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Cover motif: Opalised fossils from Lightning Ridge; Figure 2 in the paper by Simone Meakin, page 71 this volume. Photographs by Robert A. Smith courtesy of the Australian Opal Centre.

EDITORIAL

This is the last printed volume of the *Proceedings of the Linnean Society of New South Wales*. From the first volume in 1877 to 2011, our journal has adapted to many changes in the technology of printing. In 2011 it is now time to make a much more dramatic change – away from print and paper into the electronic age. From volume 133 the *Proceedings* will be published electronically on the world wide web through e-Scholarship (a division of the University of Sydney Library). Authors in 2011 require rapid publication. Authors of scientific papers require credible publication, which the Linnean Society of NSW will provide by continuing to subjecting all manuscripts to rigorous peer review. The mode of publication, through a secure site that only hosts material from scientific and academic organisations, further ensures credibility.

Papers will be put on the Net as soon as they have been reviewed, revised as necessary and accepted by the Society's publications committee. At the end of each year all papers put on the Net during that year will be "bound" into a numbered volume for permanent archiving by e-Scholarship. That volume will also be available on CD free-of-charge for all our current subscribers around the world and to members of the Linnean Society of NSW.

One huge advantage of this new mode of publication is that the papers, and hence the information provided by the scientific research therein, will be available world wide free-of-charge. It is the current policy of the Society that access to papers as they are published and archived material at e-Scholarship will remain free. At present and into the foreseeable future all of the Society's journals from Volume 1 are available free-of-charge through the American information site biodiversityheritagelibrary.org.

This change is not 100% free of paper and print, as existing requirements of the Zoological and Botanic Nomenclature Commissions force us to distribute a small number of printed copies to selected institutions. This requirement is bound to change in the future.

Also, e-Scholarship has the facility to provide (with a charge) printed and bound individual copies of the electronic volumes upon request.

This volume contains papers arising from symposium on Geodiversity, Geological Heritage and Geotourism held by the Linnean Society of New South Wales in September 2010. They comprise the first section.

The second section contains general papers.

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FOREWORD TO PAPERS FROM A SYMPOSIUM ON GEODIVERSITY, GEOLOGICAL HERITAGE AND GEOTOURISM

Geotourism, Geodiversity and Geoheritage in Australia – Current Challenges and Future Opportunities

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Geotourism, in addition to its primary role in promoting tourism to geosites, raises public awareness and appreciation of geodiversity. It fosters geoheritage conservation through appropriate sustainability measures and advances sound geological understanding through interpretation. Currently in Australia, geotourism is in its infancy and faces a range of challenges, including lack of awareness and support within the geological professions and varying degrees of acceptance by natural resource managers. Geodiversity on the other hand is now widely appreciated as part of the natural heritage, and is being integrated into government policy concerning the management of national parks and public lands to a degree approaching the stewardship of the native flora and fauna, as greater emphasis is placed on the underlying control of distribution of the living environment by geology and landscape. Conservation of geodiversity and geoheritage is thereby progressing rapidly in some areas, though in others such as the development of geoparks in the Australian context, significant barriers have yet to be surmounted. The recent Symposium on Geodiversity, Geological Heritage and Geotourism, organised by the Linnean Society of New South Wales at Port Macquarie in September 2010, provided an opportunity to discuss these matters from a number of viewpoints, including government, academic and the private sector.

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KEYWORDS: experiential tourism, geoheritage, geodiversity, geoparks, geotourism, national landscapes.

Given Australia's heavy reliance on the expertise of geologists and the exploitation of natural resources for wealth creation, it would be logical to assume that the interpretation of geology and landscape feature extensively in the character of Australia's 'nature-based' tourism industry. However, geotourism is at a very early stage of development in Australia, and faces many challenges, ranging from achieving agreement on what the term actually means, to building a support and advocacy base and further to raising awareness amongst Australian domestic travellers. In comparison, appreciation for geodiversity as an essential part of the natural environment is well advanced, and – thanks to Australia's diverse underlying geology and associated scenic landscapes – many national parks and other public lands protect a broad spectrum of geological heritage sites that are either current or potential foci of geotourism.

Natural Heritage, Geoheritage, Ecotourism, and Geotourism

Natural heritage is the legacy of natural objects and intangible attributes encompassing the countryside and natural environment, including biodiversity (the variety and distribution of flora and fauna), as well as geodiversity (involving landforms and geology). Geoheritage is exemplified by geological sites of outstanding and sometimes unique scientific and scenic value which enable us to understand the composition of the earth, the internal and external processes that have shaped it, and the evolving flora and fauna that occupied it. Geodiversity and geological heritage are best experienced by visiting natural places, thereby providing the rationale for geotourism, now increasingly considered a key driver of 'experiential' tourism. Like ecotourism, geotourism is ecologically sustainable tourism with a primary focus on experiencing natural areas that fosters environmental and cultural understanding, appreciation and conservation. Geotourism enables the public to explore the full range of geodiversity, and can be undertaken in a range of places that include geosites, geo-trails, landforms, karst areas and caves, and mine sites. In addition, geotourism can embrace a range of designated areas which include national parks/reserves/urban parks, world heritage areas, 'national landscape' areas, and geoparks and paleoparks.

The downside of the popularisation of ecotourism in recent years is that the activity itself may progressively destroy the very values that appeal to the ecotourist. This is a continuing problem, particularly now as the greatest impact of mass ecotourism is falling on the most fragile of environments. Thus geotourism must seek to understand its impact on geodiversity and strive to protect and expand geological heritage sites that form in many instances the basis for its existence.

GEOPARKS – THE AUSTRALIAN EXPERIENCE

A geopark is defined by the United Nations Educational, Scientific and Cultural Organization (UNESCO) as a territory encompassing one or more sites of scientific importance, not only for geological reasons but also by virtue of its archaeological, ecological or cultural value. There are currently 77 global geoparks operating in 24 countries around the world as part of the UNESCO Geoparks International Network.

One of the most important aspects of a geopark is the link between the geology and the people, their stories, culture and history that builds a sustainable source of geotourism, brings jobs to rural and indigenous people and in turn, helps protect sites of importance, and promotes geoheritage. Although a geopark has no formal protected lands status (unlike a nature park managed by a government agency), an existing national park or any other designated area may qualify as a geopark, if it has a management plan designed to foster socio-economic development that is sustainable (most likely to be based on geotourism). In addition, the proponents of the geopark must (1) demonstrate methods for conserving and enhancing geological heritage and provide means for teaching geoscientific disciplines and broader environmental issues, and (2) have prepared joint proposals submitted by public authorities, local communities and private interests acting together, which demonstrate the best practices with respect to geoheritage conservation and its integration into sustainable development strategies.

Kanawinka Geopark, the first (and currently, only) one in Australia, was declared in 2008. It occupies an area of 26,910 square kilometres spanning nine Shire Council areas in southwestern Victoria and eastern South Australia. The geopark represents the sixth largest volcanic plain in the world with 374 eruption points, with Recent volcanism extending from the Mount Gambier area in South Australia into the Portland (Victoria) shoreline and north as far as Penola and Mount Hamilton.

However, Kanawinka Geopark has so far been unable to gain Australian Government approval which would enable UNESCO to assign 'global geopark' status. Australian Government Ministers for the Environment and Heritage (EPHC) met in November 2009 and decided that whilst Australian governments support geological heritage, they have significant concerns with the application of the UNESCO Geoparks concept in Australia, especially without government endorsement. Furthermore they determined that existing mechanisms are considered sufficient to protect geoheritage in Australia. In its formal communiqué, the Ministerial Council also requested the Australian Government ask UNESCO to take no further action to recognise any future proposals for Australian members of the Global Geoparks Network, or to further progress Geoparks initiatives within Australia, including that for the Kanawinka Geopark, unless the formal agreement of the Australian Government has first been provided.

As a response to the EPHC decision, the author of one of the presentations at a subsequent Linnean Society of NSW Symposium suggested that several other issues need to be addressed before geopark development can proceed any further in Australia. These issues include the following.

1. There are other competing 'land designation' systems underpinned by environmental, heritage and tourism values e.g. national parks, world heritage areas, including 'national landscapes'.
2. The nature of Australia's political system means that any geopark proposal needs to be accommodated and supported by three levels of government.

3. There is a relatively low profile of geoscience in the Australian community – overshadowed by the strong influence of the Australian mining industry lobby.
4. Apathy amongst the Australian geological community is not helped by the decline in geoscience education and university geology schools in recent years.
5. The geopark concept is not yet embraced or understood by the geological profession.
6. The agricultural/mining industries (which have competing land requirements) are yet to be engaged.
7. The state/territory Geological Surveys and Geoscience Australia are not yet engaging to any significant extent in geopark development and geotourism generally.
8. No government funding programs are available for geopark development.

AUSTRALIAN GEOTOURISM – FUTURE OPPORTUNITIES

Australia's National Landscape Program

'Experiential tourism' has been captured in the Australia's National Landscapes program (a partnership of Tourism Australia and Parks Australia), where visitors can experience the best of Australia's natural, cultural and spiritual wonders – to be known as 'Experiencescapes.' These are world-class landscapes distinctive to Australia, and include many geoheritage sites. The National Landscapes program currently includes the following 10 regions: Australian Alps (New South Wales/Victoria), Australia's Green Cauldron (New South Wales/SE Queensland border region), Australia's Red Centre (Northern Territory), Australia's Coastal Wilderness (New South Wales/ Victoria), the Flinders Ranges (South Australia), Kangaroo Island (South Australia), the Great Ocean Road (Victoria), the Greater Blue Mountains (New South Wales), the Kimberley (Western Australia), and West Arnhem/Kakadu/Nitmiluk (Northern Territory).

Four other regions are also under active consideration viz. Ningaloo-Shark Bay (Western Australia), South Coast (Western Australia), the island of Tasmania, and the Great Barrier Reef (Queensland). Two other areas (i.e. Sydney Harbour and the Wet Tropics area of North Queensland) have been nominated for discussion.

Geotourism and Mining Sites Geoheritage

A significant feature of geotourism is that it does not require untouched landscapes as its playground. A great tour can equally be delivered overlooking a man-made excavation, or in a historic mining area e.g. Broken Hill in New South Wales, Chillagoe in North Queensland and the West Coast of Tasmania. Nor does geoheritage potential need to be restricted just to geological features. For example, the Australian Government Department of Environment, Water, Heritage and the Arts has been assessing both the mining and minerals (i.e. economic geology) heritage of Broken Hill from the perspective of the following attributes: (1) Broken Hill's prominent role in Australia's mining history; (2) its role in the development of innovative mining and metallurgical practices; (3) as the place where safe working practices and workers' legislation was first developed for miners; (4) for its well-known mineralogical diversity; and (5) for its importance for the associations with many individuals who have played a prominent role in the Australian mining industry.

Geoheritage, Geotourism and the Geological Profession

In July 2010, at the Australian Earth Sciences Convention (AESC 2010), a workshop was organised in collaboration with the Geological Heritage Standing Committee of the Geological Society of Australia, The AusIMM, and the Australian Department of the Environment, Water, Heritage and the Arts, to explore the interface between the issues relating to geoheritage and the emerging area of geotourism. Of nine formulated workshop conclusions, the following points are considered particularly relevant in the context of understanding opportunities for geotourism development in Australia.

1. Given the broad range of concepts encompassed by and related to geoheritage, there is a need for the geological profession (or more generally the geoscience professions) to engage further with relevant government agencies to improve mutual awareness and understanding, as well as to better coordinate interaction with relevant government agencies.
2. There is a need to make better known to established and prospective geotourism operators and others the availability of various state/territory resources which identify and promote geoheritage sites. This should include information on site suitability for geotourism.
3. There is continuing concern about the lack of understanding both within the geoscience professions and the general community of the differences between the concepts of geoheritage and geotourism.

4. Interest in mining heritage can be expanded to embrace areas of geoheritage pertaining to economic geology (i.e. relating to the minerals industry). Moreover, there is an opportunity to encourage individual mining companies and industry associations to assist with funding aimed at helping in the conservation of geoheritage and to foster higher levels of community awareness through the support of geotourism activities, where practicable.

5. There is an opportunity to foster and promote geotourism initiatives within Australia's National Landscapes with geological and geomorphological significance, as a model to advancing geotourism and geoheritage considerations in other regions, having particular regard to the recently stated views of the EPHC relating to the advancement of geopark proposals in Australia.

LINNEAN SOCIETY OF NSW SYMPOSIUM ON GEODIVERSITY, GEOLOGICAL HERITAGE AND GEOTOURISM – AN OVERVIEW

The recent Linnean Society Symposium, held at Sea Acres National Park in Port Macquarie, NSW from 6-10th September, 2010, addressed many of the issues, challenges and opportunities discussed above. The Symposium was co-sponsored by the Geological Survey of NSW (GSNSW), part of I&I NSW, and the Department of Environment, Climate Change and Water NSW (DECCW) through its Karst and Geodiversity Unit. Both organizations provided a number of speakers. Others amongst the 55 registrants came from the Commonwealth Department of Environment, Heritage and the Arts, and from the Tasmanian Department of Primary Industries, as well as researchers from several universities and museums, teachers, private sector tourism operators and ecological consultants, and retired persons active in local geotourism ventures. Several days of talks were interspersed with two day-long field trips to investigate various aspects of the regional geodiversity of the mid North Coast.

Abstracts from the papers presented at the Symposium, together with the guide to the field trip localities, were compiled into a book produced for attendees. All abstracts and most presentations given at the Symposium are available for download at http://www.dpi.nsw.gov.au/minerals/geological/info/geodiversity-symposium. A link to this site is available on the Linnean Society's website www.linneansocietynsw.org.au.

Nine of the papers from the Symposium have been submitted for publication in this volume of the *Proceedings of the Linnean Society of NSW*. Others, which were more concerned with government policy issues, legislation pertaining to geodiversity and geoheritage conservation, or geotourism, are being prepared for publication elsewhere.

*[Ian Percival publishes with permission of the Director, Geological Survey of New South Wales].

Relationships Between Geodiversity and Vegetation in South-eastern Australia

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Geodiversity, the natural range of geological, geomorphological and soil features, is thought to play a key role in the development of Australian ecosystems and evolution of their biota, due to the widespread occurrence of old soils with impoverished nutritional status and the comparatively restricted occurrence of fertile soils. While associations between soils and vegetation characteristics such as scleromorphy were first noted a century ago, modern theories propose evolutionary and ecological processes that shaped Australian flora and vegetation through interactions between soil nutrition, plant functional traits and flammability. Evidence in support of these generalisations comes mainly from site-specific empirical studies, surveys of plant traits and their associations, classification and mapping of land systems, analyses of regional environmental gradients and phylogenetic studies. The extent to which soils and the substrates from which they are derived place constraints on the climatic response of biota has important implications for understanding future responses of the biota to anthropogenic climate change. Yet, worldwide, there are few studies that examine the relative contributions of geological substrates and climate to variation in vegetation properties over extensive sub-continental regions. This study used a spatially explicit approach to examine the relationship between vegetation and geological substrates over New South Wales, a region of 80 million hectares in south-eastern Australia spanning a diverse range of geology, vegetation and climate. It aimed to assess the fidelity of major vegetation types to geological substrates and estimate the overall influence of geodiversity on vegetation composition relative to that attributable to climate. The spatial data were drawn from maps produced by geological and vegetation surveys. Geological maps were re-classified into 16 broad units reflecting textural and mineral characteristics considered likely to be influential on plant growth. They represent a component of total geodiversity related to broad landscape-scale patterns in major bedrock and regolith types. Vegetation maps were re-classified in 16 broad formations reflecting structural, physiognomic and functional characteristics of vegetation, and into a larger number of 99 classes reflecting species composition. The two spatial data sets were analysed to determine the diversity of vegetation types within geological units and fidelity of each vegetation type to each geological unit. The relative influence of climatic co-variables was also examined using spatial surfaces spline-fitted to 30 years of weather station data. The results indicate a strong non-random relationship between vegetation and geodiversity, with most vegetation types restricted to a narrow range of geological substrates. Partial variance analyses indicated that the influence of geodiversity on vegetation composition was stronger than, and largely independent of the influence of climate. Consistent with current theories, sclerophyllous vegetation formations and classes showed a strong association with geological units characterised by low levels of mineral nutrients. It was concluded that landscape patterns of geodiversity are likely to place significant constraints on the response of native vegetation to future climate change.

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KEYWORDS: climate change, environmental gradient, floristic composition, geological map, gradient analysis, landscape biogeography, Old Climatically Buffered Infertile Landscapes - OCBIL, sclerophyll, soil fertility, vegetation-soil relationships, vegetation classification, vegetation map.

INTRODUCTION

Geodiversity is the natural range (diversity) of geological (rocks, minerals, fossils), geomorphological (land form, processes) and soil features. It includes their assemblages, relationships, properties, interpretations and systems (Gray 2004). Many of the earliest phytosociological studies in south-eastern Australia noted the association between plants and the geological substrates and land forms on which they grow (McLuckie & Petrie 1927, Pidgeon 1937, Fraser & Vickery 1939, Crocker 1944, Beadle 1948). The soils produced by weathering of these substrates in particular geomorphic settings vary greatly in levels and proportions of mineral nutrients, and in their textural and structural characteristics that govern their capacity to retain moisture and conduct subterranean oxygen. Different plant species vary in their ability to extract these three essential resources and to tolerate extreme levels of supply. Species that share similar ranges of tolerance to soil-related resources may therefore be expected to co-occur within communities on particular groups of geological substrates, at least in cases where there is vertical concurrence between soils and the underlying substrate.

At biogeographic scales, geological substrates are thought to play a key role in the development of Australian ecosystems and evolution of their biota, due to the widespread occurrence of old soils with impoverished levels of nutrients and the comparatively restricted occurrence of fertile soils. Diels (1906) first noted a distinction between sclerophyll vegetation associated with sandy soils and 'savanna' vegetation associated with 'favourable' soil conditions. Andrews (1916) later proposed a connection between sclerophylly (a syndrome typified by small, thick leaves with thick cuticles and abundant sclerotic tissue) and soil nutrition, particularly nitrogen and calcium. By mid-century, empirical evidence was emerging that physiological and morphological traits related to uptake of phosphorus (Beadle 1953), acquisition of nitrogen (Hannon 1956) and accumulation of aluminium (Webb 1954) were closely associated with acidic, nutrient-deficient soils that occur in certain parts of the Australian continent. Modern theories propose evolutionary and ecological processes that shaped Australian flora and vegetation through interactions between soil nutrition, plant functional traits and flammability (Beadle 1966, Orions & Milewski 2007, Hopper 2009, Lambers et al. 2010). Evidence in support of these generalisations comes mainly from empirical site-specific or autecological studies (Beadle 1954, Webb 1954, Lamont 1982, Shane & Lambers 2005), surveys of plant traits and their associations (Gill 1975, Lambers et al. 2010), the classification and mapping of land systems – areas of recurring patterns in topography, soils and vegetation (Christian 1952), analyses of local and regional environmental gradients (Myerscough & Carolin 1986, Keith & Sanders 1990) and phylogenetic studies (Johnson & Briggs 1975, Crisp et al. 2004).

