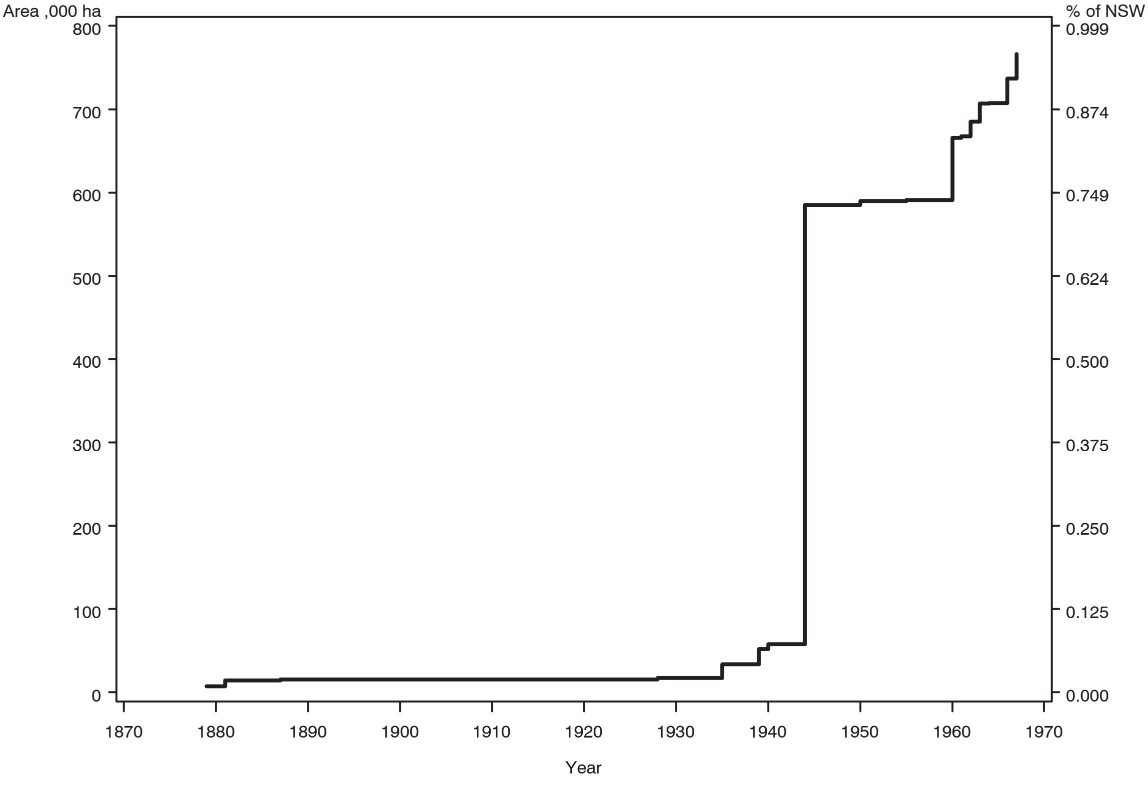


Fig. 17 (next 3 pages). The growth of NSW National Parks and Nature Reserves from the dedication of Royal National Park in 1879 to the end of the 2011-12 financial year.

Fig. 17 has been produced as a series of graphs, numbered 1-5. Graph 1 provides a context for the four subsequent graphs, which have been constructed using the same data but are produced on different scales corresponding to the area involved. Graph 2 shows the area of National Parks from 1879 until the formation of the NSW National Parks and Wildlife Service in 1967, which integrated the selection and management of National Parks and Nature Reserves into one organisation. Note that the scale has been adjusted from Graph 1 to show more detail, in accordance with the smaller areas of National Parks prior to 1967. Graph 3 shows the area of Nature Reserves from 1955-1967, dedicated under the *Fauna Protection Act* 1948. Graph 4 shows Graphs 2-3 combined. Graph 5 shows the growth of both National Parks and Nature Reserves in the period 1967-2012. In Graphs 2-5, one vertical axis shows area and the other shows the percentage of NSW that is dedicated as National Parks and Nature Reserves. These graphs are original. While the information to construct the 1897-1967 graphs is formally available, it is difficult to locate. However, we were able to construct these graphs due to the expert help of Mike Prentice and Cathy Johnson of the Reserve Establishment and Land Information Section (OEH), where meticulous records are kept. The details of the dates and area of dedication of National Parks and Nature Reserves prior to 1967 is given in Appendix 2. These are presented here to provide easy access to these data.

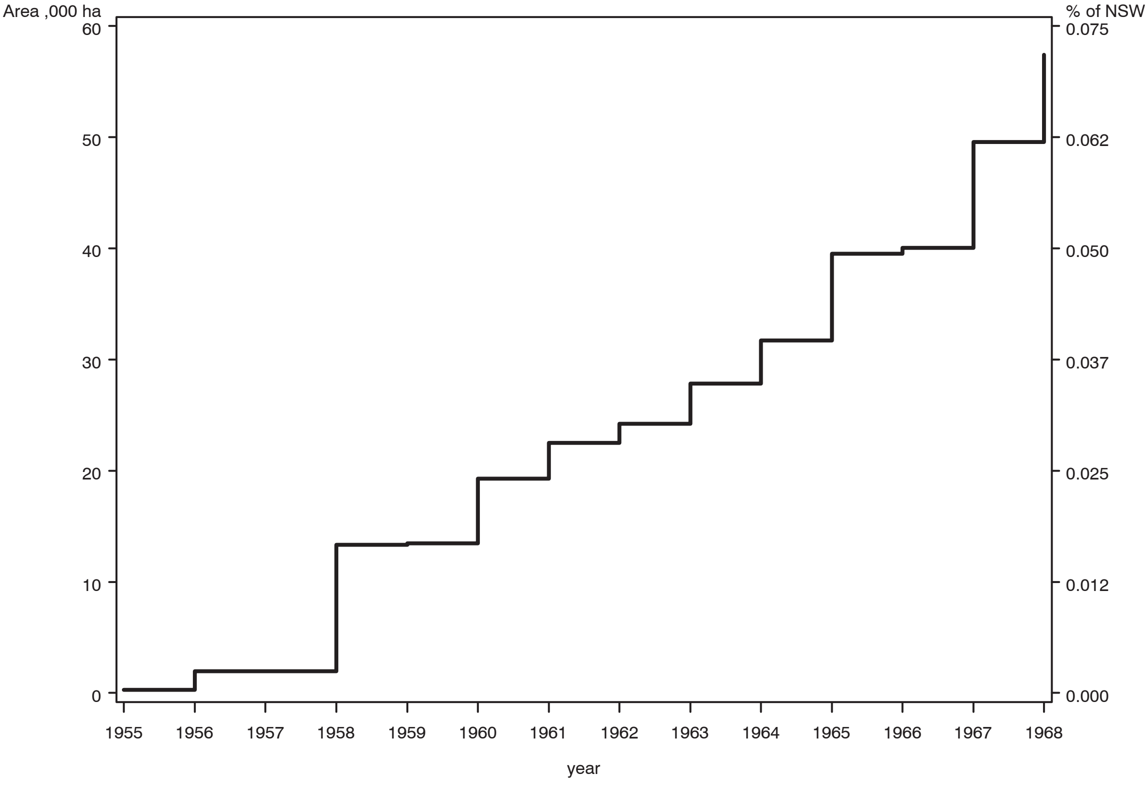


Graph 2: Area of National Parks up to 1967



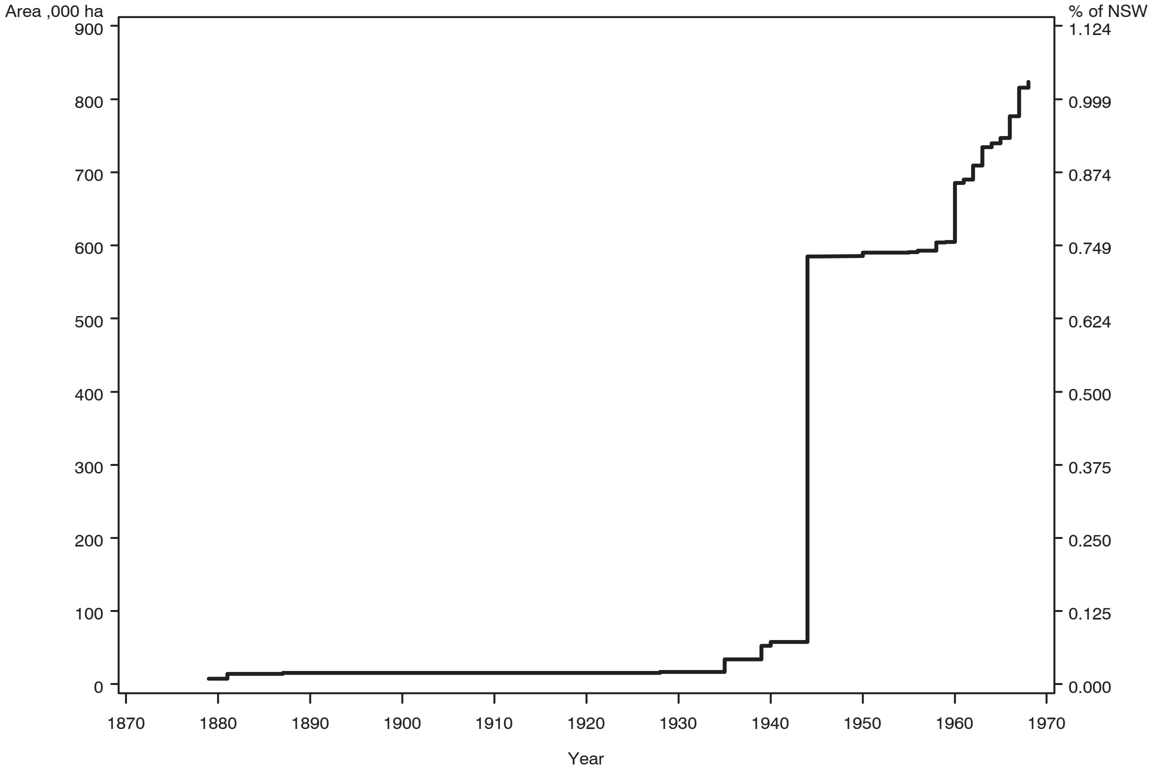
Generated on March 08, 2013 at 1:34:05 PM

Graph 3: Area of Nature Reserves up to 1967



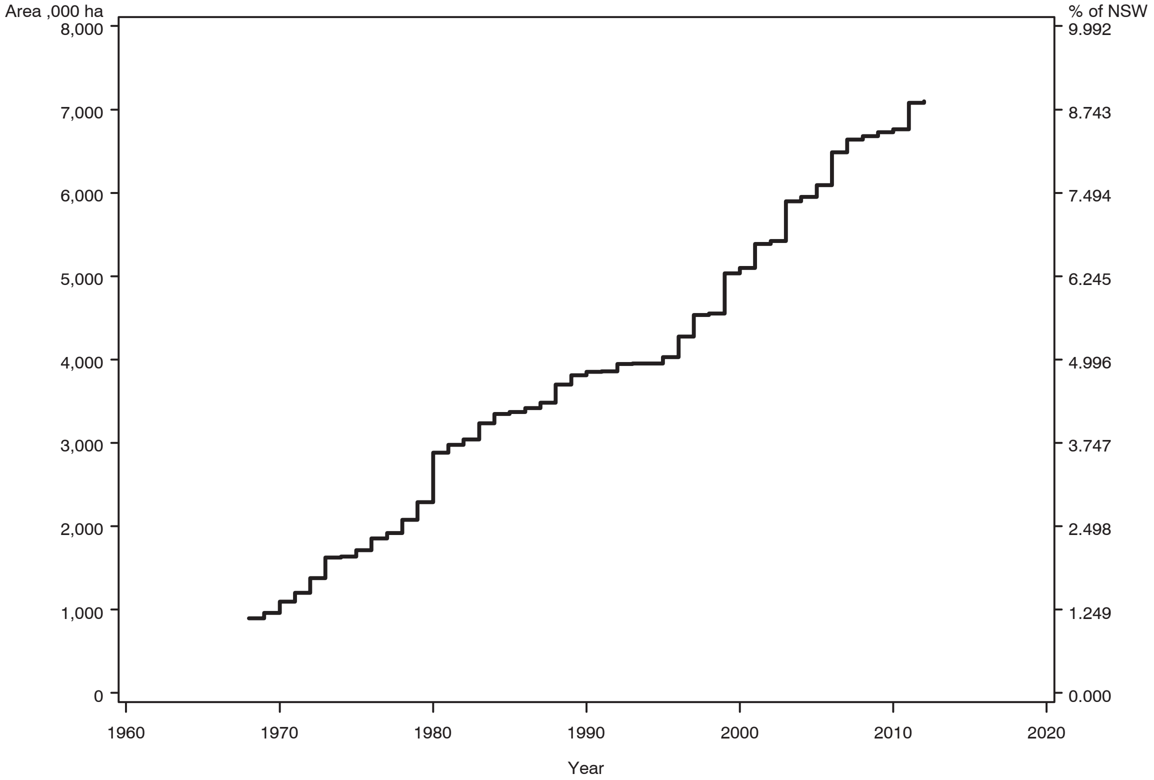
Set up on March 08, 2013 at 1:34:06 PM

Graph 4: National Parks plus Nature Reserves up to 1967



Generated on March 08, 2013 at 1:34:06 PM

Graph 5: National Parks plus Nature Reserves since 1967



Generated on March 08, 2013 at 1:34:06 PM "the exposure of articles for sale" and the hunting of both native and introduced fauna (Elwell 1893: 17). The responsibility for enforcing these policies lies with "all employees of the Park Trust", who have been "sworn in as special constables" and are henceforth "enjoined and empowered" to ensure their effective implementation. In the Trustees' estimation, they have been successful:

"This policy of preservation is already achieving the desired results, for the National Park is now the haunt of a great variety of beautiful birds. […] The almost extinct lyre-bird, free from molestation, can be daily seen, about sunrise and sunset, seeking its food among the brush glades and stately ferns on the banks of Bola Creek. Now and again the satin-bird, the regent-bird, the rifle-bird, all famed for their beauty of plumage, and which, in their wild state, are becoming rarer and rarer owing to the insatiable and wanton cruelty of prowling hoodlums and men of higher degree who degrade the name of sportsman, can be seen flitting from tree to tree in some of the deeper recesses of this guarded reserve."

The paragraph concludes with the only mention of mammals: "A few marsupials remain. Sometimes on a still night the eerie howl of the dingo can be heard on the lonely mountain sides, and the handsomely-marked native cat has been known to leave evidences of nocturnal depredations" (Elwell 1893: 17-18).

A number of points about fauna management can be drawn from these notes. The most striking is that, by 1914, the National Park was seen as a sanctuary for animals. This was not mentioned in 1879. This development could be taken to reflect the influence of the Zoological Society and its interest in acclimatisation, and the particular interests of its convenor and amateur ornithologist Walter Bradley – one of the original Trustees. Either fauna was an unheralded initial interest in setting up National Park, or it was a concern that did not come to fruition until shortly after the park was established and professionally managed. The next point of interest is that the Trustees recognised the incompatibility of stock and national park aims. However, the loss of fauna beyond the park was laid at the door of the hunter, not the clearing of land, nor the running of cattle and sheep. What is evident is the pride in the fact that the National Park did hold birds of such beauty that the Trustees knew would gain public approval. The phrase 'almost extinct' shows an insight into what fate a species might face if not protected. Although it is unclear whether this phrase refers to the state of the lyre-bird population within the Park or within Australia more widely, the use of such language is remarkable given that, at the time, no working knowledge existed of the extinction of any Australian vertebrate. Although Gould recognised that the numbers of certain species were declining, and recognised the possibility of total disappearance, there remains no evidence of any knowledge of past extinction. There were few laws that protected fauna: despite broadening the scope of protection offered to specific fauna, the *Birds and Animals Protection Act 1918* was in many ways ineffective (Stubbs 2001), and it was not until the *Fauna Protection Act 1948* that native birds and mammals received widespread legislative protection which provided for the establishment of faunal reserves. Jarman and Brock (2004) provide a history of these laws and the evolution of the concept of 'endangered species'.

As an ecologist with a particular interest in fauna conservation, I look at Royal National Park in a regional context, with a particular interest in the koala *Phascolarctos cinereus*. Royal National Park does not hold the high quality habitat that koala populations need to survive. It does hold patches of koala habitat, but it is the land in and around Campbelltown, to the west of Royal National Park, with an arc of land to the south, that carries koala habitat, and indeed a koala population that has been there continuously since European settlement (Lunney et al. 2010a,b). Koalas can literally walk from Campbelltown to Royal National Park; indeed, tagged koalas have demonstrated this ability. In view of this, the Park can be recolonised, with the major barrier being the Princes Highway, a killing zone on the western edge of Royal National Park. It is the position of koalas in Royal National Park, or the current lack of koalas, that Tim Flannery has targeted to expose what he sees as the weakness of our national parks in regard to wildlife conservation. Flannery's argument is brief: "If we look around at our national parks today, what we see in the great majority of cases are marsupial ghost-towns, which preserve only a tiny fraction of the fauna that was there in abundance two centuries ago. A classic example is Royal National Park south of Sydney. It's the nation's oldest park, yet over the last few decades it has lost its kangaroos, its koalas, its platypus and greater gliders. Clearly, it is a fallacy to believe that proclaiming more such reserves will do very much to preserve Australian wildlife." (2003:39)

My interpretation of koala distribution is that it is much more tied to factors such as soil fertility, watered lands and nutrient-rich leaves. The lands which fit these criteria are now mostly agricultural lands, which have largely been cleared so that habitat loss is the primary cause of the decline of the koala in NSW (Reed et al. 1990; Reed and Lunney 1990). Koala conservation is an issue for land use planning to protect koala habitat on private land, as is the management of other threats, such as fire, dog attack, disease and death on the roads, as stated in the NSW 2008 Koala Recovery Plan (DECC 2008). There are plans in place to tackle these matters and the Senate (2011) recently released its findings into the health and status of the koala. It is concerned for its future in Australia. It did not, however, identify the supposed failure of national parks as a problem. Flannery is right to point out that we cannot rely solely on national parks and nature reserves to conserve all our wildlife, for their conservation does depend heavily on the lands with the rich soils, which of course were the ones cleared early and so comprehensively (Lunney & Moon 2012). However, it is hard to read such a sensible cautionary note into Flannery's sentences. It is easier to read his text as being dismissive of parks and reserves for conserving wildlife. In this regard, his argument is reminiscent of the criticism of the reserve system contained in the Commonwealth's 1996 *State of the Environment* report, which contended that as the existing system did not reflect terrestrial biodiversity, it had "only limited value as an antidote" to the threats facing biodiversity (Commonwealth 1996: 49; Lunney 1998).

What is alarming is the logic of the leap that Flannery makes from saying that Royal National Park had lost its koalas to arguing that proclaiming more reserves will not do very much to preserve our wildlife. Flannery had not established that koalas were there at first settlement, or ever flourished there. Partly, this is due to the fact that the fauna records of the Park are patchy and heavily weighted towards recent decades (although he does not acknowledge this). This evidentiary deficiency, however, does not of itself justify Flannery's conclusions. I have yet to find an early record, but my general thesis is that koalas were not likely to be present so close to the coast because a large population of Aboriginal people, mostly living on the food from the sea and the estuaries, would have hunted any local koalas to extinction. Locations further from the coast, such as Campbelltown, or the adjacent locations, Bargo and Nattai, where the koala was first seen in Australia by Europeans, are more likely because, in my conjecture, the local Aboriginal population would have been at a lower density. The appearance of koalas in Royal National Park may well reflect the loss of the local Aboriginal population of hunters.

It does seem to be a limited argument to select a few large mammals, consider them to be extinct in one location, and thereby write off all the parks and reserves for wildlife conservation. We might note too that Royal National Park was not set up on modern ecological principles for wildlife conservation. Why write off all the national parks and nature reserves on the basis that the first national park in Australia does not hold all of its original fauna? By all means, Flannery can point to the limitations of our parks and reserves for wildlife conservation so that we continue to tackle all the issues facing our fauna, but those limitations present, in my view, no case for abandoning what I regard as the best means we have ever devised for fauna conservation. There is no surprise that the NSW environment minister Bob Debus should reply to Flannery and state: "Let me rebut Dr Flannery's plainly ridiculous allegation that the Royal National Park…is a 'marsupial ghost town'. […] On the contrary, the NPWS is able to demonstrate that the Royal National Park does in fact provide important habitat for numerous small marsupials." He added, "In any event, Royal National Park does not exist in isolation. It is on the very edge of a continuous reserve system that runs for hundreds of kilometres" (2003:114).

The kerfuffle over Flannery's paper raises a number of important points. It shows that we do need to examine the history of an area to be able to interpret it ecologically. Arguably Flannery blundered with koalas because he knew too little about the history of Royal National Park, the specific context for its dedication in 1879, and the history of koala management in Australia. In 1879, koalas, along with other native fauna, were shot for the fur trade and as pests. Lunney and Leary (1988) document the koala fur trade at the end of the 19th century for the Bega district in the Eden region of NSW, and Gordon and Hrdina (2004) document the millions of koalas shot for the fur trade in Queensland in the early 20th century. Given these research findings, it would seem odd to propose that the species was in need of reservation of land. As the early accounts of the Park reveal, it was the Park's beautiful birds and plants that first captured the imagination. Ecological history does rely on getting the historical part of the equation right before one can speculate successfully on the cause and effect of change in wildlife numbers and distribution. The koala story of Royal National Park has not yet run its course, but it will, in my view, not support Flannery's thesis.

Further evidence which challenges Flannery's thesis has been provided by a number of koala sightings in and around the area of Royal National Park. Park rangers have reported finding a deceased koala, initially released at Kentlyn on the west side of the Georges River on 29 July 2012. By late September

2012, the koala had returned to the Sutherland area and was found dead on the western side of the Princess Highway. Additionally, a local resident living in Kirrawee photographed a koala in September 2012 (Fig. 18) from the balcony of their house, located on the northern boundary of the Park adjacent to Savilles Creek. According to Park employee Glenn Harvey (pers. comm 2013), the koala has been observed in this area for "the past couple of years". Furthermore, she states that the koala has also been sighted in the Kirrawee High School grounds and "slightly further north on Hunter Street". Harvey also reports recent sightings of "two koalas at Deer Pool" on 23 March 2013 and of one koala crossing the road at McKell Avenue (near the Park toll box) on 25 March 2013. She states that these were "credible" but unconfirmed sightings.

These sightings demonstrate that koalas inhabit the area to the Park's west and are within walking distance of the Park. This koala population is a continuous population that inhabits Campbelltown and tagged koalas have been recorded as walking as far as Campbelltown to the western edge of the Park (Lunney et al. 2010a). The fact that koalas occur within the Park but have not proliferated is evidence that Royal National Park is essentially not koala habitat. Thus, one could conclude that the Park has not 'lost' its koalas but that, instead, it never had them in abundance. A similar story is emerging for the greater glider (*Petaroides volans*). Andrew et al. (in press) detail the reappearance of the glider after its presumed disappearance in recent decades. Royal National Park was never known for containing many greater gliders, and the extensive fires of 1994 may have eliminated the small population from the Park. This work points to the fact that this glider species was never a common animal in the Park, but is capable of reaching the Park. Thus the Park has, once again, not lost its greater gliders, for it did not (excepting small patches) provide high-quality glider habitat in the first place. More broadly, this points to the importance of conserving lands which encompass the full range of habitats in a state, including the fertile lands which support species such as the koala and the greater glider.

Whatever Flannery's views on the parks and reserves system may have been in 2003, he declares strong support for it in his latest essay 'After the Future'. He contends that "the creation of the national parks system must surely be seen as the principal environmental achievement of the past half- century" (2013: 26). His comments show that even those who criticise the parks and reserves system on the basis of the 'CAR' criteria – comprehensiveness, adequacy, and representativeness – still recognise the intrinsic value and significance of the system. Given the frequency of such criticisms, even among ecologists, it is crucial to acknowledge that the parks and reserves system is an evolving idea. Consequently, one's judgement regarding its adequacy needs to be tempered by an historical perspective which recognises the importance of context. Our focus should lie on how the system might be improved, rather than on its shortfalls in view of contemporary ecological criteria.

Fig. 18. A koala sighted at Gore Avenue, Kirrawee, New South Wales (19 September 2012). Photograph by Erin Meagher.

FUTURE THREATS

At the 'Transforming Australia' conference in July 2011, Flannery launched the report on the climate change forecast for the NSW south coast (Climate Commission 2011a). This impact statement was accompanied by 'The Critical Decade' report (Climate Commission 2011b). Both project an array of worrying impacts. Alongside concerns for biodiversity and the increasing vulnerability of coastal towns due to rising sea levels, the report notes that higher temperatures will increase the likelihood of large and intense fires in the region. At particular risk are areas such as the Royal National Park and the forested escarpment behind Wollongong, including the Woronora Plateau.

As Mooney, Radford and Hancock (2001) demonstrate, fire has long been an issue for the Park, with significant fire events occurring throughout the twentieth century. This raises the issue of scale. In our study of the impact of the 1994 bushfires on the koala population at Port Stephens, we concluded that koalas rapidly re-occupy the burnt forest within months, and are breeding in the forest by the next breeding season (Lunney et al. 2004, 2007). The issue was not how many hectares were burnt, but how many were left.

In the case of Port Stephens, the fire consumed only half of the koala habitat, so recolonisation was rapid, with individual koalas walking up to 1 km per day. For Royal National Park and its non-flying fauna, the central concerns are where the refuges lie, how to manage them, and the fire history of these sites. Fire history is an integral part of an ecological history of an area. Movement from nearby areas is possible, but the barriers, particularly the major roads, are an issue of considerable significance. For koalas, re-colonising from Campbelltown is possible, but greatly hindered by the barrier of the Princes Highway. In this context, the park can be seen as too small for some species, but not a 'ghost-town'.

The International Union for Conservation of Nature's selection of Australia as the host of the 2014 World Parks Congress reflects a growing international recognition of the global significance of Australia's parks. It is therefore opportune to place Royal National Park in historical and ecological perspective. Given that the Park has existed for 135 of the 226 years since the European settlement of Australia, it reflects enormous changes in Australian society; indeed, it can be taken as a barometer of social and political attitudes, especially in regard to the development of a conservation ethic. In the years since its dedication, our understanding of what constitutes a national park has undergone a distinctive intellectual shift. This has paralleled a transformation of our understanding of fauna conservation and land use, and the role of government in the management of land. It is tempting to examine Royal National Park solely from an historical perspective or an ecological one; what is more novel is integrating the two interpretive frameworks in order to understand what the dedication of the park signified in 1879, and how this has since changed. For the Park, this has meant analysing a variety of sources, including maps, records of fauna, media reports, and statistical data. Looking at the environment of the park in the context of its socio-political history, as a major part of our first steps toward nature conservation, and in view of future threats, all point to the necessity of integrating historical and ecological thinking.

ACKNOWLEDGEMENTS

I am indebted to many colleagues over the 43 years I have worked for OEH and its predecessors, particularly the NSW National Parks and Wildlife Service for their insights and appreciation of Royal National Park. In particular, I thank Mike Prentice, Cathy Johnson, Murray Robinson and Rob Dick for their information regarding the dates of park dedication and area size, and to biometrician Ian Shannon for the excellent graphs of the growth of national parks and nature reserves in NSW since 1879. I also thank Cathy Johnson for her efforts in creating Fig. 11 and Figs. 16a-g. I am indebted to Judith Carrick for kindly allowing me to draw on her soon-to-be-published history of Royal National Park. Finally, I am indebted to Antares Wells for applying her skills as an historian to reshaping this manuscript and thus enabling the more effective integration of historical and ecological strands of thinking.

REFERENCES

Adam, P. (2012). Royal National Park – Lessons for the Future from the Past. *Proceedings of the Linnean Society of NSW* **134**, 7-24.

Andrew, D., Koffel, D., Harvey, G., Griffiths, K., and Fleming, M. (In press). Rediscovery of the Greater Glider *Petauroides volans* (Marsupialia: Petauroidea) in the Royal National Park, NSW. Australian Zoologist 36, X-X.

Anon. 1879a. Places of Public Recreation. The Sydney Morning Herald (19 February): 3. Anon. 1879b. News of the Day. The Sydney Morning Herald (25 March): 5.

Anon. 1879c. News of the Day. *The Sydney Morning Herald* (26 March): 5.

Anon. 1879d. A National Park. *The Sydney Morning Herald* (29 March): 3.

Anon. 1879e. Untitled. *The Sydney Morning Herald* (2 April): 4.

Attenbrow, V. (2012). The Aboriginal Prehistory and Archaeology of Royal National Park and Environs: A Review. *Proceedings of the Linnean Society of NSW* **134**, 39-64.

Benson, D., and Howell, J. (1990). 'Taken for granted: The bushland of Sydney and its suburbs'. (Kenthurst, N.S.W. : Kangaroo Press).

Briggs, J., Spielmann, K., Schaafsma, H., Kintigh, K., Kruse, M., Morehouse, K., and Schollmeyer, K. (2006). Why ecology needs archaeologists and archaeology needs ecologists. *Frontiers in Ecology and the Environment* **4**, 180–188.

Carrick, J.A. (2014). 'History of Royal National Park'. (Published by Judith Carick, Austinmeer, NSW, Australia)(page numbers in text refer to the pre-publication draft).

Climate Commission Secretariat [Department of Climate Change and Energy Efficiency]. (2011a). The Critical Decade: Illawarra / NSW South Coast Impacts [Online]. Available at: <http://climatecommission.gov.au/wp-content/uploads/4246-CC-Wollongong-Key-Messages_web.pdf> [Accessed 04/03/2013].

Climate Commission Secretariat [Department of Climate Change and Energy Efficiency]. (2011b). The Critical Decade: Climate Science, Risks and Responses [Online]. Available at: <http://climatecommission.gov.au/wp-content/uploads/The-Critical-Decade_July36revision_Low- res.pdf> [Accessed 04/03/2013].

Commonwealth of Australia. (1996). 'State of the Environment. Australia. 1996'. (Collingwood, VIC : CSIRO). Available at: <http://www.environment.gov.au/soe/1996/publications/report/index.html> [Accessed 10/04/2013].

Conner, N. (2003). Some benefits of protected areas for urban communities: A view from Sydney, Australia. In 'The Urban Imperative: urban outreach strategies for protected area agencies : how those responsible for protected areas can better serve people in large cities and build stronger urban constituencies for nature conservation' (ed. Ted Trzyna) pp. 34-43 (Sacramento : InterEnvironment, California Institute of Public Affairs, 2005).

D'Arcy, P. (2006). 'The People of the Sea: Environment, Identity, and History in Oceania' (Honolulu: University of Hawai'i Press).

Debus, B. (2003). Beautiful Lies: Correspondence. *The Quarterly Essay* **11**, 112-116.

Department of Environment and Climate Change NSW. (2008). 'NSW 2008 Koala Recovery Plan'. Department of Environment and Climate Change, Sydney, N.S.W. Available at: <http://www.environment.nsw.gov.au/resources/threatenedspecies/08450krp.pdf [Accessed 14/02/2013].

Donlan, C. J., and Martin, P. S. (2004). Role of Ecological History in Invasive Species Management and Conservation. *Conservation Biology* **18**, 267-269.

Elwell, T. (1893). 'An Official Guide to the National Park of New South Wales; with map denoting roads, Port Hacking River, and Port Hacking, creeks, brooks and interesting localities, specially prepared views of picturesque scenery, and a general index. Published by authority of the Trustees' (Sydney: Charles Potter, Government Printer).

Farnell, F., Carruthers, J.H., Lee, C.A., McMillan, W., McGowen, J.S.T., Wise, B.R., Sullivan, P.H., Ashton, J., Macfarlane, J., Hogue, J.A., Nobbs, J., Mahony, W.H., McDonald, R., Nielsen, N.R.W., and Cann, J.H. (1914). 'The Official Guide to the National Park of New South Wales'. (Sydney: Government Printer).

Flannery, T. (1994). 'The future eaters: an ecological history of the Australasian lands and people'. (Chatswood, N.S.W. : Reed Books).

Flannery, T. (2001). 'The eternal frontier: an ecological history of North America and its peoples'. (Melbourne, Australia: Text Publishing).

Flannery, T. (2003). 'Beautiful lies: population and environment in Australia'. (Melbourne, Vic.: Black Inc.).

Flannery, T. (2013). After the Future: Australia's New Extinction Crisis. *Quarterly Essay* **48**, 1-80.

Foster, D. (2000). Conservation lessons and challenges from ecological history. *Forest History Today* (**Fall**), 2-11.

Fox, A. (2013). Pers. comm. [29 May].

Garran, A. (ed.) (1974). 'Australia, the first hundred years: being a facsimile of Volumes I & II of the Picturesque Atlas of Australasia, 1888'. Sydney: Ure Smith.

Goodall, H. (2010). Nets, backyards and the bush: the clashing cultures of nature on the Georges River. In 'The Natural History of Sydney' (eds. D. Lunney, P. Hutchings, and D. Hochuli) pp. 35-43 (Mosman, N.S.W. : Royal Zoological Society of New South Wales).

Grove, A., and Rackham, O. (2001). 'The Nature of Mediterranean Europe: An Ecological History'. New Haven; London: Yale University Press.

Hayashida, F. (2005). Archaeology, ecological history, and conservation. *Annual Review of Anthropology* **34**, 43-65.

Harvey, G. (2013). Pers. comm [19 April].

Hrdina, E., and Gordon, G. (2004). The Koala and Possum Trade in Queensland, 1906-1936. *Australian Zoologist* **32**, 543-585.

Jackson, S. T., and Hobbs, R. J. (2009). Ecological Restoration in the Light of Ecological History. *Science* **325**, 567-568.

Jarman, P., and Brock, M. (2004). The evolving intent and coverage of legislation to protect biodiversity in New South Wales. In 'Threatened species legislation: Is it just an Act?' (eds. P. Hutchings, D. Lunney, and C. Dickman) pp. 1-19 (Mosman, N.S.W. : Royal Zoological Society of New South Wales).

Karskens, G. (2009). 'The Colony: a history of early Sydney'. (Crows Nest, N.S.W. : Allen & Unwin).

Keast, A. (1995a). The Sydney ornithological fraternity, 1930s-1950: anecdotes of an admirer. *Australian Zoologist* **30**, 26-32.

Keast, A. (1995b). Habitat loss and species loss: the birds of Sydney 50 years ago and now. *Australian Zoologist* **30**, 3-25.

Keith, D., and Pellow, B. (2005). Effects of Javan Rusa Deer (*Cervus timorensis*) on Native Plant Species in the Jibbon-Bundeena Area, Royal National Park, New South Wales. *Proceedings of the Linnean Society of NSW* **126**, 99-110.

King, R.J. (ed.) (2013). 'Field Guide to Royal National Park, New South Wales'. (Kingsford, N.S.W. : Linnean Society of New South Wales).

Lunney, D. (1998). The role of national parks and nature reserves as a field for science. In 'National Parks: new visions for a new century' (ed. Peter Prineas) pp. 140-149 (Sydney, N.S.W. : Nature Conservation Council of New South Wales).

Lunney, D. (2010). A history of the debate (1948-2009) on the commercial harvesting of kangaroos, with particular reference to New South Wales and the role of Gordon Grigg. *Australian Zoologist* **35**, 383-430.

Lunney, D., Close, R., Bryant, J., Crowther, M.S., Shannon, I., Madden, K., and Ward, S. (2010a). Campbelltown's koalas: their place in the natural history of Sydney. In 'The Natural History of Sydney' (eds. D. Lunney, P. Hutchings, and D. Hochuli) pp. 319-325 (Mosman, N.S.W. : Royal Zoological Society of New South Wales).

Lunney, D., Close, R., Bryant, J., Crowther, M.S., Shannon, I., Madden, K., and Ward, S. (2010b). The koalas of Campbelltown, south-western Sydney: does their natural history foretell of an unnatural future? In 'The Natural History of Sydney' (eds. D. Lunney, P. Hutchings, and D. Hochuli) pp. 339-370 (Mosman, N.S.W. : Royal Zoological Society of New South Wales).

Lunney, D., Fox, A., Catling, P., Recher, H., and Lunney, H. (2012). A contribution to the ecological history of Nadgee Nature Reserve, on the south coast of New South Wales. In 'Australia's Ever- changing Forests: Proceedings of the eighth National Conference on Australian Forest History' (eds.B. J. Stubbs, J. Lennon, A. Specht, and J. Taylor) pp. 95-124 (Canberra, A.C.T.: Australian Forest History Society).

Lunney, D., Gresser, S.M., Mahon, P.S. and Matthews, A. (2004). Post-fire survival and reproduction of rehabilitated and unburnt koalas. *Biological Conservation* **120**, 567-575.

Lunney, D., Gresser, S., O'Neill, L. E., Matthews, A., and Rhodes, J. (2007). The impact of fire and dogs on koalas at Port Stephens, New South Wales, using population viability analysis. *Pacific Conservation Biology* **13**, 189-201.

Lunney, D., and Leary, T. (1988). The impact on native mammals of land-use changes and exotic species in the Bega district (New South Wales) since settlement. *Australian Journal of Ecology* **13**, 67-92.

Lunney, D., and Moon, C. (2012). An ecological history of Australia's forests and fauna, 1770-2010. In 'World Environmental History' (eds. Mauro Agnoletti, Elizabeth Johann and Simone Neri Serneri], in Encyclopedia of Life Support Systems (EOLSS), developed under the Auspices of the UNESCO (Eolss Publishers: Oxford, UK). Available at: < http://greenplanet.eolss.net/EolssLogn/mss/C09/E6- 156/E6-156-26/E6-156-26-TXT.aspx#1._Introduction_> [Accessed10/04/2013].

Maack, M. (2002). NSW Confederation Conservation History. *The Bushwalker* **28**, 3.

McMichael, D. F. (1990). The selection of land for nature conservation purposes in New South Wales. *Australian Zoologist* **26**, 78.

Mooney, S., Radford, K., and Hancock, G. (2001). Clues to the 'burning question': Pre-European fire in the Sydney coastal region from sedimentary charcoal and palynology. *Ecological Management and Restoration* **2(3)**: 203-212.

Mosley, G. (2012). 'The First National Park: A Natural For World Heritage'. (Sutherland, N.S.W. : Sutherland Shire Environment Centre).

N.S.W. Government. (1879). 'An Act to secure the protection of certain Birds and Animals'. Available at: <http://www.legislation.nsw.gov.au/sessionalview/sessional/act/1879-6a.pdf>[Accessed14/02/13].

N.S.W. Government. (1891). 'Deed of Grant, National Park'. (Sydney, N.S.W.: Charles Potter, Government Printer.

N.S.W. Government Gazette. (1879a). No. 34. 31 March 1879. 1384.

N.S.W. Government Gazette. (1879b). No. 148. 26 April 1879. 1923-1924.

N.S.W. Government Gazette. (1879c). No. 42. 6 October 1879. 4482.

N.S.W. Government Gazette. (1879d). No. 42 extension. 25 November 1879. 5249.

N.S.W. Government Gazette. (1880). No. 314. 3 August 1880. 2799.

N.S.W. Government Gazette. (1903). No. 442. 26 August 1903. 6293-6294.

Pettigrew, C., and Lyons, M. (1979). Royal National Park: a history. In 'Australia's 100 Years of National Parks'. (N.S.W. National Parks and Wildlife Service, Sydney, N.S.W.).

Pressey, R. L. (1990). Reserve selection in New South Wales: Where to from here? *Australian Zoologist* **26**, 70-75.

Rackham, O. (2003). 'Ancient woodland: its history, vegetation and uses in England'. (Dalbeattie: Castlepoint Press).

Reed, P. (1990). An historical perspective on: Conserving What? – The basis for nature conservation reserves in New South Wales 1967-1988. *Australian Zoologist* **26**, 85-91.

Reed, P., and Lunney, D. (1990). Habitat loss: the key problem for the long-term survival of koalas in New South Wales. In 'Koala Summit: Managing koalas in New South Wales' (eds. D. Lunney, C.A. Urquhart and P. Reed) pp. 9-31 (Hurstville, N.S.W. : NSW National Parks and Wildlife Service).

Reed, P., Lunney, D., and Walker, P. (1990). Survey of the koala *Phascolarctos cinereus* (Goldfuss) in New South Wales (1986-87), with an ecological interpretation of its distribution. In 'Biology of the koala' (eds. A.K. Lee, K.A. Handasyde, and G.D. Sanson) pp. 55-74 (Chipping Norton, N.S.W. : Surrey Beatty and Sons).

Robin, L. (2013). Being first: why the Americans needed it, and why Royal National Park didn't stand in their way. *Australian Zoologist* **36**, 321-329.

Schulz, M., and Magarey, E. (2012). Vertebrate Fauna: a Survey of Australia's Oldest National Park and Adjoining Reserves. *Proceedings of the Linnean Society of NSW* **134**,

Schulz, M., and Ransom, L. (2010). Rapid fauna habitat assessment of the Sydney metropolitan catchment area. In 'The Natural History of Sydney' (eds. D. Lunney, P. Hutchings, and D. Hochuli) pp. 371-401 (Mosman, N.S.W. : Royal Zoological Society of New South Wales).

Senate of the Commonwealth of Australia. (2011). 'The status, health and sustainability of the koala population. The koala - saving our national icon'. (Canberra, A.C.T., Australia).

Specht, R. L. (1990). Comment on Conserving What? – The basis for nature conservation reserves in New South Wales 1967-1988. *Australian Zoologist* **26**, 76-77.

Starling, J. (1990). Comments on an article by J. Whitehouse. Australian Zoologist 26, 79-80.

State Records NSW. (Undated). Miscellaneous papers re: proposed national park. Series: 10723. Item: 9/2188 (1 box, undated).

Stanley, H. (c1976). History of Royal National Park. Unpublished manuscript. Available at Office of Environment & Heritage Library, Hurstville NSW 2220.

Stubbs, B. (2001). From 'Useless Brutes' to National Treasures: A Century of Evolving Attitudes towards Native Fauna in New South Wales, 1860s to 1960s. *Environment and History* **7**, 23-56.

Trzyna, T. (ed.) (2003). 'The Urban Imperative: urban outreach strategies for protected area agencies: how those responsible for protected areas can better serve people in large cities and build stronger urban constituencies for nature conservation'. Proceedings of a workshop at the Fifth World Parks Congress, Durban, South Africa, 8-17 September 2003. (Sacramento : InterEnvironment, California Institute of Public Affairs, 2005).

Vermeij, G. (1987). 'Evolution and Escalation: An Ecological History of Life'. Princeton: Princeton University Press.

Whitehouse, J. F. (1990a). Conserving What? The Basis of Nature Conservation Reserves in New South Wales 1967-1989. *Australian Zoologist* **26**, 11-21.

Whitehouse, J. F. (1990b). The Future of Nature Conservation Reserve Establishment Programmes. *Australian Zoologist* **26**, 96-100.

APPENDIX 1

Gallery: Linnean Society Conference (September – October 2011). All photos by Dan Lunney.

Emma Gorrod loading Paul Adam's Royal National Park presentation in the conference room at Kamay Botany Bay National Park (29 September 2011).

Val Attenbrow on the Forest Path explaining the Aboriginal use of the Park (1 October 2011).

David Keith on the Forest Path, Royal National Park (1 October 2011).

David Keith on the heath in Royal National Park, showing where some of his long-term plots are located (1 October 2011).

John Pickett describing the geological attributes of a site (1 October 2011). What is most prominent in the photo is the clearing, and it shows what the park would look like if it were to be cleared, or had been cleared in the previous two centuries.

A sure sign of the continuing presence of the cryptic Javan rusa deer (*Cervus timorensis*) in Royal NationaLPark (1 October 2011).

John Pickett explaining the geological basis of Royal National Park (1 October 2011).

A felled tree on the Forest Path, part of which still remains, as does the stump. A education notice nearby states: “Logging was permitted on at least two occasions in the first quarter of this [20th] century”.

Appendix 2. Parks and Reserves (pre-1967).

Park/Reserve	Modifications	Financial Year	Area (Ha)
Royal NP	1	1879	7284.34
	2 (+)	1881	14164.00
	3 (+)	1883	14171.69
	4 (+)	1887	14698.18
	5 (+)	1900-1964	15383.72
	6 (+)	1964	15769.39
	7 (-)	1966	14384.55
	8 (-)	1967	14250.20
	9 (+)	1967	14851.96
Blue Mountains NP	1	1960	62726.27
	2 (+)	1963	68739.9
	3 (+)	1966	95028.28
	4 (+)	1967	98772.03
	5 (-)	1967	98367.34
Brisbane Water NP	1	1960	6070.28
	2 (+)	1960	6147.98
	3 (+)	1965	6181.98
	4 (+)	1966	6610.94
	5 (+)	1967	6692.69
	6 (-)	1967	6691.48
Dharug NP	1	1967	11748.83
Gibraltar Range NP	1	1963	13961.65
	2 (+)	1966	15378.05
Kosciusko NP (now Kosciuszko)	1	1944	527019.68
	2 (+)	1945	527270.59
	3 (+)	1950	531438.85
	4 (+)	1950	531756.93
Ku-ring-gai Chase NP	1	1962	14244.93
	2 (-)	1962	14238.46
	3 (-)	1967	14187.47
	4 (+)	1967	14285.4
Morton NP	1	1939	18210.85
	2 (+)	1963	18213.69
	3 (+)	1965	18214.9
	4 (-)	1965	18214.5
	5 (+)	1967	18240.8
Mount Kaputar NP	1	1960	4168.26
	2 (+)	1967	14244.93
New England NP	1	1935	16855.16
	2 (+)	1940	22520.76
	3 (+)	1942	22723.1
	4 (+)	1959	22724.72
	5 (-)	1959	22723.1
	6 (-)	1967	22237.48
	7 (+)	1967	22844.5

Warrumbungle NP	1	1962	3237.49
	2 (+)	1967	6239.04
Barangary State Park	1	1887	849.84
	2 (-)	1967	797.23
Bouddi State Park	1	1959	473.48
	2 (+)	1959	518
	3 (+)	1967	530.14
Bundanoon State Park	1	1961	1347.6
Dorrigo State Park	1	1928	1416.4
	2 (-)	1930	1415.59
	3 (+)	1936	1566.13
Gloucester Tops State Park	1	1960	1550.76
Heathcote State Park	1	1963	1578.27
Mount Warning State Park	1	1966	2116.51
Muogamarra State Park	1	1955	829.61
	2 (+)	1962	1120.98
	3 (-)	1967	1112.89
Bare Island Historic Site	1	1965	1.21
Captain Cook's Landing Place	1	1900	95.51
	2 (+)	1965	105.22
	3 (+)	1967	283.28
Hill End Historic Site	1	1967	27.52
La Perouse Monuments Historic Site	1	1956	7.28
	2 (+)	1967	7.69
Mootwingee Historic Site	1	1967	485.62
Vaucluse House Historic Site	1	1967	7.69
Barren Grounds Nature Reserve	1	1956	1489.241
	2 (+)	1960	1776.5674
Bell Bird Creek Nature Reserve	1	1965	53.4184
Bermaguee Nature Reserve	1	1967	607.0275
Bird Island Nature Reserve	1	1960	7.2843
Black Ash Nature Reserve	1	1965	89.0307
Boondelbah Nature Reserve	1	1960	9.3078
Boorganna Nature Reserve	1	1955	267.0921
	2 (+)	1958	308.2688
	3 (+)	1962	382.7308
Bowraville Nature Reserve	1	1963	54.6325
	2 (+)	1964	58.477
Brush Island Nature Reserve	1	1964	46.5388
Buddigower Nature Reserve	1	1964	137.5929
Cocopara Nature Reserve	1	1964	1308.347
	2 (+)	1965	4646.998
Cook Island Nature Reserve	1	1960	4.6539
Coolbaggie Nature Reserve	1	1963	381.2133
Cudmirrah Nature Reserve	1	1959	125.4522
Curumbenya Nature Reserve	1	1965	2832.795
	2 (+)	1967	8599.556

Devils Glen Nature Reserve	1	1965	40.4685
Five Islands Nature Reserve	1	1960	26.7092
Georges Creek Nature Reserve	1	1968	1189.774
Goonawarra Nature Reserve	1	1967	437.0598
Goura Nature Reserve	1	1967	390.521
Gurumbi Nature Reserve	1	1956	151.757
Illawong Nature Reserve	1	1964	50.5856
John Gould Nature Reserve	1	1955	26.3045
Julian Rocks Nature Reserve	1	1961	0.4047
Limpinwood Nature Reserve	1	1963	2321.273
	2 (+)	1967	2442.6785
Lion Island Nature Reserve	1	1956	8.0937
Little Broughton Island Nature Reserve	1	1961	36.4217
Macquarie Nature Reserve	1	1966	2.4477
Manobalai Nature Reserve	1	1968	2913.732
Moon Island Nature Reserve	1	1960	1.0117
Mount Seaview Nature Reserve	1	1965	194.2488
Munghorn Gap Nature Reserve	1	1961	2853.029
	2 (+)	1968	2994.6688
Muogamarra Nature Reserve	1	1960	303.5147
	2 (+)	1965	801.2788
	3 (+)	1967	803.9093
Nadgee Nature Reserve	1	1958	11331.18
	2 (+)	1961	11655.9397
	3 (+)	1966	11836.0245
Narrandera Nature Reserve	1	1966	72.8433
North Rock Nature Reserve	1	1959	4.0469
Pulletop Nature Reserve	1	1963	145.0796
Quanda Nature Reserve	1	1963	429.3708
	2 (+)	1967	853.8854
Round Hill Nature Reserve	1	1960	5179.968
	2 (+)	1964	5252.8113
	3 (+)	1967	5637.2621
Rowleys Creek Gulf Nature Reserve	1	1962	1659
Sherwood Nature Reserve	1	1967	1359.742
South West Solitary Island Nature Reserve	1	1961	3.2375
Split Solitary Island Nature Reserve	1	1961	3.6422
Tabletop Nature Reserve	1	1966	103.5184
The Basin Nature Reserve	1	1964	2272.711
The Charcoal Tank Nature Reserve	1	1966	86.4002
The Hole Gulf Nature Reserve	1	1965	737
The Rock Nature Reserve	1	1963	271.139
Tollgate Islands Nature Reserve	1	1959	12.1406

Tucki Tucki Nature Reserve	1	1963	1.4948
	2 (+)	1964	3.2375
	3 (+)	1967	4.0026
Winburndale Nature Reserve	1	1968	3642.165
Wongarbon Nature Reserve	1	1966	99.1478

Appendix 3. National Parks Estate (1968-2013) at 30 June of the financial year.

Financial Year	Area (ha)
1968	894,872
1969	960,901
1970	1,096,776
1971	1,201,814
1972	1,379,278
1973	1,626,702
1974	1,638,563
1975	1,714,789
1976	1,852,407
1977	1,917,887
1978	2,076,950
1979	2,291,591
1980	2,884,692
1981	2,975,628
1982	3,039,640
1983	3,236,999
1984	3,346,667
1985	3,368,447
1986	3,415,196
1987	3,485,124
1988	3,697,308
1989	3,811,073
1990	3,853,541
1991	3,859,959
1992	3,945,810
1993	3,951,314
1994	3,955,318
1995	4,030,559
1996	4,273,545
1997	4,536,513
1998	4,553,084
1999	5,032,553
2000	5,099,674
2001	5,387,102
2002	5,419,344
2003	5,899,882
2004	5,948,814
2005	6,092,447
2006	6,487,055
2007	6,641,256
2008	6,682,405
2009	6,725,069
2010	6,763,629
2011	7,077,769
2012	7,079,707
2013	7,083,343

A Comparative Study of the Australian Fossil Shark Egg-Case *Palaeoxyris duni*, with Comments on Affinities and Structure

GRAHAM McLEAN

21 Loxton Place, Forestville, NSW 2087, Australia. (mcleangg@bigpond.com)

McLean, G. (2014). A comparative study of the Australian fossil shark egg-case *Palaeoxyris duni,* with comments on affinities and structure. *Proceedings of the Linnean Society of New South Wales* **136**, 201-218.

The enigmatic fossil noted by Dun in 1913 as *Spirangium* and named by Crookall in 1930 as *Palaeoxyris duni* is described in detail in the light of the discovery of other *Palaeoxyris* specimens, which are now accepted by most workers to be shark egg-cases. *Palaeoxyris duni* is the only Australian shark egg-case yet described and is one of the largest *Palaeoxyris* species so far discovered. Comparison of the macro morphology of *P. duni* with other described *Palaeoxyris* specimens confirms that it is a separate form species. The palaeoenvironment in which *P. duni* was deposited was a Triassic low lying fluvial and lacustrine coastal floodplain. One of the Triassic species of hybodontid sharks was the possible egg producer as these fishes have been shown to penetrate freshwater environments. The process of egg production in the nidamental gland of modern sharks is applied to conjecture about the egg-case structure of ancient sharks. The egg-cases of *Heterodontus* have a helical structure broadly similar to that of *Palaeoxyris* except that *Palaeoxyris* have four or six bands in their construction compared to two for the modern *Heterodontus*. Evidence of shark nurseries, clustered egg-cases and tendril attachment of *Palaeoxyris* egg-cases indicates ancient shark breeding behaviour was similar to that of modern oviparous sharks.

Manuscript received 1 March 2013, accepted for publication 23 July 2014.

Keywords: Beacon Hill, Brookvale, Hybodontoidea, *Heterodontus*, nidamental gland, *Palaeoxyris*, shark egg-case, Sydney Basin, Triassic.

INTRODUCTION

Palaeoxyris was an enigmatic fossil when first described by Brongniart (1828) as a rhombic patterned capsule with tapered ends. Plant and animal affinities were subsequently suggested for these fossils, but mounting evidence of their shark egg-case origin has finally been accepted by most workers (Fischer and Kogan 2008).

Dun (1913) briefly described four imperfect specimens found at the Beacon Hill Quarry in Brookvale, NSW, Australia, classifying them as *Spirangium* and alluding to the possibility that they could be either fructifications of plants or the egg-cases of primitive selachians. Since then, work has been carried out by Crookall (1928, 1930, 1932), Brown (1950), Zidek (1976), Böttcher (2010), Fischer et al. (2010, 2011, 2013) and others on specimens found in Britain, Europe, Kyrgizstan and North America and a considerable amount of taxonomic data has been assembled for specimens found in the northern hemisphere. However, apart from the Brookvale specimens mentioned by Dun (1913) there have been no further specimens described in the southern hemisphere and no detailed comparative taxonomic study has been carried out on the Brookvale specimens.

This paper provides a detailed description of the Brookvale specimens and compares them to other specimens described from the northern hemisphere, as well as discussing the palaeoenvironmental implications and the links to extant shark behaviour and egg-case structure.

BRIEF REVIEW OF HISTORICAL RESEARCH

A thorough historical literature review on *Palaeoxyris* has previously been presented by Fischer and Kogan (2008), but a brief summary of that paper and other references will help put this study into context.

In 1828 Brongniart was the first to describe a rhombically patterned enigmatic fossil which he named *Palaeoxyris regularis,* considering it a plant inflorescence. During the 19th century further similar specimens were discovered. Three form genera were erected (*Palaeoxyris, Vetacapsula* and *Fayolia*) and a number of species named. Workers continued to allocate a plant origin to them, until Beer (1856) compared them to a specimen tentatively identified as an egg-case. Schenk (1867) noted their external similarity to egg-cases of extant sharks. The rhombic pattern on specimens was recognised as a taphonomic effect of compressing a body with spirally wound ribs (Quenstedt 1867; Schenk 1867). However, by the end of the 19th century many workers still considered the fossils to be of plant origin.

Moysey (1910) advanced the argument for a shark origin with a detailed morphological description of pedicle, body and beak and the concept that ancient sharks could enter river estuaries to breed. It was at this time that the only Australian specimens of *Palaeoxyris* were found at the Beacon Hill Quarry in Brookvale, a northern suburb of Sydney. These specimens were referred to the genus *Spirangium* in a brief note by Dun (1913). Crookall (1928, 1930, 1932) presented a series of detailed studies of the morphology and affinities of the three form genera, drawing on specimens from the Carboniferous Coal Measures of Britain and Europe, and named many new species, including the Australian specimens which he named *Palaeoxyris duni.* Crookall (1932) rejected a plant origin for these genera and advocated the elasmobranch egg-case hypothesis. After Crookall's thorough analyses, discussion turned to the most likely producer of the eggs. Both xenacanthid and hybodontid sharks were suggested, and palaeoecological studies were carried out to link shark remains with the egg-case sites (Zidek 1976). Additional specimens were described from North America (Brown 1950; Zidek 1976).