Sclerophyll elements of Australian vegetation appear to have originated on pockets of oligotrophic soils in the Cretaceous (Hill et al. 1999, Crisp et al. 2004), yet they did not diversify and rise to dominance until 25 – 10 million years ago. Their expansion and diversification was at the expense of mesic forest vegetation, and coincided with climatic cooling, drying and increased seasonality as separation of Australia and South America from Antarctica initiated circum-polar oceanic currents (Crisp et al. 2004). Expansion and diversification of the Australian arid flora occurred more recently, 5 – 2 million years ago, as the continent moved still further north and experienced extreme wet-dry glacial cycles (Crisp et al. 2004). Fires also became prominent periodically and influential on vegetation during this period (Keeley & Rundel 2005). Yet strong edaphic patterns apparently persisted through this history and remain in the contemporary vegetation (Hopper 2009) and, despite major extinctions and radiations associated with climatic upheavals, there is evidence of biome conservatism in a large majority of lineages (Crisp et al. 2009).

While both soils and climate play prominent roles in theories of the evolutionary history of species within Australian vegetation (Crisp et al. 2004, Orians & Milewski 2007, Hopper 2009), their historical inter-relationships are poorly understood. How much did soils constrain the historical responses of vegetation to climate change? This question seems crucial to understanding the future response of biota as anthropogenic climate change unfolds, yet the spatial dimensions of historical biomes are difficult to quantify and hitherto remain largely unexplored. Insights can possibly be gained by using spatially explicit data to study contemporary relationships between vegetation, soils and climate, yet this has not been examined at the level of assemblages over extensive bioregional scales.

This study investigated the relative influence of geological substrates and climate on the biogeography of vegetation at a sub-continental spatial scale. Its aims were: i) to determine the fidelity between major vegetation types and geological substrates; and ii) to estimate the relative contribution of substrates and climatic variables to variation in species composition of the vegetation. The study was carried out across

New South Wales, a region of 80 million hectares in south-eastern Australia that currently encompasses a diverse range of vegetation, geology and climate. Historically, the region underwent profound climatic upheaval since the appearance of flowering plants in the Cretaceous. A spatially explicit approach was applied using map data synthesised from extensive vegetation and geological surveys carried out within the region (Keith 2004, Stewart et al. 2006). The two spatial data sets were first analysed to assess the fidelity between vegetation types and geological units. A second analysis was carried out to assess the relative influences of geological substrate and climatic factors on the species composition of vegetation. Both analyses were carried out on broad scale classifications reflecting on respective maps the broad structural, physiognomic and functional characteristics of vegetation and the broad textural and mineral characteristics of geological substrates.

METHODS

Vegetation map

The vegetation map was assembled from 105 source maps covering various subregions within New South Wales. These source maps employed a range of different vegetation classifications, varying spatial scales and overlapped with one another spatially to varying degrees. To simplify and standardise the source maps to a common format, the legend of each was re-classified into the vegetation formations and classes described by Keith (2004). In this classification 16 broad formations and sub-formations represent variation in structural, physiognomic and functional characteristics of vegetation (Table 1), and 99 vegetation classes nested within them represent variation in vascular plant species composition (Keith 2004). Classes are not strictly nested within formations, as structure may vary considerably within compositionally defined units, however, classes were assigned to the vegetation formation representing the most commonly expressed structural, physiognomic and functional features of a mature stand (Keith 2004).

The 105 source vegetation maps were ranked according to their relative reliability based on assessments of classification skill, thematic and spatial resolution and currency using a protocol adapted from the one described by Keith & Simpson (2006). After standardising their spatial projections to the Australian Geodetic Datum 66 and Lamberts Conformal projection in a geographic information system, the source maps were merged sequentially so that features of the most reliable source map were displayed in preference to those of other maps wherever there were spatial overlaps (Keith 2004). A similar procedure was used to prepare a mask of extant native vegetation by reclassifying each legend category of each source map as native or non-native and then merging according to the currency of remote imagery from which each source map was derived. The mask was then applied to the composite map to derive an updated version (v3.0) of the vegetation map of NSW and the ACT prepared earlier by Keith (2004) (Fig. 1).

Geological substrate map

A map of geological substrates was derived from spatial data on the surface geology of Australia (Stewart et al. 2006) which, for New South Wales, was based primarily on mapping prepared by the Geological Survey of New South Wales (GSNSW, http://www.dpi.nsw.gov.au/minerals/geological/geological-maps). This dataset shows the distribution of 785 geological units (mainly at Geological Formation level) and was generalised largely from the state digital geology dataset as at 2003, comprising the GSNSW 1:100 000 and 1:250 000 geological map series. Some areas in the north-east of the state (eg: Moree, Inverell, Tamworth, Manilla) and central-west (eg: Goulburn, Lake Cargellico) were re-compiled from more recent data sourced from GSNSW in 2004-5 (Stewart et al. 2006). The basement geology of the Broken Hill region was compiled from 1996 1:500 000 scale data from the national, NSW and South Australian geological surveys. Mapping for the Murray Basin region was compiled from 1991 1:1 000 000 scale data from the Australian Geological Survey Organisation (AGSO). To compile a seamless state dataset, the original map data were edited along the edges of source datasets (edge-matching), which varied in age and spatial scale of compilation. Adjustments to some older geological data were made using geophysical data interpretation where particularly poor edge-matching or spatial accuracy (± 1 km) was identified in the source data (Stewart et al. 2006).

The spatial data prepared by Stewart et al. (2006) generally did not distinguish contrasting depositional environments of unconsolidated Quarternary sediments along the coast. To resolve this deficiency, the coastal portion of Stewart's map was overlain by more recent 1:25 000 scale mapping of coastal Quarternary geology, which discriminated a further 48 units of sediments with alluvial, estuarine and coastal barrier depositional systems (Troedson & Hashimoto

Table 1. Vegetation formations of New South Wales.

Formation	Description
Rainforests	Forests of broad-leaved mesomorphic trees, with vines, ferns and palms. Includes Cunoniaceae, Sapindaceae, Monimiaceae, Lauraceae, Meliaceae, Myrtaceae, Apocynaceae, Rubiaceae, Aspleniaceae, Dryopteridaceae. Coast and tablelands in mesic sites on fertile soils.
Wet sclerophyll forests (shrubby subformation)	Tall forests of scleromorphic trees (typically eucalypts) with dense understories of mesomorphic shrubs, ferns and forbs. Includes Myrtaceae, Rubiaceae, Cunoniaceae, Dryopteridaceae, Blechnaceae, Asteraceae. Relatively fertile soils in high rainfall parts of coast and tablelands.
Wet sclerophyll forests (grassy subformation)	Tall forests of scleromorphic trees (typically eucalypts), with grassy understories and sparse strata of mesomorphic shrubs. Includes Myrtaceae, Poaceae, Euphorbiaceae, Fabaceae, Casuarinaceae and Asteraceae. Coast and tablelands in high rainfall regions on relatively fertile soils.
Grassy woodlands	Woodlands of scleromorphic trees (typically eucalypts), with understories of grasses and forbs and sparse shrubs. Includes Myrtaceae, Poaceae, Asteraceae, Epacridaceae and Pittosporaceae. Rolling terrain with fertile soils and moderate rainfall on the coast, tablelands and western slopes.
Grasslands	Closed tussock grasslands with a variable compliment of forbs. Includes Poaceae, Asteraceae, Fabaceae, Geraniaceae and Chenopodiaceae. Fertile soils of the maritime zone, tablelands and western floodplains.
Dry sclerophyll forests (shrub/grass subformation)	Forests of scleromorphic trees (typically eucalypts), with mixed semi-scleromorphic shrub and grass understories. Includes Myrtaceae, Poaceae, Asteraceae, Ericaceae, Dilleniaceae and Fabaceae. Moderately fertile soils in moderate rainfall areas of the coast, tablelands and western slopes.
Dry sclerophyll forests (shrubby subformation)	Low forests and woodlands of scleromorphic trees (typically eucalypts), with understories of scleromorphic shrubs and sparse groundcover. Includes Myrtaceae, Proteaceae, Ericaceae, Fabaceae and Cyperaceae. Regions receiving high to moderate rainfall on the coast, tablelands and western slopes.
Heathlands	Dense to open shrublands of small-leaved scleromorphic shrubs and sedges. Includes Proteaceae, Fabaceae, Myrtaceae, Casuarinaceae and Cyperaceae. High rainfall regions of the coast and tablelands on infertile soils, often in exposed topographic positions.
Alpine complex	Mosaics of herbfields, grasslands and shrublands. Includes Ericaceae, Asteraceae, Gentianaceae, Ranunculaceae, Poaceae and Cyperaceae. High, snow-prone parts of the southern ranges.
Freshwater wetlands	Wet shrublands or sedgelands, usually with a dense groundcover of graminoids. Includes Cyperaceae, Restionaceae, Juncaceae, Haloragaceae, Polygonaceae, Ranunculaceae and Myrtaceae. Throughout NSW on peaty, gleyed or periodically inundated soils with impeded drainage.
Forested wetlands	Forests of scleromorphic trees (eucalypts, paperbarks, casuarinas) with sparse shrub strata and continuous groundcover of hydrophilous graminoids and forbs. Includes Myrtaceae, Cyperaceae, Ranunculaceae, Blechnaceae, Poaceae. Floodprone plains and riparian zones principally along the coast and inand rivers.
Saline wetlands	Low forests, shrublands and herbfields of mangroves, succulent shrubs or marine herbs. Includes Verbenaceae, Chenopodiaceae, Juncaceae and Poaceae. Coastal estuaries and saline sites of the western plains.
Semi-arid woodlands (grassy subformation)	Open woodlands of scleromorphic trees (eucalypts, acacias), with open understories mostly of chenopod shrubs, usually with strong representation of perennial and ephemeral grasses and forbs, including many ephemeral species. Includes Myrtaceae, Fabaceae, Chenopodiaceae, Asteraceae, Poaceae and Polygonaceae. Low-moderate rainfall regions of the near western plains on clay soils, including infrequently flood-prone sites.
Semi-arid woodlands (shrubby subformation)	Open woodlands of scleromorphic trees (eucalypts, acacias, casuarinas), with open understories of xeromorphic shrubs, grasses and forbs, including many ephemeral species. Includes Myrtaceae, Cupressaceae, Fabaceae, Myoporaceae, Sapindaceae, Asteraceae, Poaceae and Acanthaceae. Low-moderate rainfall regions of the near western plains, including infrequently flood-prone sites.
Arid shrublands (chenopod subformation)	Open shrublands of chenopod shrubs, with perennial tussock grasses and ephemeral herbs and grasses. Includes Chenopodiaceae, Asteraceae, Aizoaceae, Fabaceae and Poaceae. Low rainfall regions of the far western plains.
Arid shrublands (acacia subformation)	Open shrublands of xeromorphic shrubs, hummock or tussock grasses and ephemeral herbs and grasses. Includes Fabaceae, Proteaeceae, Myoporaceae, Asteraceae, Casuarinaceae and Poaceae. Sandy or rocky landscapes in low rainfall regions of the far north-western plains.

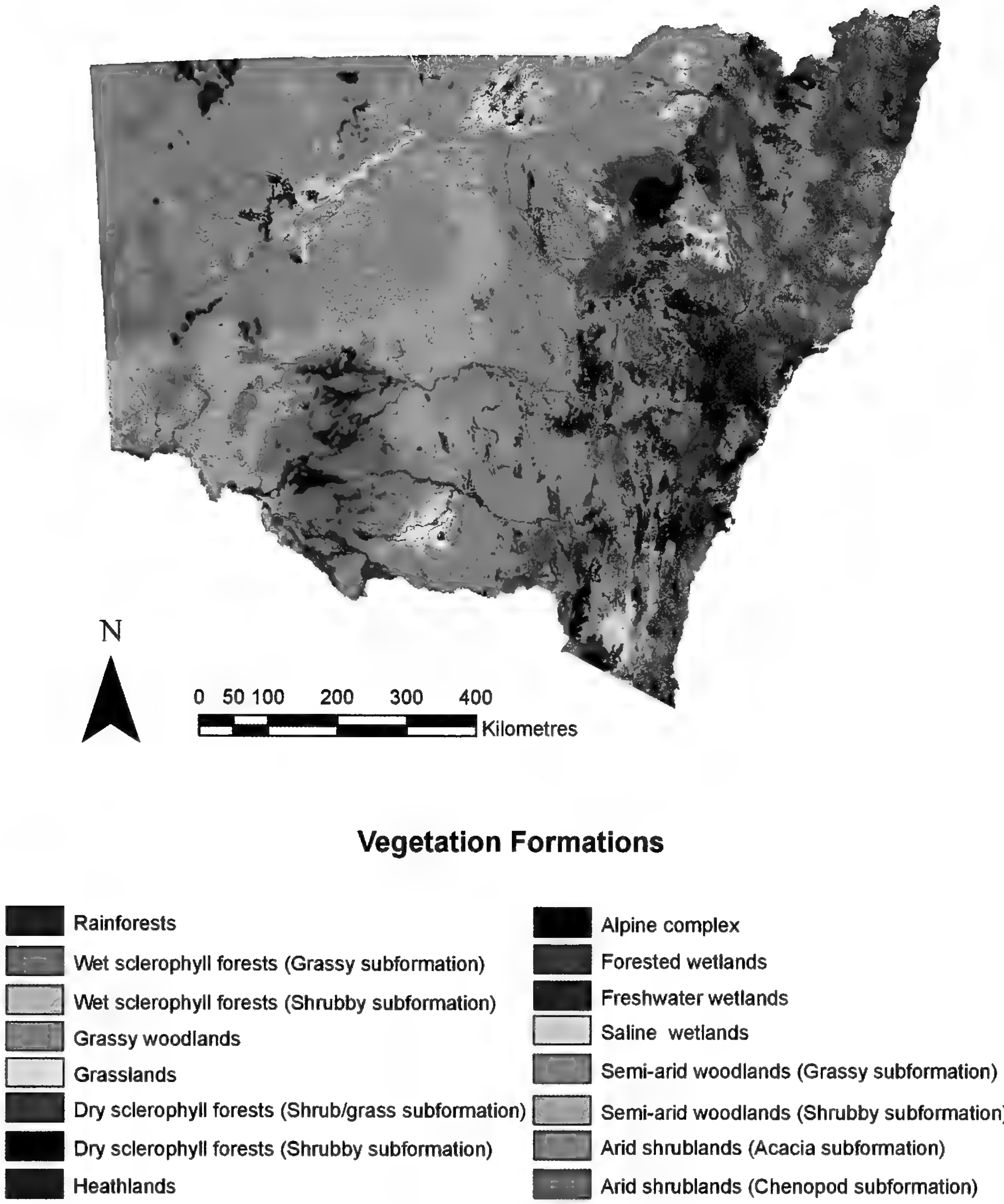

Figure 1. Vegetation map of New South Wales (version 3.0) showing the distribution of 16 formations and subformations (see Table 1 and Keith 2004 for description) prior to intersection with extant mask.

2008). In total, the combined spatial dataset mapped the distribution of 833 geological units across New South Wales and was re-projected to the Australian Geodetic Datum 66 and Lamberts Conformal projection in a geographic information system. As for the vegetation data, the map legend was simplified by assigning each lithological unit to one of 16 substrate types (Table 2). Substrate types were defined on the basis of attributes that were considered important influences on the supply of plant resources: mineral composition; weathering characteristics; texture and depth of derivative soils. The resulting map is shown in Fig. 2.