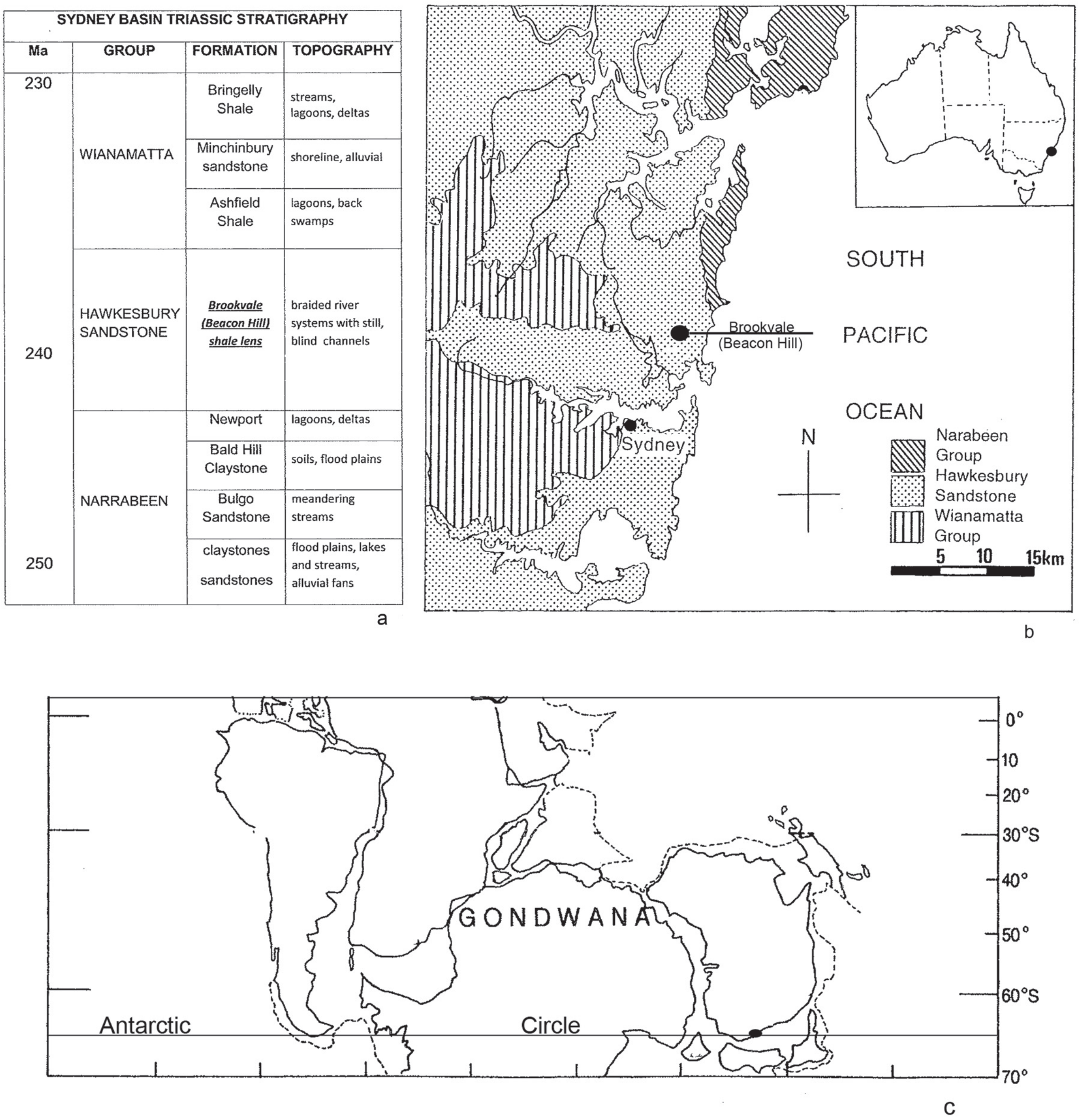
By the beginning of the 21st century new evidence pointed to hybodontid sharks being the producers of *Palaeoxyris* and xenacanthids being producers of *Fayolia* (Fischer and Kogan 2008), whereas the producer of *Vetacapsula* has been attributed to the holocephalans (Fischer et al. 2013). Elasmobranch egg-cases were found in Kyrgyzstan (Fischer et al. 2007), Triassic *Palaeoxyris* have been found in North America (Fischer et al. 2010) and Germany (Böttcher 2010), and Triassic juvenile shark teeth microfossils have been discovered in association with *Palaeoxyris* in Kyrgyzstan (Fischer et al. 2011). Fischer et al. (2013) carried out a phylogenetic analysis of the morphology of ancient and modern chondrichthyan egg-cases as a step towards resolving the identity of the egg producers.

GEOLOGY AND PALAEOENVIRONMENT

Palaeoxyris duni was found within a shale lens embedded in the Middle Triassic Hawkesbury Sandstone of the Sydney Basin (Fig. 1a,b). This sandstone was probably deposited on a vast coastal floodplain that lay close to sea level and contained braided rivers, scour channels, sand dunes and lakes (Conaghan 1980). The shale lenses were formed by deposition of finely suspended sediment in low energy basins (Conaghan 1980), which provided ideal anaerobic conditions in which organisms could be preserved and fossilised.

A comparison between the flora of the Late Carboniferous and the Middle Triassic of this area indicated that the climate had returned to cool temperate after the glaciation of the Permian (Retallack 1980), even though by the Middle Triassic the Sydney Basin was within the Antarctic Circle (the poles were ice free during this period) (Fig. 1c).

The shale lens quarried on Beacon Hill was deposited during the Anisian Stage of the Middle Triassic and was composed of fine grey to black laminated mudstone about eight metres thick. It preserved a wide range of Triassic fossils including the bony fishes *Ceratodus, Megapteriscus, Agecephalichthys, Belichthys, Mesembroniscus, Myriolepis*, *Brookvalia, Cleithrolepis, Macroaethes, Leptogenichthys, Geitonichthys, Molybdichthys, Phlyctaenichthys, Schizurichthys, Manlietta, Procheirichthys, Saurichthys, Promecosemina* (Wade 1932, 1933, 1935; Hutchinson 1973,1975), the temnospondyl *Parotosuchus brookvalensis* (Watson 1958; Welles and Cosgriff 1965), insects *Clatrotitan, Choristopanorpa, Austroidelia, Mesacredites, Prohaglia, Fletcheriana, Mesonotoperla, Triassocytinopsis, Beaconella, Triassodoecus* (Tillyard 1925; McKeown 1937; Riek 1950, 1954; Evans 1956, 1963; Béthoux and Ross 2005), crustaceans *Anaspidites, Synaustrus, Palaeolimnadiopsis* and *Estheria* (Chilton 1929; Brooks 1962; Riek 1964, 1968; Webb 1978), the xiphosurian *Austrolimulus fletcheri* (Riek 1955, 1968), the mollusc *Protovirgus brookvalensis* (Hocknull 2000) and plants *Lepidopteris, Dicroidium*, *Cladophlebis, Ginkgoites, Rissikia, Taeniopteris, Xylopteris, Phyllotheca, Marchantites, Rienitsia, Asterotheca, Cylostrobus* (Townrow 1955; Retallack 1977, 1980, 2002; Holmes 2001). This biota points strongly to a freshwater environment.



SYDNEY BASIN TRIASSIC STRATIGRAPHY

Ma	GROUP	FORMATION	TOPOGRAPHY
230	WIANAMATTA	Bringelly Shale	streams, lagoons, deltas
		Minchinbury sandstone	shoreline, alluvial
		Ashfield Shale	lagoons, back swamps
240	HAWKESBURY SANDSTONE	***Brookvale (Beacon Hill) shale lens***	braided river systems with still, blind channels
	NARRABEEN	Newport	lagoons, deltas
		Bald Hill Claystone	soils, flood plains
		Bulgo Sandstone	meandering streams
250		claystones sandstones	flood plains, lakes and streams, alluvial fans

Figure 1 - a. Sydney basin stratigraphic timeline showing the position of the Brookvale (Beacon Hill) shale lens and the topographies during sedimentation. (Data sourced from Packham 1969; Herbert and Helby 1980) b. Location of the Brookvale (Beacon Hill) site (modified after Damiani 1999). c. In the Early Triassic the Sydney Basin entered the Antarctic Circle as Gondwana, containing Australia, drifted south (modified after Hallam 1994).

INSTITUTIONAL ABBREVIATIONS

AM – Australian Museum, Sydney, New South Wales.
BMNH – Natural History Museum, London.
MM – Geological Survey of New South Wales (refers to Mining Museum).

SYSTEMATIC DESCRIPTION

Genus: *Palaeoxyris* Brongniart 1828

Type species: *Palaeoxyris regularis* Brongniart 1928 – Anisian, Middle Triassic. Vosges, France.

Diagnosis: (after Fischer et al. 2011:943) – "Chondrichthyan egg capsule; three-fold division into beak, body, and pedicle; body broadly fusiform, gradually tapering toward each end, composed of three or more parallel helicoidally twisted bands; anterior end gradually tapering into shorter pointed beak; posterior end tapering to long slender pedicle marked by either spiral ribbing or parallel ribs; collarettes accompanying band margins; fine longitudinal striations on bands and collarettes; compressed specimens with transverse rhomboidal pattern".

Palaeoxyris duni Crookall 1930

Synonomy: *Spirangium*: Dun 1913, 205-206 pl.14.
Holotype: MMF 42697a (Figs 2, 3a,b,c, 4a)
Paratype: MMF 42697b (Figs 2, 3d, 4b)
Type Horizon: Hawkesbury Sandstone Formation, Anisian, Middle Triassic (within a shale lens).
Type Locality: Beacon Hill Quarry, Brookvale, New South Wales, Australia.
Etymology: Named after W.S. Dun, the palaeontologist who first presented the specimen to the Royal Society of New South Wales on Dec 12, 1912 (published 1913).
Storage Location: The two specimens are contained on one block which is deposited in the collection of the Geological Survey of New South Wales at Londonderry, New South Wales, Australia.

Figure 2. *Palaeoxyris duni* holotype MMF 42697a (left) and paratype MMF 42697b (right) on a single slab. Scale bar 10 mm.

Description

Palaeoxyris duni is a chondrichthyan egg-case divided into a beak, a body and a pedicle. The beak is greater than 25 mm long and tapers to a point. The body is fusiform and shows a spiral pattern of ribs, and is approximately 90 mm long and 30 mm wide. The two specimens are compressed and exhibit a rhomboidal pattern of ribs and grooves on the body, which is a result of the rear spiral ribs being impressed as grooves on the front spiral pattern of ribs. The pedicle is slightly waisted, tapers, then proceeds as a parallel stem to its end. The pedicle is at least 90 mm long. The body structure consists of four helical bands with a total clockwise twist of 630 degrees from the beak to the pedicle. The bands are an average of 7 mm wide and the twist rate forms seven segments. The ribs formed by the longitudinal suturing of the bands are 2 mm wide. The tapered ends of the bands form tendrils which run parallel to each other to form the beak and pedicle (i.e. there is no twist in the beak or pedicle).

Remarks

Although Dun (1913) stated that he had four imperfect specimens in his possession, only the block figured in Dun (1913) can now be located.

The single block of fine grey shale (MMF 42697) holds two specimens, one almost complete (MMF 42967a) and one with the beak and a section of the body missing (MMF 42697b) (Fig. 2). MMF 42967a appears to have been abraded after discovery and has lost some of its relief. MMF 42967b retains more structural detail. They are compressed specimens.

MMF 42697a has an incomplete beak 25 mm long and a body 90 mm long. At the first impression it has a pedicle 80 mm long. However, microscopic examination of the apparent end of the pedicle shows that the pedicle appears to be broken at this point and bent back at an acute angle. The broken section can be traced back for five mm, but this still may not be the end which could be buried in the substrate. There is a rhomboidal pattern of ribs and grooves on the body of the specimen. The rhomboidal pattern can be interpreted as four bands spiralling clockwise (Fig. 4c). The bands make an angle of 40 degrees with a latitudinal line running through the centre of the body. Each band travels around the body for 630 degrees,

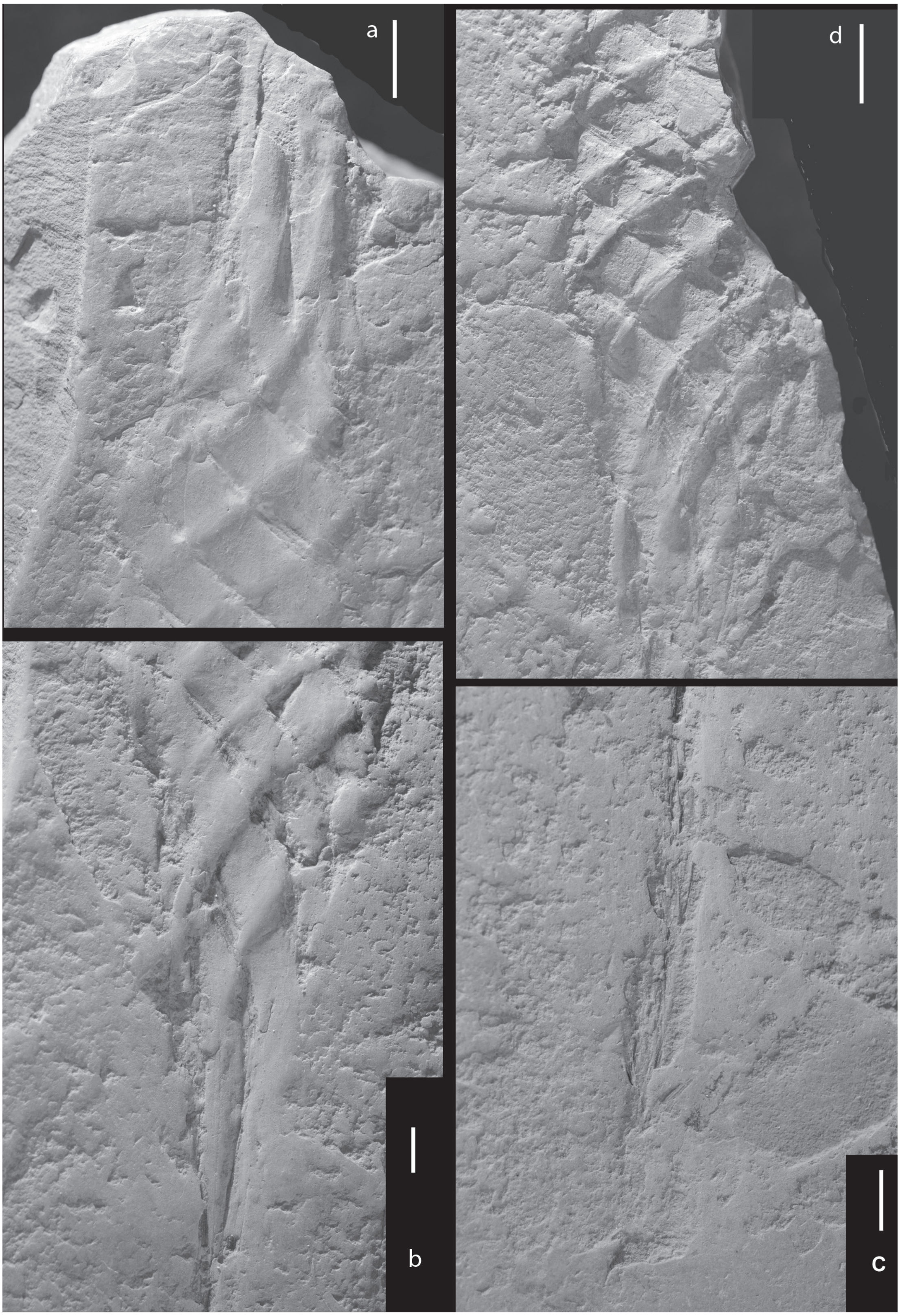


Figure 3 – a. Detail of MMF 42697a beak structure. Scale bar = 7.5 mm. b. Detail of MMF 42697a pedicle structure. Scale bar = 5 mm. c. Detail of MMF 42697a pedicle tip. Scale bar = 5 mm. d. Detail of MMF 4267b ribs showing striae. Scale bar = 10 mm.

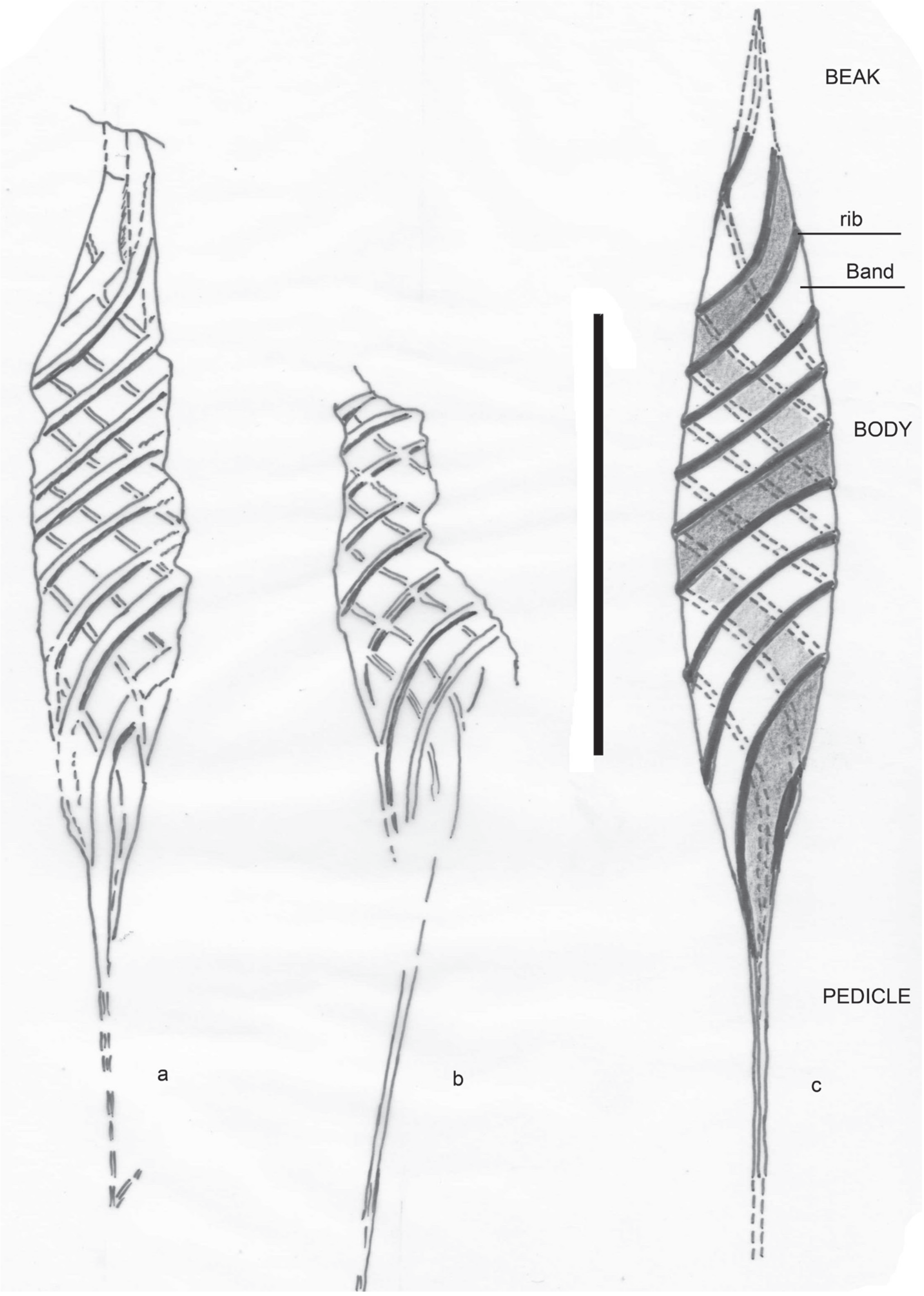


Figure 4 – a. Line tracing of MMF 42697a. b. Line tracing of MMF 42697b. c. Idealised structure of *P. duni* showing the bands wrapping around the body and the band terminations in the beak and pedicle. Scale bar = 100 mm.

then tapers, forming a tendril, and runs parallel with the others longitudinally along the beak and pedicle. The number of segments visible on the body formed by the spiralling bands is seven. Including the ribs, the body is 28 mm wide at the widest point. The ribs have a width of 2 mm. Striae running parallel to the bands are visible on some sections of the grooves. The band margins are defined by ribs, but there are no obvious flanged collarette extensions from the ribs.

MMF 42697b has similar dimensions and a similar rhomboidal pattern of ribs and grooves to MMF 42697a, and is also composed of four bands. Its pedicle is at least 90 mm long. The full length of the pedicle is uncertain as it, too, may have been broken.

However, its total length matches closely the total observable length of the pedicle (including the broken section) of MMF 42697a. The beak and an upper section of the body are missing. Striae are observable in the grooves and there is a faint indication of striae on some sections of the ribs (Fig. 3d).

Comparison with Some Other *Palaeoxyris* Species

From Table 1 it can be seen that *P. duni* has the longest body of any of the Mesozoic taxa and the widest body except for *P. friessi*. Only one species from the Carboniferous has a longer body (*P. bohemica*) and the specimens attributed to this species display a wide range of body sizes which may indicate that more than one species is involved.

The basic structure of all *Palaeoxyris* species is made up of a number of spirally wound bands sutured together longitudinally. Palaeozoic specimens studied early in the 20th century were not analysed for the number of bands. Mesozoic specimens studied later (e.g. Böttcher 2010; Fischer et al. 2010, 2011) were analysed for band number and this analysis showed that all Mesozoic species (with the one exception of one *P. humblei* specimen) were determined to be constructed with four or six bands (Table 1). *P. duni* is one of four Mesozoic taxa to have four bands, whereas another four species have six bands. The total wrap angles of these bands around the body vary from 180 to 630 degrees for those species known. *P. duni* has the highest total band wrap angle of 630 degrees. This high total band wrap angle is a product of a high wrap angle rate and a large body size. Böttcher (2010) observed that all *Palaeoxyris* species have bands that twist in a clockwise direction. Based on the premise that the grooves in the rhombic pattern on the body are the impressed spiral ridges from the unexposed side of the specimen (Böttcher 2010), the bands on *P. duni* twist in a clockwise direction, conforming to this observation.

Comparison of beak and pedicle lengths is not a strong diagnostic tool, as they are often broken, incomplete or missing. However, in general, beak lengths are shorter than pedicle lengths (except for those of *P. friessi,* which are virtually equal). *P. duni* has a longer observable pedicle than all others except *P. friessi*, but its incomplete beak does not allow length comparison.

A number of structural features noted on other *Palaeoxyris* specimens are not observable on *P. duni*. These are flanged collarette extensions reported *on P. alterna* (Fischer et al. 2011), *P. friessi* (Böttcher 2010), *P. humblei* (Fischer et al. 2010) and on a Mazon creek specimen (Brown 1950), and long tendril extensions to the beak reported on *P. alterna* (Fischer et al. 2011).

There are no close matches with specimens listed in Table 1 to the combined parameters of 'body length', 'body width', 'band number' and 'total band wrap angle' for *P. duni.*

AFFINITIES AND STRUCTURE

Over the last 190 years there has been sporadic discussion concerning the origins of *Palaeoxyris.* Initially its cone-like shape with rhombic patterning caused Brongniart (1828) and Schenk (1864) to allocate a plant origin to these specimens. The realisation by Schenk (1867) and Quenstedt (1867) that the rhombic patterning could be produced by compression of a spirally wound object led to the comparison by Renault and Zeiller (1888) to shark egg-cases with spiral collarettes produced by *Heterodontus* sharks. Specimens were tested for plant cell structure but none was found (Crookall 1932). With no evidence of plant structure, opinion swung strongly to the specimens being of shark origin (Moysey 1910; Crookall 1932; Zidek 1976).The palaeoenvironment in which all *Palaeoxyris* species had been found is considered to be one of either deltaic or shallow, freshwater fluvial or lacustrine conditions (Moysey 1910; Crookall 1928; Fischer and Kogan 2008). Ancient sharks are known to have inhabited these environments (Patterson 1967; Rees and Underwood 2008). In at least two instances, in North America and Kyrgyzstan, shark remains have been found closely associated with *Palaeoxyris* specimens (Fischer et al. 2010, 2011). Fischer et al. (2013) carried out a cladistics analysis of ancient and modern chondrichthyan egg-cases based on morphological traits. Their results showed the egg-case *Vetacapsula* (Fig.5b) clustered with the egg-cases of the Chimaeridae (ratfishes), while the egg-cases *Palaeoxyris* and *Fayolia* (Fig.5a) were clustered next to all egg-cases of the neoselachans (modern sharks and rays). Egg-cases of the Heterodontidae were positioned as the basal egg-case type morphology of the neoselachans.

This circumstantial evidence has led to conjecture about the actual egg producer, its breeding behaviour and its egg-case structure.

The Egg Producer

Sharks being cartilaginous do not leave frequent evidence of their existence in the fossil record – teeth, fin spines and scales are the main indicators (Kemp 1982). However, there is enough evidence to plot the time span of the existence of possible egg producer families. Xenacanthids (Fig.5d) appeared in the Carboniferous (Garvey and Turner 2006;

Table 1 - List of the *Palaeoxyris* species described in some taxonomic detail in literature. A small number are yet to be described and these have been omitted. Where there are no data shown, the parameters have not been published. This particularly applies to the Carboniferous species which were described in the early 20th century. The referenced paper(s) are the source of the parameters in Table 1 and are not necessarily the original taxonomic papers. Note the puzzling lack of Permian specimens.

SPECIES	AGE	BODY LENGTH mm	MAX BODY WIDTH mm	NO. OF BANDS	TOTAL WRAP ANGLE degrees	NO. OF SEGMENTS	BEAK LENGTH mm	PEDICLE LENGTH mm	REFERENCES
P. (Spirangium) jugleri	Cretaceous	40 to 50	30 to 40			6	30	80 (incompl)	Crookall 1930, 1932.
?Palaeoxyris sp. (Kansas)	Cretaceous	28	14			3	8 (incompl)	30	Crookall 1930, Brown 1950.
P. muelleri	Rhaetian, Late Triassic	20 to 25	11	4	180	3	17	35	Bottcher 2010.
P. muensteri (quenstedti)	Rhaetian, Late Triassic	30 to 40	23	6		9	25	58	Crookall 1930, Bottcher 2010
P. humblei	Norian, Late Triassic	13	9	3 & 4		6	12.5	(incompl)	Fischer et al. 2010.
P. alterna	Ladinian-Carnian, Mid-LateTriassic	22 to 25	11 to 14	6	540	11	24	55	Fischer et al. 2011.
P. friessi	Ladinian, Middle Triassic	53	39	6	300	6	112	110	Bottcher 2010.
P. becksmanni	Anisian, Middle Triassic	15		4					Bottcher 2010.
P. regularis Type species	Anisian, Middle Triassic	35 to 40	13	6		8	55	85	Brongniart 1828, Crookall 1930, Bottcher 2010.
P. duni	Anisian, Middle Triassic	90	28	4	630	7	25 (incompl)	85 & 90	This paper.
P. bohemica	Carboniferous	50 to 140	15 to 50			11 to 13	20	missing	Crookall 1930.
P. helictoroides	Carboniferous	26 to 60	7 to 30			8 (alternating broad/narrow)	25	20 (incompl)	Crookall 1928.
P. carbonaria	Carboniferous	26 to 32	8 to 12			6 to 8	missing	missing	Crookall 1928.
P. prendeli	Carboniferous	25 to 34	12 to 18			4 to 8	missing	missing	Crookall 1928.
P. trispiralis	Carboniferous	90	30 to 34			3	17	17	Crookall 1928.
P. warei	Carboniferous	18	7			6		10 (incompl)	Crookall 1928.
P. pringlei	Carboniferous	22	10			14	20	missing	Crookall 1928.
P. edwardsi	Carboniferous	22	3.5			5			Crookall 1928.
P. lewisi	Carboniferous	42	7.5			10	9	8 (incompl)	Zidek 1976.

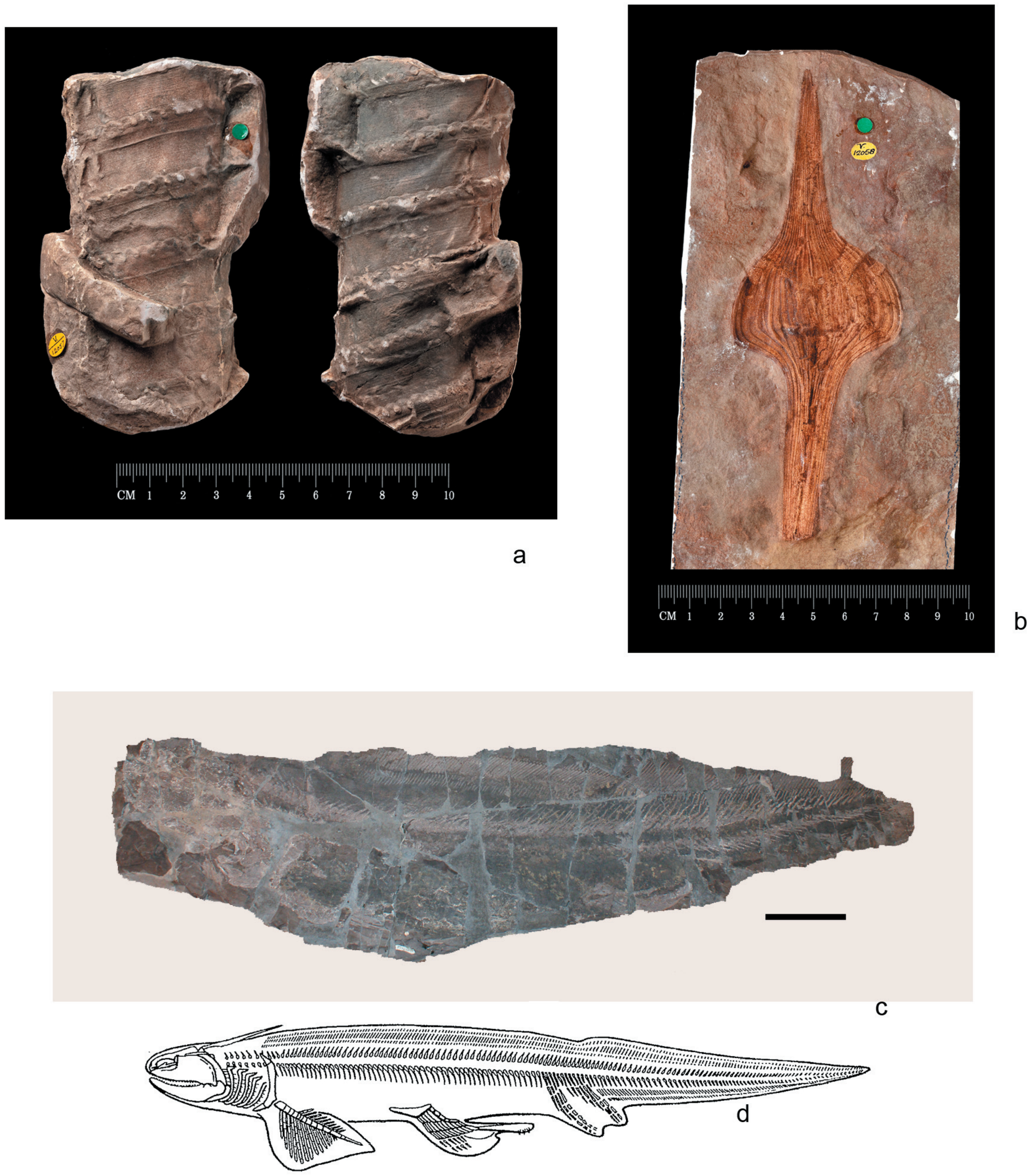


Figure 5 – a. Carboniferous *Fayolia crenulata*, BMNH V12057, part and counterpart, attributed to xenacanthid sharks, showing diagnostic scar-lines parallel to the collarette. b.Carboniferous *Vetacapsula cooperi*, BMNH V12058, tentatively attributed to the Holocephali. (Photos of shark egg-cases by courtesy of the Natural History Museum, London ©) c. Triassic *Xenacanthus* (*Pleuracanthus*) *parvidens*, MMF 13430, from St. Peters Brickpits, Sydney, Australia (photo courtesy of Geological Survey of New South Wales). d. The xenacanthid shark *Xenacanthus sessilis* (after Schaeffer and Williams 1977:297, by permission of the Oxford University Press).

Turner and Burrow 2011). Well preserved articulated xenacanthid fossils have been discovered in the Middle Triassic rocks of the Sydney Basin at St Peters Brickpits (Woodward 1908) (Fig.5c), at Picton (an as yet undescribed specimen held in the Australian Museum – AM F 137124) and at Somersby Quarry (two as yet undescribed specimens – AM F 78948, AM F 78958 and their counterparts) (pers. comm. S. Turner, Queensland Museum). They died out by the Late Triassic (Kemp 1982), whereas the hybodontids (Fig.6e) appeared in the Carboniferous and became extinct by the end of the Cretaceous (Springer and Gold 1989). By matching the span of *Palaeoxyris* ages with the family life spans of sharks, some workers

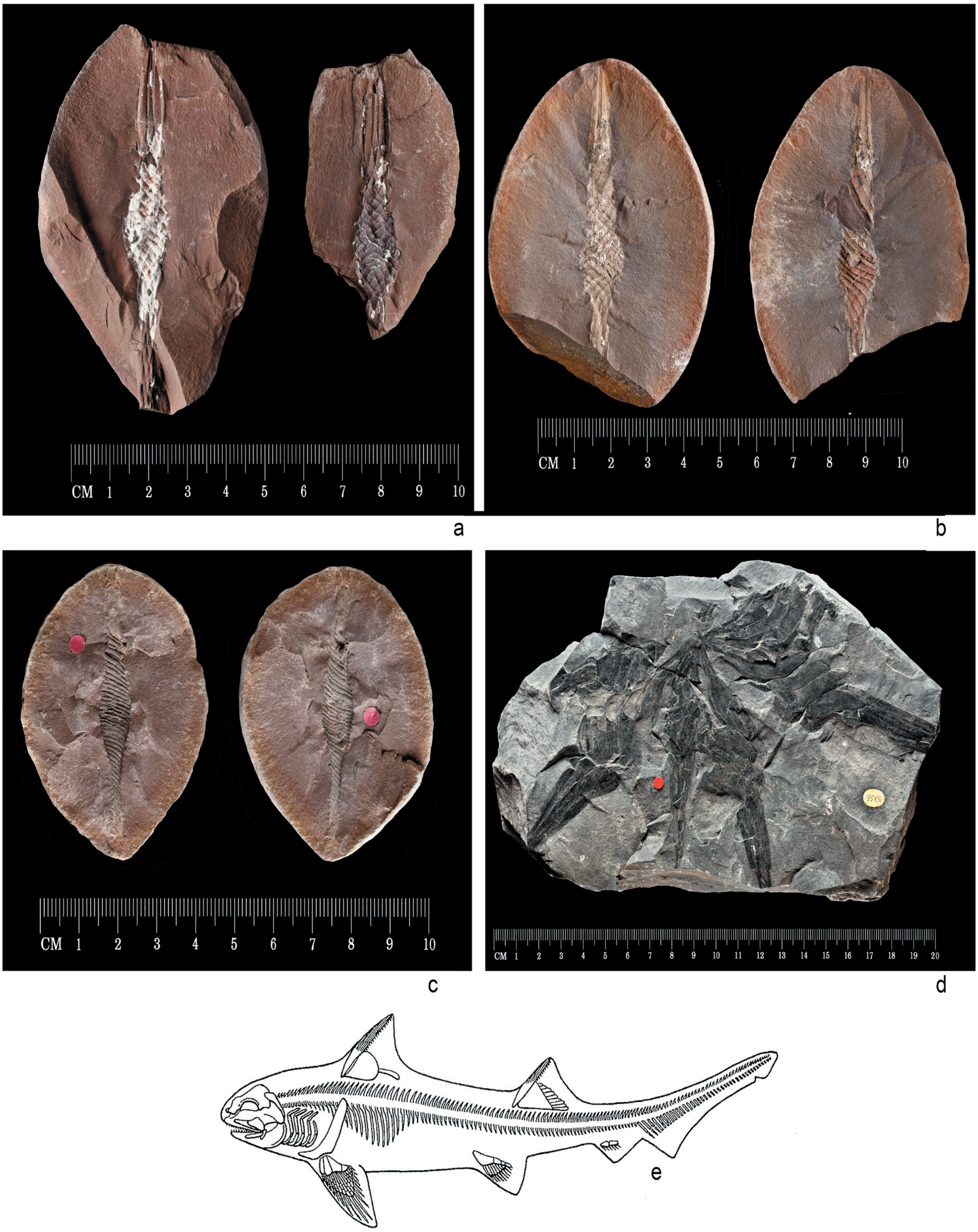


Figure 6 – a. Carboniferous *Palaeoxyris carbonaria*, BMNH V1173, part and counterpart, showing rhombic impressions on body and pedicle. b. Another *Palaeoxyris carbonaria*, also registered as BMNH V1173, part and counterpart, showing partly uncompressed banding on left specimen. c. *Palaeoxyris carbonaria*, BMNH V12928, part and counterpart, showing uncompressed spiral banding. d. Clustered group of Cretaceous *Palaeoxyris* (*Spirangium*) *jugleri*, BMNH 38856, with joined beaks. (Photos of shark egg-cases by courtesy of the Natural History Museum, London ©). e. The hybodontid shark *Hybodus* (after Schaeffer and Williams 1977:300, by permission of the Oxford University Press).

(Crookall 1932; Zidek 1976; Böttcher 2010; Fischer et al. 2010, 2011, 2013) have proposed hybodontid sharks as the producers of *Palaeoxyris.* The earliest *Palaeoxyris* species (e.g. Figs 6a,b,c) were found in the Carboniferous and the latest in the Cretaceous (e.g. Fig.5d), the most recent specimens being discovered in the Wealden Group of the Lower Cretaceous rocks near Hastings, England.

Hybodontids grew to about two metres in length, had an amphistylic jaw and a terminal mouth (Springer and Gold 1989). Their two dorsal fins each contained a spine at the leading edge, and they had heterodont dentition (piercing and crushing) which allowed a range of food options such as fish, crustaceans and molluscs (Springer and Gold 1989). Claspers were present on the male (Springer and Gold 1989) which confirmed they practiced internal fertilisation.

Hybodontid teeth have been found in deposits interpreted as originating in estuarine and river palaeoenvironments (Patterson 1967; Rees and Underwood 2006, 2008) and oxygen and strontium isotopic analyses of juvenile teeth found in lacustrine sediments in Kyrgyzstan have confirmed that the young sharks had developed in fresh water (Fischer et al. 2011). Some hybodontids therefore appear to have inhabited brackish and freshwater environments, at least to breed.

Modern Shark Breeding Behaviour

Many workers have noted similarities between modern Heterodontidae egg-cases and *Palaeoxyris* (Moysey 1910; Brown 1950; Zidek 1976; Böttcher 2010; Fischer et al. 2010). Heterodontidae is a family of extant oviparous sharks that produce egg-cases with helical ribs (in the form of collarettes). Fossil evidence of this family has been found in the early Miocene sediments of Victoria (Kemp 1982; Long and Turner 1984). They have an external spine on the leading edge of each dorsal fin and crushing toothplates suitable for a diet of molluscs. They breed in marine waters (O'Gower 1995).

The egg-case of the Port Jackson Shark, *Heterodontus portusjacksoni*, is constructed of two spiral bands of collagenous material approximately 0.25 mm thick that are overlapped and sutured longitudinally. The overlapping along the sutures forms the collarettes (Figs 7a,b). The egg case is cone shaped with a vent at the larger (anterior) end which opens a few weeks after deposition allowing the circulation of water through the egg during incubation. Finally the young shark escapes fully formed through this vent at the larger end, leaving a durable, empty egg-case.

The egg-case of the Crested Horn Shark, *Heterodontus galeatus*, is similar to *H. portusjacksoni* (Whitley 1940), but has two long tendrils that are extensions of the collarettes. These tendrils are used to anchor the egg-case to algae (Fig. 7c).

Tagged *Heterodontus portusjacksoni* has been tracked from Cape Naturaliste, north-east Tasmania (latitude 41°S) to Sydney (latitude 38°S), a distance of 850 km, during an annual migration cycle to lay eggs in specific sites, thus exhibiting breeding fidelity as well as spatial memory of long migration routes (O'Gower 1995). Females have been observed carrying an egg-case in their mouth and egg-cases have been found pushed into crevices so that the collarettes hold the egg-case firmly in place (Springer and Gold 1989; O'Gower 1995) (Fig. 7d).

The pattern of modern shark breeding behaviour, particularly that of the oviparous sharks such as the *Heterodontus*, leads to speculation about similar ancient shark behaviour, particularly relating to migration, breeding fidelity and the finding of ancient shark egg-cases in consistently similar fluvial and lacustrine environments around the world.

Modern Shark Egg-Case Structure

Knight et al. (1996) described in detail the macrostructure, biochemistry and microstructure of selachian egg-case formation in the nidamental (or shell) gland of oviparous sharks. Briefly, they explained that the nidamental gland lies in line with the oviduct (Fig.8a). The anterior end of the gland faces the ostium, which is the source of the fertilised ovum. The gland in recent species is composed of two similar halves surrounding a lumen. Each half works in parallel to extrude a complex collagenous lamellated sheet along its internal surface from the anterior zone (Fig 8b). The extruding sheets are fed by material secreted by tubules through a row of spinnerets, and a jelly is secreted between the sheets to divide and "inflate" the egg-case within the lumen. As the two parallel sheets progress down the gland the fertilised ovum enters the anterior end of the gland and is held between the forming sheets. The sheets continue forming around and past the ovum and finally join together to provide full encapsulation. During the extrusion of the sheets that form the two enclosing walls of the egg-case, special rib material is also secreted to "glue" the lateral edges of the laminar sheets together to form lateral ribs. In egg-cases that develop horns or tendrils (which are extensions of the lateral ribs), the posterior horns or tendrils form initially and the anterior ones form as the very end of the process. The final result for almost all recent

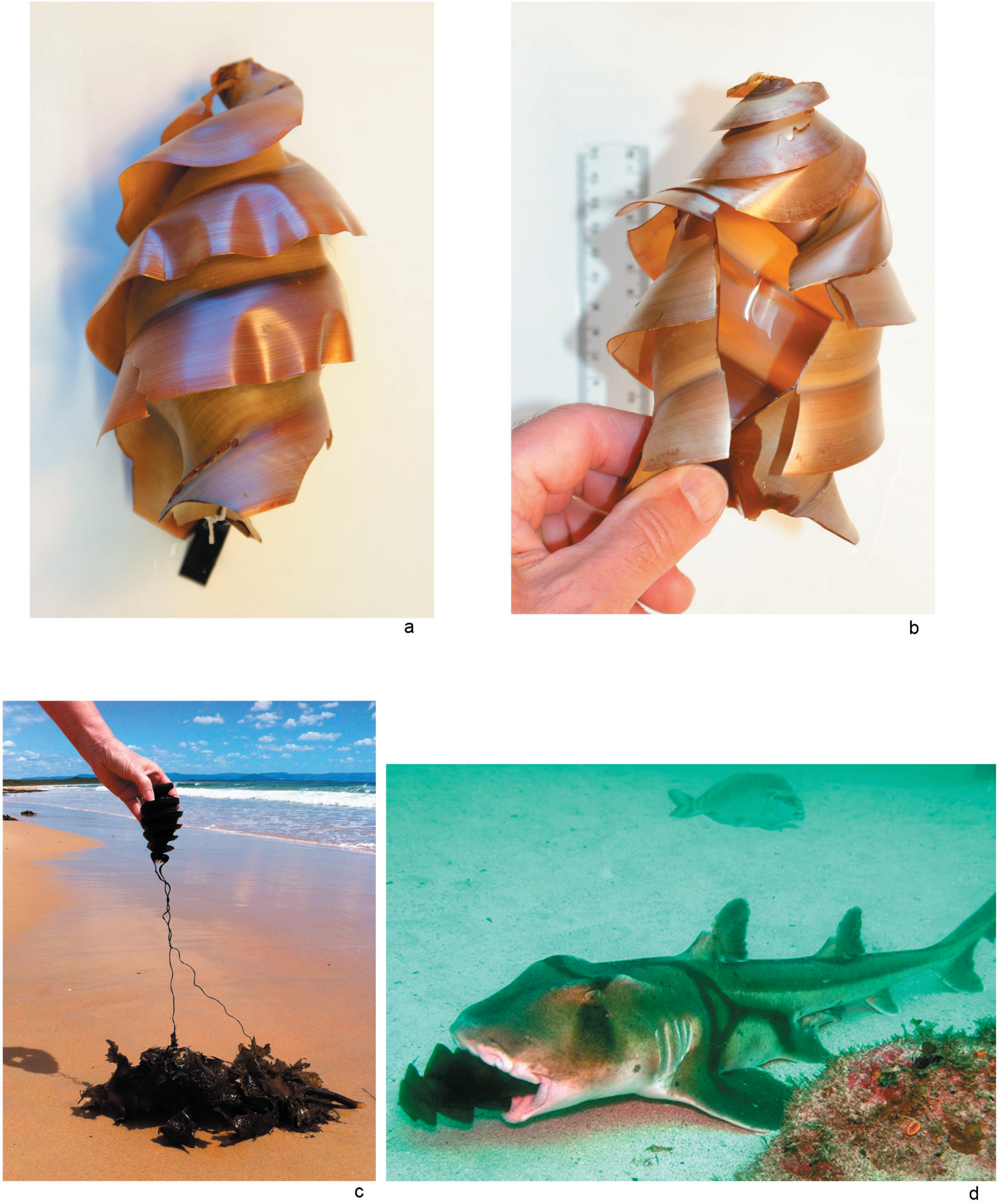


Figure 7 – a. Egg-case of *Heterodontus portusjacksoni* specimen AMS IB.673. Note the striae on the collarettes and bands. b. Sectioned egg-case of *Heterodontus portusjacksoni* specimen AMS I.30753-002. c. Egg-case of the Crested Horn Shark *Heterodontus galeatus* showing its long tendrils attached to marine algae. d. An *Heterodontus portusjacksoni* carries an egg for safe placement in a crevice. (Photos a,b courtesy of the Australian Museum, Sydney. Photo c courtesy of Mark McGrouther at the Australian Museum, Sydney. Photo d courtesy of Jayne Jenkins).

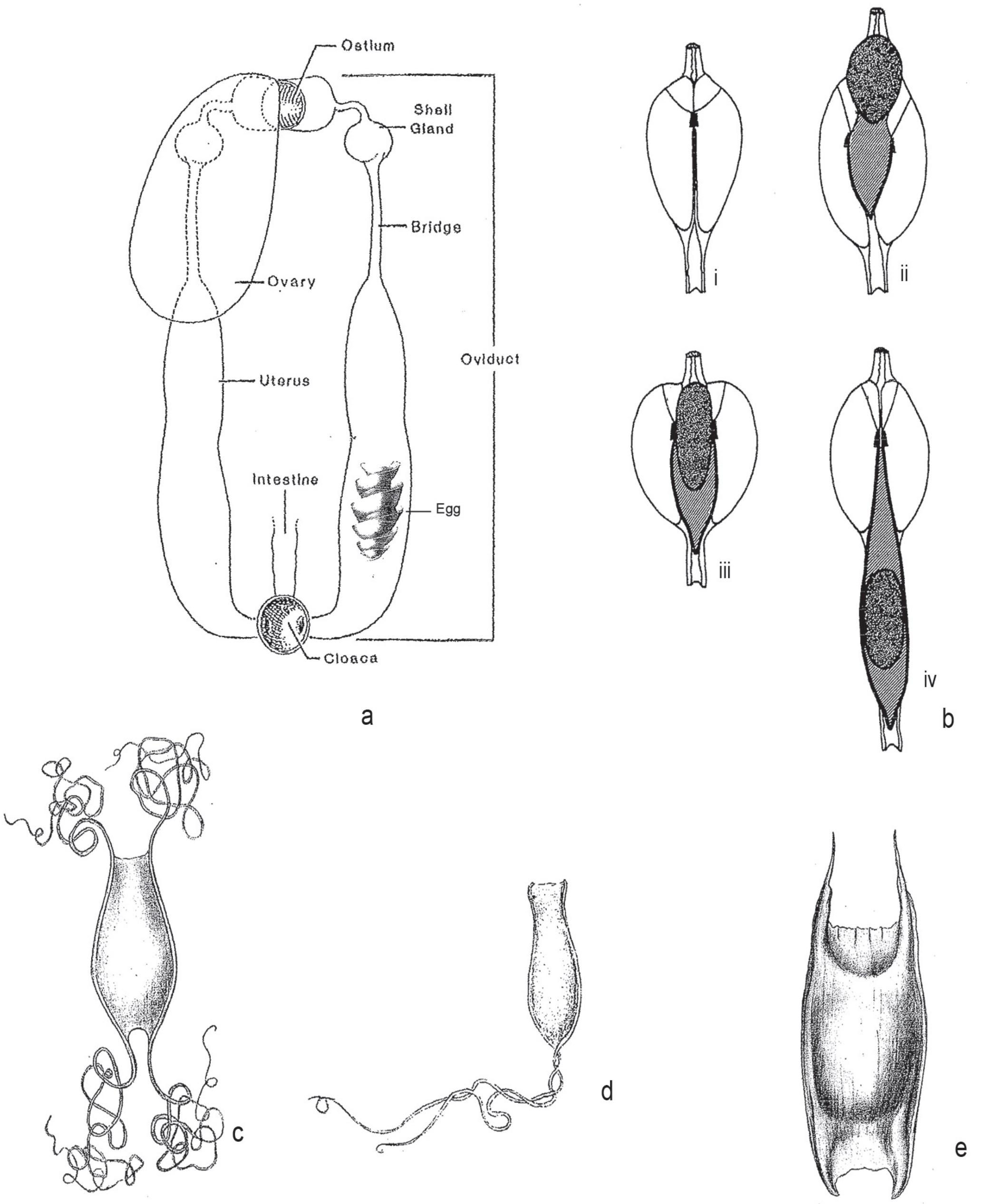


Figure 8 – Modern sharks and egg-cases. a. Simplified diagram of a modern shark reproductive system (modified after Springer and Gold 1989:68). b. Simplified diagram of a section through an active nidamental gland of a modern shark – i. resting gland. ii. formation of the posterior section of the egg case wall with fertilised ovum ready to enter the lumen. iii. the fertilised ovum enters the lumen. iv. production of the walls of the egg case continues around and behind the ovum forming the anterior end of the egg-case and sealing it. (modified after Knight et al. 1996:98). c. Egg-case of an *Atelomycterus* (a catshark) from the China Sea. d. Egg-case of an unknown species of catshark from the Timor Sea. e. Egg-case of *Zearaja nasuta* (a skate) from New Zealand. (Egg-case drawings after Whitley 1940:42,44).

egg-cases is a subrectangular structure containing the ovum and comprising two curved sheets sealed at the two lateral margins by ribs and sealed at the posterior and anterior ends, with tendrils or horns protruding from the four corners (Figs 8c,d,e). After many months (in the case of the genus *Heterodontus* between 9 to 12 months (Springer and Gold 1989)) the hatching fish finally escapes through the anterior end of the egg-case after the anterior seal has opened into a slit.

However, the egg-cases of the genus H*eterodontus* have a strikingly different shape – that of a helix. At first sight it appears very different to that of all other recent oviparous sharks. Knight et al. (1996) point out that if the ribs are flattened and the egg-case is twisted during formation, the above process will produce the egg-case of the *Heterodontus* complete with collarettes which are the flattened ribs. Thus a bifurcated nidamental gland can produce a spiral egg-case with two parallel bands. Striae are observable on *H. portusjacksoni* egg-case collarettes, possibly due to the extrusion process during formation (Figs 7a,b). Understanding the process of formation of the modern egg-case with two bands has implications for the study of fossil helical egg-cases with four or six bands.

DISCUSSION

Morphology

The macromorphology of MMF 42697a and MMF 42697b conforms to the diagnosis of *Palaeoxyris* thus confirming Crookall's decision. As the pedicle is not twisted this confirms previous observations by Fischer and Kogan (2008) and Böttcher (2010) that all Mesozoic *Palaeoxyris* have pedicles constructed with tendrils laid parallel longitudinally, whereas Carboniferous species have twisted pedicles which, when compressed, exhibit rhomboidal patterning (Figs 6a,b,c).

Comparison with other *Palaeoxyris* species (e.g. Table 1) indicates that the body length of *P. duni* is only matched or exceeded by one specimen of *P. bohemica* and *P. trispirilis* which are both Late Carboniferous in age. Although some extant sharks such as the catshark *Scyliorhinus canicula* produce an intra-species range of egg-case sizes which is determined by the size of the female and its habitat (Springer and Gold 1989), the range is still limited and it is therefore reasonable to conjecture that the size of the egg-case of *P. duni* indicates that the egg producer was one of the comparatively larger Triassic hybodontids.

The combination of the *P.duni* macro morphology parameters of 'body length', 'body width', 'band number' and 'total band wrap angle' is unique and therefore justifies its classification as a definite form species.

A particular feature of the modern *Heterodontus* egg-case is the wide flanged collarette (Figs 7a,b). Flanged collarettes have been detected on Palaeozoic and Mesozoic *Palaeoxyris* specimens (Brown 1950; Böttcher 2010; Fischer et al. 2010, 2011), although they are not seen on *P. duni*. The Carboniferous *P. helictoroides* exhibits a wide/narrow pattern of segments. The narrow segments could possibly be a collarette impression. The *Heterodontus* collarette is thin (0.25 mm) and friable when dry. It is possible that many more ancient egg-cases might have had flanged collarettes but that these were destroyed during the taphonomic process.

Striae running longitudinally parallel span the bands and collarettes of *Heterodontus* egg-cases (Figs 7a,b). It is likely that these are produced by the extrusion process within the nidamental gland by the array of spinnerets that form the bands. Striae are observable in many *Palaeoxyris* specimens (Crookall 1932; Fischer et al. 2010) including *P. duni*, particularly in the sheltered regions like the grooves. Striae are thus strong circumstantial evidence that *Palaeoxyris* had a similar egg-case formation process to that of the modern shark genus *Heterodontus*.

Palaeoenvironment

The interpreted palaeoenvironment in which *P. duni* was produced bears a close resemblance to that described for many other northern hemisphere species. The eggs were laid in a still, shallow, freshwater lacustrine or lagoonal environment, most likely accessible from the sea. Fossils recovered from the fine grained shale lens in which *P. duni* was found (Dun 1913) are a close match to those found with other Triassic *Palaeoxyris* specimens, for example the plants *Taeniopteris*, *Cladophlebis* and horsetails, and invertebrates such as conchostrachans and brackish water bivalves (Böttcher 2010). A similar environment was described for *P. alterna* (Fischer et al. 2011), *P. friessi* (Böttcher 2010) and *P. humblei* (Fischer et al. 2010). Carboniferous species described by Crookall (1928, 1930, 1932) were found in the British Coal Measures that formed in freshwater swamps. Fischer et al. (2011) postulated that the producers of *P. alterna* might have lived as adults in an enclosed freshwater lake. Patterson (1967) and Rees and Underwood (2008) conjectured that hybodonts, already capable of travelling up rivers and lakes to breed, might have radiated and diversified within wholly freshwater environments under pressure of the developing marine neoselachians in the early Jurassic and Cretaceous.

Hybodontid Sharks in Eastern Australia

There is scant evidence for the presence of hybodontids along the coast of eastern Australia in the Triassic and Jurassic. Woodward (1890) described a selachian with two dorsal fins complete with spines found in the Narrabeen Group of the freshwater Triassic sediments of Gosford, NSW. (Unfortunately, that specimen has not been traced (pers. comm. Susan Turner 2012)). Another eastern Australian Triassic hybodontid is in the process of being described (pers. comm. Susan Turner 2012). There is also a Jurassic specimen from the freshwater deposits of Talbragar, NSW yet to be described (Turner et al. 2009).

Shark Behaviour

Heterodontus portusjacksoni has been shown to migrate long distances to feeding sites, and to return regularly to known, shallow water marine breeding sites (O'Gower 1995). The palaeogeographic position of the Sydney Basin in the Triassic was within the Antarctic Circle (Hallam 1994), meaning that during winter there was probably a long, unbroken period of darkness. During this darkness it was likely that food sources for the hybodontids would either migrate north or seasonally reduce in numbers (as do modern krill). This would force hybodontids to migrate north in winter. It is therefore likely that hybodontids in these latitudes followed an annual migration pattern of northern migration in winter, then a return to known breeding sites in the rivers and lakes of the Sydney Basin in summer.

Modern oviparous sharks, such as *Heterodontus*, have been observed to gather at common shark nurseries to lay their eggs (O'Gower 1995). It is an advantage to a marine species that produces only a few eggs to secure them in a safe place and protect them from predation, random current transport and storms. *H. portusjacksoni* does this by pushing them into rocky crevices (Springer and Gold 1989; O'Gower 1995) (Fig.7d), *H. galeatus* anchors its eggs to marine algae using long, flexible tendrils (Fig. 7c). A flexible tendril has been discovered protruding from beak of one *Palaeoxyris alterna* specimen (Fischer et al. 2011). Fischer et al. (2010) noted the finding of a *Palaeoxyris* specimen from Mazon Creek, attached to wood fragments by beak tendrils. Crookall (1932) described and figured five *P. jugleri* jointly attached by their beaks (Fig. 6d). MMF 42697 shows the beaks of the two *P. duni* oriented in the same direction, which indicates they may have been joined or jointly anchored by their beaks. Fischer et al. (2011) describe the finding of 31 specimens of *P. alterna* (some fragmentary) in association with juvenile shark teeth. This circumstantial evidence links ancient shark breeding behaviour to modern shark nursery breeding habits.

Egg-Case Formation

Fischer et al. (2013) identified nine ancient and modern morphotypes of chondrichthyan egg-cases, seven of which appeared in the fossil record. They carried out a cladistics analysis of 11 taxa, based on 15 morphological characters, which clustered *Palaeoxyris* and *Fayolia* and grouped this cluster next to neoselachan egg-cases.

Considering the process by which the nidamental gland produces a shark egg-case leads to some valuable insights into the morphology of ancient shark egg-cases. Although the shapes of extant shark, ray and skate egg-cases (except for the genus *Heterodontus*) at first sight appear quite different from the helically twisted *Palaeoxyris* (Figs 8c,d,e), they are in fact all variations on a fundamental structure. This structure comprises extruded posterior tendrils, enclosing sheets (or bands), the longitudinal suturing of these bands together, the sealing of the ends and the final production of anterior tendrils. The egg-case of each species varies in the size, the number or absence of pairs of tendrils, the shape of the end seals and the size and shape of the longitudinal sutures. In the case of the genus *Heterodontus* the complete structure is twisted into a helix. All extant sharks, rays and skates produce egg-cases with two enclosing sheets (or bands). The morphology of *Palaeoxyris* reveals all the same elements of the fundamental structure – sheets (or bands) longitudinally sutured forming ribs, twisted into a helix, and a beak and pedicle formed by the joining of tendrils which each originate at the end of a rib. *Palaeoxyris* species, however, have four or six bands. This leads to the conjecture that ancient nidamental glands were divided into four or six parallel sections, which each extruded a separate band. This in turn leads to the conclusion that the combination of egg-case body size (within a tolerance), the number of bands and the helical twist rate would identify separate egg producer species, as each egg producer species would have a common nidamental gland structure.

Diagnostic Parameters

Based on the premise that each egg producing species would have a common nidamental gland structure, for the reasons set out above, the number of bands and the helical twist rate for each egg-case form species would be diagnostic, coupled with body size. Böttcher (2010) commented that all Mesozoic *Palaeoxyris* specimens so far described had even numbers of bands (either four or six or even greater). Recent egg laying sharks and rays all have two bands, thus supporting the concept that the fossil egg-cases were produced by a different clade, such as the hybodonts.