Table 2. Characteristics of geological substrate types in New South Wales

Substrate type	Origin	Mineral content	Texture	Depth	Examples	Other characteristics
Active floodplain alluvium	Regolith (alluvial)	Fluvial silts, fine sands, muds and clays with high-moderate levels of phosphorus & exchangeable cations	Fine sand & silt, with some clay and localised organic mud. Also includes heavy self-mulching clays	>1m	Coastal & inland floodplains. Richmond River, Moree plains.	Flat-undulating terrain, levees, plains, backswamps and black soil plains. Quarternary deposits
Aeolian (red) sandplains	Regolith (aeolian)	Low-moderate levels of phosphorus and exchangeable cations, calcareous subsoil in SW NSW	Fine sandy loam with clay	>1m	Red sand dunefields and sanplains. Woorinen Formation in Pooncarie district	Flat-undulating terrain, arid & semi-arid climates
Calcarinite*	Sedimentary (marine)	Rich in calcium carbonate	Sandy loams	typically <1m	Very restricted on Lord Howe Island	Flat-undulating terrain, near coast
Estuarine sediments	Regolith (marine/ fluvial)	High concentration of sodium chloride	Silts	typically >1m	Tidal mudflats. Kooragang Island (Hunter River estuary)	Marine & fluvial origin, flat coastal terrain
Felsic intrusives	Igneous	High levels of felsic minerals (quartz, orthoclase & plagioclase) producing soils with high levels of aluminium, potasssium & sodium, but somewhat deficient in phosphorus, magnesium	Coarse-grained weathering to sandy loams	typically >1m, some <1m	Granites, granodiorites, tonalites. New England, Bathurst and Bega batholiths	Steep-undulating terrain, sometimes with tors on hilltops
Felsic volcanics	Igneous	High levels of felsic minerals (quartz, orthoclase & plagioclase) producing soils with high levels of aluminium, potasssium & sodium, but somewhat deficient in phosphorus, magnesium	Fine-grained weathering to loams and clays	typically <1m	Rhyolites, syenites, dacites of the western New England and southern tablelands	Typically steep terrain
High quartz sedimentary	Sedimentary	Abundance of coarse quartz grains bound in a matrix of iron- or aluminium-rich minerals such as siderite or kaolinite with low levels of phosphorus and exchangeable cations, high levels of iron and aluminium	Coarse-grained quartz particles in a fine-grained matrix weathering to sandy loams	typically <1m	Quartzose sandstones.Sydney & Clarence-Morton basins, Pilliga	Steep-flat terrain, limited soil profile development
Lacustrine sediments	Regolith (alluvial)	Moderate levels of most nutrients, depending on source, inundation regime & leaching	Silts & limited sands	typically >1m	Dry or ephemeral lake beds. Mungo Lake, Lake George	Mostly ephemeral lakes of semi-arid zone, some examples in temperate humid tablelands, flat terrain.
Laterite	Regolith (in situ)	High concentrations of iron, aluminium, low concentrations of potassium phosphorus	Loams	<1m	Very restricted in NSW arid zone	Typically on flat terrain, surface or subsurface duricust layer depending on profile weathering
Limestone, dolostone	Sedimentary & metamorphic	Rich in calcite with variable silica component, producing soils with high calcium:magnesium ratios. Also includes domomite, which comprises both calcium and magnesium	Clays and clay loams	typically >1m, some surface exposure	Limestone, dolostone. Jenolan Caves, Bungonia	Steep-flat terrain

Low quartz sedimentary	Sedimentary & metamorphic	Mixture of clay minerals (e.g. montmorillinite, illitie, kaolinite, chlorite) mixed with silt particles of quartz, calcite, etc. producing soils with moderate-high levels of phosporus & exchangeable cations	Clay & loam	mostly >1m	Siltstones, mudstones, shales, greywacke, phyllites, schists. Apsley-Macleay.	Steep-flat terrain
Mafic volcanics & intrusives	Igneous	High levels of mafic minerals (hornblende, pyroxene, olivine, amphibole, biotite) producing soils with relatively high levels of phosphorus, magnesium, iron	Fine-grained weathering to clays and clay loams	typically >1m	Basalt, dolerite, gabbro. Liverpool plains, Geringong volcanics	Often flat-undulating terrain, occasionally steep, the former sometimes producing deep laterised soil profiles
Marine siliceous (white) sandplains	Regolith (marine)	Low-very low in most mineral nutrients, except where influenced by salt spray	Sands	typically 1-5 m	Coastal sand plains. Eurunderee sand mass	Near-coastal, flat sandplains and dunes, often podsolised, mostly marine but some aeolian redeposition (e.g. perched headland dunes)
Residual alluvial clay	Regolith (fluvial)	Low-moderate levels of phosphorus and exchangeable cations	Clay loams	>1m	Riverina plain. Shepparton formation	Flat terrain
Residual alluvial sands	Regolith (alluvial)	Moderate to low levels of most nutrients	Sands & silts	typically >2m	Antecedent stream beds, lunettes, sand plains. Hay plain, rises on the Macquarie-Castlereagh floodplains	Prior streams & inactive alluvial plains, mainly of semi-arid climates on flat terrain
Residual colluvial/ \ alluvial sand & gravel	Regolith (colluvial/ alluvial)	Low-moderate levels of phosphorus and exchangeable cations	Sandy loams & gravels	>1m	Screes, toe slopes. Margins & lower slopes of the Cobar Peneplain	Flat-undulating terrain, Tertiary deposits
Ultramafic igneous & metamorphics	Igneous, metamorphic	Very high levels of mafic minerals and low levels of silica, producing soils with very high magnesium: calcium ratios, high levels of iron, chromium and nickel, and deficiencies in phosphorus and potassium	Fine-grained weathering to clays and clay loams	typically <1m	Serpentinites, peridotites, dunites. Nandewar serpentine belt	Steep-flat terrain, sometimes rocky

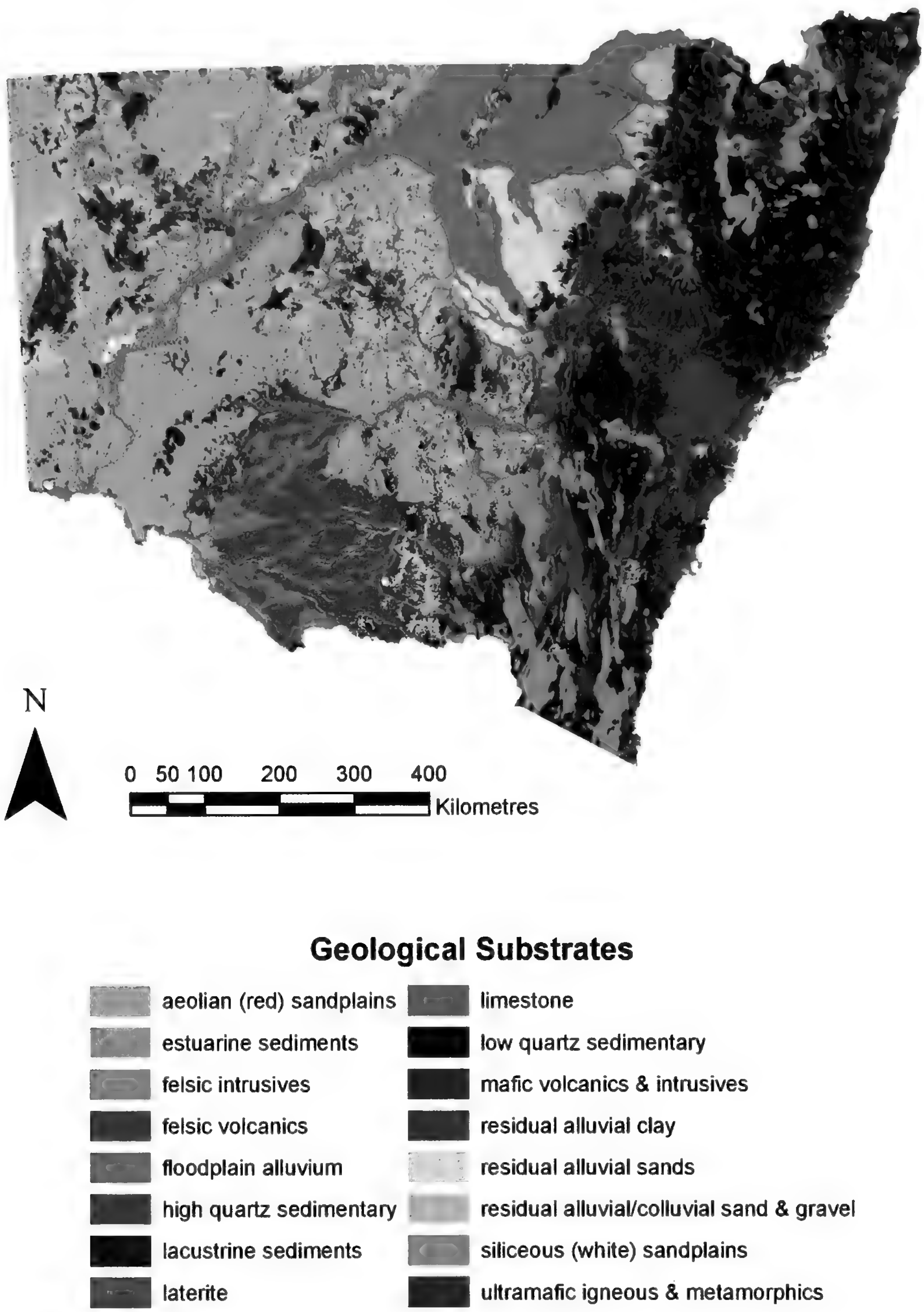

Figure 2. Geological map of New South Wales showing the distribution of 16 substrate types (see Table 2 for description).

Climate surfaces

Spatial grids for monthly precipitation, temperature and radiation parameters were generated by fitting spline functions (Hutchinson 1991) to weather station data across Australia. Using ANUCLIM v6.1 (http://fennerschool.anu.edu.au/publications/software/anuclim.php#overview), the weather station data were aggregated to monthly averages for a 30-year period (1975-2005) and interpolated across the continent on a 9-second latitudinal-longitudinal grid (approx. 250 m). The weekly climate averages were used to calculate the following parameters: MeanTemp- Mean temperature across all weeks of the year; MinTmp- mean of lowest weekly minimum temperature; MaxTmp- mean of highest weekly maximum temperature; DiRngTmp- mean of weekly diurnal temperature ranges; AnnRain- Mean annual rainfall; SummRain – Mean rainfall of December-February; RainDryMth- Mean rainfall of the driest month; MIdry- Mean moisture index of the driest month. Moisture index is calculated from weekly rainfall, evaporation and soil moisture storage (see http://fennerschool.anu.edu.au/publications/software/anuclim/doc/params.html). Spatial data for these parameters were re-projected to the Australian Geodetic Datum 66 and Lamberts Conformal projection in a geographic information system.

Data analyses

To examine the fidelity between vegetation types and geological substrates, 500 randomly located points were generated in a GIS to sample each of the 100 mapped vegetation classes. Subsequently, these were randomly sub-sampled to obtain 1000 points in each of the 16 vegetation formations and subformations. The points sampling vegetation formations and classes were intersected with the geology map (i.e. vegetation cross-tabulated with geology) to estimate their frequencies of occurrence on each substrate type. Similarly, 1000 randomly located points were generated to sample each of the 16 mapped geological substrates, and these were intersected with the vegetation map to estimate the diversity of vegetation formations and classes represented on each substrate type. Calculations of the number of points represented in the cross-tabulations were based on 90th percentile of points to reduce the effect of boundary errors in mapping that may cause spurious occurrences of vegetation types on particular substrates. Thus, the number of substrate types per vegetation unit was taken as the minimum number of substrates accounting for 90% of points within that unit. Pearson correlation coefficients were calculated to assess the association between the area of vegetation classes and formations and the number of substrates that they occupy.

The variation in species composition among vegetation classes attributable to geological substrate and climate was evaluated using ordinations and partial variance analyses (Leps & Smilauer 2003). This required construction of three data matrices characterising the species composition, geological substrates and climatic habitat of vegetation classes. A presence/absence species matrix (99 classes x 1625 species) was constructed from the floristic descriptions (vascular flora) of vegetation classes in Keith (2004), which had been compiled from frequently mentioned species and identified dominant species in the descriptions of source map units. A substrate matrix (99 classes x 16 geological substrates) was constructed from the relative representation of substrates types within each mapped vegetation class, estimated from frequencies of 500 random points per class, as described above. A climate matrix (99 classes x climate variables) was constructed from mean climate parameters across the same samples of 500 random points, which were intersected with each of the nine climate surfaces. Unfortunately, climate surfaces were unavailable for offshore areas, so four vegetation classes (Oceanic Rainforests, Oceanic Cloud Forests, Coastal Headland Heaths and Maritime Grasslands) were omitted from the analysis. Hence the species matrix was reduced to 95 classes x 1500 species.

To determine whether species responses best fitted a linear or unimodal response to environmental gradients, redundancy analysis and canonical correspondence analyses were each carried out on the species matrix constrained by the combined matrices for geological substrates and climate parameters. The first four Eigen vectors of each analysis accounted for a similar proportion of floristic-environmental relationships (25%), although the redundancy analysis accounted for slightly more floristic variation than the canonical correspondence analysis (7.8% cf. 7.2%). A linear response model was therefore assumed for subsequent analyses.

An unconstrained principal components analysis was first carried out on the species matrix. This allowed display of floristic relationships and examination of environmental relationships using indirect gradient analysis to fit vectors representing each variable in the substrate and climate matrices to the floristic ordination.

Two partial redundancy analyses were then carried out to quantify the proportion of floristic variation uniquely attributable substrate types and climatic variables. These were done as constrained ordinations with substrate and climate defined as the environmental and covariable matrices, respectively, and then vice versa for the second analysis (ter Braak & Smilauer 1999). A third partial redundancy analysis was then carried out to determine the combined (union) proportion of floristic variation attributable to either substrate or climate with both sets of variables combined within a single environmental matrix. Finally, the (intersection) proportion of variation attributable to both substrate and climate combined was calculated by subtracting the sums of all canonical eigen values from the first two partial redundancy analyses from the sum of canonical eigen valyes in the third partial redundancy analysis (Leps & Smilauer 2003). All redundancy analyses were carried out in CANOCO for windows v4.02 (ter Braak & Smilauer 1999).

RESULTS

Fidelity of vegetation types to geological substrates

While none of the vegetation formations was restricted to a single geological unit, there was a strong non-random relationship between vegetation formation and geological substrate (χ^2 = 21562, P<<0.001, df = 225). Approximately 27-61% of the extent of each formation occurred on one substrate. More than 90% of the distribution of ten of the 16 formations was restricted to five or less geological substrates and all but one formation was restricted to seven or fewer substrates (Fig. 3). The number of substrates occupied by a vegetation formation was unrelated to the extent of its distribution (R=-0.078, P>0.5, df=15), indicating that vegetation formations were not restricted to a small number of substrates simply by virtue of small distributions. Furthermore, geological substrates supported a limited range of vegetation formations. Four or fewer vegetation formations accounted for more than 90% of the area covered by eleven of the 16 substrate types and none of the substrate types supported more than seven formations. The number of formations per substrate type was unrelated to substrate area (R=0.43, P~0.1, df=15).

At the level of vegetation class, the association with geological substrates was even more strongly expressed. Seven vegetation classes were essentially restricted to a single substrate type, while two-thirds of the 99 classes had at least 90% of their distribution restricted to three or fewer substrates (Fig. 4). As for formations, the number of substrates occupied by a vegetation class was unrelated to the extent of its distribution (R=0.027, P>0.5, df=98).

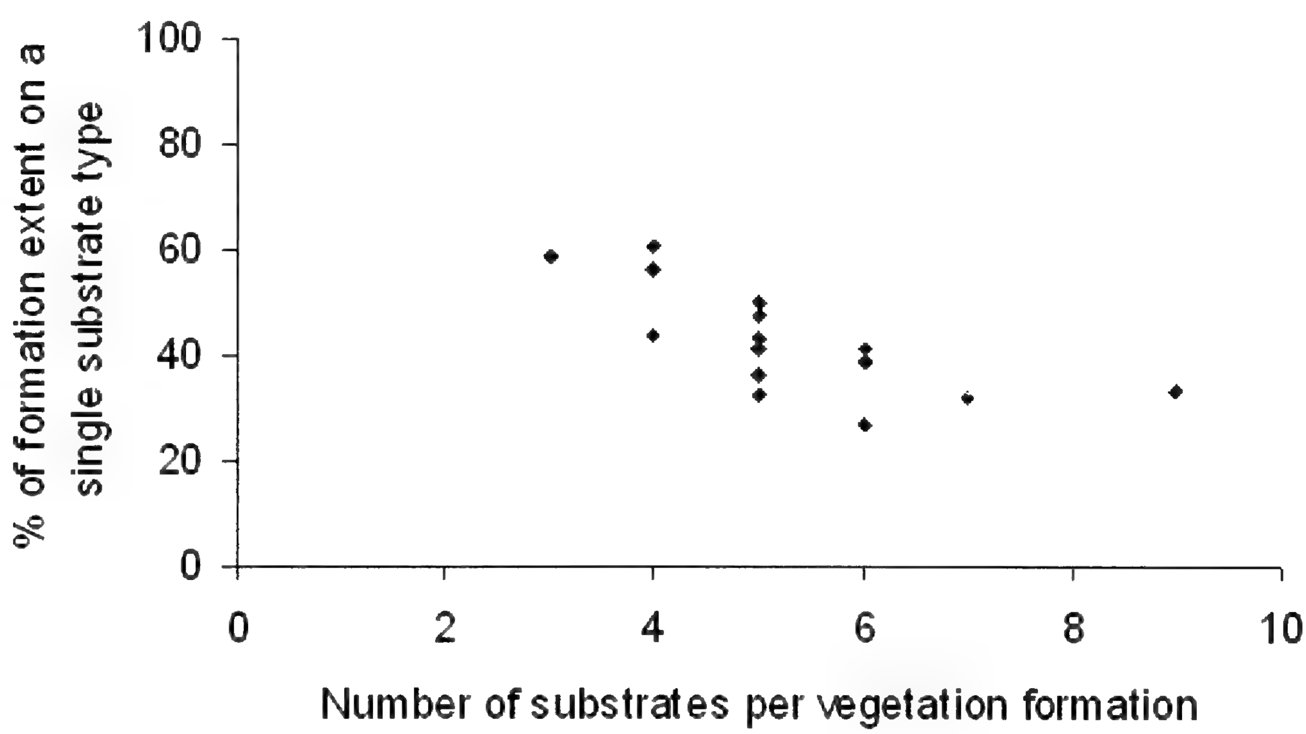

Figure 3. Fidelity of 16 vegetation formations to 16 geological substrate types.

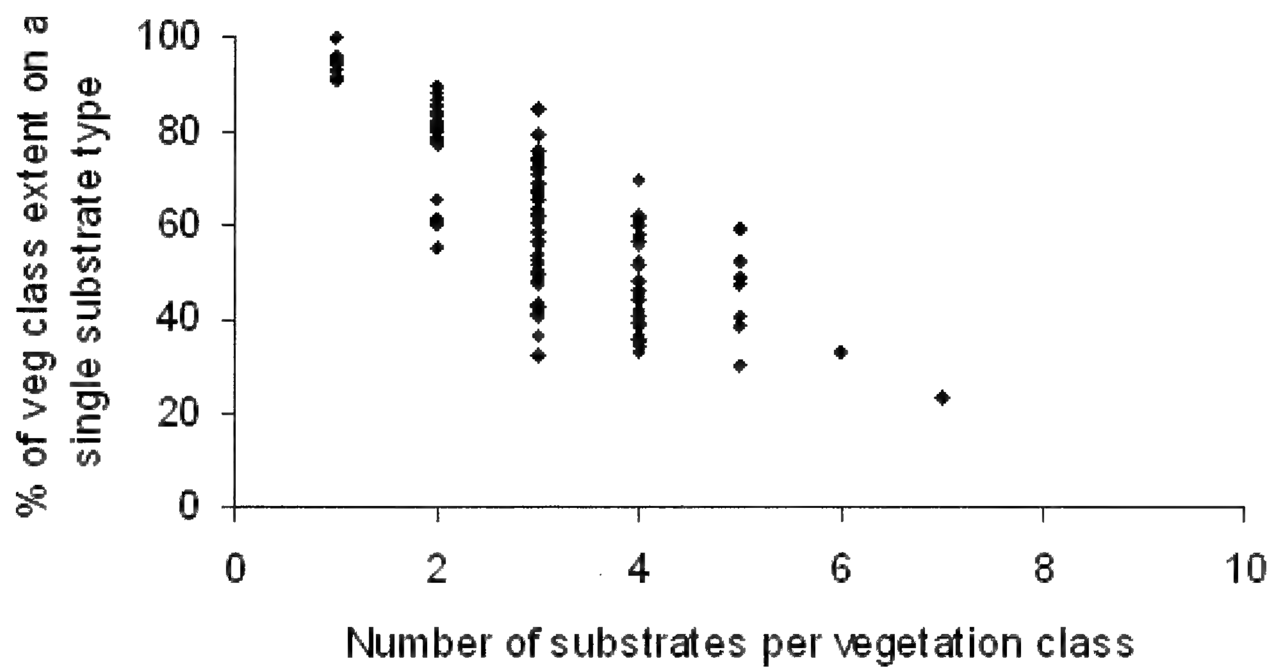

Figure 4. Fidelity of 99 vegetation classes to 16 geological substrates.

Rainforests, both Wet Sclerophyll Forest subformations and Grassy Woodlands were strongly associated with low-quartz sediments and metasediments (Appendix 1). Rainforests also occurred frequently on felsic volcanics, while the wet sclerophyll forests and grassy woodlands were more strongly associated with felsic intrusives. It is likely that the rainforests, grassy woodlands and grasslands were also well represented on mafic volcanics, but much of this substrate has been cleared of its native vegetation. The Heathlands and shrubby subformation of Dry Sclerophyll Forests were strongly associated with high-quartz sediments and siliceous (white) sands of marine origin, but also had significant representation on low-quartz sediments. In contrast, the shrub/grass subformation of Dry Sclerophyll Forests was primarily associated with low-quartz sediments and felsic intrusives (Appendix 1). The Alpine Complex occurred mainly on felsic intrusives and low-quartz sediments. All three wetland formations and the Grasslands were strongly associated with active fluvial alluvium, with lower frequencies of occurrence across a range of other substrates. The shrubby Semi-arid Woodlands and Arid (acacia) Shrublands were strongly associated with aeolian (red) sands, while the grassy Semi-arid Woodlands occurred primarily on floodplain alluvium and residual alluvial clays and Arid (chenopod) Shrublands were on aeolian sands and residual clays (Appendix 1).

The vegetation classes that were essentially restricted (>90% of occurrence) to one substrate type included a range of Rainforests, Dry Sclerophyll Forests, Heathlands and Semi-arid Woodlands (Appendix 2). The geological substrates that supported the broadest ranges of vegetation formations include low- and high-quartz sedimentaries, felsic intrusives and floodplain alluvium (Appendix 1).

Relative influence of geology and climate on vegetation

The Principal Components ordination showed that vegetation classes within the same formation generally clustered together (Fig. 5a). This suggests considerable floristic affinities within formations, even though classes were grouped together within formations on the basis of structural and functional resemblance, rather than compositional resemblance. Indirect gradient analysis showed that geological substrates and climatic parameters account for a diverse array of compositional gradients within vegetation of the region (Fig. 5b). Individual climatic parameters appeared to exert a stronger influence on vegetation, as their vectors were generally longer than those representing individual geological substrates, indicating stronger correlations with species composition. However, geological substrates appeared to exert a more diverse range of influences, as their vectors spanned a greater range of directions than those representing climate parameters (Fig. 5b).

Partial variance analysis showed that, in combination, the full set of geological substrates accounted for a greater proportion of variation in species composition than the climate variables (Fig. 6).

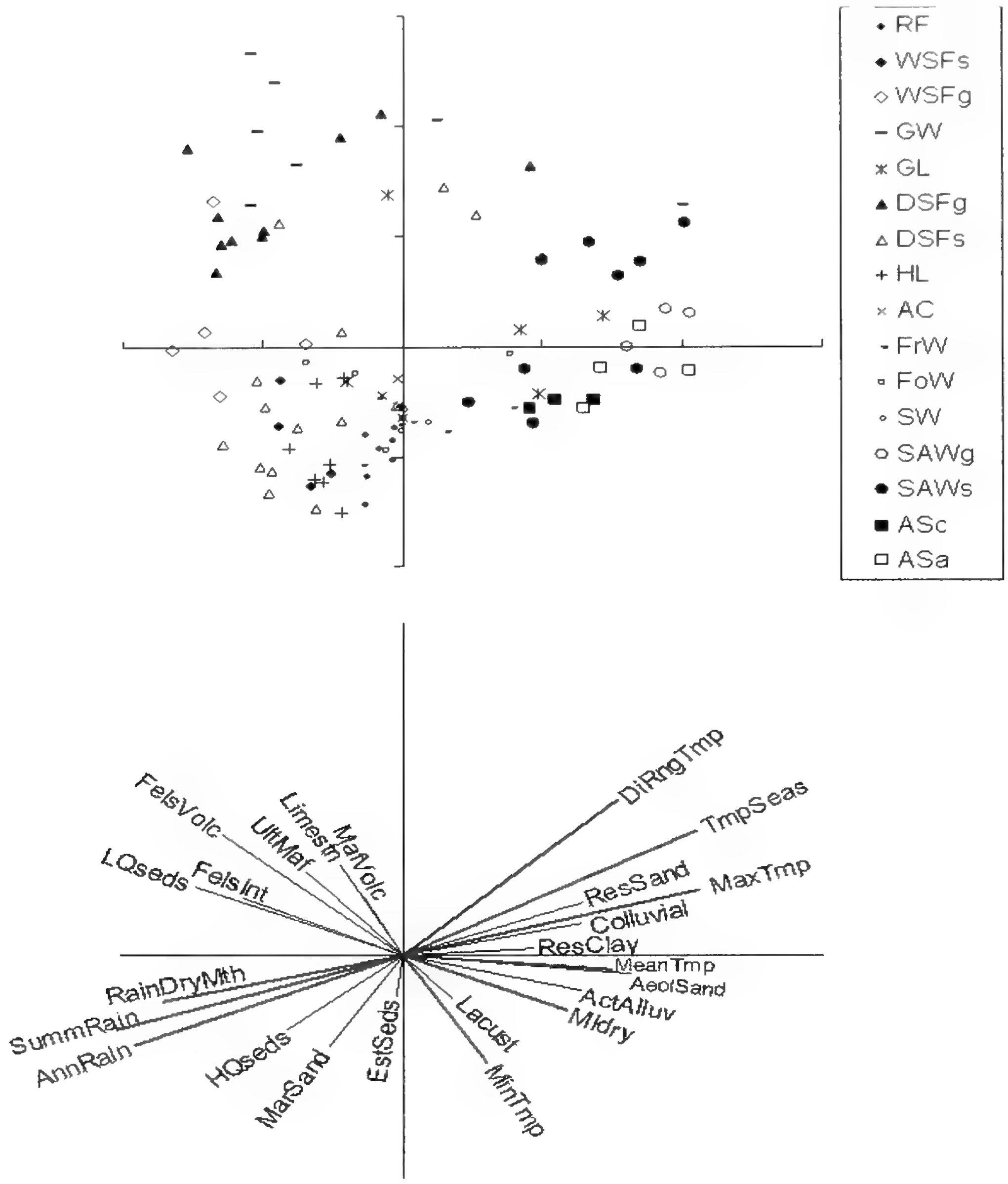

Figure 5. (a) Scatter plot of unconstrained Principal Components Analysis of 99 vegetation classes grouped by formations: RF- Rainforests, WSFs- Wet Sclerophyll Forests (shrubby subformation), WSFg- Wet Sclerophyll Forests (grassy subformation), GW- Grassy Woodlands, GL- Grasslands, DSFg- Dry Sclerophyll Forests (shrub/grass subformation), DSFs- Dry Sclerophyll Forests (shrubby subformation), HL- Heathlands, AC- Alpine Complex, FrW- Freshwater Wetlands, FoW- Forested Wetlands, SL- Saline Wetlands, SAWg- Semi-arid Woodlands (grassy subformation), SAWs- Semi-arid Woodlands (shrubby subformation), Arid Shrublands (chenopod subformation), Arid Shrublands (acacia subformation). (b) Plot of vectors representing 16 geological substrates (thin black lines) and 9 climate parameters (thick grey lines) fitted to the Principal Components ordination. The substrate types are: ResSand- Residual Alluvial Sand, Colluvial- Colluvial/alluvial sand and loam, ResClay- Residual alluvial clay, ActAlluv- Active alluvium, Lacust- Lacustrine sediments, EstSeds- Estuarine sediments, MarSand- Marine sands, Hqseds- High-quartz sedimentary rocks, Lqseds- Low-quartz sedimentary & metamorphic rocks, FelsInt- Felsic intrusives, FelsVolc- Felsic volcanics, UltMaf- Ultramafic volcanic and metamorphic rocks, Limestn- Limestone, MafVolc- Mafic volcanics. The climate parameters are: DiRngTmp- Diurnal range of temperature, MaxTmp- Mean temperature of the warmest month, MeanTemp- Mean annual temperature, MIdry- Mean moisture index (see text) of the driest quarter, MinTmp- Mean temperature of the coldest month, AnnRain- Mean annual rainfall, SummRain – Mean rainfall of December-February, RainDryMth- Mean rainfall of the driest month. Note the vector plot (5b) is enlarged by a factor of 2 relative to the scatter plot (5a).

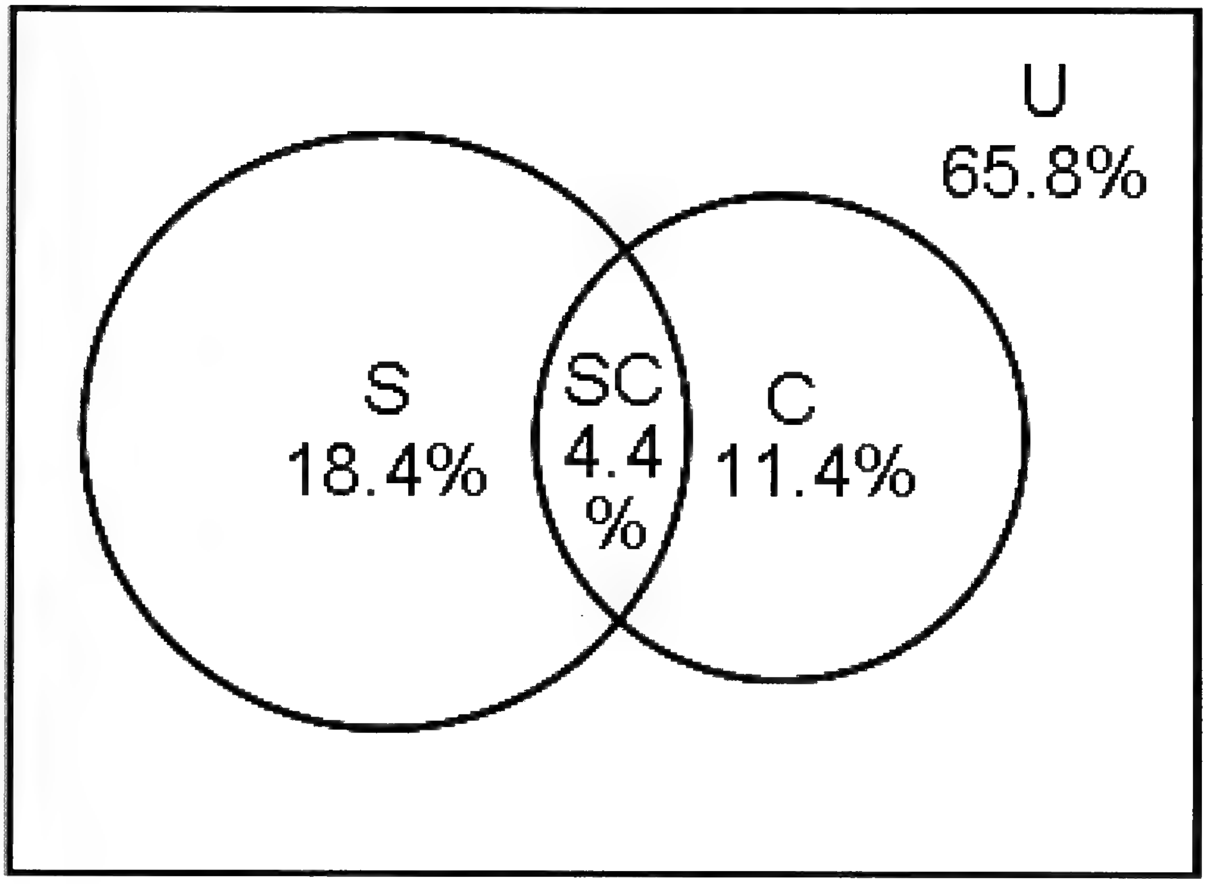

Figure 6. Venn diagram showing portions of variation in floristic composition of vegetation classes attributable to substrate only (S), climate alone (C), both substrate and climate (SC) and unexplained variation (U), as determined by partial redundancy analysis.

Geological substrates and climate accounted for largely independent components of variation in species composition, as only 4.4% of total floristic variation was correlated with both geology and climate in combination. Together, geology, climate and their overlapping component accounted for just over one-third of total floristic variation, leaving two-thirds unexplained (Fig. 6).

DISCUSSION

The influence of geodiversity on vegetation

Vegetation exhibited strong relationships with geodiversity at both class- and formation level across 80 million hectares of south-eastern Australia. Almost one-fifth of floristic variation across this large temperate region was uniquely attributable to geological substrates, independent of climatic variables. Each vegetation formation and class showed strong fidelity to a small range of geological substrates, with some classes restricted to a single substrate type. Stronger fidelity at the class level, relative to vegetation formations, indicates that relationships between vegetation and geodiversity are scale-dependent. At finer levels of vegetation classification than class, a still greater proportion of plant assemblages are restricted to a single type of substrate (e.g. Tozer et al. 2010).

Indirect gradient analysis showed that species composition of vegetation was more strongly correlated with individual climate parameters, notably rainfall, than any single substrate type. However, the compositional trends associated with substrates encompassed a broader array of gradients than those associated with climate parameters. As a consequence, partial variance analysis showed that the substrate types collectively accounted for more variation than a set of parameters encompassing the means and extremes of climatic moisture, temperature and patterns in their seasonality. The overlapping component of floristic variation attributable to both geodiversity and climate was remarkably small.

Among the climate variables, floristic relationships with the three rainfall parameters were positively correlated with one another and negatively correlated with vectors representing maximum temperature, diurnal range and seasonality. This major gradient was associated with the transition from forested vegetation classes to semi-arid woodlands and arid shrublands. Minimum temperature and moisture index of the driest month (which incorporates evapo-transpiration as well as precipitation) displayed somewhat different floristic trends.

A strong contrast was evident between substrates that produce impoverished soils (high-quartz sediments, marine (white) sands) and those that produce more fertile soils (low-quartz sediments, felsic intrusives and volcanics). The former were strongly associated with vegetation types dominated by sclerophyllous shrubs (as understorey or canopy species), while the latter were associated with vegetation types with abundant mesophyllous shrubs and/or grasses. The mafic volcanic substrates generally define the upper limit of this soil fertility gradient, while vectors representing substrates with extreme levels of some mineral elements (ultramafics, limestone) are intermediate between those of mafic and felsic substrates. A similar but more subtle distinction is evident between vegetation classes found within dry-climate regions. Shrubby semi-arid woodlands and arid (acacia) shrublands are associated primarily with impoverished aeolian (red) sands and residual alluvial sands, clays and colluvium, while grassy semi-arid woodlands and arid (chenopod) shrublands are more common on active alluvium and residual clays. Estuarine and lacustrine sediments are uniquely associated with various types of wetlands, which are also associated with active fluvial alluvium.

Support for biogeographic landscape theories

The patterns described above are consistent with early comparative work between the flora of low- and high-quartz substrates in the Sydney region (Beadle 1953, 1966) and with soil-vegetation relationships inferred from early survey work in western New South Wales (Beadle 1948). This work highlighted the association between sclerophylly and soil nutrients, notably phosphorus, which are more abundant in clay minerals derived from mafic substrates than felsic substrates and least abundant in quartz-rich substrates (Table 2).

The observed vegetation-substrate patterns generally support Hopper's (2009) characterisation of two general landscape types: Young Often Disturbed Fertile Landscapes (YODFELs) and Old Climatically Buffered Infertile Landscapes (OCBILs). 'Young' and 'old' in Hopper's sense refer to age of landscape, rather than underlying geology. Hence YODFELs are characterised by relatively fertile soils whose nutrient capital has not been greatly depleted by leaching and which may undergo frequent disturbance related to fluvial or maritime events or mass movement. Their flora is dominated by recently evolved species with long-distance dispersal capabilities, propensity for colonisation, extensive distributions, generalist nutritional and reproductive biology, and tolerance of disturbance (Hopper 2009). The YODFEL profile fits many species of the grassy vegetation formations and subformations, which occur on the more fertile substrates (e.g. low-quartz sediments, volcanics, active alluvium). It also generally fits a large portion of the flora that characterises the three wetland formations, which may generally be viewed as occupying resource-rich sinks within regional landscapes (Keith 2004).

In contrast, OCBILs are characterised by a diversity of ancestral species lineages with limited dispersal and colonisation capability, often with restricted distributions, specialised nutritional and reproductive biology, prominent sclerophylly and limited resilience to physical disturbance. Additional species traits associated with the sclerophyll syndrome were described in mechanistic detail and for a broader range of biota by Orions & Milweski (2007) in their "Nutrient-Poverty/Intense-Fire Theory". The OCBIL profile describes many of the sclerophyll plant species that characterise substrates associated with impoverished soils (e.g. high-quartz sediments, leached marine sands, aeolian sands). Both landscape types appear to extend throughout the humid – arid climatic gradient of the region.

It is noteworthy that much of rainforest flora does not readily fit either profile. Many of the taxa occupy climatically buffered environments and belong to ancient lineages that generally lack recent radiation and have suffered numerous extinctions (Crisp et al. 2004). Yet their habitats are not the most nutrient-impoverished nor very ancient landscapes and many of the taxa are widely dispersed with large distributions, some are ready colonisers.

Axiomatic to both Nutrient-Poverty/Intense-Fire and OCBIL theories is the proposition that plants growing on nutrient-deficient soils with periodically adequate moisture, can synthesize 'excessive' carbohydrates, which are deployed to produce well-defended foliage, large quantities of lignified tissues and readily digestible exudates (Orions & Milewski 2007, Hopper 2009). The nutritional properties of geological substrates therefore define a fundamental basis for evolution of Australian biota and retain a distinctive signature on the present-day distribution of vegetation formations and assemblages in the region of south-eastern Australia examined here. Given their strong influence on contemporary vegetation patterns, geological substrates which, with few exceptions, are essentially fixed landscape features over millenial time scales, appear to impose significant constraints on vegetation response to climate change, especially in landscapes with OCBIL characteristics.