However, there is one recent paper that tests this concept. Fischer et al. (2010) reported the finding of three specimens of *P. humblei*, two with four bands and one with three bands. Due to taphonomic distortion it is often difficult to determine the exact number of bands (Böttcher 2010), particularly if the specimens are compressed and the edges of the body are not well defined or are buried in the substrate. If further evidence of variation of band number within form species is found, doubt may be thrown on band number as a significant diagnostic parameter.

CONCLUSIONS

The basic morphology of *Palaeoxyris duni* shows a strong relationship to northern hemisphere Mesozoic *Palaeoxyris* species, but the essential diagnostic indicators of 'body size', 'band number' and 'total wrap angle' in combination do not match other specimens, confirming that *P. duni* is a separate form species.

The existence of common structures, such as helical bands, collarettes, tendrils and striae in *Palaeoxyris* form species and modern oviparous shark egg-cases is convincing evidence that ancient sharks produced *Palaeoxyris*. Geographic, temporal and environmental constraints lead to the initial consideration that either xenacanthid or hybodontid sharks produced *Palaeoxyris* species. Currently the weight of circumstantial evidence favours the family Hybodontidae. If hybodontid species were the egg-case producers, specimen MMF 42697 is further evidence of their presence on the eastern coast of Australia during the mid-Triassic along with the specimens known from the Sydney Basin.

It is probable that the nidamental glands of hybodont shark species produced egg cases in a similar manner to modern oviparous sharks, except that the glands were divided into more than two parallel sections. Thus the diagnostic features that define a *Palaeoxyris* form species by association define a shark species.

The palaeoenvironment in which *P. duni* was deposited matches that described for most, if not all, other *Palaeoxyris* species. This is essentially a deltaic or shallow, freshwater, fluvial, lacustrine or lagoonal coastal environment accessible from the sea. A significant body of evidence for hybodontid movement into freshwater systems, particularly the finding of fossil teeth and fin spines, shows that these sharks were capable of making the transition from marine to freshwater, if only to breed. There are indications that breeding habits such as the formation of shark nurseries and egg-case attachment were practiced by ancient sharks in a similar manner to those of modern sharks.

As the Sydney Basin where the *P. duni* specimens were found was within the Antarctic Circle during the Middle Triassic Period, it is likely that hybodontids followed an annual migration pattern of northward winter movement and a return to regular favoured breeding areas to the south during summer for breeding purposes.

Most workers accept the hypothesis that *Palaeoxyris* are shark egg-cases. There are still some questions to be answered. The search is on for any fossil egg-cases, including *Palaeoxyris,* containing embryonic shark remains.

ACKNOWLEDGEMENTS

My thanks go to Yong Yi Zhen (Geological Survey of New South Wales) who has been a friend and mentor over the last eight years and encouraged me to write this paper. I also thank Robert Jones (Australian Museum) for his constructive criticism that guided the honing of my arguments and for his help in preparations of specimens for photography. Ian Percival (Geological Survey of New South Wales) furnished me with the key specimen and was just as excited as I was when we tracked down W.S. Dun's enigmatic *Palaeoxyris* fossil in the Geological Survey of New South Wales collection. Ian also generously gave his time to suggest scientific and grammatical improvements to the first draft of this paper. Mark McGrouther (Australian Museum) contributed valuable information on modern sharks as well as access to the Australian Museum's collection of *Heterodontus* shark egg-cases. Martha Richter, Peta Hayes and Martin Munt (Natural History Museum, London) made me welcome and arranged for my examination of their *Palaeoxyris* specimens and the subsequent production of photographs. Sue Turner (Queensland Museum) willingly provided her expert knowledge on the evidence for existence of hybodontid sharks along the ancient eastern coast of Australia. My thanks go to Glenn Brock (Macquarie University) whose enthusiasm for the teaching of palaeontology spurred and consolidated my own desire to make a contribution to this field of earth sciences. Finally, I would like to thank the referees and the editor who spent considerable time and effort reviewing and improving the manuscript.

REFERENCES

Beer, J.G. (1856). Einiges uber Bromeliaceen. *Bonplandia-Zeitschrift für die gesammte Botanik* IV **24**, 382-384.

Béthoux, O. and Ross, A.J. (2005). *Mesacridites* Riek, 1954 (Middle Triassic; Australia) transferred from Protorthoptera to Orthoptera: Locustavidae. *Journal of Paleontology* **79**, 607-610.

Böttcher, R. (2010). Description of the shark egg capsule *Palaeoxyris friessi* n. sp. from the Ladinian

(Middle Triassic) of SW Germany and discussion of all known egg capsules from the Triassic of the Germanic Basin. *Palaeodiversity* **3**, 123-139.

Brongniart, A. (1828). Essai d'une Flore du grès bigarré. *Annales des science naturelles* **15**, 435-460.

Brooks, H.K. (1962). On the fossil Anaspidacea, with a revision of the classification of the Syncarida. *Crustaceana* **4**, 229-242.

Brown, R.W. (1950). Cretaceous fish egg capsule from Kansas. *Journal of Paleontology* **24**, 594-600.

Chilton, C. (1929). Note on a fossil shrimp from the Hawkesbury Sandstones. *Journal and Proceedings of the Royal Society of New South Wales* **62**, 366-368.

Conaghan, P.J. (1980). The Hawkesbury Sandstone: gross characteristics and depositional environment. In 'Bulletin No. **26** - A Guide to Sydney Basin' (Eds. C. Herbert and R. Helby), 188-253. (Department of Mineral Resources – Geological Survey of New South Wales: Sydney, Australia).

Crookall, R. (1928). XIII.-Palaeozoic species of *Vetacapsula* and *Palaeoxyris*. *Summary of Progress of the Geological Survey of Great Britain and the Museum of Practical Geology for the Year 1927 Part II*, 87-107.

Crookall, R. (1930). II.-Further morphological studies in *Palaeoxyris*, etc. *Summary of Progress of the Geological Survey of Great Britain and the Museum of Practical Geology for the Year 1929 Part III,* 8-36.

Crookall, R. (1932). IX.-The nature and affinities of *Palaeoxyris*, etc. *Summary of Progress of the Geological Survey of Great Britain and the Museum of Practical Geology for the Year 1931 Part II*, 122-140.

Damiani, R.J. (1999). Giant temnospondyl amphibians from the Early to Middle Triassic Narrabeen Group of the Sydney Basin, New South Wales, Australia. *Alcheringa* **23**, 87-109.

Dun, W.S. (1913). Note on the occurrence of the genus *Spirangium* in the Hawkesbury Series of New South Wales. *Journal and Proceedings of the Royal Society of New South Wales 45,* 205-206.

Evans, J.W. (1956). Palaeozoic and Mesozoic Hemiptera (Insecta). *Australian Journal of Zoology* **4**, 165-258.

Evans, J.W. (1963). The systematic position of the Ipsviciidae (Upper Triassic Hemiptera) and some new Upper Permian and Middle Triassic Hemiptera from Australia (Insecta). *Journal of the Entomology Society of Queensland* **2**, 17-23.

Fischer, J., Axsmith, B.J. and Ash, S.R. (2010). First unequivocal record of the hybodont shark egg capsule *Palaeoxyris* in the Mesozoic of North America. *Neues Jahrbuch fur Geologie und Pälaontologie Abhandlungen* **255**, 327-344.

Fischer, J. and Kogan, I. (2008). Elasmobranch egg capsules *Palaeoxyris*, *Fayolia* and *Vetacapsula* as subject of palaeontological research - an annotated bibliography. *Freiberger Forschungshefte* **528**, 75-91.

Fischer, J., Licht, M., Kriwet, J., Schneider, J.W., Buchwitz, M. and Bartsch, P. (2013). Egg capsule morphology provides new information about the interrelationships of chondrichthyan fishes. *Journal of Systematic Palaeontology,* DOI: 10.1080/14772019.2012.762061, 1-11.

Fischer, J., Voigt, S. and Buchwitz, M. (2007). First elasmobranch egg capsules from freshwater lake deposits of the Madygen Formation (Middle to Late Triassic, Kyrgyzstan, Central Asia*). Freiberger Forschungshefte* **524**, 41-46.

Fischer, J., Voigt, S., Schneider, J.W., Buchwitz, M. and Voigt, S. (2011). A selachian freshwater fauna from the Triassic of Kyrgyzstan and its implication for Mesozoic shark nurseries. *Journal of Vertebrate Paleontology* **31**, 937-953.

Garvey, J.M. and Turner, S. (2006). Vertebrate microremains from the presumed earliest Carboniferous of the Mansfield Basin, Victoria. *Alcheringa* **30**, 43-62.

Hallam, A. (1994). An outline of Phanerozoic biogeography. (Oxford University Press: United Kingdom).

Herbert, C. and Helby, R. (1980) (eds). A Guide to the Sydney Basin. *Geological Survey of New South Wales Bulletin* **26,** 1-603.

Hocknull, S.A. (2000). Mesozoic freshwater and estuarine bivalves from Australia. *Memoirs of the Queensland Museum* **45**, 405-426.

Holmes, W.B. (2001). Equisetalean plant remains from the Early to Middle Triassic of NSW, Australia. *Records of the Australian Museum* **53**, 9-20.

Hutchinson, P. (1973). A revision of the perleidiform fishes from the Triassic of Bekker's Kraal (South Africa) and Brookvale (New South Wales). *Bulletin of the British Museum (Natural History) Geology* **22**, 235-354.

Hutchinson, P. (1975). Two Triassic fish from South Africa and Australia, with comments on the evolution of Chondrostei. *Palaeontology* **18**, 613-629.

Kemp, N.R. (1982). Chondrichthyans in the Tertiary of Australia. In 'The Fossil Vertebrate Record of Australia' (Eds. P.V. Rich and E.M. Thompson), 88-117. (Monash University Offset Printing Unit: Clayton, Victoria, Australia).

Knight, D.P., Feng, D. and Stewart, M. (1996). Structure and function of the selachian egg case. *Biological Reviews of the Cambridge Philosophical Society* **71**, 81-111.

Long, J. and Turner, S. (1984). A checklist and bibliography of Australian fossil fish. In 'Vertebrate Zoogeography and Evolution in Australia. Animals in Space and Time' (Eds. M. Archer and G. Clayton), 235-254. (Hesperian Press: Carlisle, Western Australia).

McKeown, K.C. (1937). New fossil insect wings (Protohemiptera, family Mesotitanidae). *Records of the Australian Museum* **20**, 31-37.

Moysey, L. (1910). On *Palaeoxyris* and other fossils from the Derbyshire and Nottinghamshire coalfield. *The Quarterly Journal of the Geological Society of London* **66**, 329-345.

O'Gower, A.K. (1995). Speculations on a spatial memory for the Port Jackson Shark (*Heterodontus portjacksoni*) (Meyer) (Heterodontidae). *Marine Freshwater Research* **46**, 861-871.

Packham, G.H. (1969) (ed.). The Geology of New South Wales. *Journal of the Geological Society of Australia* **16**, 1-653.

Patterson, C. (1967). British Wealden sharks. *Bulletin of the British Museum (Natural History): Geology* **11**, 283-350.

Quenstedt, A. (1867). 'Handbuch der Petrefaktenkunde' Zweite umgearbeitete und vermehrte Auflage p982. (H. Laupp'sche Buchhandlung: Tübingen).

Rees, J. and Underwood, C.J. (2006). Hybodont sharks from the Middle Jurassic of the Inner Hebrides, Scotland. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **96**, 351-363.

Rees, J. and Underwood, C.J. (2008). Hybodont sharks of the English Bathonian and Callovian (Middle Jurassic). *Palaeontology* **51**, 117-147.

Renault, B. and Zeiller, R. (1888). Sur l'attribution de genres *Fayolia* et *Palaeoxyris*. *Comptes rendus hebdomadaires des séances de l'Académie des sciences* **107**, 1022-1025.

Retallack, G. (1977). Reconstructing Triassic vegetation of eastern Australasia: a new approach for the biostratigraphy of Gondwanaland. *Alcheringa* **1**, 247-277.

Retallack, G. (1980). Late Carboniferous to Middle Triassic megafossil floras from the Sydney Basin. In 'Bulletin No. 26 - A Guide to Sydney Basin' (eds. C. Herbert and R. Helby), 385-430. (Department of Mineral Resources – Geological Survey of New South Wales: Sydney, Australia).

Retallack, G. (2002). *Lepidopteris callipteroides*, an earliest Triassic seed fern of the Sydney Basin, southeastern Australia. *Alcheringa* **26**, 475-500.

Riek, E.F. (1950). A fossil mecopteron from the Triassic beds at Brookvale, NSW. *Records of the Australian Museum* **22**, 254-256.

Riek, E.F. (1954). Further Triassic insects from Brookvale, NSW (orders Orthoptera Saltatoria, Protorthoptera, Perlaria). *Records of the Australian Museum* **23**, 161-168.

Riek, E.F. (1955). A new xiphosuran from the Triassic sediments at Brookvale, New South Wales. *Records of the Australian Museum* **23**, 281-282.

Riek, E.F. (1964). Merostromoidea (Arthropoda, Trilobitomorpha) from the Australian Middle Triassic. *Records of the Australian Museum* **26**, 327-332.

Riek, E.F. (1968). Re-examination of two arthropod species from the Triassic of Brookvale, New South Wales. *Records of the Australian Museum* **27**, 313-321.

Schaeffer, B. and Williams, M. (1977). Relationships of fossil and living elasmobranchs. *American Zoologist* **17**, 293-302.

Schenk, A. (1867). 'Die fossile Flora der Grenzschichten' (Eds Keupers und Lias Frankens) pp 149, 195-198, 204-205. (C.W. Kreidel's Verlag: Wiesbaden).

Springer, V.G. and Gold, J.P. (1979). 'Sharks in question: the Smithsonian answer book'. (Smithsonian Institution Press: Washington,D.C., USA).

Tillyard, R.J. (1925). A new fossil insect wing from Triassic beds near Dee Why, NSW. *Proceedings of the Linnean Society of New South Wales* **50***,* 374-377.

Townrow, J.A. (1955). On some species of *Phyllotheca*. *Journal and Proceedings of the Royal Society of New South Wales* **89***,* 39-63.

Turner, S., Bean, L.B., Dettmann, M., McKellar, J.L., McLoughlin, S. and Thulborn, T. (2009). Australian Jurassic sedimentary and fossil successions: current work and future prospects for marine and non-marine correlation. *GFF* **131**, 49-70.

Turner, S. and Burrow, C.J. (2011). A Lower Carboniferous xenacanthiform shark from Australia. *Journal of Vertebrate Paleontology* **31**, 241-257.

Wade, R.T. (1932). Preliminary note on *Macroethes brookvalei*, representing a new family of chondrostean fishes, the Pholidopleuridae. *Annals and Magazine of Natural History (Series 10)* **9**, 473-475.

Wade, R.T. (1933). On a new Triassic catopterid fish from New South Wales. *Annals and Magazine of Natural History (Series 10)* **12**, 121-125.

Wade, R.T. (1935). 'The Triassic fishes of Brookvale, New South Wales'. (British Museum (Natural History) and The Oxford University Press: United Kingdom).

Watson, D.M.S. (1958). A new labyrinthodont (*Paracyclotosaurus*) from the Upper Trias of New South Wales. *Bulletin of the British Museum (Natural History) Geology* **3**, 233-263.

Webb, J.A. (1978). A new Triassic *Palaeolimnadiopsis* (Crustacea: Conchostraca) from the Sydney Basin, New South Wales. *Alcheringa* **2**, 261-267.

Welles, S.P. and Cosgriff, J.W. (1965). A revision of the labyrinthodont family Capitosauridae and a description of *Parotosaurus peabodyi* n. sp. from the Wupatki Member of the Moenkopi Formation of northern Arizona. *University of California Publications in Geological Science* **54**, 1-61.

Whitley, G.P. (1940). 'The fishes of Australia Part 1: The sharks, rays, devil-fish, and other primitive fishes of Australia and New Zealand'. (Royal Zoological Society of New South Wales: Sydney, Australia).

Woodward, A.S. (1890). The fossil fishes of the Hawkesbury Series at Gosford. *Memoirs of the Geological Survey of New South Wales, Palaeontology* **4***,* 1-55.

Woodward, A.S. (1908). The fossil fishes of the Hawkesbury Series at St. Peter's. *Memoirs of the Geological Survey of New South Wales, Palaeontology* **10***,* 1-29.

Zidek, J. (1976). A new egg capsule from the Pennsylvanian of Oklahoma, and remarks on the chondrichthyan egg capsules in general. *Journal of Paleontology* **50**, 907-915.

Reproductive Biology of Estuarine Pufferfish, *Marilyna pleurosticta* and *Tetractenos hamiltoni* (Teleostei: Tetraodontidae) in Northern New South Wales: Implications for Biomonitoring

Rumeaida Mat Piah[1,2] and Daniel J. Bucher[1*]

[1]Marine Ecology Research Center, Southern Cross University, P.O. Box 157, Lismore NSW, 2480, Australia;
[2]School of Fisheries and Aquaculture Sciences, University Malaysia Terengganu, 21030 Kuala Terengganu,
Malaysia. Corresponding author: daniel.bucher@scu.edu.au

Mat Piah, R. and Bucher, D.J. (2014). Reproductive biology of estuarine pufferfish, *Marilyna pleurosticta* and *Tetractenos hamiltoni* (Teleostei: Tetraodontidae) in northern New South Wales: implications for biomonitoring. *Proceedings of the Linnean Society of New South Wales* **136**, 219-229.

Because of their broad distribution, site fidelity and long lifespan pufferfish (family Tetraodontidae) show potential as biomonitors of estuarine water quality, and as understanding the reproductive cycle is crucial to interpreting variations in contaminant loads in the tissues of biomonitors, we investigated the spawning season, length at maturity and body condition of two small sympatric pufferfish species (*Marilyna pleurosticta* and *Tetractenos hamiltoni*), in the Richmond Estuary, NSW. *M. pleurosticta* spawned in spring while *T. hamiltoni* spawned in winter. Female and male *M. pleurosticta* matured at a similar size (50% mature at 90 mm total length). In *T. hamiltoni* there was a more marked difference in size at 50% maturity, with males maturing at 80 mm and females at 110 mm TL. From the high values for hepatosomatic index (HSI) and its strong inverse relationship with gonadosomatic index (GSI) we inferred that lipid reserves in the liver play an important role in gonad maturation and spawning. Somatic condition factor (K_r) also varied, albeit less so, throughout the year, suggesting that body fat and muscle play lesser roles in providing energy for reproduction. Seasonality of liver lipid content and different spawning seasons have important implications for designing sampling strategies using these fish, especially when monitoring lipophilic contaminants.

Manuscript received 24 May 2014, accepted for publication 17 September 2014.

Key words: banded pufferfish, biomonitoring, common pufferfish, condition, gonadosomatic index, hepatosomatic index, *Marilyna pleurosticta,* reproduction, spawning, *Tetractenos hamiltoni*.

INTRODUCTION

Pufferfish (Family Tetraodontidae) are common in tropical, subtropical and temperate estuaries (Bell et al. 1984; Hindell and Jenkins 2004), occuring around the Australian coast and throughout the full range of estuarine salinities from freshwater to marine conditions (Gomon et al. 2008; Allen 2009). Whilst they are potentially susceptible to being caught in unsustainable numbers as trawl by-catch (Stobutzki et al. 2001), few are of conservation concern in Australia. Tetraodontids show potential to be used as biomonitors of estuarine contamination because they are widely abundant, long-lived, appear to remain within a small home range and are carnivorous (Booth and Schultz 1999; Alquezar et al. 2006; Mat Piah 2011). Despite this, there are very few studies of the biology of estuarine pufferfish (NSW Department of Primary Industries 2006).

Reproductive processes may influence the storage, mobilisation and transfer of lipids (Merayo 1996; Alonso-Fernandez and Saborido-Rey 2012) and hence the partitioning of lipophilic contaminants among different tissues (Fletcher and King 1978), so the reproductive cycles and changes in condition of any species to be used as a biomonitor should therefore be well understood. A species on the west coast of Australia, *Torquigener pleurogramma,* is a broadcast spawner during summer and sexual maturity is reached at two years of age (Potter et al.

1988). A similar species in New Zealand *Contusus richei* also matures at two years old and spawns in summer (Habib 1979) whereas the smooth puffer *Tetractenos glaber* in the Sydney region spawns in winter (Booth and Schultz, 1999). The reproductive biology of other tetraodontids, other than the few large pelagic species used commercially for human consumption (e.g. Sabrah et al. 2006) has not been documented.

The balance between the metabolic demands for energy and the quantity and quality of food intake determines the amount of energy that can be stored as lipids to fuel growth and reproduction and can be indicated by several indices. Some commonly used indirect measures of a fish's energy status are Fulton's condition factor K, which is an index of the body weight of a fish relative to its length and the hepatosomatic index (HSI), which is a measure of the relative weight of the liver, a major energy store especially in non-fatty fish (McPherson et al. 2011). In pufferfish, the liver is large and easily dissected from other organs. Condition factor indices that use gutted (somatic) weight (K_r) (e.g. Encina and Granado-Lorencio 1997) can provide a better indicator of changes in the food reserves stored in muscle and body fat than indices using total weight, especially in light-framed fishes such as puffers where variations in large organs such as gonad and liver and gut fullness can mask changes in body fat and muscle (McPherson et al. 2011). At high K_r values, excess energy results in accumulation of fat and oil reserves and little demand on protein for energy production, resulting in greater muscle development. At low K_r values, the metabolic energy demands have depleted lipid reserves and are supplemented by catabolism of proteins, resulting in reduced muscle development.

In preparation for spawning HSI may decline during gamete development as lipid reserves are reduced (Htun-han 1978). Somatic condition may also reduce in this time if somatic fat deposits or protein are catabolised during gametogenesis or for spawning migrations (Htun-han 1978). After spawning HSI gradually increases as energy reserves are restored prior to commencement of the next gametogenic cycle (Htun-han 1978). This cycle is dependent on food intake being sufficient to allow reserves to increase between spawning events. If not, fecundity, egg size or yolk content will be reduced in the subsequent spawning (e.g. Burton 1994). The immediate post-spawning period is also generally the time of most rapid somatic growth (Chellapa et al. 1995).

Our study examined the reproductive cycles and condition indices of two pufferfish species commonly found in tropical and sub-tropical Australian estuaries, *Marilyna pleurosticta* and *Tetractenos hamiltoni*. These two species commonly occur from northern New South Wales and Queensland (Grant 1987; Edgar 2000), north to Papua New Guinea (Coates 1993), where they inhabit a broad range of habitats from near the mouth of the estuary to its upper low-salinity reaches. If these two widespread species were to be used as biomonitors of estuarine water quality then any differences between the reproductive cycles of the species would need to be considered when choosing the species and time of year to sample. The specific objectives of this study were therefore to quantify the spawning season, and length at 50% maturity of *M. pleurosticta* and *T. hamiltoni*, to determine if seasonal variations of body condition indices occur and differ in *M .pleurosticta* and *T. hamiltoni* and to quantify the relationship between body condition indices and spawning activity of the fish.

MATERIALS AND METHODS

Study area and sampling procedure

Fish were captured each month from March 2008 to March 2010 in a tributary of the Richmond River Estuary, New South Wales, Australia (Fig. 1). Fishes were collected as they returned from foraging over intertidal mangrove forests by setting 12 fyke nets with a mesh size of 12 mm, entrance radius 30 to 45 cm and wing length up to 5m in tidal channels on the ebbing tide. Nets were set on daylight spring high tides and retrieved as they were exposed by the falling tide. After capture, the fish were euthanised using 1 ppt solution of Benzocaine (ethyl-p-aminobenzoate) in water from the capture site, transported on ice packs and frozen within 2 hours of capture.

In the laboratory, thawed fish were measured from snout to distal edge of the caudal fin (total length, TL to the nearest 1 mm). Total weight (TW to the nearest 0.1g) was measured using a pan balance (Mettler Toledo PL3002). Gutted carcasses were weighed on the same balance to provide the somatic weight (SW). Liver and gonad tissues were removed and weighed (LW and GW to the nearest 0.001g) using an analytical balance (Mettler Toledo AL204)..

Reproductive biology analysis

Fish gender was determined using a gonad visual census, in which testes appeared as smooth-textured and ivory-white in colour and ovaries pink to orange in colour with a granular texture of developing oocytes within. Fish in which the gonads were small, thin and transparent and unable to be confidently

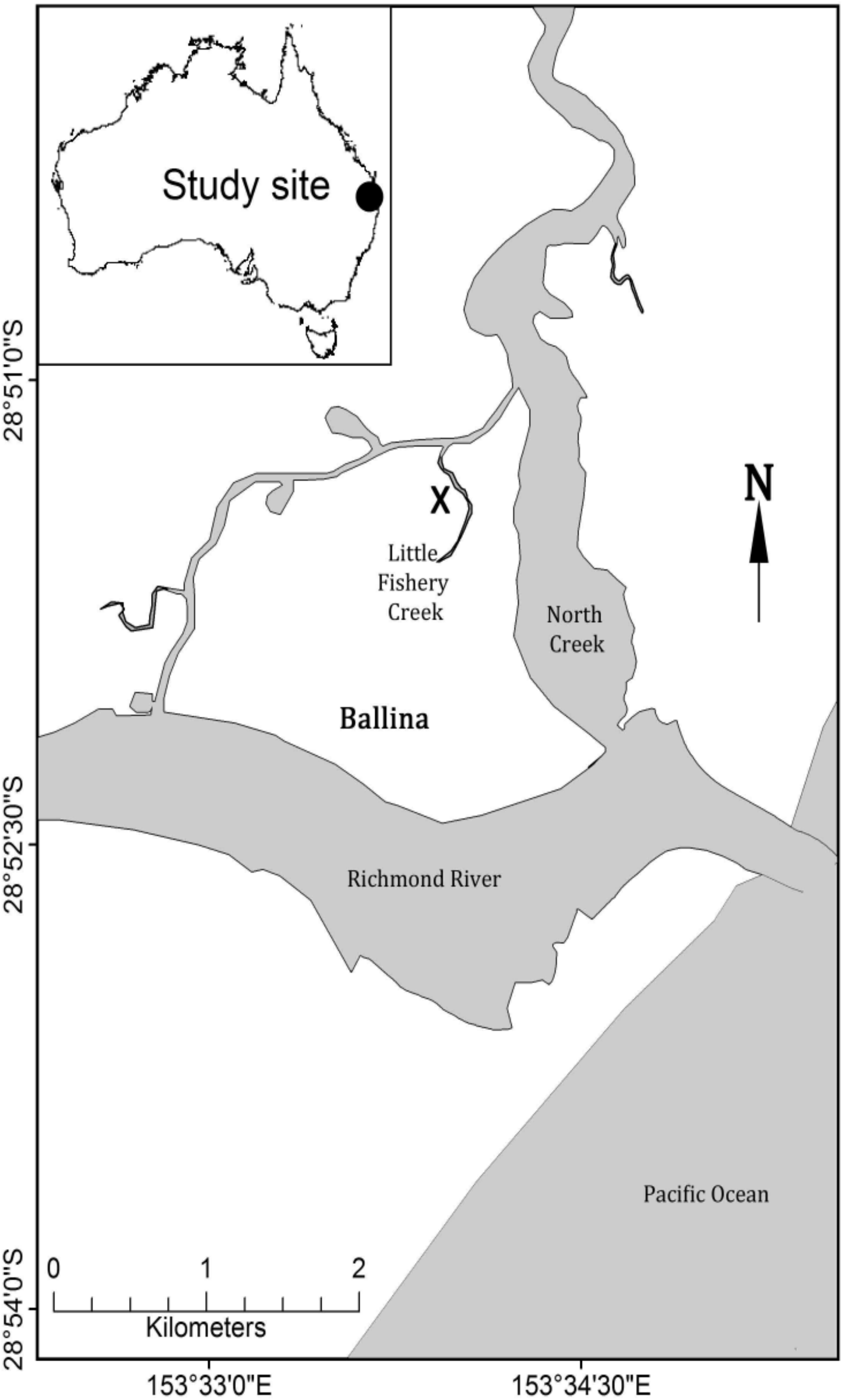


Fig. 1. Location of study site (X) in Little Fishery Creek, a tributary of the Richmond River estuary at Ballina, NSW (base map courtesy of D. Maher, Center for Coastal Biogeochemistry, Southern Cross University).

assigned to male or female were categorised as immature.

A total of 358 gonads from *M. pleurosticta* and 89 gonads from *T. hamiltoni* were examined. Maturity stages were determined macroscopically and were classified as either I, immature; II, developing; III, spawning-capable; IV, spent/resting (= regressing/ regenerating) (modified from Brown-Peterson et al., 2011). The spawning season was determined by following the changes in proportions of the three non-immature stages on a seasonal basis and by following monthly changes in mean gonadosomatic index (GSI), where GSI = 100 * GW/TW. Elevated GSI in mature fish indicates that they are approaching spawning season and a rapid reduction in GSI indicates that spawning has recently occurred.

Length at maturity was determined as the length at which 50% of individuals were at maturity stages III or IV, during the spawning season. The length at 50% sexual maturity (L_{50}) was estimated by fitting a logistic model to the combined percentage of fish with maturity stages III and IV in each 1 cm size class (Rogers *et al.,* 2009). The logistic curve was fitted by minimising the sum of squares using the Solver 'add-in' function in Excel (Microsoft Corporation, 2007).