Approximately two-thirds of the floristic variation remained unexplained in the direct gradient analysis. Part of this unexplained variation may include unrepresented influences of soils and climate. For example, substrate types were defined very broadly and often encompass considerable heterogeneity, not only in the complexes of rocks juxtaposed within them, but in the mineral composition and texture and structure of soils produced across catenary sequences of the landscape. The movement and availability of water across the landscape is also an important source of variation that is not fully represented by the climatic variables included in the current analysis. This essential resource almost certainly accounts for some of the unexplained floristic variation, particularly in the wetland component of the biota.

Fire regimes are also likely to account for a fraction of the unexplained variation, as a lack of suitable spatial data precluded any consideration of them in the analysis. Fire regimes have been identified as driving evolutionary forces in Australia and other continents (Bond 2005, Bowman et al. 2009). They are an important component of Nutrient-Poverty/Intense-Fire theory, as rapid accumulation of nutrient-poor biomass, a result of low rates of herbivory, provides fuel for intense fire, which in turn promotes nutrient poverty through volatilisation (Orions & Milewski 2007). Any remaining variation in floristic composition of south-eastern Australia is mostly attributable to sampling error and inherent spatial autocorrelation, as time lags in vegetation dynamics and limited dispersal processes impose an inherently clustered spatial structure on the composition of biota in the landscape.

Map-based approach to ecological analysis

The map-based approach employed in this study has both strengths and limitations. A major advantage is that it permits a balanced stratified random sampling design across the entire study area. This overcomes a significant constraint for analyses based on field samples over such a large region – the available data are inevitably skewed and non-randomly distributed across the landscape to varying degrees. A complementary analysis based on field samples may nonetheless be profitable, as it permits a more direct location-based exploration of vegetation-environment relationships, and hence exploration of finer-scale patterns than can be represented on sub-continental maps.

A potential limitation of the map-based approach is that imprecision in the boundaries of both maps may have resulted in some combinations of vegetation and substrate types that do not occur in nature, as well as a margin of error in estimated frequencies of association. Non-concurrence of soil, soil parent material and bedrock could occur, for example, where there is significant lateral movement of sediment downslope from its origin. This promotes a tendency for the fidelity of vegetation types to substrate types to be under-estimated (i.e. vegetation types are more restricted to vegetation types than the data indicate). To offset such effects, frequencies in Figs. 3 and 4 were based on the 90^{th} percentile of sampled points, although it is uncertain whether this adjustment adequately compensated spatial errors in the absence of field validation data. A second limitation of the map-based approach is that it does not allow relationships between floristics and environmental data to be explored directly. This was because the species and substrate matrices were based on descriptive data averaged across the mapped range of each unit, rather than location-specific estimates. Thirdly, depending on the methods employed to generate source maps of for corresponding areas, the spatial data for vegetation and geology may not be independent throughout the mapped area. For example, in some cases geological boundaries may have been used as proxies for vegetation mapping and conversely remote sensing of vegetation may have been used to identify geological boundaries. Such non-independence may inflate map-based correlation between vegetation and geology. However, such effects are mitigated by the use of multi-criteria in remote sensing and modelling, only some of which will be non-independent proxies, as well as varying levels of field sampling to directly verify mapped units. Independent reclassification of the vegetation and geological maps further reduced any non-independence. While these methodological issues limited the resolution of relationships that could be examined, the analytical methods employed were sufficiently sensitive to detect major influences of geological substrates on vegetation that, collectively, appeared to be stronger than, and largely independent of climatic influences.

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Appendix 1. Percentage of 1000 random points in each vegetation formation on each geological substrate type

Substrate type: / Vegetation Formation:	aeolian (red) sands	calcarinite	estuarine sediments	felsic intrusives	felsic volcanics	floodplain alluvium	high quartz sedimentary	lacustrine sediments	limestone	low quartz sedimentary	mafic volcanics & intrusives	residual alluvial clay	residual alluvial sands	residual alluvial/ colluvial sand & gravel	marine siliceous (white) sandplains	ultramafic igneous & metamorphics
Alpine complex	0	0	0	59	3	1	0	0	1	20	16	0	0	0	0	0
Arid shrublands (Acacia subformation)	56	0	0	0	0	14	0	2	0	11	0	0	0	16	0	0
Arid shrublands (Chenopod subformation)	33	0	0	0	0	13	0	5	0	11	0	24	0	14	0	0
Dry sclerophyll forests (Shrub/grass subformation)	5	0	0	22	6	2	10	0	0	47	3	0	0	4	0	0
Dry sclerophyll forests (Shrubby subformation)	0	0	0	11	5	5	36	0	0	28	3	0	0	2	9	0
Forested wetlands	1	0	0	6	3	39	5	12	0	21	7	1	0	2	4	0
Freshwater wetlands	9	0	0	11	1	33	11	7	0	8	2	6	0	2	8	0
Grasslands	10	0	0	4	1	32	1	1	0	6	10	19	0	1	15	0
Grassy woodlands	1	0	0	24	7	5	6	0	1	38	12	2	1	2	0	0
Heathlands	0	0	0	10	5	5	27	0	0	24	3	0	0	5	21	0
Rainforests	0	4	0	4	20	2	7	0	0	43	15	0	0	0	4	0
Saline wetlands	14	0	27	0	0	41	6	12	0	5	0	0	0	2	16	0
Semi-arid woodlands (Grassy subformation)	13	0	0	0	0	41	0	1	0	9	2	16	4	14	0	0
Semi-arid woodlands (Shrubby subformation)	50	0	0	1	1	13	1	1	0	13	0	5	5	13	0	0
Wet sclerophyll forests (Grassy subformation)	0	0	0	24	5	1	15	0	0	44	10	0	0	0	0	0
Wet sclerophyll forests (Shrubby subformation)	0	0	0	20	5	1	8	0	0	61	5	0	0	0	0	0

Appendix 2. Percentage of 500 random points in each vegetation class on each geological substrate type (see Keith 2004 for description of classes).

	aeolian (red) sandplains	calcarinite	estuarine sediments	felsic intrusives	felsic volcanics	floodplain alluvium	high quartz sedimentary	lacustrine sediments	laterite	limestone	low quartz sedimentary	mafic volcanics & intrusives	residual alluvial clay	residual alluvial sands	residual alluvial/colluvial sand & gravel	siliceous (white) sandplains	ultramafic igneous & metamorphics
Subtropical Rainforests	0	0	0	5	2	5	2	0	0	0	50	36	0	0	0	0	0
Northern Warm Temperate Rainforests	0	0	0	6	10	0	19	0	0	0	63	2	0	0	0	0	0
Cool-Temperate Rainforests	0	0	0	9	1	0	0	0	0	0	56	33	0	0	0	0	0
Dry Rainforests	0	0	0	4	7	0	8	0	0	0	76	4	0	0	0	0	0
Littoral Rainforests	0	0	0	0	1	11	24	0	0	0	21	4	0	0	1	37	0
North Coast Wet Sclerophyll Forests	0	0	0	4	3	2	22	0	0	0	64	5	0	0	0	0	0
South Coast Wet Sclerophyll Forests	0	0	0	13	5	2	8	0	0	0	71	0	0	0	1	0	0
Northern Escarpment Wet Sclerophyll Forests	0	0	0	9	9	0	0	0	0	0	68	14	0	0	0	0	0
Southern Escarpment Wet Sclerophyll Forests	0	0	0	56	3	0	1	0	0	0	39	1	0	0	0	0	0
Northern Tableland Wet Sclerophyll Forests	0	0	0	16	5	0	1	0	0	0	53	25	0	0	0	0	0
Southern Tableland Wet Sclerophyll Forests	0	0	0	33	12	0	17	0	0	0	30	7	0	0	0	0	0
Sydney Coastal Dry Sclerophyll Forests	0	0	0	0	0	1	89	0	0	0	10	0	0	0	0	0	0
Sydney Hinterland Dry Sclerophyll Forests	0	0	0	0	0	0	93	0	0	0	7	0	0	0	0	0	0
Sydney Montane Dry Sclerophyll Forests	0	0	0	0	0	0	77	0	0	0	22	1	0	0	0	0	0
Coastal Dune Dry Sclerophyll Forests	0	0	0	0	1	9	4	0	0	0	7	0	0	0	0	79	0
North Coast Dry Sclerophyll Forests	0	0	0	1	1	5	60	0	0	0	31	2	0	0	0	0	1
Northern Hinterland Wet Sclerophyll Forests	0	0	0	3	2	4	16	0	0	0	67	6	0	0	0	1	0
South Coast Sands Dry Sclerophyll Forests	0	0	0	0	1	12	9	0	0	0	9	1	0	0	9	59	0
Southern Lowland Wet Sclerophyll Forests	0	0	0	8	2	3	38	0	0	0	48	1	0	0	1	0	0
Northern Escarpment Dry Sclerophyll Forests	0	0	0	82	7	0	0	0	0	0	9	2	0	0	0	0	0
South East Dry Sclerophyll Forests	0	0	0	17	8	1	10	0	0	0	61	0	0	0	3	0	0
Northern Tableland Dry Sclerophyll Forests	0	0	0	36	21	0	0	0	0	0	36	4	0	0	0	0	2
Southern Tableland Dry Sclerophyll Forests	0	0	0	16	16	0	9	0	0	1	52	3	0	0	3	0	0
Western Slopes Dry Sclerophyll Forests	1	0	0	4	6	6	49	0	0	0	26	6	0	0	1	0	0
Pilliga Outwash Dry Sclerophyll Forests	48	0	0	0	0	9	13	0	0	0	10	2	0	4	15	0	0
Wallum Sand Heaths	0	0	0	0	0	19	4	0	0	0	4	0	0	0	1	71	0
Sydney Coastal Heaths	0	0	0	0	0	2	95	0	0	0	2	0	0	0	0	1	0
Northern Montane Heaths	0	0	0	69	16	0	2	0	0	0	4	9	0	0	0	0	0
Sydney Montane Heaths	0	0	0	0	0	0	82	0	0	0	17	0	0	0	0	0	0

	aeolian (red) sandplains	calcarinite	estuarine sediments	felsic intrusives	felsic volcanics	floodplain alluvium	high quartz sedimentary	lacustrine sediments	laterite	limestone	low quartz sedimentary	mafic volcanics & intrusives	residual alluvial clay	residual alluvial sands	residual alluvial/colluvial sand & gravel	siliceous (white) sandplains	ultramafic igneous & metamorphics
Southern Montane Heaths	0	0	0	6	11	0	0	0	0	0	74	5	0	0	3	0	0
Alpine Heaths	0	0	0	72	1	0	0	0	0	0	10	18	0	0	0	0	0
Tableland Clay Grassy Woodlands	0	0	0	41	8	1	1	0	0	0	36	13	0	0	0	0	0
New England Grassy Woodlands	0	0	0	19	12	2	1	0	0	0	48	17	0	0	0	0	0
Western Slopes Grassy Woodlands	1	0	0	5	2	5	9	0	0	0	41	34	0	0	2	0	0
Western Peneplain Woodlands	28	0	0	0	1	18	0	0	0	0	14	0	0	6	33	0	0
Subalpine Woodlands	0	0	0	45	11	0	0	0	0	2	29	12	0	0	0	0	0
Temperate Montane Grasslands	0	0	0	18	5	18	1	1	0	0	17	39	0	0	1	0	0
Semi-arid Floodplain Grasslands	10	0	0	0	0	84	0	0	0	0	2	0	0	0	5	0	0
Coastal Swamp Forests	0	0	0	0	0	65	6	0	0	0	7	0	0	0	0	21	0
Coastal Floodplain Wetlands	0	0	1	2	0	61	10	0	0	0	23	1	0	0	1	2	0
Eastern Riverine Forests	2	0	0	11	8	21	14	0	0	0	33	10	0	1	1	0	0
Inland Riverine Forests	4	0	0	1	0	85	0	2	0	0	1	0	4	2	1	0	0
Inland Floodplain Woodlands	20	0	0	0	0	53	0	3	0	0	2	0	10	2	9	0	0
Coastal Heath Swamps	0	0	0	3	0	16	43	0	0	0	6	1	0	0	1	31	0
Montane Bogs and Fens	0	0	0	53	8	6	3	0	0	0	18	8	0	0	4	0	0
Coastal Freshwater Lagoons	0	0	0	0	0	79	3	0	0	0	5	1	0	0	2	9	0
Inland Saline Lakes	44	0	0	0	0	8	0	37	0	0	5	0	0	0	5	0	0
Mangrove Swamps	0	0	4	0	0	48	12	0	0	0	5	0	0	0	0	30	0
Riverine Chenopod Shrublands	12	0	0	0	0	16	0	9	0	0	1	0	60	0	2	0	0
Aeolian Chenopod Shrublands	70	0	0	0	0	13	0	6	0	0	3	0	6	0	2	0	0
Dune Mallee Woodlands	95	0	0	0	0	1	0	0	0	0	1	0	0	0	3	0	0
Sand Plain Mallee Woodlands	88	0	0	0	0	0	0	1	0	0	3	0	0	0	8	0	0
Semi-arid Sand Plain Woodlands	87	0	0	0	0	4	0	3	0	0	2	0	1	0	3	0	0
Sydney Sand Flats Dry Sclerophyll Forests	0	0	0	0	0	22	36	0	0	0	26	0	0	0	15	0	0
South Coast Heaths	0	0	0	1	0	5	0	0	0	0	43	0	0	0	30	22	0
Northern Gorge Dry Sclerophyll Forests	0	0	0	16	5	0	2	0	0	0	72	4	0	0	0	0	0
Clarence Dry Sclerophyll Forests	0	0	0	2	5	0	10	0	0	0	81	1	0	0	0	0	1
New England Dry Sclerophyll Forests	0	0	0	75	9	0	0	0	0	0	14	3	0	0	0	0	0

	aeolian (red) sandplains	calcarinite	estuarine sediments	felsic intrusives	felsic volcanics	floodplain alluvium	high quartz sedimentary	lacustrine sediments	laterite	limestone	low quartz sedimentary	mafic volcanics & intrusives	residual alluvial clay	residual alluvial sands	residual alluvial/colluvial sand & gravel	siliceous (white) sandplains	ultramafic igneous & metamorphics
Hunter-Macleay Dry Sclerophyll Forests	0	0	0	0	4	2	31	0	0	0	61	0	0	0	0	1	0
Coastal Headland Heaths	0	0	0	1	0	8	5	0	0	0	17	0	0	0	0	69	0
Saltmarshes	0	0	7	0	0	61	4	0	0	0	5	0	0	0	1	22	0
Coastal Valley Grassy Woodlands	0	0	0	16	1	8	15	0	0	0	56	3	0	0	0	0	1
Montane Lakes	0	0	0	2	0	4	0	65	0	0	0	28	0	0	1	0	0
Southern Warm Temperate Rainforests	0	0	0	14	4	1	7	0	0	0	62	12	0	0	0	0	0
Montane Wet Sclerophyll Forests	0	0	0	62	1	0	0	0	0	1	23	12	0	0	0	0	0
Central Gorge Dry Sclerophyll Forests	0	0	0	4	17	0	21	0	0	0	57	0	0	0	0	0	0
Cumberland Dry Sclerophyll Forests	0	0	0	0	2	2	11	0	0	0	52	0	0	0	34	0	0
Southern Hinterland Dry Sclerophyll Forests	0	0	0	83	1	1	0	0	0	0	15	0	0	0	0	0	0
Southern Wattle Dry Sclerophyll Forests	0	0	0	7	1	1	0	0	0	0	91	0	0	0	0	0	0
Upper Riverina Dry Sclerophyll Forests	0	0	0	31	9	1	3	0	0	0	54	1	0	0	0	0	1
Southern Tableland Grassy Woodlands	1	0	0	30	17	1	6	0	0	1	43	1	0	0	1	0	0
Riverine Sandhill Woodlands	14	0	0	0	0	8	0	2	0	0	14	0	30	23	8	0	0
Inland Rocky Hill Woodlands	6	0	0	6	6	2	4	0	0	0	58	0	0	0	19	0	0
Riverine Plain Woodlands	1	0	0	0	0	14	0	0	0	0	4	1	67	11	2	0	0
Inland Floodplain Shrublands	12	0	0	0	0	42	0	24	0	0	1	0	18	1	2	0	0
Subtropical Semi-arid Woodlands	30	0	0	0	0	7	0	1	0	0	21	0	0	0	41	0	0
Desert Woodlands	92	0	0	0	0	1	0	0	0	0	0	0	0	0	7	0	0
North-west Floodplain Woodlands	16	0	0	0	0	78	0	2	0	0	0	0	0	2	3	0	0
Gibber Chenopod Shrublands	19	0	0	1	0	16	0	0	0	0	28	0	0	0	36	0	0
Stony Desert Mulga Shrublands	32	0	0	1	0	5	0	1	0	0	32	1	0	0	29	0	0
Sand Plain Mulga Shrublands	86	0	0	0	0	5	0	2	0	0	2	0	0	0	5	0	0
Brigalow Clay Plain Woodlands	2	0	0	0	0	30	0	0	0	0	20	9	0	4	34	0	0
North-west Plain Shrublands	52	0	0	0	0	11	0	2	0	0	10	0	0	0	26	0	0
Gibber Transition Shrublands	55	0	0	0	0	38	0	3	0	0	3	0	0	0	2	0	0
Alpine Fjaeldmarks	0	0	0	55	0	0	0	0	0	0	45	0	0	0	0	0	0

	aeolian (red) sandplains	calcarinite	estuarine sediments	felsic intrusives	felsic volcanics	floodplain alluvium	high quartz sedimentary	lacustrine sediments	laterite	limestone	low quartz sedimentary	mafic volcanics & intrusives	residual alluvial clay	residual alluvial sands	residual alluvial/colluvial sand & gravel	siliceous (white) sandplains	ultramafic igneous & metamorphics
Yetman Dry Sclerophyll Forests	1	0	0	6	0	2	59	0	0	0	26	7	0	0	1	0	0
North-west Alluvial Sand Woodlands	0	0	0	0	0	84	0	0	0	0	2	0	0	7	6	0	0
Inland Floodplain Swamps	28	0	0	0	1	39	0	15	0	0	4	0	6	1	6	0	0
Floodplain Transition Woodlands	10	0	0	4	1	23	7	1	0	0	17	2	16	7	12	0	0
Western Slopes Grasslands	33	0	0	0	1	46	1	2	0	0	6	8	0	0	1	0	0
Seagrass Meadows	0	0	1	1	0	51	20	0	0	0	11	1	0	0	1	15	0
North-west Slopes Dry Sclerophyll Woodlands	0	0	0	9	4	3	7	0	0	0	57	18	0	0	1	0	1
Alpine Herbfields	0	0	0	29	11	2	0	0	0	2	21	35	0	0	0	0	0
Alpine Bogs and Fens	0	0	0	80	2	2	0	0	0	0	5	11	0	0	0	0	0
Maritime Grasslands	0	0	0	0	0	5	2	0	0	0	1	3	0	0	0	88	0
Oceanic Rainforests	0	5	0	0	0	25	0	0	0	0	0	70	0	0	0	0	0
Oceanic Cloud Forests	0	0	0	0	0	0	0	0	0	0	0	100	0	0	0	0	0
Western Vine Thickets	0	0	0	0	7	2	8	0	0	0	41	41	0	0	1	0	0
Temperate Swamp Forests	0	0	0	24	11	3	3	0	0	0	52	5	0	0	3	0	0
Riverina Grasslands	1	0	0	0	0	2	0	1	0	0	0	0	96	1	0	0	0
Wadi Woodlands	25	0	0	0	0	39	0	1	0	0	15	0	0	0	20	0	0

The Tasmanian Geoconservation Database: A Tool for Promoting the Conservation and Sustainable Management of Geodiversity

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The Tasmanian Geoconservation Database (TGD) is a source of information about earth science features, systems and processes of conservation significance in Tasmania. It evolved when a number of sources were compiled as a single geoconservation digital dataset as part of the National Estate component of the 1997 Commonwealth-Tasmanian Regional Forest Agreement. The latest version of the TGD (version 7) was published in 2010 and lists some 1049 sites ranging in scale from individual rock outcrops and cuttings that expose important geological sections, to landscape-scale features that illustrate the diversity of Tasmania's geomorphic features and processes. The TGD is accessible to the public through Departmental websites. It is used as a planning tool in land management and in assessing development proposals at various scales. Under Tasmania's three major environmental codes of practice, the TGD must be consulted and certain actions are prescribed where a TGD site is present.

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KEYWORDS: Database, Geoconservation, Geodiversity, Geoheritage, Tasmania

INTRODUCTION

Tasmania is Australia's smallest state, and lies to the south east of mainland Australia separated by Bass Strait. It is comprised of 344 islands covering 68,401 square kilometres of which the main island occupies 62,409 square kilometres. Except for the outlying Macquarie Island, Tasmania and its islands lie between 39°14' and 43°51'S latitude and 143°50' and 148°29'E longitude. The isolated subantarctic Macquarie Island, located at 54°30'S 158°57'E is also part of Tasmania. Within this relatively small area lies an enormous range of geodiversity. There are geological units from every one of the 12 major periods of earth history from the Precambrian to the Holocene spanning some 4,600 million years. Geologically, it could be described as a microcosm of eastern Australia, with additional distinctive Tasmanian elements, such as extensive dolerite intrusions associated with the break-up of Gondwana. Landforms in Tasmania are also very diverse and include: rugged mountain ranges, spectacular glacial features, periglacial landforms, largely pristine river catchments, extensive limestone and dolomite karstlands, inland dunefields and a range of coastal features including a number of relic features. Soil types vary across the state and are controlled by the bedrock and a range of soil forming processes. In short, Tasmania is a very geodiverse state.

Given the geodiverse nature of Tasmania, perhaps it is no surprise that Tasmanian earth scientists have played key roles in the relatively recent field of Geoconservation (Dixon 1995, Gray 2004 and Sharples 2002). Houshold and Sharples (2008) provide a history of geoconservation in Tasmania. Sharples (2002) defined the terms geoconservation and geodiversity as follows: *Geoconservation* is the identification and conservation of geodiversity for its intrinsic, ecological or heritage values. *Geodiversity* is the natural range (diversity) of geological (bedrock), geomorphological (landform) and soil features, assemblages, systems and processes. Geodiversity includes evidence for the history of the earth (evidence of past life, ecosystems and environments) and a range of processes (biological, hydrological and atmospheric) currently acting on rocks, landforms

Table 1. List of geoheritage inventories consulted as part of the process to compile version 1 of the Tasmanian Geoconservation Database under the Commonwealth- Tasmania Regional Forest Agreement.

Year	Inventory	Reference
1979	Geological monuments in Tasmania	Eastoe (1979)
1987	Geomorphological Reconnaissance of the Southern Forests area, Tasmania	Kiernan 1987
1991	Earth Resources of the Tasmanian Wilderness World Heritage Area	Dixon (1991)
1993	A Preliminary Geoheritage Inventory of the Eastern Tasmania Terrane	Bradbury (1993)
1994	A reconnaissance of landforms and geological sites of geoconservation significance in the North-Eastern Forest District (Eastern Tiers and Bass Forest Districts)	Sharples (1994)
1995	Continuation of Preliminary Inventory of Sites of Geoconservation Significance in Tasmania Central, Northern and Western Tasmania	Bradbury (1995)
1995	Geomorphological Reconnaissance of the Southern Forests area, Tasmania	Kiernan (1995)
1995	A reconnaissance of landforms and geological sites of geoconservation significance in Eastern Tasmania (parts of Derwent and Eastern Tiers Forest Districts)	Sharples (1995)
1996	Inventory and management of Karst in the Florentine Valley, Tasmania	Eberhard (1996)
1996	A reconnaissance inventory of sites of geoconservation significance on Tasmanian islands'	Dixon (1996)
1996	A reconnaissance of landforms and geological sites of geoconservation significance in the Murchison Forest District	Sharples (1996a)
1996	A reconnaissance of landforms and geological sites of geoconservation significance in the Circular Head Forest District	Sharples (1996b)

and soils. These definitions have been adopted in Tasmania and the concepts of geoconservation and geodiversity are considered an integral part of nature conservation within Tasmanian land management authorities.

With the recognition of geoconservation in Tasmania, a tool to assist in the management of Tasmania's significant geoconservation features was required and the Tasmanian Geoconservation Database (TGD) evolved. Details of the TGD, its history, structure and uses are described below.

There are a number of different approaches to managing information about geoconservation values within other Australian States, however it is beyond the scope of this paper to assess or compare these.

Development of the Tasmanian Geoconservation Database

The TGD was developed as part of the process leading up to the 1997 Commonwealth - Tasmania Regional Forest Agreement (RFA) under the comprehensive regional assessment (Dixon and Duhig 1996). This process enabled the compilation of a single digital database of significant geoconservation sites across Tasmanian. In generating the list of sites, a number of documents already listing geoconservation values across Tasmania as a whole or dealing with specific regions of the state were consulted. The earliest of which dated back to 1979, when the Geological Society of Australia published a report on Geological Monuments of Tasmania – a descriptive list of fifty or so geological features and landforms (Eastcote 1979). A number of subsequent geoheritage inventories produced by the Parks and Wildlife Service and the (then) Forestry Commission in the 1990s formed a significant resource in compiling the initial database. Table 1 lists key inventories referenced as part of this process.

The RFA process led to a database with 900 geoconservation sites. The (then) Department of Primary Industries and Water took responsibility for managing the database in 1999 and established an expert panel (see *Listing Process* below) to advise on the listing of sites. In 2005 a summary version of the TGD was first published on the web establishing it as a standard reference for planning and land management within Tasmania (Eberhard and Hammond 2007). The latest version of the TGD (version 7) was published in 2010 and lists some 1049 sites.

Further development of the TGD, and the

Table 2. Primary level and type site classification in the Tasmanian Geoconservation Database (Dixon and Duhig 1996 and Version 7 TGD). These fields are intended to illustrate those elements of the site which are significant and are not used in a purely descriptive manner. In classifying sites, additional types are permitted if the listed ones do not provide a relevant option.

Primary level	Type
Geology	Classical (a)
	Historical (b)
	Igneous – intrusive
	Igneous – volcanic
	Metamorphic
	Mineralogy
	Palaeoenvironment
	Palaeontology
	Petrology
	Relationship
Geomorphology	Aeolian
	Coastal
	Karst
	Glacial
	Marine
	Estuarine
	Lacustrine
	Periglacial
	Fluvial
	Periglacial
	Mass movement
	Weathering
	Erosion Surface
	Structural landform
Soil	Organic (undifferentiated)
	Swamp peat
	Blanket bog
	Basalt
	Soil
	Laterite
	Palaeosol
	Duricrust
	Alkaline pan
	Mineral soils undifferentiated

(a) Refers to features known from the literature or some other way to earth scientists
(b) Refers to features with local historical interest additional to their geological interest.

provision of advice concerning listed sites, is core business for the Geodiversity Conservation and Management Section, part of the Tasmanian Department of Primary Industries, Parks, Water and Environment (DPIPWE).

Structure

Currently the TGD comprises two data sets, with textual information stored in a Microsoft® Access database and spatial information (stored as polygon data) along with a subset of the text fields in an Oracle database. A program to transfer all TGD data onto a restructured Oracle database is currently underway (see *Future Directions* below).

The database comprises a number of fields that describe various attributes of the sites. Dixon and Duhig (1996) and Sharples (2000) describe the fields more fully. A separate spatial layer is attached to each site. Many of the fields are simple identification or broad descriptive fields (e.g. ID code, GIS code, Site name, Coordinate description, Coordinates, Size, Physical form of site etc) and are generally self explanatory.

Sites are primarily classified into geology, geomorphology and soil types and are further subdivided as shown in Table 2. These fields are intended to illustrate those elements of the site which are significant and are not used in a purely descriptive manner. A site may have multiple entries where it is considered significant for more than one type or sub type. Significance, level, age, sensitivity, degradation and conservation fields are common to each of the geology, geomorphology and soils types or sub types.

Each listed site is assigned a significance level on a scale that includes world, Australia, Tasmania, region, or local. These are described by Sharples (2000). The sensitivity field is a number that gives a general indication of the kinds of impacts that would degrade the value of the site. The scale is roughly linear on a scale of 1 to 10 following Kiernan (1997). A site with a sensitivity of 1 is very sensitive to damage, while a site with a sensitivity of 10 is robust such as large regions whose geoconservation values reside essentially in their large scale form. For all sites there is an overall significance and sensitivity field that encapsulates the most significant and most sensitive aspects of the site.

A limited number of sites within the database are listed as restricted and specific site information is not available to the general public for these sites. Such sites are very sensitive and vulnerable to physical damage or complete loss through collection. Typically localised fossil or gemstone sites fall within this class. When a web-based spatial search is done on an area where such sites occur a message will appear to inform the user that a restricted site is located in the search area and to contact DPIPWE.

Public access to the database through DPIPWE websites provides access to spatial information and limited site textual information. The Department also provides full copies of the database to interested parties (typically Government agencies or large private land managers and consultants) under a standard licence agreement.

Listing process

Any person can nominate a site for consideration for listing on the TGD or propose an amendment to an existing TGD site. Proposals to add, delete or amend sites are assessed by an independent scientific panel. The panel, known as the Tasmanian Geoconservation Database Reference Group (TGDRG) is comprised of members with demonstrable expertise in aspects of Tasmanian geodiversity. The composition and roles of the TGDRG are defined under Terms of Reference (DPIWE 2009) and state that the TGDRG will comprise at least six persons and that the disciplines of geology, geomorphology and soil science will be each represented by at least two persons. Current membership of the TGDRG includes representatives from staff at the University of Tasmania, Tasmanian Minerals Council, government departments and independent consultants. There are currently fourteen members. Members are appointed by the General Manager, Resource Management and Conservation Division (RMC) of DPIPWE. The group generally meets annually to consider nominations and amendments. DPIPWE provides a secretary to the group. Subcommittees of the TGDRG may be formed to address specific issues and advice may be sought from non-member peers acknowledged by the TGDRG.

Recommendations from the TGDRG on listing and de-listing of sites are made to the General Manager, RMC who has ultimate responsibility for the TGD. Listing criteria for TGD sites are as follows and are set out in the Terms of Reference (DPIPWE 2009). The criteria are general and provide scope for considering a broad range of values, including the more traditional geological reference sites e.g. type sections, as well as landforms and assemblages of geodiversity related values. The expert panel validates site nominations and provides scientific rigour to the listing process.

- Consideration will only be given to listing sites that have developed as a result of natural processes. Natural features exposed artificially (e.g. road cuttings, quarries etc) will be considered.
- When listing sites, consideration will be given to the degree and clarity with which sites exhibit or exemplify the important characteristics and values of their type.
- Where appropriate classificatory frameworks are available, priority will be given to the inclusion of representative exemplars of the different classes of geodiversity.
- In the absence of appropriate classificatory frameworks, priority will be given to the inclusion of the widest possible range of distinctive elements within each geodiversity theme.
- The assessment will take account of the integrity of natural features and processes that contribute to site significance. Degraded sites may be listed provided they maintain part or all of their relevant geoconservation values.
- Sites will be assessed according to their significance within a hierarchy of levels ranging from global to local. The assessment will consider the georegional context where appropriate.
- In cases where other natural values contribute to the geoconservation significance of the site, sites may be included, conditional upon appropriate professional advice.
- Sites under consideration will be deleted from the TGD if not accepted as listed sites within five years of being nominated.

A nominated site must be supported by an explicit statement of significance, justifying its importance with reference to other potentially comparable sites and/or unique or distinctive elements. This information is then evaluated by the TGDRG and a recommendation made regarding the suitability of the site for listing in the TGD. The listing criteria emphasise representativeness – the degree to which a site encapsulates characteristic elements of Tasmania's geodiversity – in order to ensure that good examples of even common features are considered. The intent here is to ensure that commonplace features do not ultimately become rare through lack of recognition that they too contribute to geodiversity. Further work is required to develop appropriate classificatory frameworks for geodiversity to implement this goal in a comprehensive way.

The listing status of new sites goes through the following stages:

- *Proposed site* – sites submitted to the TGDRG, prior to being formally considered by that group. These sites are not included in published versions of the database.
- *Site under consideration* – site tabled at the TGDRG, where the group determines that the site potentially satisfies the criteria for listing but requires more information before accepting it for listing in full. Sites under consideration are included in published versions of the TGD.
- *Listed sites* – sites accepted for listing by the TGD Reference Group.

Implications of TGD listing

The database is a resource for anyone with an interest in conservation and the environment, however, the principal aim is to make information on sites of geoconservation significance available to land managers in order to assist them manage these values. The TGD is used extensively in land use planning within Tasmania.

Under present Tasmanian law, the TGD has no statutory basis and geodiversity generally lacks statutory protection comparable to that applicable to threatened species or Aboriginal heritage for example, which cannot be interfered with without authority, irrespective of the tenure of the land. Explicit legal protection for geodiversity is restricted to Crown reserves managed under the *National Parks and Reserves Management Act 2002*, which establishes the conservation of 'geological diversity' as a statutory management objective for reserves under the Act (evidently the term 'geological diversity' was adopted in drafting the legislative because 'geodiversity' was not defined in the Macquarie Dictionary. However, the Act indicates an essentially identical meaning for geological diversity:'the natural range of geological, geomorphological and soil features, assemblages, systems and processes'). Under s4 of the *National Parks and Reserved Land Regulations 2009*, it is an offence to 'interfere with, dig up, cut up, collect or remove any sand, gravel, clay, rock or mineral or any timber, firewood, humus or other natural substance' or to 'remove, damage or deface any rock, stalactite, stalagmite or other formation in a cave'. This requirement applies to about 2,350,000 ha or 35% of Tasmania's land mass, including many sites listed in the TGD.

Notwithstanding the lack of broader statutory protection, sites listed in the TGD are subject to constraints under a variety of administrative processes. Of particular importance are three key State Codes of Practice: the Forest Practices Code (Forest Practices Board 2000), Mineral Exploration Code of Practice (Bacon 1999) and the Reserve Management Code of Practice (PWS *et al.* 2003). These documents specify acceptable standards of environmental practice during forest operations, mineral exploration and mining and reserve management respectively. They require development proponents to consult the TGD and seek expert advice on protection requirements where listed sites are present.

The State Environment Protection Authority has produced guidelines to assist proponents prepare development proposals and environmental management plans for developments classified as Level 2 activities under Tasmania's *Environmental Management and Pollution Control Act 1994*. S4.7.2 (f) of the guidelines requires proponents to consider 'effects on sites of geoconservation significance or natural processes (such as fluvial or coastal features), including sites of geoconservation significance listed on the Tasmanian Geoconservation Database'. Some local government planning authorities require development proponents to address the potential presence of TGD sites on land subject to planning applications.

In addition to formal requirements of this kind, the TGD has become a standard reference in virtually all contexts requiring consideration of environmental effects in Tasmania, ranging from major projects of State significance to farm dams to local government planning schemes. Its success in this regard evidently reflects growing awareness that geodiversity underpins ecosystem processes generally and must be considered alongside biodiversity in conservation and sustainable land management initiatives.

A limitation of the database is that the TGD lists sites of known significance, but is not based on a comprehensive State-wide inventory of geoconservation values, and the absence of identified values at a particular location may reflect gaps in the database rather than as conclusive evidence that geoconservation values are not present. Most systematic geoconservation surveys that have been conducted to date have been based on public land based around land management boundaries (see Table 1).