Body condition and HSI analysis

Condition factor index, K_r and hepatosomatic index (HSI) were calculated as indirect indices of energy status. The two parameters were estimated as follows (McPherson et al. 2011):

a) HSI = 100 x LW (g) / SW (g)

b) K_r = 100 x SW (g) / FL^3 (cm)

RESULTS

Maturity stages

Catch rates for *T. hamiltoni* were much lower than for *M. pleurosticta*, especially for males, so maturity stages were pooled for each season (three-month intervals). Both testes and ovaries of *M. pleurosticta* showed a seasonal progression of developmental stages, culminating in a switch from a majority of fully mature fish in spring to a majority of spent and resting individuals in summer (Fig. 2). For *T. hamiltoni* the pattern is less clear but most spent or resting individuals of both sexes were caught in spring and summer whereas spawning-capable fish were more common in autumn and winter. Fish commencing a new gametogenic cycle were most common in summer (Fig. 2).

Gonadosomatic Index

Male and female *M. pleurosticta* both followed similar patterns of monthly mean GSI (Fig. 3a). The pattern was consistent for both years, elevated from September and decreased in December. It is assumed that the GSI value probably peaked in November but no fish were captured in this month in either 2008 or 2009 presumably having left the mangrove habitat to spawn elsewhere in the estuary or at sea. For *T. hamiltoni*, GSI of females in both 2008 and 2009 showed a double peak with a maximum in April, declining in May and increasing to a second larger maximum in June or July (Fig. 3b). Catch rates for males were too low to display meaningful patterns, although they too peaked in April of both years.

Length at maturity

Fifty percent of female *M. pleurosticta* reached sexual maturity at 89 mm and for males 50% reached sexual maturity at 92 mm (Fig. 4a, b). At the total length of 120 mm, all females were sexually mature while all males above 130 mm were mature. In contrast, male *T. hamiltoni* reached sexual maturity at smaller size than females. Fifty percent of males were sexually mature at 70 mm and by the total length at 80 mm all males were sexually mature whereas 50 percent of females attained sexual maturity at 83 mm and all females were sexually mature at 110 mm (Fig. 4c, d).

Seasonal changes in GSI, K_r and HSI

The ranges of seasonal mean condition factor indices K_r were very similar for both sexes of both species. For each species the seasonal patterns of average HSI were similar for the two sexes and have been pooled for analyses, but the patterns for the two species are very different to each other (Fig. 5). The seasonal mean hepatosomatic and gonadosomatic indices have an inverse relationship to each other in both species. In *M. pleurosticta*, there is little seasonal change in K_r. However, both K_r and GSI values were highest when HSI was decreasing. In *T. hamiltoni*, the pattern of seasonal mean HSI is similar to K_r while the GSI was peaking in winter when the HSI was at its lowest.

DISCUSSION

Spawning season

Despite the superficial similarity of these two species and their similar habitats, they display quite different reproductive cycles. While *M. pleurosticta* spawns in late spring, *T. hamiltoni* spawns in winter, possibly with a split spawning in early and late

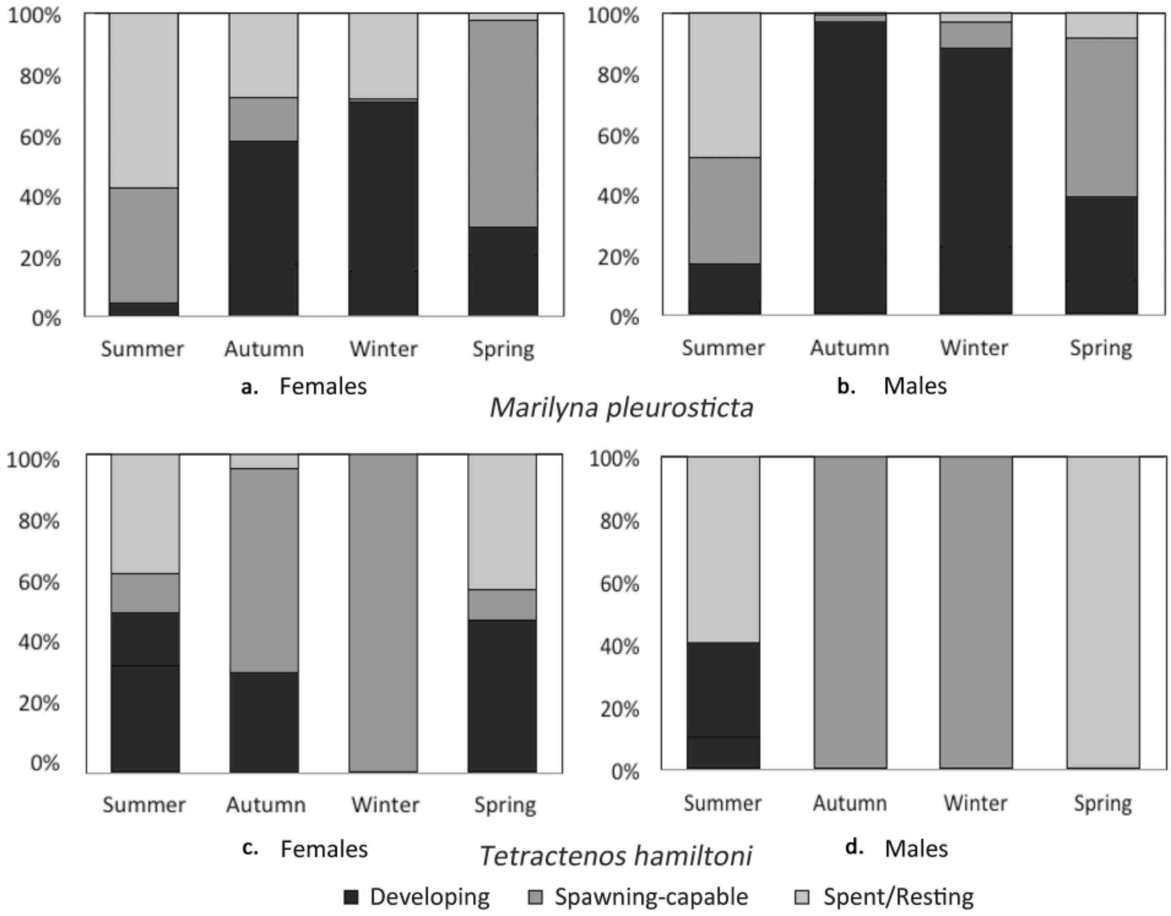


Fig. 2. Seasonal proportions of the three mature categories of gonad development for females (left) and males (right) of *M. pleurosticta* (top) and *T. hamiltoni* (bottom).

winter. The reproductive cycle of *M. pleurosticta* in this study was different to other tetraodontid species reported, most of which spawn in summer (Habib 1979; Potter et al. 1988; Sabrah et al. 2006). However, the spawning season for *T. hamiltoni* is very similar to the closely related *T. glaber* in the Hawkesbury estuarine system, which also spawns in winter (Booth and Schultz 1999).

Spawning location

The consistent lack of captures of both species in November and December of both years followed by an increase in capture rates in subsequent months suggests that both species probably leave the mangrove systems at this time. Tag returns (Mat Piah 2011) suggest that at least some adults subsequently return to the same channel system. Gonadosomatic indices indicated that the majority of *M. pleurosticta* caught prior to November were mature and the largest proportion of stage IV (spent/resting) individuals were captured in the months shortly after November, indicating that the absence of that species coincided with spawning. This finding is similar to the studies in Swan River estuary (Potter *et al*. 1988), where mature *T. pleurogramma* migrate out of the estuary to spawn in shallow coastal waters between October and January. At these times, large schools of this species have often been observed passing out to sea by fishers (Potter et al. 1988). *T. hamiltoni* were also not caught in November and December of both years. However, at this time their declining GSI suggests that, while this species also leaves the mangroves in early summer it is for reasons other than a spawning migration.

Length at maturity

Although gonad development and subsequent spawning may depend on various environmental stimuli, individuals must reach a certain age or size before they are capable of spawning (King 2001),

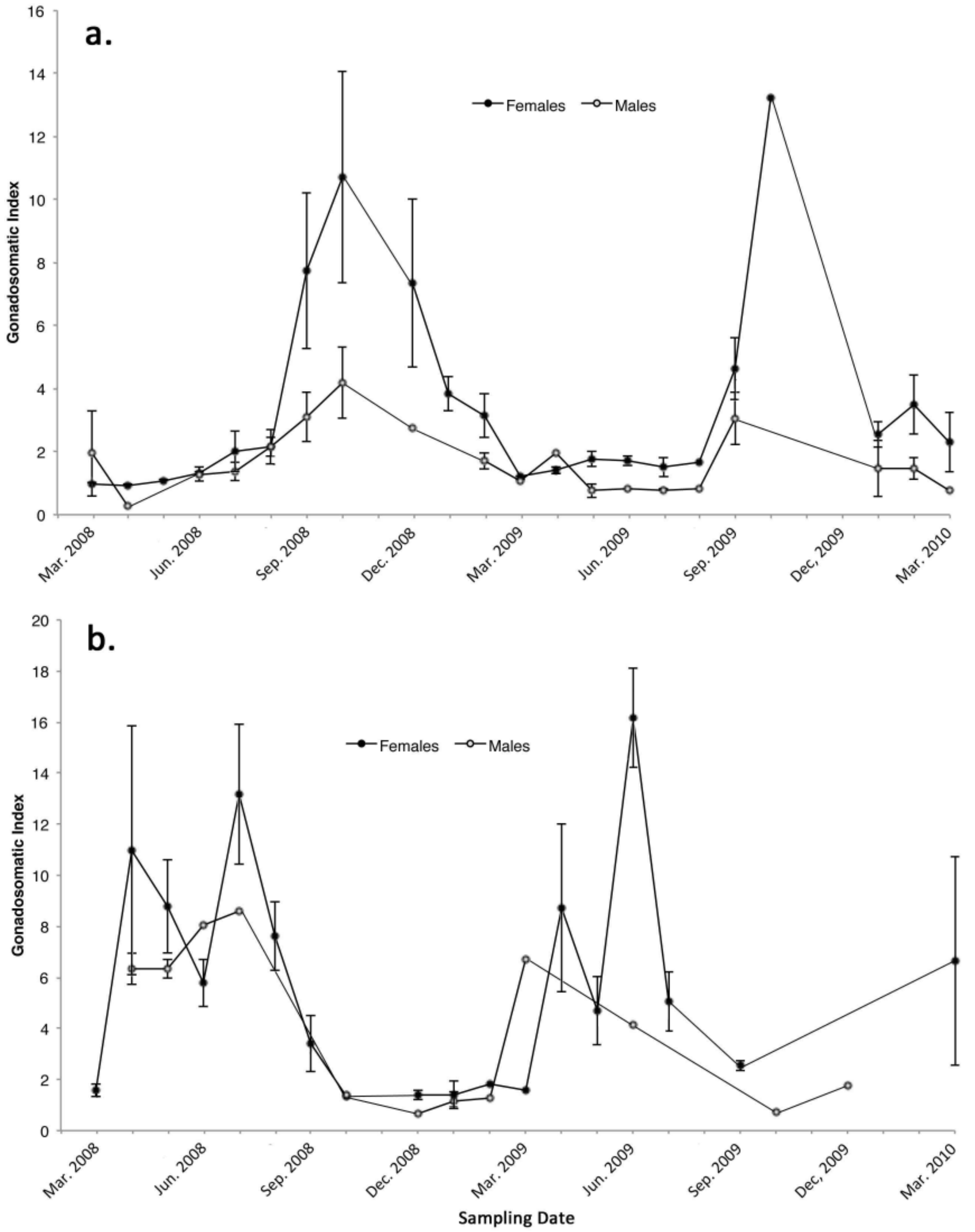


Fig. 3. Monthly mean (± S.E.) of Gonadosomatic Index (GSI) of females and males of (a) *M. pleurosticta* and (b) *T. hamiltoni.*

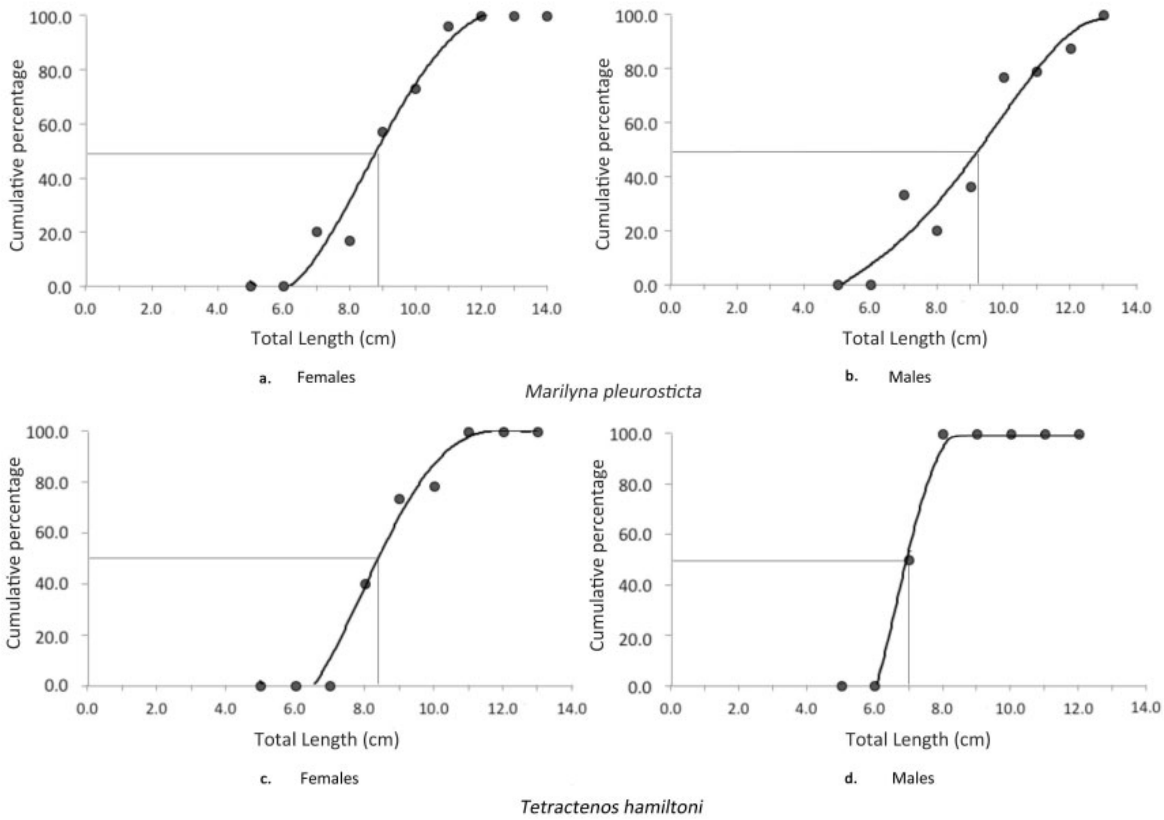


Fig. 4. Length at maturity for *M. pleurosticta* (a and b) and *T. hamiltoni* (c and d). Lengths at which 50% of individuals are mature are indicated.

and dependency of maturation to the age or length is strongly linked to growth and is also regulated by the water temperature and feeding success (Yoneda et al. 2001; Takemura et al. 2004).

In this study, female *M. pleurosticta* reached sexual maturity at a similar size to males, whereas, male *T. hamiltoni* start to mature at a much smaller size than females. It is not known if these size differences are due to different growth rates or different ages at maturity. Preliminary unvalidated age estimates from otolith growth checks suggest that age at maturity for both species may be as high as 10 years (Mat Piah 2011). The length at maturity in pufferfish in this study was similar to that of *U. richei* that matures at 7.5 to 11.6 cm (Habib 1979) while Sabrah et al. (2006) determined that the large oceanic species *Lagocephalus sceleratus* in the Gulf of Suez reached maturity at a length of 42.1 cm for males and 43.3 cm for females.

Relationship between energy storage and reproductive activity

Many studies calculate K using total weight including the gonads. In the case of puffers that have relatively light bodies with reduced skeletal components and large gonads and liver, such formulae would have been strongly influenced by individual organ development and variable gut fullness, potentially masking changes in muscle and fat body mass. For this reason, K_r was calculated by excluding visceral weight from the numerator. The cyclical variation in hepatosomatic index while condition changed much less suggests a central role for the liver a source of lipid and metabolic energy fuelling gamete production.

There is usually a direct correlation between hepatosomatic index and body condition index, and an inverse correlation of these factors to gonadosomatic index (Htun-han 1978). In this study HSI displayed a strong inverse correlation with GSI in both species, but K_r in *M. pleurosticta* showed no correlation with either of the other two indices. However, in *T. hamiltoni* K_r showed a positive relationship with HSI. The increase in GSI during the period of gonad maturation is mainly due to the deposition of large amounts of proteins and lipids in the developing eggs and spermatozoa (Htun-han 1978). Part of this material comes directly from ingested food

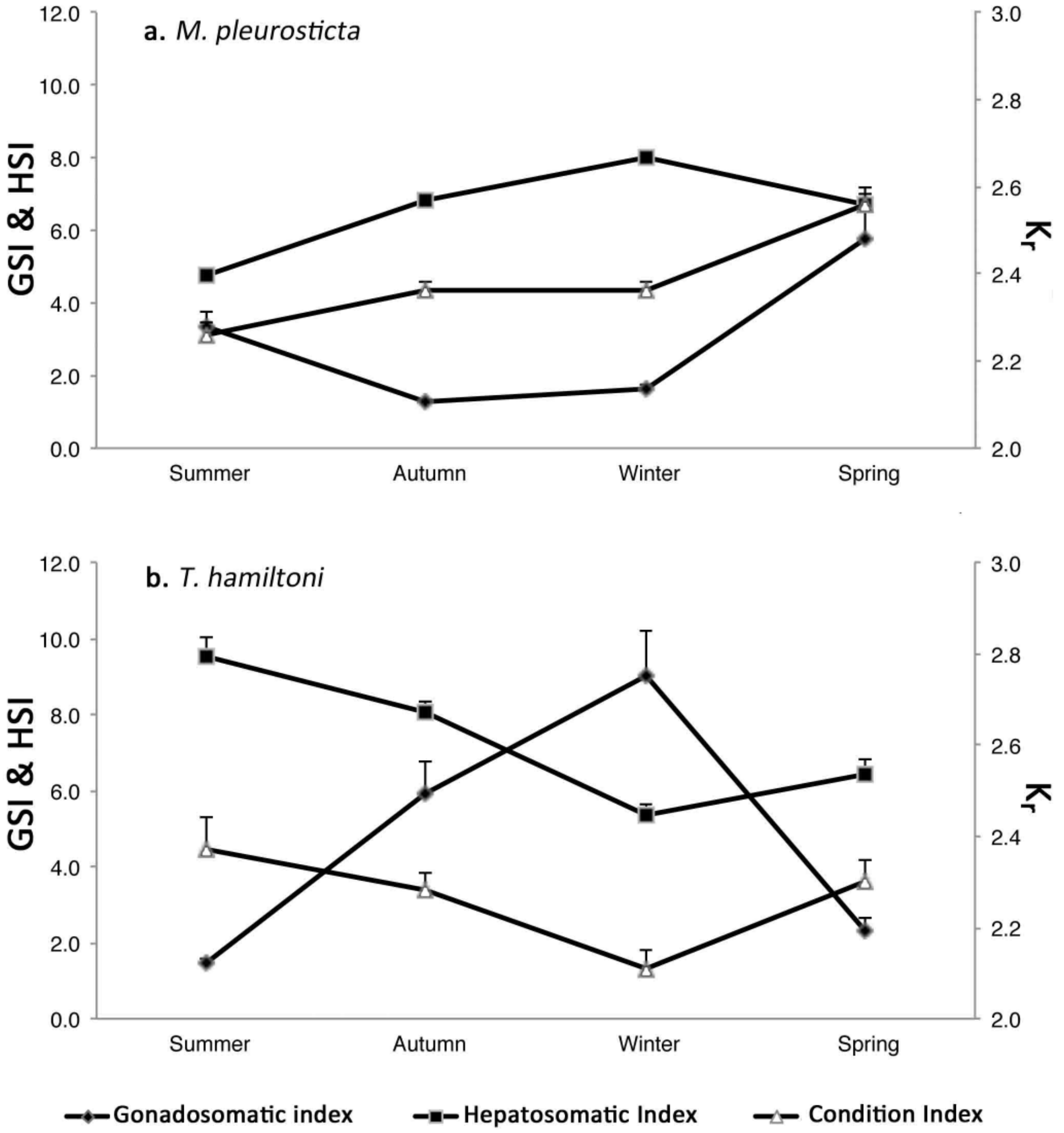


Fig. 5. Seasonal relationships between mean hepatosomatic Index (HSI), condition factor (Kr) and gonadosomatic index (GSI) of (a) *M. pleurosticta* and (b) *T. hamiltoni* (sexes combined).

but a major proportion comes from reserves of food deposited during the active feeding season in organs such as liver and muscles (Larson 1974). It is therefore reasonable to expect that the weight of liver and muscle would reflect the cycle of accumulation and utilization of these energy reserves.

Summer is important for both species because it is the time of greatest growth after spawning as energy is going into somatic tissue rather than gonads. The increase in HSI also indicates an excess of energy intake over immediate needs in this season. Thiswould be a critical time for the species and feeding success at this time could affect fecundity in the next spawning. A flood in January 2008 resulting in low dissolved oxygen and low pH for several months afterwards may have substantially affected these, and potentially other species during the first year of this study by reducing feeding opportunities during this critical period and may explain the interannual differences in the proportions of mature and spent gonads, which were more common in samples from 2009 than in 2008.

The strong inverse relationship between HSI and GSI suggests that lipid storage in the liver is critical to reproductive success in both species. With mean HSI values of between 6 and 10% of somatic weight, the liver of these small pufferfish is unusually large for the size of the fish. For comparison, other fish species collected from the Richmond River in August 2004 (Bucher, unpublished data) produced mean HSI values for mature bream *Acanthopagrus australis* of 0.7 percent, luderick *Girella tricuspidata* of 1.0 percent and sand whiting *Sillago ciliata* of 1.8 percent. Mean GSI values of pufferfish at full maturity (8-9) are also large compared to mature bream *Acanthopagrus australis* of 4.0, luderick *Girella tricuspidata* of 7.6 and sand whiting *Sillago ciliata* of 2.1 (Bucher, unpublished data).

There was a different pattern in the relative dynamics of HIS, K_r and GSI between these two species. *Marilyna pleurosticta* starts reserving lipids during the pre-spawning period, for use during spawning. The same pattern was found in Irish Sea plaice, *Pleuronectes platessa* (Wingfield and Grimm 1977), where HSI was also highest in the pre-spawning period and lowest in the post-spawning period. The reduction in HSI and K_r over the reproductive season may be explained by mobilization of lipid reserves, and especially vitellogenin (Vg), a lipophosphoprotein yolk-precursor synthesized by the liver (Maldonado-Garcia et al. 2005). Somatic condition mirrored the pattern of HSI in both species, indicating that lipids stored outside the liver are also important in fuelling the reproductive process.

In *T. hamiltoni*, HSI and K_r declined during pre-spawning presumably for gonad maturation. This pattern is similar to that of smooth pufferfish *Tetractenos glaber* in the Sydney region (Booth and Schultz 1999). In a study of liver weights of brook trout Larson (1974), suggested that the decrease in liver weight during pre-spawning season was due to the passage of materials from the liver to the gonads and concluded that weight changes of the liver plays an important role in gonad maturation.

There was not only a change in weight but also a change in colour and texture of the liver with different stages of the gametogenic cycle. The pre-spawning liver of both species was firm and pale while the post-spawning liver was soft, dark and flaccid. This supports the concept that that lipids in the liver have been used for the spawning process. Rossouw (1987) reported that the liver colour was in synchrony with the variation in the total liver lipid content in both sexes of sand sharks. He found that the higher liver lipid concentration in the liver, the lighter the livers become in appearance.

High values for hepatosomatic indices and their strong inverse relationship with gonadosomatic indices demonstrate that mobilisation of lipid stores in the large liver is important for fuelling gametogenesis and low feeding success during periods of high river flow at critical times of the year could therefore potentially severely affect spawning success. The large variability in lipid content of the liver has implications for tissue loads of lipophilic pollutants if these ubiquitous, long-lived fishes are to be used as biomonitors of estuarine pollution. The differences in timing of lipid mobilisation for gonad development also mean that the species being used for a biomonitoring program will determine the timing of sampling.

ACKNOWLEDGEMENTS

We gratefully acknowledge the technical assistance by staff at the Biology Laboratory, School of Environment, Science and Engineering, in particular Craig Taylor. The project was funded by a Postgraduate Research Grant from Southern Cross University and a Malaysian Government Scholarship. Research was conducted under NSW DPI permit no: P08/0031 and SCU Animal Care and Ethics Approval 09/20.

REFERENCES

Allen, G. (2009). ‘Field Guide to Marine Fishes of Tropical Australia and South-east Asia’. 4th ed. (Western Australian Museum, Perth).

Alonso-Fernandez, A. and Saborido-Rey, F. (2012). Relationship between energy allocation and reproductive strategy in *Trisopterus luscus*. *Journal of Experimental Marine Biology and Ecology* **416**, 8-16.

Alquezar, R., Markich, S.J. and Booth, D.J. (2006). Metal accumulation in the smooth toadfish, *Tetractenos glaber*, in estuaries around Sydney, Australia. *Environmental Pollution*, **142**, 123-131.

Baker, J.L. (2009). ‘Marine species of conservation concern in South Australia. Vol.1-Bony and cartilaginous fishes.’ South Australian Working Group for Marine Species Conservation Concern. Available at http://www.reefwatch.asn.au/pages/bin/view/Publication/SamsccTETRAODONTIDAE (Accessed 1 September 2010).

Bell, J.D., Pollard, D.A., Burchmore, J.J., Pease, B.C. and Middleton, M.J. (1984). Structure of a fish community in a temperate tidal mangrove creek in Botany Bay, New South Wales. *Australian Journal of Marine and Freshwater Research* **35**, 33-46.

Burton, M.P.M. (1994). A critical period for nutritional control of early gametogenesis in female winter flounder, *Pleuronectes americanus* (Pisces: Teleostei). *Journal of Zoology* 233, 405–415.

Booth, D.J. and Schultz, D.L. (1999). Seasonal ecology, condition and reproductive patterns of the smooth toadfish, *Tetractenos glaber* (Freminville) in the Hawkesburry estuarine system, Australia. *Proceedings of the Linnnean Society of New South Wales* **121**, 71-84.

Brown-Peterson, N.J., Wyanski, D.M., Saborido-Rey, F., Macewicz, B.J. and Lowerre-Barbieri (2011). A standardized terminology for describing reproductive development in fishes. *Marine and Coastal Fisheries: Dynamics, Management and Ecosystem Science* **3**, 52-70

Chellapa, S., Huntingford, F.A., Strang, R.H.C. and Thomson, R.Y. (1995). Condition factor and hepatosomatic index as estimates of energy status in male three-spined stickleback. *Journal of Fish Biology* **47**, 775-787.

Coates, D. (1993). Fish ecology and management of the Sepik-Ramu, New Guinea, a large contemporary tropical river basin. *Environmental Biology of Fishes* **38**, 345-368.

Edgar, G.J. (2000). 'Australian marine life: the plants and animals of temperate waters'. (2nd ed., Reed New Holland: Australia).

Encina, L. and Granado-Lorencio, C. (1997). Seasonal changes in condition, nutrition, gonad maturation and energy content in barbel, *Barbus sclateri*, inhabiting a fluctuating river. *Environmental Biology of Fishes* **50**, 75–84

Fletcher, G.L. and King, M.J. (1978). Seasonal dynamics of Cu^{2+}, Zn^{2+}, Ca^{2+}, and Mg^{2+} in gonads and liver of winter flounder (*Pseudopleuronectes americanus*): evidence for summer storage of Zn^{2+} for winter gonad development in females. *Canadian Journal of Zoology* 56(2):284-290

Grant, E. (1987). 'Fishes of Australia'. (E.M. Grant Pty. Ltd: Redcliffe, Australia).

Gomon, M., Bray, D. and Kuiter, R. (2008). 'Fishes of Australia's Southern Coast'. (Museum Victoria, Melbourne).

Habib, G. (1979). Reproductive biology of the pufferfish, *Uranostoma richei* (Plectognathi: Lagocepalidae), from Lyttelton Harbour. *New Zealand Journal of Marine & Freshwater Research* **13**, 71-78.

Hindell, J. S. and Jenkins G. P. (2004). Spatial and temporal variability in the assemblage structure of fishes associated with mangroves (*Avicennia marina*) and intertidal mudflats in temperate Australian embayments. *Marine Biology* **144**, 385-395.

Htun-han, M. (1978). The reproductive biology of the dab *Limanda limanda* (L.) in the North Sea: gonosomatic index, I_H and condition factor. *Journal of Fish Biology* **13**, 369-378.

King, M. (2001). 'Fisheries Biology, Assessment and Management'. (Fishing News Books: Oxford, England).

Koops, M.A., Hutchings, J.A. and McIntyre, T.M. (2004). Testing hypotheses about fecundity, body size and maternal condition in fishes. *Fish and Fisheries* **5**, 120-130.

Larson, G.L. (1974). Liver weight of brook trout in a high-mountain lake in Washington State. *Progressive Fish Culturalist* **35**, 234-236.