Sites

Currently there are 1049 sites listed on the TGD (version 7). The distribution of these sites is shown in Figure 1. Sites vary in size from small individual rock outcrops and fossil sites less than one hectare, to large landscape sites of several hundred thousand hectares. The three largest sites are the: Central Highlands Cainozoic Glacial Area (781,455 ha); the Tyennan region (643,412 ha) and the Western Tasmanian

Figure 1. Distribution of Tasmanian Geoconservation Database listed sites (version 7). Macquarie Island, 1200 km to the south east of Tasmania is not shown nor are islands containing sites north of Flinders Island in Bass Strait (Hogan, Kent group, Curtis, and Moncoeur Island group)

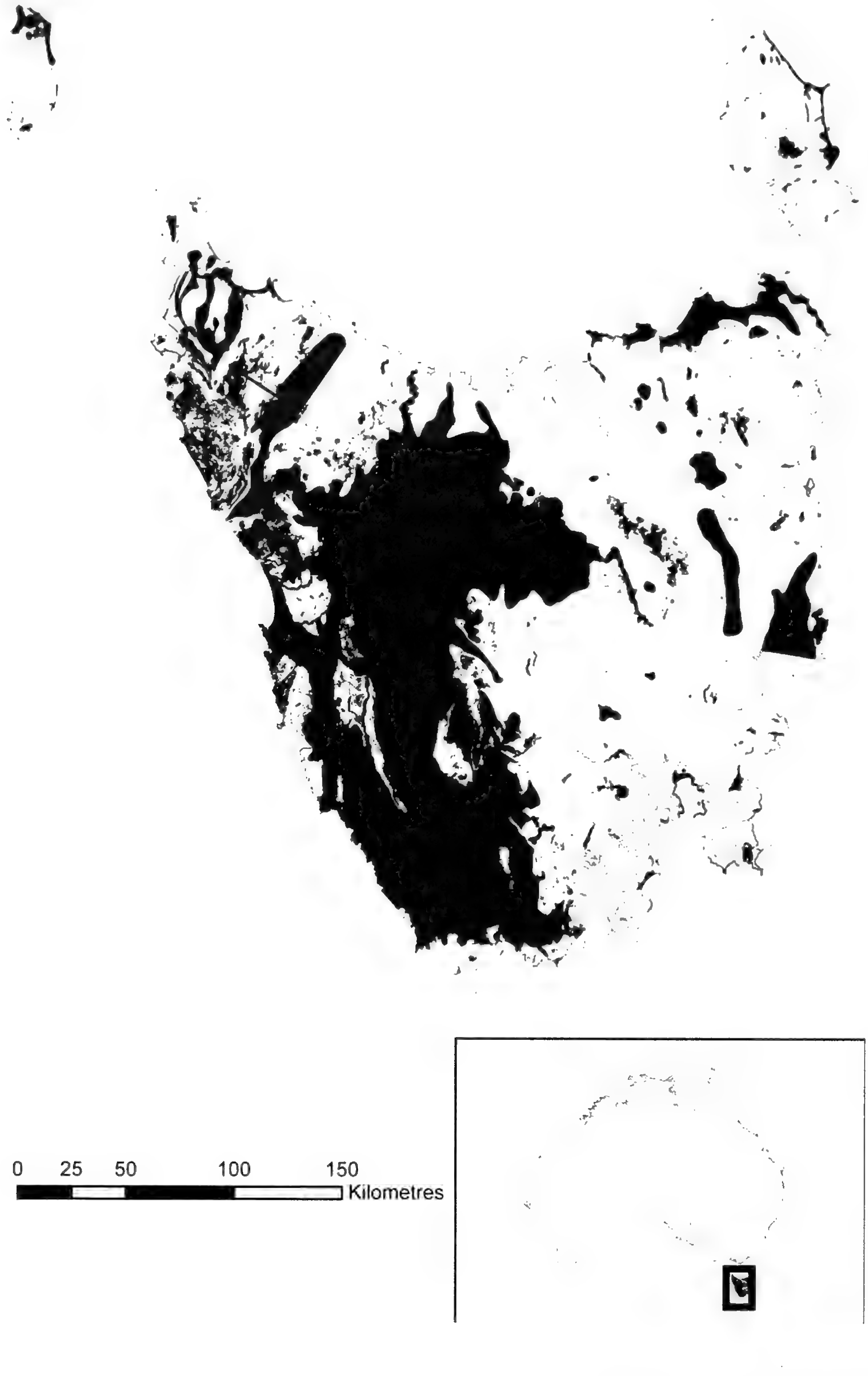

Table 3. World significant sites listed on the Tasmanian Geoconservation Database (version 7).

Sulphur Creek Pillow Lava and Folds
Hellyer River Insect Fossil Locality
Reward Creek Mineralisation
Lemonthyme Creek Glacials
Poatina Fossil Crab Site
Little Rapid River Early Oligocene Plant Fossil Site
Lake Fidler and Sulphide Pool Meromictic Lakes
Lake Morrison
Collingwood River White Schist
Balfour 'String of Beads' Fossil Locality
Tessellated Pavement
Cape Surville Dolerite Feeder Intruding Basement
Dianas Basin Folds
Penguin Megabreccia
Florentine Road Gordon Group Stratigraphic Sections
Lords Siltstone Unit/Gordon Group Stratigraphic Sections
The Fossil Cliffs
City of Melbourne Bay Foreshore
Upper Gordon Group Stratigraphic Sections
Florentine Valley Gordon Group Stratigraphic Sections
Darwin Crater
Adamsfield Workings Mineralogy
Rodway Valley Blockfield
Lower Gordon River Levee - Flood Basin System
Cynthia Bay Moraines
Mt Anne (North East Ridge) Glaciokarst
Lake Pedder (the original)
Exit Cave - D'Entrecasteaux Valley Karst Area
World Heritage Area Sandy Coasts
Macquarie Island Oceanic Lithosphere
New River Undisturbed Fluvial and Karst systems
Weld River Basin Karst and Fluvial Systems
Macquarie Graben Fluvial Geomorphic Systems
Central Plateau Terrain
Western Tasmania Blanket Bogs
Cashions Creek Limestone/Gordon Group Stratigraphic Sections

Blanket Bogs (596,637 ha). Many sites overlap one another and the total area of the state covered by TGD listed sites is about 4,105,000 ha or some 60 percent of Tasmania. 49 sites are classed as very large (>1,000 ha), 395 as large (25-1,000 ha), 335 as medium sized sites (1-25 ha) and 277 as small sites (< 1 ha).

The western half of the state has a greater density of TGD listed sites. This is due in part to the more complex geology to the west and also reflects a bias in previous geoconservation inventories that have largely been confined to public lands (Table 1), with the largest state reserves (e.g. Tasmanian Wilderness World Heritage Area) located in the west of the state. The west also contains a number of the very large landscape scale individual TGD sites.

There are TGD sites representing geological ages from the Precambrian to the Holocene. Quaternary sites account for some forty per cent of listed sites. Twenty percent of sites are of Tertiary age and Triassic, Devonian, Cambrian and Precambrian sites each comprise approximately five percent of the total.

Levels of significance have been assigned to most sites (27 are listed as unknown) with 15 per cent of sites considered significant at a local level, 30 percent at a regional level, 35 percent at a Tasmanian level, 12 percent at an Australian level and 3 percent at the world level. World significant sites are considered to be rare in the world and/or, by the nature of scale, state of preservation or display, comparable with examples known internationally and may be illustrative of processes occurring or having effects at a continental or national scale. The 35 world significant sites listed on the TGD are shown in Table 3. Detailed notes on a few of these sites follow by way of example of the type of information stored on the TGD.

The *New River Undisturbed Fluvial and Karst systems* TGD site situated roughly halfway along the south coast of Tasmania is considered a site of world significance (figure 2). It includes the entire New River drainage basin from Federation Peak (source) to Prion Beach (river mouth), including the Salisbury River tributary catchment basin. It is contained within the Southwest National Park and Tasmanian Wilderness World Heritage Area.

It is the largest complete source-to-sea fluvial geomorphic system in Tasmania that is entirely mantled by old growth forest, is undisturbed by contemporary human activities including land clearance, roads or walking tracks, and shows no evidence for late Holocene disturbance to fluvial processes due to former Aboriginal activity (Sharples 2003). The basin also contains extensive high-relief Precambrian dolomites and Ordovician limestones (Dixon & Sharples 1986) that are mostly unexplored but are both known to contain extensive undisturbed karst landform systems. These include

Figure 2. Photographs of selected sites from the Tasmanian Geoconservation Database (TGD). (a) Undisturbed New River fluvial and Karst systems (photo Grant Dixon), (b) Vanishing Falls (photo Rolan Eberhard), (c) TGD listed Precambrian ripple marks, Gardiner Point (Photo R Eberhard), (d) Complex geology in Devonian Mathinna group sediments Maria Island coastline (photo Michael Comfort), Organic rich soils of the Western Tasmanian Blanket Bog TGD site (photo Mike Pemberton), and (f) Interview River transgressive sand sheets (photo Rolan Eberhard).

extensive caves below Precipitous Bluff and at Salisbury River (limestone), Tasmania's largest stream sink (Vanishing Falls), and a poorly documented karst system at Forest Hills (dolomite). The New River fluvial system is considered outstanding as the largest undisturbed complete source – to – sea, temperate maritime climate, fluvial geomorphic system in Australia, and as such is probably comparable to the best examples globally. The presence within the undisturbed catchment of extensive undisturbed karst landform systems is an additional geomorphic value of outstanding significance at a global level.

The fluvial and karst geomorphic systems of the New River Basin constitute benchmark geomorphic systems of outstanding universal scientific and intrinsic value by virtue of their extent and undisturbed geomorphic processes, and were assessed to be of outstanding universal value (World Heritage significance) in their own right by Sharples (2003).

Another world significant site on the TGD is the *Western Tasmania Blanket Bogs* (figure 2). This is a large area covering much of western Tasmania and isolated pockets across other parts of the state. It covers a combined area of nearly 600,000 ha. It is the most extensive organosol terrain in Australia and the Southern Hemisphere. Blanket bogs cover undulating country but can also form on slopes of 40°. Various geological types are covered, but the best development is on infertile, siliceous substrates. The blanket bogs developed in response to high precipitation, high humidity, and low evaporation, similar to other temperate maritime areas such as Ireland. The conservation values of the site relate to the total extent and size of the organosol terrain. The site also contains various significant component features including peat mounds, subfossils and palaeosols.

A number of TGD sites are found on King Island at the western end of Bass Strait including a world significant site, the *City of Melbourne Bay Foreshore*. The site is a shore platform and includes a section of Cambrian rocks, including sediments (sandstone, siltstone, dolomite and mixtite), pyroclastics and lavas (flows and pillows). Pillows indicate seafloor volcanism and are spectacular, with individual pillows and flows visible in plan and section. The mixtite, once thought to be a tillite, is now considered to have a non-glaciogenic density flow origin. More recent studies indicate that the site consists of superb coastal exposures of the Late Neoproterozoic Grassy Group, including glacial deposits of the Marinoan ice age, 'cap dolostone', shale, peperites and pillow lavas (tholeiitic and picritic), and petrologically unusual felsic intrusives. The dated volcanics (579+/-16 Ma) and intrusives (575+/-3 Ma) provide globally important constraints on the age of the beginning of the Ediacaran Period as well as the hypothesised 'snowball Earth' episode.

Future directions

As noted above, DPIPWE is currently in the process of restructuring the existing database and combining both the textual and spatial data into a single database on Oracle software, to be housed within the Department's Natural Values Atlas, a web-based product for publishing information on natural values. A number of the fields of the database reflect the fact that the TGD was developed over a decade ago as part of the Regional Forest Agreement process and with developments in geoconservation principles and practice since the TGD was first developed a number of changes to the database are proposed. Some of these are related to increased software capacity and functionality while other changes are more fundamental to database fields. The sensitivity and classification fields are likely to see the most changes. The new proposed sensitivity ratings will be related to specific activities or threats and for each site there will be a number of ratings depending on the proposed activity compared to the existing database that has a generalised sensitivity rating based on a roughly linear scale. This will enable more meaningful assessments across a broader range of activities, reflecting the expanded use of the TGD in assessing developments across a range of land tenure and land use settings. The second field where a major change is proposed is the classification field. Currently sites are classified according to categories applied during the RFA based on earlier work by Dixon (1991). Despite its then innovative nature, it is no longer considered adequate for present purposes and a new classificatory system has been developed and trialled. It is expected that this will greatly improve the functionality of the TGD and enable enhanced searching functionality.

The new software will also enable site nominations to be entered on-line, with various innovations to ensure more consistent and complete data entry. Once sites have been assessed by the TGDRG and approved by DPIPWE a new version of the database will be available to users directly and not as is the current practice of having to wait several months for new versions to be issued. Users of the new database will also be able to see a more comprehensive range of information relating to sites and it is hoped over time to expand this information to include photos, site condition reports and other information.

It is envisaged the restructured database and operating system will facilitate its use as a standard planning reference, while freeing up existing staff resources to systematically survey and review sites based on geo themes or the new classificatory system to enhance the TGD. Access to the revised database will be through the Natural Values Atlas portal at www.naturalvaluesatlas.tas.gov.au

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Diversity within Geodiversity, Underpinning Habitats in New South Wales Volcanic Areas

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New South Wales National Parks, Nature Reserves, State Conservation Areas and other reserves lie in diverse geological settings. One component, Cenozoic volcanic rocks, includes eroded basaltic fields, some representing shield volcanoes with central cores of silicic rocks. The central shields provide diverse habitats in the Tweed-Main Range, Nandewar, Ebor-Dorrigo, Warrumbungle and Canobolas areas. These shields result from deep geodynamic causes and increase in age, size and degree of erosion northwards giving systematic habitat variations. The northern Tweed structure (23–25 mya) exhibits lava aprons, erosional caldera rims, basement valley floors and an isolated central intrusive peak, whereas the southern Canobolas structure (11–13 mya) retains a general shield profile. Some basaltic fields had prolonged eruptive histories, as in Barrington Tops NP (60–4 mya). There, lavas form an incised plateau rimmed by valleys and escarpments. Similar lava fields occur in other parks and reserves, e.g. Mummel Gulf NP and Ben Hall Gap NP, but fertile basalt soils mostly promoted agricultural/forestry use. A marine park at Lord Howe Island lies on a submarine plateau cut into a 7 mya basaltic volcano. The volcanic landscapes provide scenic recreational parks and platforms for habitat studies, aboriginal history, geo-education and geo-tourism.

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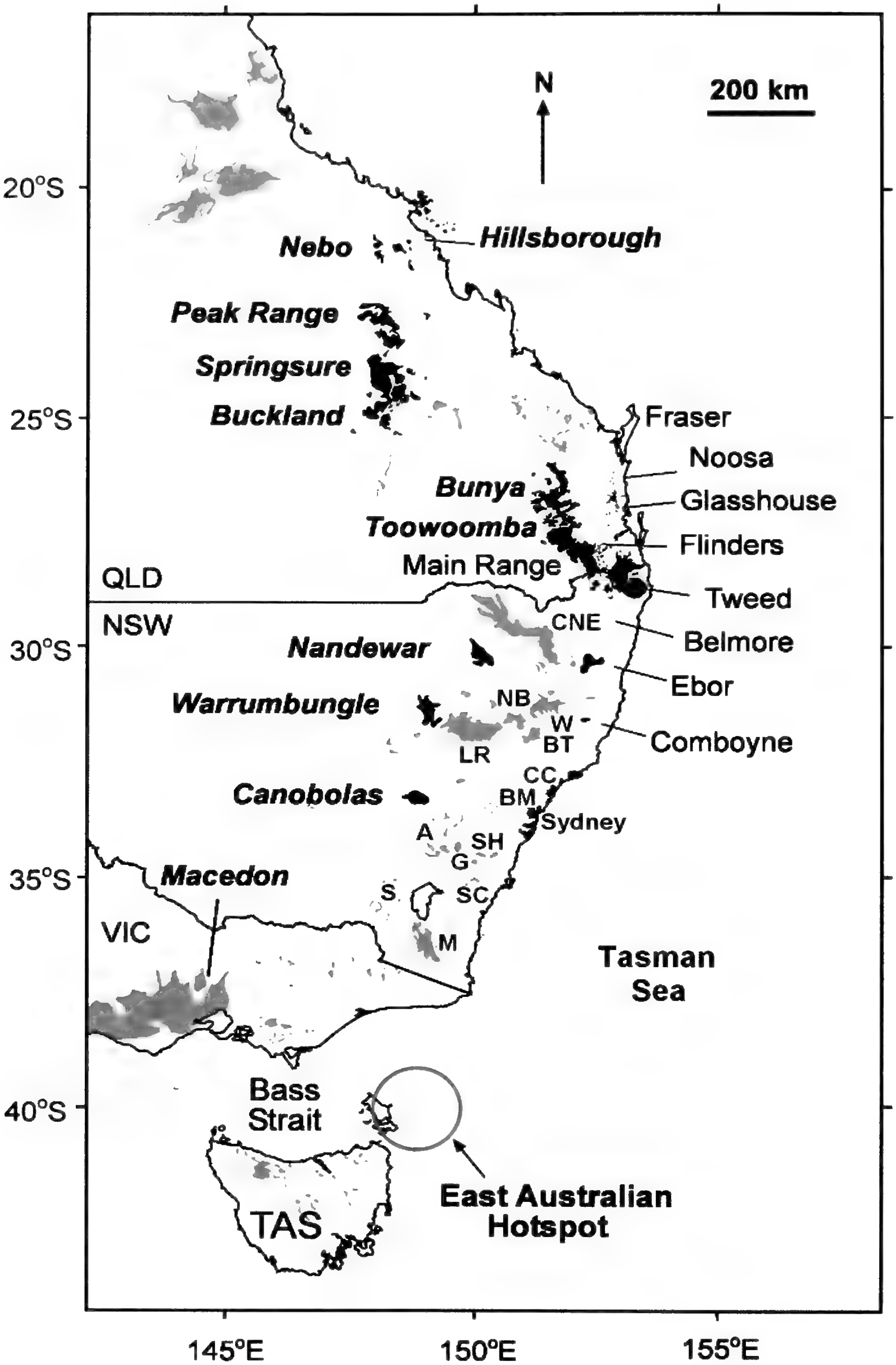
KEYWORDS: basalt fields, central volcanoes, geodiversity, habitats, Lord Howe Island, National Parks, New South Wales.

INTRODUCTION

New South Wales encompasses diverse geological settings related to different times within an extended geological history from Precambrian to Recent. The different units have been subjected to a range of erosional events since the break-up of eastern Gondwana (Scheibner 1999; Branagan and Packham 2000; Veevers 2001). One component that plays a prominent role within many National Parks, forestry and conservation reserves is Cenozoic volcanic rocks. This stems from their relatively widespread distribution, particularly in eastern NSW, and contrasting erosional forms and soil development given by silicic and basaltic lithologies within them (Sutherland 1995). This NSW component is part of a more extended array of such rocks along eastern Australia (Fig.1), which also includes seamounts and island chains along the Tasman and Coral Seafloors (Vasconcelos et al. 2008). This paper aims to summarise this volcanic component in NSW where it underpins a range of habitats in National Parks (NP), State Conservation Areas (SCA), Nature Reserves (NR), Marine Parks (MP), Forestry Reserves (FR) and Aquatic Reserves (AR). Among c. 570 landscape types identified in NSW, two thirds are found in these reserves (Mitchell 2003). Photographic images will illustrate a range of these landforms and habitats that exist within their precincts. It is hoped that this survey will stimulate more detailed biological studies within these linked habitats and allow further assessments of these areas for geo-heritage values, potential geo-education themes and geo-tourist activities.