Maldonado-Garcia, M., Gracia-Lopez, V., Carillo, M., Hernadex-Herrera, A. and Rodriguez-Jaramillo, C. (2005). Stages of gonad development during the reproductive cycle of the blackfinsnook, *Centropomusmedius* Gunther. *Aquaculture Research* **36**, 554-563.

Mat Piah, R. (2011). Aspects of the ecology of small estuarine pufferfish relevant to their value as biomonitors of pollution. PhD thesis. Southern Cross University, Lismore, NSW.

McPherson, L.R., Slotte, A., Kvamme, C., Meier, S., and Marshall, C.T. (2011). Inconsistencies in measurement of fish condition: a comparison of four indices of fat reserves for Atlantic herring (*Clupea harengus*). *ICES Journal of Marine Science*, **68**, 52–60.

Merayo, C.R., (1996). Seasonal changes in the biochemical composition of the muscle and liver of bib (*Trisopterus luscus* L.) (Pisces, Gadidae) from the Cantabrian Sea (N Spain), *Scientia Marina*, **60**, 489-495.

NSW Department of Primary Industries (2006). 'A strategic approach to the management of ornamental fish in Australia'. Natural Resource Management Ministerial Council. Available at http://www.dpi.nsw.gov.au/__data/assets/pdf_file/0011/288425/Management-of-ornamental-fish-in-Australia.pdf (Accessed 12 June 2009).

Potter, I.C., Cheal, A.J. & Loneragan, N.R. (1988). Protracted estuarine phase in the life cycle of the marine pufferfish, *Torquigener pleurogramma*. *Marine Biology* **98**, 317-329.

Rogers, P.J., Ward, T.M., McLeay, L.J., Lowry, M., Saunders, R.J. and Williams, D. (2009). Reproductive biology of blue mackerel, *Scomber australasicus*, off southern and eastern Australia: suitability of the daily egg production method for stock assessment. *Marine and Freshwater Research* **60**, 187-202.

Rossouw, G.J. (1987). Function of the liver and hepatic lipids of the lesser sand shark, *Rhinobatus annulatus* (Müller & Henle). *Comparative Biochemistry Physiology* **86B**, 785-790

Sabrah, M.M., El-Ganainy, A.A. and Zaky, M.A. (2006). Biology and toxicity of the pufferfish *Lagocephalus sceleratus* (Gmelin, 1789) from the Gulf of Suez. *Egyptian Journal of Aquatic Research* **32**, 283-297.

Stobutzki, I., Miller, M. and Brewer, D. (2001). Sustainability of fishery bycatch: a process for assessing highly diverse and numerous bycatch. *Environmental Conservation* **28**, 167-181.

Takemura A., Rahman M.S., Nakamura S., Park Y.J. and Takano, K. (2004). Lunar cycles and reproductive activity in reef fishes with particular attention to rabbitfishes. *Fish and Fisheries* **5**, 317-328.

Wingfield, J. C. and Grimm, A. S. (1977) Seasonal changes in plasma cortisol, testosterone and oestradiol-17β in the plaice, *Pleuronectes platessa* L. *General and Comparative Endocrinology* **31**, 1-11

Yoneda, M., Muneharu T., Fujita H., Takeshita N., Takeshita K., Matsuyama M. and Matsuura S. (2001). Reproductive cycle, fecundity, and seasonal distribution of the anglerfish *Lophius litulon* in the East China and Yellow Seas. *Fisheries Bulletin* **99**, 356-370.

The Effect of Disturbance Regime on *Darwinia glaucophylla* (Myrtaceae) and its Habitat

Carmen Booyens[1], Anita Chalmers[2] and Douglas Beckers[3]

[1] School of Science & Mathematics, Lake Macquarie Campus, Avondale College of Higher Education,
Cooranbong, 2265, NSW, Australia.
[2] School of Environmental & Life Sciences, Ourimbah Campus, The University of Newcastle,
Ourimbah 2258, NSW, Australia.
[3] National Parks and Wildlife Service, Gosford Office,
Gosford 2250, NSW, Australia.

Booyens, C., Chalmers, A. and Beckers, D. (2014). The effect of disturbance regime on *Darwinia glaucophylla* (Myrtacease) and its habitat. *Proceedings of the Linnean Society of New South Wales* **136**, 231-244.

The effect of disturbance regime (time since last fire or slashing) on the vulnerable plant species, *Darwinia glaucophylla*, was assessed on the Central Coast of New South Wales, Australia. The abundance, growth and flowering of *D. glaucophylla* adults and abundance and growth of seedlings was measured within sites that had either been recently burnt (≤ 5 years), long unburnt (≥ 14 years) or regularly slashed (30 cm above ground) along a utility easement. Our results showed that *D. glaucophylla* was most abundant at slashed sites, followed by recently burnt sites; it was present but not abundant at unslashed sites that were burnt ≥ 14 years ago. Seedlings were only found at one, recently burnt site. Disturbance regime had no significant effect on the timing or density of flowering. Fruit collected from sites with different disturbance regimes did not germinate after exposure to various combinations of heat, smoke-water and/or scarification. Recently burnt sites contained plants producing a significantly greater number of viable fruits compared to those from other disturbance regimes. Fire and slashing altered the habitat of *D. glaucophylla* in different ways. Our findings suggest that slashing promotes favourable conditions for adults by creating a habitat with higher light and less competition. However, it is not apparent whether these same conditions are favourable for seedling recruitment.

Manuscript received 4 August 2014, accepted for publication 3 December 2014.

KEYWORDS: conservation management, fire, flowering, germination, slashing, threatened, utilities easement

INTRODUCTION

Many Australian plant species are considered disturbance-dependent, while others are sensitive to significant disturbance (in which case the disturbance may become a threatening process) (Ross et al. 2004; Kirkpatrick 2007). To be a threat, the disturbance must deleteriously interfere with transfers in the life cycle of a species and/or significantly affect the number of individuals at a particular life stage (Keith 1996). Fire is a natural disturbance that can pose a threat to some species if the long-term regime is disrupted in some way (Keith 1996). Fire frequency, fire interval variability, fire intensity, season of burn and pattern of burn are all elements of a fire regime (Gill 1975; Bond and van Wilgen 1996) which, when considered on a landscape scale, affect biodiversity (Keith 1996). Keith (1996) identified twenty possible fire-driven mechanisms of plant extinction. He concluded that high and low fire frequency, as well as repeated fires with little heat penetration of the soil or the production of smoke derivatives, are fire regimes likely to result in plant population decline and extinction (Keith 1996). Therefore, management of rare plants in fire-prone habitats typically requires knowledge of life-cycle attributes critically involved in population processes and the population response to different fire regimes.

Other disturbances common to urban habitats include sewer, water, gas and electricity services, all of which require installation of hard infrastructure, often at the expense of biotic components of a landscape (Foreman 2003). Slashing, whether by hand or machinery, is the main means by which utilities easements are maintained. Slashing allows easy access for maintenance and surveillance, and reduces fuel loads in order to decrease the threat of fire on such services. Slashing of easements may advantage some plant species, such as those well represented in earlier successional stages and which would subsequently be less well represented in mature ecosystems. The current area of occupancy of *D. glaucophylla* includes regularly slashed gas pipeline and powerline easements located within National Parks, raising the question as to whether slashing is beneficial or detrimental to the species. Although there has been a great deal of research on the effects of slashing (hay-cropping) in grassland ecosystems in Europe, where it is used as a management tool to restore plant diversity to former agricultural land (see review by Walker et al. 2004), only one study (Ellis and Allen 2013) could be found on the impacts of slashing in coastal heathland vegetation in Australia.

Darwinia glaucophylla B.G.Briggs is listed as vulnerable under schedule 2 of the *NSW Threatened Species Conservation Act* 1995. It is a prostrate shrub found in fire-prone coastal heath where it occurs on skeletal soils surrounding Hawkesbury sandstone outcrops in the Gosford Local Government Area (Department of Environment Climate Change and Water 2009a). Its small extent of occurrence, high endemism and habitat specificity has afforded this vulnerable status (Department of Environment Climate Change and Water 2009b). Previous studies of *D. glaucophylla* include descriptive observations of its morphology and phenology (Briggs 1962), seed germination response to heat (Auld and Ooi 2009) and the role of myrmecochory (Auld 2009). Auld and Ooi (2009) found that heat (80°C) enhanced germination and reported that seedlings emerge in the field 2-3 years after fire. However, the effect of smoke on the seed germination of *D. glaucophylla* has not yet been determined.

The current study aims to increase our understanding of the ecology of *D. glaucophylla* in a way that informs the management of the species. As the species grows in fire-prone habitat and is conspicuous in slashed areas along sections of the Sydney to Newcastle gas/oil pipeline, but rarely detected in adjacent unslashed areas, we ask the following research questions: (1) Is the above ground abundance of *D. glaucophylla* in slashed easements and unslashed sites (adjacent to easements) similar ? (2) Does the above ground abundance of *D. glaucophylla* differ between sites that have been burnt in recent times compared with sites that were burnt more than a decade ago? (3) Do the physical characteristics of the habitat of *D. glaucophylla* differ among disturbance regimes (fire, slashing) and, if so, how? (4) Does the flowering phenology of *D. glaucophylla* differ between disturbance regimes (fire, slashing)? and (5) Does smoke water, heat and/or scarification enhance seed germination?

METHODS

Study area

NSW National Parks and Wildlife Service (NPWS) atlas records were used to choose four main locations (Figure 1) within the extent of occurrence of the species: Popran National Park (151°13’05”E, 33°26’09”S), Girrakool Track (151°15’44”E, 33°25’46”S), Lyre Trig (151°17’51”E, 33°27’06”S) and Rifle Range road (151°16’34”E, 33°27’24”S). The latter three locations are all within Brisbane Water National Park. The four locations were no more than 12 kilometres apart and their elevation ranged between 50 to 250 m ASL (Table 1). The Central Coast region of NSW has a warm, temperate climate and a summer maximum rainfall distribution (Murphy 1993). Mean annual rainfall at Narara Meteorological Station (29 years of record) is 1280 mm (Bureau of Meteorology 2009). This station was the closest to most of the sites in this study. The mean maximum temperature of 23° C occurs in January and the mean minimum temperature of 11° C occurs in July (Narara Meteorological Station 12 years of record) (Bureau of Meteorology 2009). According to Murphy (1993), the Rifle Range, Lyre Trig and Girrakool locations belong to the Lambert soil landscape, having undulating to rolling hills on Hawkesbury sandstone. Slopes are typically < 20% and rock benches are common (Murphy 1993). Soils are shallow and sandy and within a pH 3.5 - pH 5.5 range (Murphy 1993). Benson (1986) has categorised the vegetation at these locations as consisting of open forest, woodland, open scrub, open heath and sedgeland. Characteristic flora present includes *Banksia* spp., *Hakea* spp., *Grevillea* spp., *Kunzea* spp., *Dillwynia* spp., *Acacia* spp. and *Leptospermum* spp. The Popran location differs in that it belongs to the Gymean soil landscape, but it also has a substrate comprising Hawkesbury sandstone with similar vegetation communities to the other locations (Benson 1986; Murphy 1993).

At each location, a plot measuring 10 m x 100 m (1000 m^2) was established in an area where *D. glaucophylla* was present. At two of the locations

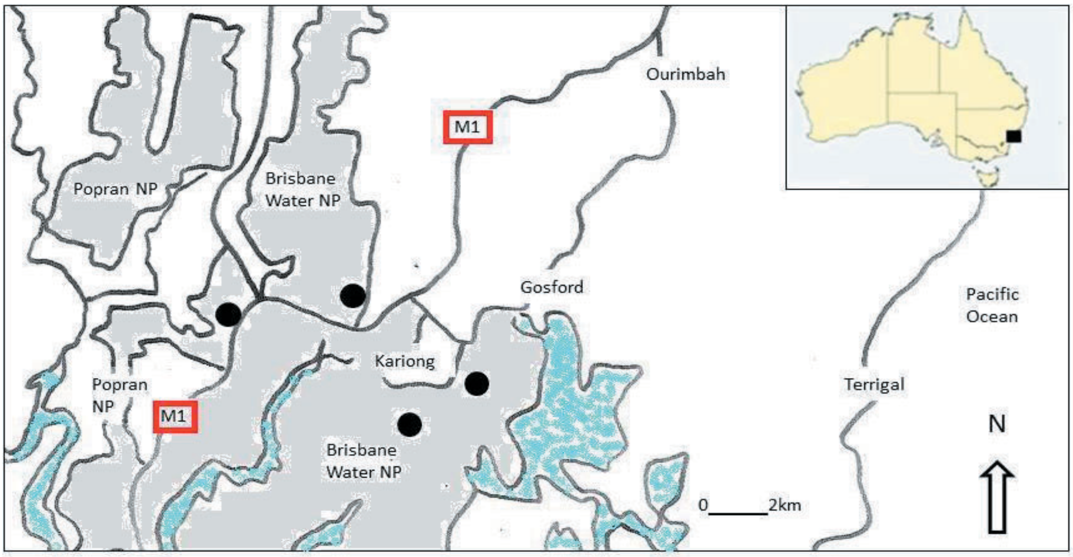


Figure 1. The four *Darwinia glaucophylla* sampling locations on the Central Coast of New South Wales.

(Girrakool and Popran), adjacent unslashed and slashed plots were set up, giving a total of six 1000 m^2 plots (hereafter referred to as sites). An orthogonal design, to test for interactive effects between slashing and fire, was not possible because there were no sites available that were both recently (≤ 5 years ago) burnt and slashed (Table 1). Thirty 1m^2 quadrats were placed randomly within each site. The size and number of quadrats was based on a pilot study by Booyens (2010) which found that 1m^2 quadrats showed less variance in the percentage cover of *D. glaucophylla* than 25m^2 quadrats. Post-hoc power analysis demonstrated that for a one-way ANOVA conducted on the percentage cover of *D. glaucophylla*, a high level of power (> 0.9) could be obtained with twenty-seven 1 m^2 quadrats (Booyens 2010). The pilot study also demonstrated that density could not be used as a measure of abundance because *D. glaucophylla* has a prostrate growth form and can root at the nodes. Percentage cover of the species was estimated using the projected foliage photos of MacDonald et al. (1990). Frequency of occurrence (mix of ramets and genets) within the 30 quadrats at each site was also determined. During the field component of the study (i.e. spring 2008) new apical growth of 30 randomly selected branchlets at each site was measured with a ruler each fortnight. New growth was easily recognised by its non-woody texture and pink/red colour at the tips of branches. Flowering density was estimated by counting the total number of flowers within each quadrat at fortnightly increments over a 3 month period (10/8/08 – 6/11/08). The number of *D.*

Table 1. Characteristics of the locations where *Darwinia glaucophylla* was sampled in this study.

Location	Slope (°)	Elevation (m)	Mean Fire interval (years)	Time since last fire (years)	Slashing
Girrakool NP	3.5	50	8.5[a]	14	biannually with hand-held brush cutters at 30 cm above ground
Popran NP	4.5	120	9[b]	19	biannually with hand-held brush cutters at 30 cm above ground
Lyre Trig	4	230	9.3[c]	2	No slashed sites available
Rifle Range	4	180	9.5[d]	5	No slashed sites available

a Burnt in 1977, 1980 & 1994; b Burnt in 1980 & 1989; c Burnt in 1969, 1977, 1987, 2000 & 2006; d Burnt in 1965, 1969, 1989, 1994 & 2003.

glaucophylla seedlings located within each quadrat was recorded and each seedling was marked and their survival monitored for the duration of the project. The sites and quadrats were permanently marked for the duration of the project.

For each quadrat, the mean height and percentage cover of surrounding vegetation was recorded. Photosynthetically active radiation (PAR) was also measured 1 m above the ground using a LI-190SA quantum light photometer and expressed as µmol/sec/m^2. Soil samples (0.1 m deep) were collected from a stratified random subset of the 1 m x 1 m quadrats (n = 30). Soil pH was determined using a 1:5 dilution and a Hanna pH meter and electrode (Rayment 1992). Electrical conductivity (EC) was measured in a similar manner with a Hanna meter and electrode (Rayment 1992). Soil moisture was determined using the gravimetric method of Rayment (1992). Total nitrogen (mg/kg), phosphorous (mg/kg) and percentage organic matter tests were performed by Sydney Analytical Laboratories using Australian Standard (AS) methods. Samples were dried, split and crushed to 150 microns prior to testing. Phosphorus levels were determined using H_2SO_4 digestion (APHA 4500BF), nitrogen by the APHA 4500B method and organic matter by the AS method 1289.4.1.1.

The indehiscent fruits (containing one 'large' seed) of *D. glaucophylla* were collected shortly after the majority of flowering had occurred in late November and early December 2008. Fruits were collected with forceps from the ground at the base of plants in the 1 m^2 quadrats and those fruits from each site were pooled. A total of about 1800 fruits were collected across the four sites and represented < 10% of what was available. Fruits were not collected from unslashed plots as low numbers of fruits meant that collection would have been ecologically irresponsible. Fruits were stored in paper envelopes in a cool, dry place until a germination experiment could be conducted (about six months).

The treatments chosen for the germination experiment (Figure 2) were based on previous studies (Auld and Scott 1995; Kenny 2000; Cochrane et al. 2002; Tierney and Wardle 2005) which showed that smoke water, heat and piercing the fruit coat enhanced germination in other species, including other *Darwinia* species. The fruit/seed coat of half of the collected fruit was pierced with a fine needle to reduce any impedance to germination imposed by the seed coat (Cochrane et al. 2002). The fruit were placed on agar (15g/L) plates to minimise desiccation and the need for repeated watering during the experimental period. Twenty-five fruit per plate were set up in duplicate for each treatment and placed in a germination cabinet (set at 12 hrs light/dark and 25°C / 15°C).

Fruits were soaked for four hours in a 0.1% (w/v) solution of Thiram (a fungicide) or in a second solution containing both Thiram and 2% commercial smoke water (Regen 2000) according to the methods of Tierney (2006). Where a heat treatment was performed, fruits were heated in an equilibrated glass Petri dish at 80° C for 10 mins and then the appropriate solution (Thiram or Thiram plus smoke water) was added (Baskin & Baskin, 1998; Tierney & Wardle 2005). Fruits were placed equidistant on the agar Petri dishes, sealed with Petri film and placed one layer deep in the germination cabinet. Germination was then monitored for a period of two weeks (Baskin and Baskin 1998; ISTA 2003; Mt Annan staff pers. comm. 2009). At the conclusion of the experiment, the viability of the ungerminated fruits was assessed using the 'cut' test (Baskin and Baskin 1998; Cochrane et al. 2001; Ooi et al. 2005; Mt Annan staff pers. comm., 2009).

Statistical analyses

Univariate two-factor analysis of variance (ANOVA) was used to test for significant differences (at the 0.05 level) among means for each of the variables measured and to test for any significant interactions (Tabachnick and Fidell 1996). The available combinations of disturbance in the field meant that the ANOVAs involved both orthogonal and nested designs. The orthogonal design

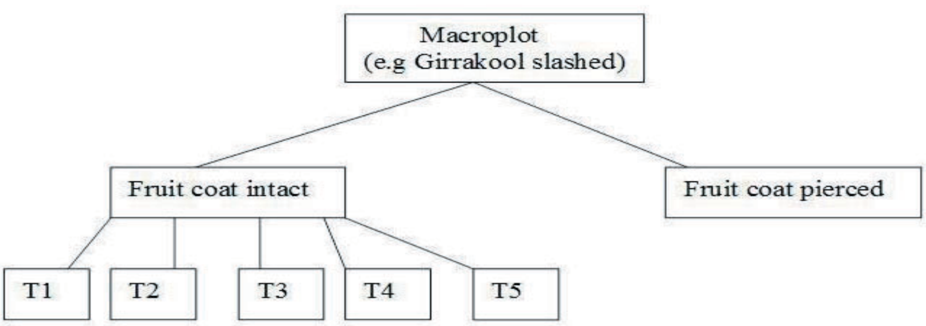


Figure 2. Germination experiment design. T1 = buffered Thiram, no smoke water, no heat; T2 = buffered Thiram, smoke water, no heat; T3 = buffered Thiram, no smoke water, heat; T4 = buffered Thiram, smoke water, heat; T5 = distilled water. Each treatment was performed in duplicate (Note: Macroplot = Site).

tested the effect of slashing or not slashing on sites within the same fire regime (i.e. time since last fire ≥ 14 years), while the nested design tested the effect of time since last fire at unslashed sites. For both types of ANOVAs, homogeneity of variance was tested using Cochran's test and normality was tested using the Shipiro-Wilk test. Where necessary, the data were transformed (arcsine or ln) to improve homogeneity. If transformation did not improve homogeneity, ANOVA was conducted on untransformed data as ANOVA is reportedly fairly robust to departures from this assumption (Underwood 1997a). *Post hoc* comparisons were made using Tukey –Krammer tests. As the flowering data was not independent from one sample time to the next, a repeated measures ANOVA was conducted to test for differences in flowering over time (Tabachnick and Fidell 1996) and *post hoc* comparisons were made using Scheffe (Ho 2006). Correlations between variables were tested using non-parametric Spearman's *rho* as a number of variables were not normally distributed. Chi-squared (χ^2) tests were used to test for significant differences among categorical data such as seed viability. All statistical analyses were conducted with JMP (version 8), SPSS (version 17) or GMAV (Underwood 1997b).

RESULTS

Effects of disturbance on abundance and growth

Darwinia glaucophylla was present in 59 of the 180 (33%) quadrats sampled in this study, with the highest frequency occurring in the slashed/fire ≥ 14 years ago disturbance regime (Table 2). Percentage cover ranged from 1% to 90%, with a mean percentage cover of 5.2% (± 1.2) across all quadrats. Mean percentage cover was significantly ($p < 0.0001$) higher in the slashed/fire ≥ 14 years ago disturbance regime compared to the two other disturbance regimes (Figure 3). There was no significant difference in cover between unslashed/fire ≤ 5 years ago locations and the unslashed/fire ≥ 14 years ago locations (Figure 3 and Table 2). The effect of slashing on percentage cover was consistent across the sites (i.e. no interaction between slashing and site).

Only 5 (3%) of the 180 quadrats in this study contained seedlings, with a total of 12 individuals being recorded. All of these seedlings occurred at the Lyre Trig site, which had an unslashed/fire ≤ 5 years ago regime. Seven of the 12 seedlings survived over the 12-month monitoring period, with five being killed by off-road vehicular damage. Those remaining showed an average increase in height/length of 1.3 cm (range 0.7 cm to 2 cm) over the 12-

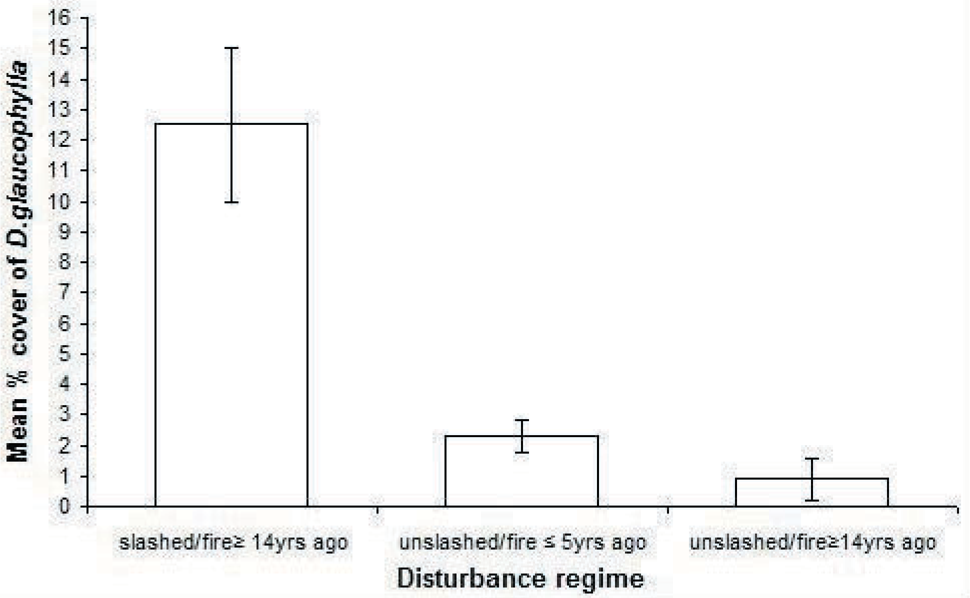


Figure 3. Mean percentage (%) cover of *Darwinia glaucophylla* for each disturbance regime (n = 60). Columns with the same letter are not significantly ($p \leq 0.05$) different. Bars represent ± 1 standard error of the mean.

Table 2. Frequency of occurrence (%), mean percentage (%) cover and mean apical growth of *Darwinia glaucophylla* at the six study sites (n = 30 at each site). Within rows, means with the same letter are not significantly different from one another (at the 0.05 level). The effect of slashing (orthogonal design) compares the Girrakool and Popran sites, while the effect of fire (nested design) compares the unslashed sites at Girrakool and Popran with the last two columns in the table.

	Girrakool NP fire ≥ 14 years		Popran NP fire ≥ 14 years		Lyre Trig fire ≤5 years	Rifle Range fire ≤5 years
	unslashed	slashed	unslashed	slashed	unslashed	unslashed
Frequency (% of quadrats at each site)	3.3	60	3.3	53.3	30	46.7
Mean (± SE) percentage cover (%)	0^{a}	13 (±4)^{b}	1(±1)^{a}	12 (±3)^{b}	2 (±1)^{a}	3 (±1)^{a}
Mean (± SE) apical growth (cm/month)	0^{a}	5.5 (±0.3)^{b}	0^{a}	4.0 (±0.2)^{c}	4.5 (±0.4)$^{b/c}$	3.7 (±0.2)^{c}

month period and none produced flowers during this period. By comparison, the mean apical growth rate (in one month) of mature, established plants was 4.4 cm. Disturbance had a significant effect (p= 0.0007) on mean apical growth and was largely attributable to the absence of growth under the unslashed/fire≥ 14years ago regime (Table 2).

Flowering

Of the quadrats containing *D. glaucophylla* (59), all but one contained individuals producing flowers. At the height of flowering intensity in spring, around 9000 flowers were counted within a combined area of 58 m^2. Repeated measures ANOVA showed no significant difference in the mean number of flowers among disturbance regimes, nor a significant interaction between sampling time and disturbance regime. However, there was a significant difference in mean number of flowers among sampling times (Figure 4). The mean number of flowers significantly increased with subsequent visits until flowering peaked in September, after which it began to decline. *Post hoc* pair-wise analysis showed no significant difference in mean number of flowers between time 1 & 7 but flowering at these times were significantly different from time 2 & 6 (which were similar to one another) and from time 3, 4 & 5 (which were similar to each other). There was a significant difference in the mean number of flowers between sites under the same fire regime, which was due to the absence of flowers in the Girrakool unslashed site (data not shown).

Seeds

No seeds germinated despite the various treatments used. Microscope examination of fruits collected from the ground beneath and adjacent to established adults revealed that only 94/1600 (5.9%) were filled. Cut tests showed that of those fruits containing material, 21/94 (22%) had potentially viable seed. Across the four sites from which fruits were collected, greater than 90% of fruits were empty. The percentage of fruits containing *potentially viable seed* was significantly greater (χ^2 =14.8; d.f. = 1; p = 0.01) in the unslashed/fire ≤ 5years ago sites compared to the slashed/fire ≥ 14years ago sites. Of the four sites able to be sampled, Popran had no viable material within the collected fruits.

Effects of disturbance on the habitat of *D. glaucophylla*

Mean percentage cover of associated vegetation (1m above ground level) across the 180 quadrats was 44%. Significant differences among the three disturbance regimes were found for this variable, with slashed/fire ≥ 14 years ago areas having significantly lower percentage cover of associated vegetation compared to that of the other two disturbance regimes (Table 3). For sites burnt ≥ 14 years ago, mean percentage cover of associated vegetation (1 m above the ground) was significantly (p<0.01) lower in the slashed compared to the unslashed areas. However at Girrakool, slashing had no significant effect on percentage cover of associated vegetation. Further, the unslashed site at Girrakool had significantly (p < 0.05) less cover of associated vegetation compared

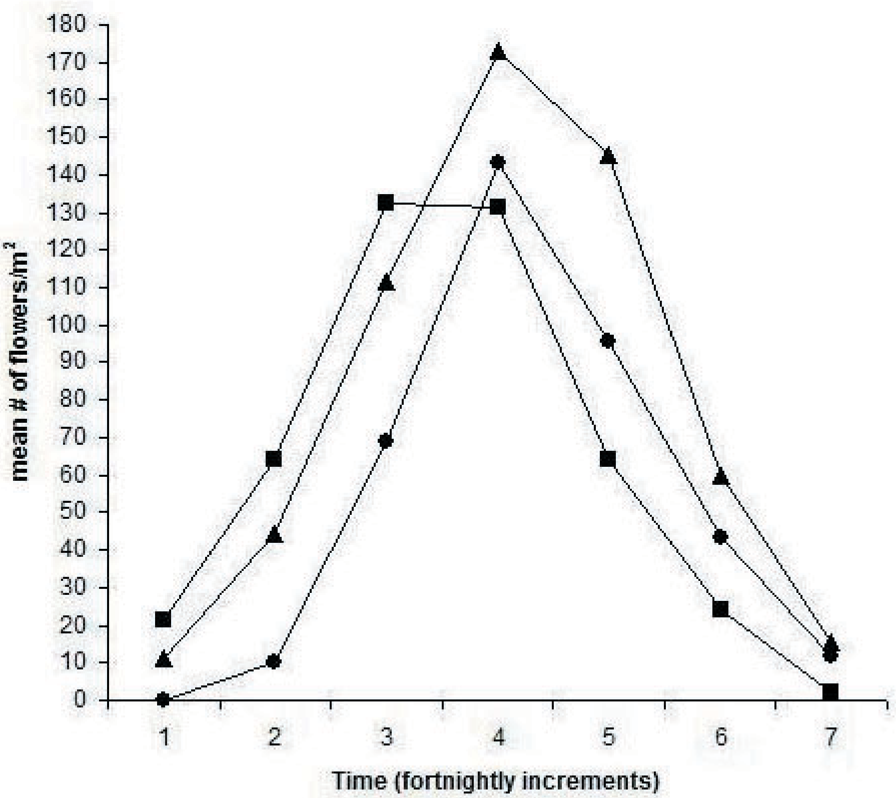


Figure 4. Flowering density of *Darwinia glaucophylla* over time for each disturbance regime (▲= slashed/fire≥14years ago, n= 33; ■ = unslashed/fire≤5years, n=22; ● = unslashed/fire≥14 years ago, n= 2). Monitoring commenced (Time 1) on the 10/8/08 and ceased (Time 7) on the 6/11/08.

to the unslashed site at Popran even though the time since last fire was similar (≥ 14 years ago). There was no significant effect of time since last fire (unslashed) on the percentage cover of associated vegetation (Table 3).

Mean maximum height of vegetation across all quadrats (n=180) was 1.7 m (range 0.15 m to 10 m). Mean maximum vegetation height differed significantly amongst the three disturbance regimes ($p<0.0001$) with vegetation under an unslashed/fire ≥ 14 years ago regime being significantly taller than the other two regimes (Table 3). Within the slashed/fire ≥ 14 years ago regime, the maximum vegetation height at Girrakool was significantly greater than at Popran. Within the unslashed sites, time since last fire had a significant effect with maximum vegetation height being lower when fire was ≤ 5 years ago compared to fire ≥ 14 years ago (Table 3). Photosynthetic active radiation (PAR) was significantly affected by time since last fire (Table 3). Among the unslashed sites, mean PAR was lower in areas burnt ≥14years ago compared to those burnt ≤ 5years ago (Table 3). The effect of site was due to PAR being similar at the two unslashed/fire ≤ 5 years ago sites (Lyre Trig and Rifle range), while within the unslashed/fire ≥ 14 years ago regime, Girrakool had significantly higher PAR compared to Popran. PAR of the slashed sites was similar to sites with an unslashed/ fire ≤ 5years ago regime (Table 3).

Of the suite of soil variables investigated, most showed significant differences between disturbance regimes and/or sites, but there were no significant interactions between these two factors (Table 3). Time since last fire had a significant effect on percentage soil moisture (Table 3), with areas burnt ≤ 5 years ago having lower mean percentage soil moisture compared to areas burnt ≥ 14 years ago (within unslashed sites). Soil pH, electrical conductivity, percentage organic matter, total soil nitrogen and phosphorus were not significantly affected by time since last fire (Table 3). However, the effect of fire on soil nitrogen was close to significance ($p = 0.052$). Slashing had a significant effect on soil pH, electrical conductivity, total soil nitrogen and percentage of organic matter in the soil (Table 3). Mean soil pH was significantly higher while EC, organic matter and total soil nitrogen was

Table 3. ANOVA results (F-values) for percentage cover of associated vegetation, mean height of vegetation, photosynthetically active radiation (PAR) and soil chemistry within quadrats. Sl (slashing), St (site), F (fire) . L – R: the effects of slashing (orthogonal design) are conveyed in columns 2, 3 & 4 of the table while the effects of fire (nested design) are shown in columns 5 & 6. *p<0.05, **p<0.01, ***p<0.001.

Variable	Sl x St	Sl	St	St (F)	F
d.f	1	1	1	2	1
Percentage (%) cover of associated vegetation	3.00	7.03**	5.31*	4.00*	1.85
Mean height (m) of vegetation	0.03	106.38***	7.19**	1.50	41.88*
PAR	25.39**	134.23***	18.05***	20.78**	183.3***
pH of soil	0.97	10.98**	1.18	0.72	0.65
Electrical conductivity (µS) of soil	0.26	11.79**	5.49*	1.17	0.02
Percentage (%) soil moisture	0.00	2.30	15.52**	0.0018	7.20*
Total soil nitrogen (mg/kg)	1.28	7.98*	2.00	3.16	1.01
Total soil phosphorous (mg/kg)	0.17	1.27	3.91	9.32*	0.07

significantly lower in the slashed areas compared to the unslashed areas. Total soil phosphorus and percentage soil moisture were not significantly affected by slashing (Table 3).

Several environmental variables were significantly correlated with quadrats containing *D. glaucophylla* and with percentage cover of the species (Table 4). Presence of, and/or percentage cover of, *D. glaucophylla* was negatively correlated with mean maximum height of vegetation, percentage cover of associated vegetation, soil moisture content and soil EC , and positively correlated with PAR and soil pH. Average apical growth was positively and negatively correlated with PAR and maximum height of vegetation, respectively. Seedling presence was positively corrected with soil N, P, percentage organic matter and EC, while percentage of viable seeds was positively correlated with the maximum height of vegetation, percentage cover of associated vegetation and soil N (Table 4). Although these correlations were significant, some of the correlation co-efficients were small indicating that the relationship between some of the variables was weak and therefore should be treated with caution.

DISCUSSION

Abundance and habitat

While 33% of quadrats surveyed in this study contained *D. glaucophylla*, mean percentage cover was only 5%, indicating that the above ground abundance of the species is lower than initial field observations suggested. The patchy nature of growth in specific habitats such as rocky shelves often gives the impression of local abundance (Booyens pers. ob. 2007). Large spreading mats of *D. glaucophylla* at slashed sites (along the pipeline easement) also give the impression of abundance, but our results show that the mats in this location are due to the intentional management of the over-storey. *Darwinia glaucophylla* was also found in unslashed areas where fire had passed through more than 14 years ago, but it was less frequent compared to sites burnt less than 5 years ago. This finding is consistent with the reported decline of heathland sub-shrubs during long fire intervals, as a result of density-dependent interactions (Keith 1996). Species that are subordinate in stature are particularly prone to competitive elimination (in the absence of disturbance) but these competitive

Table 4. Significant correlations between measured environmental variables and attributes of *D. glaucophylla*. PAR – photosynthetically active radiation; EC = electrical conductivity; N = total nitrogen; P = total phosphorus; OM = organic matter. *p<0.05, **p<0.01, ***p<0.001.

Environmental Variable	*D.glaucophylla* attribute	Spearman ρ	p-value
PAR (µmol/sec/m)	% cover	0.3565	***
PAR (µmol/sec/m)	Average apical growth (cm)	0.6510	***
Max. height of vegetation (m)	% cover	-0.4482	***
Max. height of vegetation (m)	Average apical growth (cm)	-0.5597	***
Max. height of vegetation (m)	% viable seeds	0.6365	***
% cover associated vegetation	% cover	-0.4121	***
% cover associated vegetation	% viable seeds	0.2893	**
pH	Presence in quadrat	0.4110	*
pH	% cover	0.5578	**
EC (µS/cm)	% cover	-0.4112	*
EC (µS/cm)	quadrats containing seedlings	0.4218	*
% moisture (field)	Presence in quadrat	-0.3746	*
N (mg/kg)	% viable seeds	0.4802	*
N (mg/kg)	quadrats containing seedlings	0.4661	*
P (mg/kg)	quadrats containing seedlings	0.3941	*
% OM	quadrats containing seedlings	0.4081	*

interactions only affect the standing plant life stages of populations (Keith 1996). Most plant species from fire-prone communities are expected to have soil seed banks (Auld et al. 2000). Depending on the longevity of their dormant seeds, these species may persist in the community long after standing plants have been eliminated (Keith 1996). Although not examined in this study, it is expected that *D. glaucophylla* is also present in the soil seed bank at the long unburnt sites. *Darwinia* species are known to have persistent soil seed banks (Auld and Ooi 2009), which would allow hidden (below ground) populations of *D. glaucophylla* to persist during fire intervals typical of the current study.

Both slashing and time since last fire had a significant effect on the attributes and habitat of *D. glaucophylla* (Table 5). Overall our results show that there were more similarities between the sites with differing times since last fire (unslashed) than between sites with different slashing regimes (Table 5). That is, the presence of slashing had a greater number and magnitude of effects than time since last fire. However, slashed habitats did resemble areas burnt less than five years ago in the following ways: vegetation of lower stature, greater light penetration and less soil moisture compared with those areas burnt more than 14 years ago and not slashed. The effects of slashing were not all negative though; slashing resulted in the greatest frequency and percentage cover of *D. glaucophylla*.

As soil variables are inter-related, it is difficult to isolate the importance of individual soil factors to the abundance of *D. glaucophylla* (especially because correlation does not confer causality). However, the results confirm that the soil characteristics of the species habitat were typical of that found in heathland vegetation on Hawkesbury sandstone (Murphy 1993) and that mature *D. glaucophylla* individuals can tolerate a range of nitrogen levels (230 – 880mg/kg). The species ability to tolerate low nitrogen may be possible because of existing ectomycorrhizal associations (Booyens 2010). *Darwinia glaucophylla* was more likely to be present, and more abundant, in quadrats with higher soil pH and lower soil moisture (Table 5). The fact that phosphorus levels were similar across the different disturbance regimes

Table 5. Summary of effects of disturbance regime (time since last fire or slashing) on *D.glaucophylla* and its habitat. * Due to presence of permanent creek through this site.

Slashed/fire
≥ 14 years ago

- High frequency of quadrats containing *D .glaucophylla*
- High % cover of *D. glaucophylla*
- High apical growth
- No seedlings
- Similar flowering density
- Low seed viability
- No overstorey
- Low stature vegetation
- High PAR
- Mean pH 5.1
- Low EC
- Medium soil moisture (field)*
- Low N
- Similar P
- Low % OM

Unslashed/fire
≤ 5 years ago

- Low frequency of quadrats containing *D. glaucophylla*
- Low % cover of *D. glaucophylla*
- High apical growth
- Seedlings present
- Similar flowering density
- Higher seed viability
- No overstorey
- Low stature vegetation
- High PAR
- Mean pH 4.9
- High EC
- Low soil moisture (field)
- High N
- Similar P
- High % OM

Unslashed/fire
≥ 14 years ago

- Low frequency of quadrats containing *D. glaucophylla*
- Low % cover of *D. glaucophylla*
- No apical growth
- No seedlings
- Similar flowering density
- No seeds collected
- Overstorey present
- Tall stature vegetation
- Low PAR
- Mean pH 4.8
- High EC
- High soil moisture (field)
- High N
- Similar P
- High % OM

(Table 5) is not surprising, as most studies have found that soil chemical properties return to pre-fire conditions within a year (Raison 1979) and two years had elapsed since the most recent fire in the current study. Any nutrient pulse resulting from soil heating and ash residues would have since been taken up by the existing vegetation, been re-immobilised by microbes or lost by leaching (Raison 1979). Despite this, there was a weak positive correlation between the presence of *D. glaucophylla* seedlings in a quadrat and total soil nitrogen and phosphorus levels. As seeds of the species contain no endosperm (Auld and Ooi 2009) the ash-bed effect, which provides a temporary nutrient-rich substrate allowing enhanced seedling growth (Hobbs 2002), may be particularly important.

Flowering

Slashing had no significant effect on flowering, with mean density of flowers and progression of flowering over time similar across the different disturbance regimes. Flowering fecundity and timing may be affected by resource availability such as adequate soil moisture (Craine 2005). However in our study, differences in soil resources (i.e. moisture and nitrogen) between the treatments (Table 5) appeared to have little effect on flowering. Differences in flowering response between individual sites under the same disturbance regime (e.g. unslashed Popran and unslashed Girrakool) may be attributable to other site-specific features such as aspect and degree of shading from vegetation surrounding the pipeline easement. Despite being surrounded by vegetation, the Popran unslashed site showed much higher levels of flowering compared to the unslashed Girrakool site. This may be explained by the maximum height of vegetation at the latter site being greater and site elevation being considerably lower; both factors likely to increase the degree of shading. In agreement with previous studies (Briggs 1962; Myerscough 1998) we found that peak flowering occurs in September. Peak flowering came earliest to the Rifle Range (fire ≤ 5 years) site and latest to the Girrakool slashed site, further indicating some site specific differences. Fecundity could not be ascertained as an unexpectedly large number of flowers developed, preventing each marked flower being followed over time. It is recommended that future studies of flowering in this species use the density estimates presented here to determine a suitable quadrat size or number of branchlets to sub-sample.

Seeds and seedlings

Whilst one sampling period is insufficient to make conclusions about seedling recruitment in this species, the only site containing seedlings was Lyre Trig, which was burnt two years prior to the study. *Darwinia glaucophylla* is an obligate-seeder with a soil-stored seed bank and therefore fire is important for the recruitment of this species (Auld and Ooi 2009). Auld and Ooi (2009) found that the viability of fresh seed collected from *D. glaucophylla* was high (85-94%), irrespective of site and the year of collection. Our seed viability results aren't comparable because it was tested at the end of the germination experiment, by which time the seeds were at least 7 months old. Greater than 90% of fruits collected in the current study were empty at the end of the germination trial (as determined by a cut test). Possible reasons for empty fruits include: abscission of immature fruits due to weather conditions, lack of resources, competition with developing fruit for limited resources, genetic abnormalities or lack of appropriate insect pollinators, post-dispersal decomposition of fruits deposited on the soil surface, pre- or post-dispersal insect predation of fruit contents, or decomposition while on agar plates despite addition of fungicidal agents (Stephenson 1981; Baskin and Baskin 1998). Myrmecochory has also been reported for *Darwinia* spp. in south-eastern Australia, with removal of abscised fruits being rapid (within 4 - 5 days) (Auld 2009). As fruits in the current study were collected post-dispersal, our findings raise the question as to whether ants could be selectively removing filled, and potentially viable, fruits. We also found that twice as many fruits containing viable seed were collected from the unslashed recently burnt sites compared to the unslashed long unburnt sites. This finding is worthy of further study.

For most of the south eastern Australian *Darwinia* species, a large proportion (80-100%) of the seed is dispersed in a dormant state (Auld and Ooi 2009). However for *D. glaucophylla*, the proportion of fresh seed that were dormant was lower (40-75%) and varied considerably between sites and slightly between years (Auld and Ooi 2009). The findings of the current study confer with Auld & Ooi (2009) in that most of the annually produced seed were dormant (100% in our study). However, Auld and Ooi (2009) also found that heat elicited a germination response in *D. glaucophylla* although the response was quite variable. Three of the four seed crops (two sites over two collection years) germinated at low rates (20 - 40%) without heat treatment (i.e. controls), one seed crop showed a temperature response after being exposed to 60 – 110°C and two seed crops showed a response to 80 – 100°C (Auld and Ooi 2009). The fact that no viable seeds in the current study germinated (with or without treatment) cannot be explained by differences in methods between the two studies, with the exception of the seed collection method. The different methods of seed collection meant that post-dispersal environmental conditions would have differed between the two studies, raising the possibility that a short period (about 1 month) of exposure to ground surface conditions in the current study may have induced secondary dormancy. This hypothesis is worthy of further study because Auld *et al.* (2000) suggested that *D. biflora* may exhibit seasonal secondary dormancy.

The maximum age of the seedlings at Lyre Trig is two years and is therefore consistent with Auld and Scott (1995) who found that seedlings of this species emerge within 2-3 years after fire. Auld and Ooi (2009) suggest that most seedlings don't establish as a result of over storey competition. The post-fire soil nutrient status and above average rainfall during the current study may have been favourable for the growth of seedlings (Keith and Tozer 2012). Unfortunately few seedlings were available to monitor in this project and a more extensive search for seedlings across the species range, followed by a longer monitoring period, is needed to improve knowledge of seedling recruitment and survival rates in different habitats. Adults growing in sites that had either been slashed or burnt less than 5 years ago showed a growth spurt well after peak flowering, which may have been associated with the higher than average rainfall experienced in February 2009. It cannot be determined whether the absence of apical growth of individuals in the unslashed sites that were burnt ≥ 14 years ago was due to competition for resources or an artefact of species abundance being so low that it was less likely that a plant with apical growth was encountered. However, it has been previously noted (Hobbs 2002) that a post-fire environment in Australian heath is conducive to high rates of growth at ground level.

Management implications

One of the disturbances to which *D. glaucophylla* is currently indirectly exposed is slashing of overstorey vegetation along the Sydney to Newcastle gas/oil pipeline. Slashing or mowing under power lines and within other utility easements serves to reduce biomass in an area, limiting fuel for potential fires and improving visibility of, and access to, the easement. In cases where biomass is removed, soil nutrient status and levels of organic matter may be adversely affected (Walker 2004). Findings generally vary as to whether nitrogen (N) or phosphorous (P) decline and the extent of the decline (Walker et al.

2004). The current study found that slashed sites had significantly higher soil pH and lower EC, nitrogen and organic matter compared to unslashed sites (Table 5). It is proposed that removal of biomass reduced inputs of organic matter into soil, which would have also reduced available nitrate and ammonium ions, contributing to lower electrical conductivity of soil water. Disturbance of the soil profile during the initial laying of the pipeline in 1978 (> 30 years ago) may also explain the lower levels of nitrogen and organic matter along the easement if the subsoil material was brought to the surface and left exposed.

While current slashing practices (hand-held cutter 30 cm above ground) along the Sydney to Newcastle gas/oil pipeline easement appear to promote the survival and growth of existing mature individuals, it is not known how long these practices have been in place. Given that the species has a life expectancy of around 20 - 30 years (Auld and Scott 1995), there has been insufficient time to see the effects of slashing over several generations. Further, it is not known whether slashing can provide conditions necessary for future recruitment. The current study found that slashing did not affect flowering but we were unable to determine whether fruit production was affected. Although Auld and Scott (1995) demonstrated that 6-month old seed of *D. glaucophylla* is viable, the long-term persistence of seeds in the soil is not known. If fire related cues are the only mechanism by which seed dormancy is broken and the species doesn't produce any non-dormant seeds, then the population along the pipeline at Popran may only be temporary. Keith et al. (2002) reports that "most heath species with persistent seed banks also produce a fraction of non-dormant seeds" (p. 214) but Auld and Ooi (2009) show that the proportion of *D. glaucophylla* seeds that germinate without treatment is low. Increased nitrogen levels in recently burnt areas often contribute to more successful establishment of seedlings (Bell et al. 1999). Thus even if seeds were to germinate in the slashed sites in the absence of fire, the lower soil nutrient levels together with a lack of a nutrient pulse after fire may limit seedling establishment. The life-span of *D. glaucophylla* is around 20 - 30 years (Auld and Scott 1995) and the site has not experienced a fire event for around 20 years. Auld and Scott (1995) recommend a 5-10 year minimum interval between fires for this species, but this may not be practicable under power lines or above the pipeline. It is likely that existing populations in Popran outside the unburnt easement are too far away to allow natural dispersal and recolonisation if the slashed population (including the soil-stored seed bank) was to reach the end of its life. If smoke alone can promote germination, this may provide a management alternative for populations where ecological burns cannot be conducted. Field trials using aqueous smoke extracts, pelletised smoke products or pile burns could then be conducted and recruitment monitored.

CONCLUSION

The current study confirms that fire and slashing both have positive effects on the above ground abundance of *D. glaucophylla*. Our results demonstrate that the above ground abundance of *D. glaucophylla* was very low in long unburnt sites, unless they have been slashed. The above ground abundance of *D. glaucophylla* was greater at sites that were recently burnt compared to those burnt more than a decade ago, and seedlings were only found at one site that was burnt < 5 years ago. Fire and slashing affected the habitat of *D. glaucophylla* differently. While both types of disturbance reduced the biomass of the surrounding vegetation and increased light penetration, slashing also resulted in lower levels of soil nutrients and organic matter. Ideally, components of the fire regime other than time since last fire should be investigated to refine fire management strategies. However given the species' restricted distribution, finding sites with suitable fire regimes may not be possible. Flowering in *D. glaucophylla* peaked in September and flowering density followed a similar pattern over time, irrespective of the disturbance regime. The results of the germination experiment indicated that further study of the seed ecology of this species is required.

The finding that the above ground abundance of *D. glaucophylla* is higher at slashed sites and flowering rates are unaffected by slashing goes some way to support the conclusion of Monsted and McMillan (2007) that current slashing practices along the Sydney to Newcastle pipeline in habitats containing *D. glaucophylla* are not adversely affecting existing mature individuals. However, insufficient time has elapsed to examine the effects of slashing over several generations. Although the soil seed bank of *D. glaucophylla* has the potential to allow the population to persist after the above ground plants reach the end of their life span, it was not apparent from the current study whether slashing creates conditions that are favourable for seedling recruitment.

ACKNOWLEDGEMENTS

We would like to thank K. Smith of National Parks and Wildlife (Gosford) for assistance with ArcView to create fire maps and all those who assisted with field work. We also wish to thank D. Warman and K. O'Neil for assistance with germination trials and statistics respectively. Finally, the authors would like to thank the journal referees for their constructive comments. This study was conducted under a Scientific licence (S12556) from the NSW Office of Environment and Heritage.

REFERENCES:

Auld, T. D. (2009). Petals may act as a reward: myrmecochory in shrubby *Darwinia* species of south-eastern Australia. *Austral Ecology* **34**, 351-356.

Auld, T. D., Keith, D. D. and Bradstock, R. A. (2000). Patterns in longevity of soil seedbanks in fire-prone communities of south-eastern Australia. *Australian Journal of Botany* **48**, 539-548.

Auld, T. D. and Ooi, M. K.J. (2009). Heat increases germination of water-permeable seeds of obligate-seeding *Darwinia* species (Myrtaceae). *Plant Ecology* **200**, 117-127.

Auld, T. D. and Scott, J. (1995). *Conservation of endangered plants in urban fire-prone habitats*. Species and Habitats Conference Nov. 13-16 Idaho.

Baskin, C. C. and Baskin, J. M. (1998). ' Seeds'. (Academic Press: San Diego).

Bell, D. T., King, L. A.and Plummer, J. A (1999). Ecophysiological effects of light quality and nitrate on seed germination in species from Western Australia. *Australian Journal of Ecology* **24**, 2 – 10.

Benson, D.H. (1986). Vegetation of the Gosford and Lake Macquarie area. *Cunninghamia* **1**(4), 467- 489.

Bond, W. J. and van Wilgen, B. (1996). ' Fire and Plants'. (Chapman and Hall: London).

Briggs, B. G. (1962). The New South Wales Species of *Darwinia*. *Contributions from the N.S.W. National Herbarium* **3**(3), 129-143.

Bureau of Meteorology (2009). www.bom.gov.au [accessed 12/12/2009]

Cochrane, A., Kelly, A., Brown, K. and Cunneen S. (2002), Relationships between seed germination requirements and ecophysiological characteristics aid the recovery of threatened native plant species in Western Australia. *Ecological Management & Restoration* **3**(1), 47-59.

Craine, J. M. (2005). Reconciling plant strategy theories of Grime and Tilman. *Journal of Ecology* **93**, 1041-1052.

Department of Environment, Climate Change and Water (2009a) *Darwinia glaucophylla* profile (online) http://www.environment.nsw.gov.au/threatenedSpeciesApp/profile.aspx?id=1020 [accessed 3/9/09]

Department of Environment, Climate Change and Water (2009b) *Key Threatening Process* (online) http://www.environment.nsw.gov.au/threatenedspecies/keythreateningprocesses.[accessed 3/9/09]

Ellis, M. and Allen T. (2013). A trial of slash and burn management of Coast Tea-tree *Leptospermum laevigatum* on Wonthaggi Heathland. *The Victorian Naturalist* **130**, 212-218.

Foreman, R. T. T., Sperling, D., Bissonette, J. A., Clevenger, A. P., Cutshall, C. D., Dale, V.H. Fahrig, L., France, R., Goldman, C. R, Heanue, K., Jones, J. A.,Swanson, F. J., Turrentine, T. and Winter, T .C. (2003). ' Road Ecology' . (Island Press: Washington).

Gill , A.M. (1975). Fire and the Australian flora: a review. *Australian Forestry* **38**, 4-25.

Ho, R. (2006). ' Handbook of univariate and multivariate data analysis and interpretation with SPSS' (Chapman and Hall: London).

Hobbs, R. (2002). Fire regimes and their effects in Australian temperate woodland. In 'Flammable Australia: The fire regimes and biodiversity of a continent' (Eds R.A. Bradstock, J.E. Williams and M.A. Gill) (Cambridge University Press: Cambridge).

International Seed Testing Association (ISTA) (2003). *International Rules for Seed Testing*. Switzerland.

JMP (v 8.0) (2008). SAS Institute Inc, Cary, USA.

Keith, D.A. (1996). Fire-driven extinction of plant populations: a synthesis of theory and review of evident from Australian vegetation. *Proceedings of the Linnean Society NSW* **116**, 37-78.

Keith, D.A., McCaw, W.L. and Whelan, R.J. (2002). Fire regimes in Australian heathlands and their effects on plants and animals. In ' Flammable Australia: The fire regimes and biodiversity of a continent' (Eds R.A. Bradstock, J.E. Williams and M.A. Gill) (Cambridge University Press: Cambridge).

Keith, D.A and Tozer, M.G. (2012). The influence of fire , herbivores and rainfall on vegetation dynamics in the mallee: a long-term experiment. *Proceedings of the Linnean Society of NSW **134,** 40-54*

Kenny, B. J. (2000). Influence of multiple fire-related germination cues on three Sydney *Grevillea* (Proteaceae) species. *Austral Ecology* **25**, 664-669.

Kirkpatrick, J.B. (2007). Collateral benefit: unconscious conservation of threatened plant species. *Australian Journal of Botany* **55**, 221-224.

MacDonald, R.C., Isbell, R.F., Speight, J.G., Walker, J. and Hopkins, M.S. (1990). 'Australian Soil and Land Survey' (2nd ed). (Inkata Press: Melbourne).

Monsted, P. and McMillan, A . (2007). S*ydney to Newcastle Gas Pipeline Easement Biodiversity Assessment and EMP for maintenance works.* Parsons Brinckerhoff, Sydney.

Murphy, C.L. (1993). *Soil Landscapes of the Gosford-Lake Macquarie 1:100 000 Sheet* Report, Department of Conservation and Land Management.

Myerscough, P.J. (1998). Ecology of Myrtaceae with special reference to the Sydney region. *Cunninghamia* **5**(4), 787-807.

Ooi, M., Auld, T. and Whelan, R. (2005). Comparison of the cut and tetrazolium tests for assessing seed viability : a study using Australian native *Leucopogon* species. *Ecological Management and Restoration* **5**(2), 141-143.

Raison, R. J. (1979). Modification of the soil environment by vegetation fires, with particular reference to nitrogen transformations: a review. *Plant and Soil* **51**, 73-108.

Rayment, G.E. (1992). *'Australian laboratory handbook of soil and water chemical methods'*. (Inkata Press: North Ryde).

Ross, K. A., Taylor, J. E., Fox, M. D. and Fox, B. J. (2004). Interaction of multiple disturbances importance of disturbance interval in the effects of fire on rehabilitating mined areas. *Austral Ecology* **29**, 508-529.

Stephenson, A. G. (1981). Flower and fruit abortion: proximate causes and ultimate functions. *Annual Review of Ecology & Systematics* **12**, 253-279.

Tabachnick, B. G. and Fidell, L. S. (1996). 'Using Multivariate Statistics' (3rd ed). (Harper Collins College Publishers: California).

Tierney, D. A. (2006). The effect of fire-related germination cues on the germination of a declining forest understory species. *Australian Journal of Botany* **54**, 297-303.

Tierney, D.A. and Wardle, G. A. (2005). Differential seed ecology in in the shrubs *Kunzea rupestris, K. capitata* and associated hybrids (Myrtaceae): the function of thin-walled fruit in a fire-prone vegetation. *Australian Journal of Botany **53***, 313-321.

Underwood, A.J (1997a). 'Experiments in Ecology: Their Logical Design and Interpretation Using Analysis of Variance'. (Cambridge University Press: Cambridge).

Underwood, A.J. (1997b). 'GMAV statistical software'. (Cambridge University Press: Cambridge).

Walker, K.J., Stevens, P.A., Stevens, D.P., Mountford, J.O., Manchester, S.J. and Pywell, R.F. (2004). The restoration and re-creation of species-rich lowland grassland on land formerly managed for intensive agriculture in the UK. *Biological Conservation* **119**, 1-18.

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 82, Kingsford, N.S.W. 2032, 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 136

CONTENTS

Volume 136
Papers published in 2014, compiled 31 December 2014

Published at http://escholarship.library.usyd.edu.au/journals/index.php/LIN
(date individual papers were published online at eScholarship)

Volume 136
Compiled 31 December 2015

TABLE OF CONTENTS

Section 1 – Papers arising from a symposium held at Jenolan Caves in May 2013.

Section 2 – General papers