Brief descriptions of these volcanic features within the main NSW parks and preservation areas (Explore Australia Publishing 2010) incorporate new dating on the rocks and some unpublished data. Updated information on the national parks, reserves, conservation areas and forestry reserves can be accessed on a range of websites, e.g. www.bigvolcano.com.au/; www.environment.nsw.gov.au/; www.nationalparks.nsw.gov.au/. A progress report



N
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Peak Range
Springsure
Buckland
Fraser
Noosa
Glasshouse
Bunya
Toowoomba
Flinders
Main Range
Tweed
QLD
NSW
CNE
Belmore
Nandewar
Ebor
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lists geoheritage values for some of the volcanic holdings (Osborne et al. 1998).

GEOLOGICAL SETTING

The Late Cretaceous-Cenozoic volcanism that created the range of remnant land forms now exposed in New South Wales was similar to that now seen in active volcanoes observed in other within-plate basaltic areas such as the Hawaiian Islands. Volcanic activity would have ranged from relatively calm effusions and lava fountaining, through more continuous gas blasting of larger ejected blocks and in some cases more extreme explosive activity forming towering Plinian-style eruptive columns (Parfitt and Wilson 1995, 1999). Lava flows ranged from blocky to ropy forms that could encase internal drainages of lava and extend into long lava flows (Cashman et al. 1998; Sheth 2003). As in Hawaii, some of the volcanoes developed large shields over deep magma chambers (Kauhikau et al. 2000) from which more evolved silicic rocks could rise into their summits (Bohrson and Reid 1997; Van der Zander et al. 2010). Such volcanos are called central volcanoes in eastern Australia and the Tasman Sea; in similar fashion to their Hawaiian and other counterparts they show a progressive increase in age away from a deep fixed mantle 'hot spot', as the overlying plate moved across the melting zone (Duncan and McDougall 1989; Vasconcelos et al. 2008). These linear chains of central volcanoes show some gaps and bends in their paths, which are related to further deep geodynamic processes or crustal collisions (Sutherland 2003; Knessel et al. 2008). In inland NSW, several minor volcanoes formed of a potassic lava leucitite also formed a linear age chain related to Australia's northward movement (Cohen et al. 2008). These

Figure 1. LEFT, Eastern Australia, showing relationships of NSW volcanic fields to the overall Cenozoic volcanic distribution. Central volcano fields (black areas) are named as major centres (inland, bold italics; coastal. non-italics) and are shown in relation to a present East Australian hotspot position. Basalt fields (grey areas) are designated in NSW by symbols for the main fields described in this study (CNE Central New England; NB North Barrington; W Walcha; LR Liverpool Range; BT Barrington Tops; CC Central coast; BM Blue Mountains; A Abercrombie, SH Southern Highlands; S Snowy ; M Monaro). The diagram is adapted from Cohen et al. (2008).

leucitite volcanoes do not include significant parks or reserves and are not considered further in this paper. The majority of volcanoes in eastern Australia are basalt-only lava fields. These volcanoes are less clearly related to Australia's northward plate motion and were erupted in sporadic bursts from c. 100 mya to near-recent times.

The main New South Wales volcanic fields discussed in this paper show differences in age distribution between the central volcanoes and basalt lava fields (Fig. 2). General ages of basalt lava fields and central volcanoes in NSW based on K-Ar dating and the relationship of the central volcano trend to past plate motions of eastern Australian from 90 mya to the present are depicted in Fig. 3. Where more reliable dating of the rocks is available using the $^{40}Ar/^{39}Ar$ method (Cohen 2007), it is designated as Ar-Ar dating in this account. The contrast in the compositional ranges for typical rock types found in central and basaltic lava field sequences is illustrated using two examples from northern NSW (Table 1).

CENTRAL VOLCANO COMPONENT

Tweed Volcano

This is the largest central shield (80 x 100 km across) and straddles the NSW-Qld border region (Duggan et al. 1993). Its growth is now dated as at least 24.3 ± 0.4 to 23.1 ± 0.2 mya (Ar-Ar dating; Knessel et al. 2008), although the full stratigraphical range of lavas from Tweed remains to be analysed (B. E. Cohen, pers. comm. 2010). Progressive erosion of the original structure (Willmott 2003, 2010) has reduced its landscape to (1) remnant basaltic lava aprons on its northern, western and southern sides, (2) escarpments where an 'erosional' caldera occupies the valley floors of the Tweed River systems (Fig. 4a) and (3) a prominent isolated central peak (Mount Warning), with some surrounding ring dyke protrusions, left by the more resistant intrusive conduit of the volcano (Fig. 4b). The highest remnant lies at 1175 m asl and the flows extend to below sea level. Tomewin Rock on the NSW border is a coarse rhyolite agglomerate that seems to represent an initial violent phase of the Tweed Volcano (Willmott 2010).The basaltic apron does not extend south into the Alstonville-Ballina area where older (27–41 mya) flows are exposed (K-Ar dating; Cotter 1998). The Border Ranges NP, Wollumbin NP (including Mount Warning NP), Mebbin NP, Nightcap NP, Whian Whian SCA and Cook Island AR are areas where views of remnant rocks of the Tweed volcano are encountered. Mount Warning is also named 'Wollumbin' an aboriginal

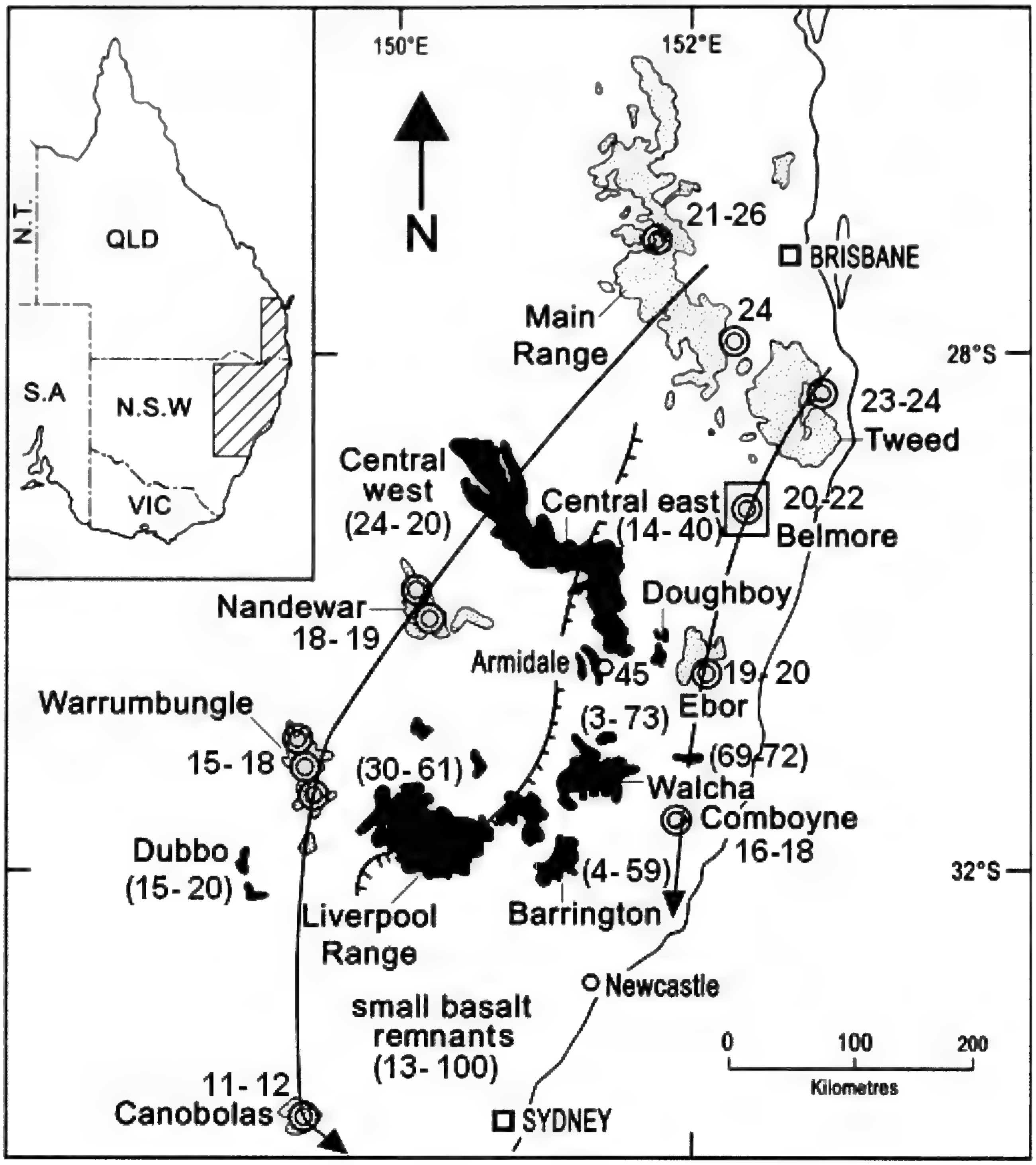

Figure 2. Distribution of central volcanoes (stippled areas) and basalt lava fields (black areas), Qld-NSW (26–34°S), showing ages in mya (Ar-Ar ages, no brackets; K-Ar ages, brackets), general central volcano progressive age trends (arrowed lines) and western edge of the Sydney Basin (hatched line). The Belmore central volcano is outlined by a box to indicate its unusual silicic nature. The diagram is modified from Sutherland et al. (2005b).

name for a fighting chief, although some applications of aboriginal place names and history in the area are controversial. One elder source maintains the peak and adjacent caldera was known as 'Walambing Momoli' by the Ngarakwal people, which described its silhouette as a scrub turkey and its nest (Boileau 2006).

Many of the parks and reserves within this volcanic apron form part of the Gondwana Rainforests of Australia World Heritage Site (UNESCO 2010). The geology, characteristic land forms, typical soils and vegetation regimes of these areas are listed for the North Coast subregions (www.environment.nsw.gov.au). The Border Ranges NP, because of its many

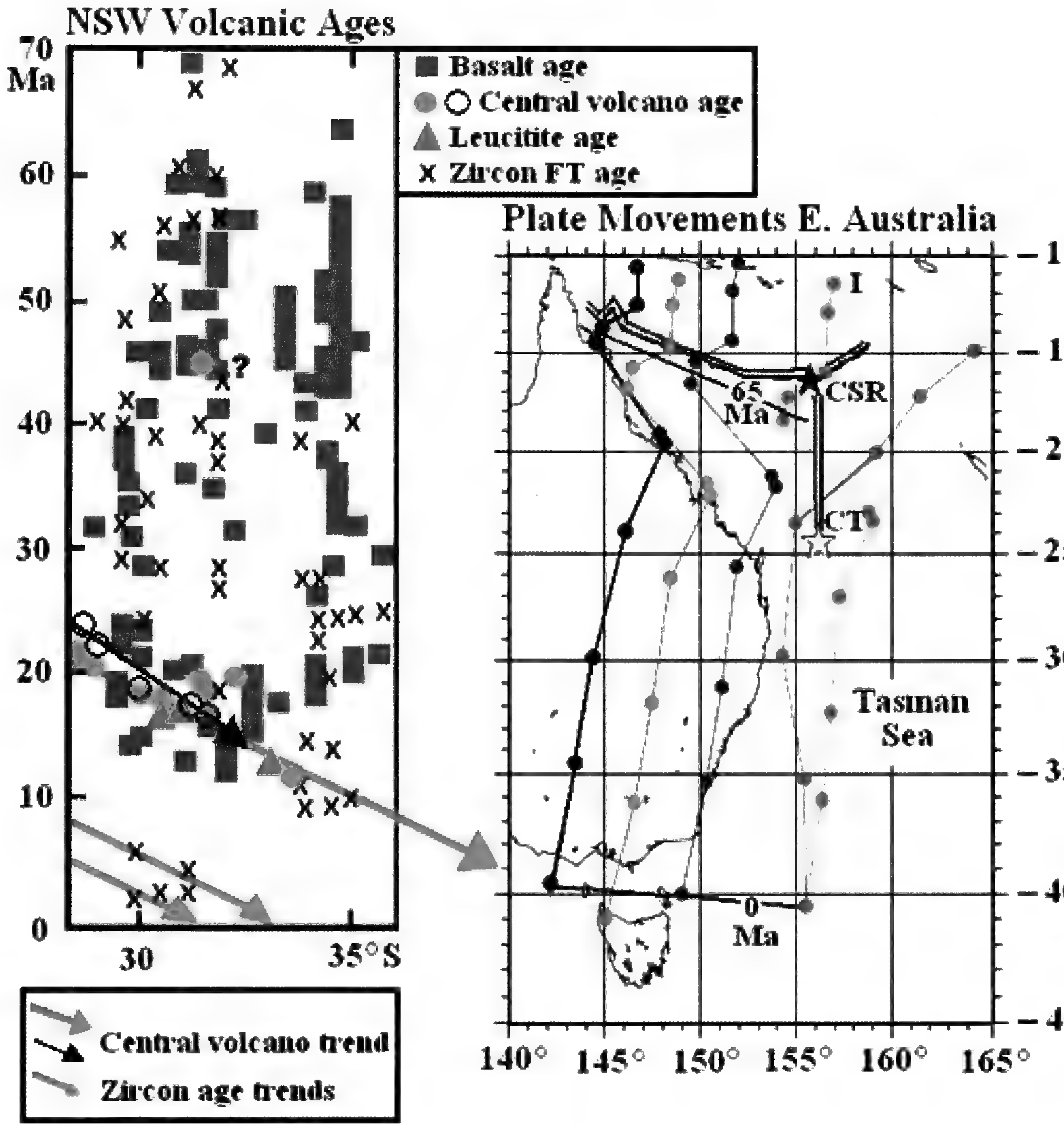

Figure 3. Left side: Age (K-Ar)-Latitude plots for NSW basaltic fields (filled spaces), central volcanoes (filled circles), leucitite fields (filled triangles), zircon fission track eruptive reset ages (crosses) and progressive age trends (arrows). The diagram is adapted from Sutherland (2003). Note that the Central volcano trend (arrow) would differ slightly in position using Ar-Ar dating (open circles trend). The central volcano age trend (arrow head) is related to a present East Australian plume line positions at 0 mya (0 Ma line), shown in the right hand side map. Right side: Plate movement map showing past plume line positions (coloured circles with tracks) reconstructed at increasing 10 mya intervals northwards from 0–90 mya. The past positions are based on an Indian-Atlantic Ocean hotspot reference frame (I); one track (purple circles) is based on a Pacific hotspot reference frame for comparison (Maria Seton, University of Sydney, plate movement program). The Coral Sea Ridge (CSR) and Cato Trough (CT) spreading ridge system (double line) and triple point positions (stars) are shown relative to a 65 mya position

Table 1. Comparative compositional ranges for some NSW volcanic fields Compositional ranges are summarised from cited literature and earlier listed references

Rock Type	SiO_2	Al_2O_3	Total FeO	MgO	Na_2O	K_2O
Tweed-Focal Peak central volcano sequence (significant silicic component)						
Basanite suite	44.5–46.8	14.7–15.1	12.4–11.3	8.7–9.0	3.6–3.8	0.8–1.5
Alkali basalt suite	45.6–47.5	13.5–16.3	10.8–13.3	4.5–10.2	3.0–4.7	0.7–2.0
Transitional basalt suite	47.9–48.1	15.6–16.9	9.0–12.2	4.7–4.9	3.9–4.1	1.5–1.6
Tholeiitic basalt suite	50.6–55.7	14.4–15.4	8.9–12.9	2.4–8.1	3.3–4.2	0.5–3.6
Silicic suite	58.5–74.3	11.3–15.0	2.3–11.0	0.1–2.8	2.7–5.8	1.9–4.8
Liverpool Range basalt field sequence						
Alkali basalt suite	45.6–47.7	14.9–16.1	9.9–10.2	10.3–11.2	3.0–3.2	1.5–1.8
Tholeiitic basalt suite	47.0–47.6	14.8–15.3	9.9–11.3	9.6–11.1	2.2–2.4	0.9–1.5

distinct landscape habitats in a relatively small area, has the highest concentrations of marsupial species and among the highest concentrations of bird, reptile, amphibian and bat species in Australia. It has particular interest in representing a transition between northern tropical and southern temperate faunal regions. The Lost Wilderness FR within the area includes over 60 threatened plant species. Nightcap NP with its eroded basalt and rhyolite landscape includes significant faunas such as the little-bent winged bat, woompoo fruit dove, masked owl, Stephens banded snake and red legged pademelon, while Whian Whian SCA within the park protects quoll, koala and platypus habitats. Cook Island AR incorporates a basalt pedestal as an important breeding ground for migratory birds and protects surrounding off shore marine reef communities.

Main Range-Focal Peak Volcanoes

This extended volcanic complex (80 x 80 km) west of Tweed volcano is largely exposed in Qld where the youngest basalt cap lies at 1156m asl (Stevens and Willmott 1996, 1998), but its most southern basaltic and silicic parts overlap into NSW (Thompson 1974). The Focal Peak volcano is overlapped by the Tweed lavas but rhyolite plugs assigned to it extend south to Nimbin (Willmott 2010) The Ar-Ar ages for the Qld sector range from 26.4 ± 0.4 to 20.7 ± 0.5 mya, which suggests a wider age span than for the Tweed volcano, but the NSW exposures remain undated. The Nimbin Rocks are rhyolite peaks that mark a sacred aboriginal site named after 'Nyimbunji', a ruler of supernatural powers (Tacon 1998).

The Border Ranges NP includes basalt lavas and some rhyolite plugs, such as Mount Glenie, erupted from the Focal Peak Volcano. Toonumbar NP, Richmond Range NP and Mallanganee NP extend across the more southern eroded remnants of the Focal Peak centre. Toonumbar NP, with peaks such as Dome Mountain, contains World Heritage listed rainforests, where unlogged tree species have been compared with those in surrounding logged areas (Kariuki et al. 2006). The habitats provide protection for threatened animals such as the sooty owl, red-legged pademelon and yellow-tailed glider. Richmond Range NP, which incorporates peripheral basalt flows from Focal Peak Volcano, includes the World Heritage listed Cambridge Plateau and holds an astounding diversity of flora and fauna, with many rare and endangered species. The Koreelah NP, Mount Clunie NP, Tooloom NP and Toobin NP lie within the less investigated NSW volcanic remnants to the west. Tooloom NP follows basalt ridges, includes the World Heritage listed Tooloom Scrub, and is a critical haven

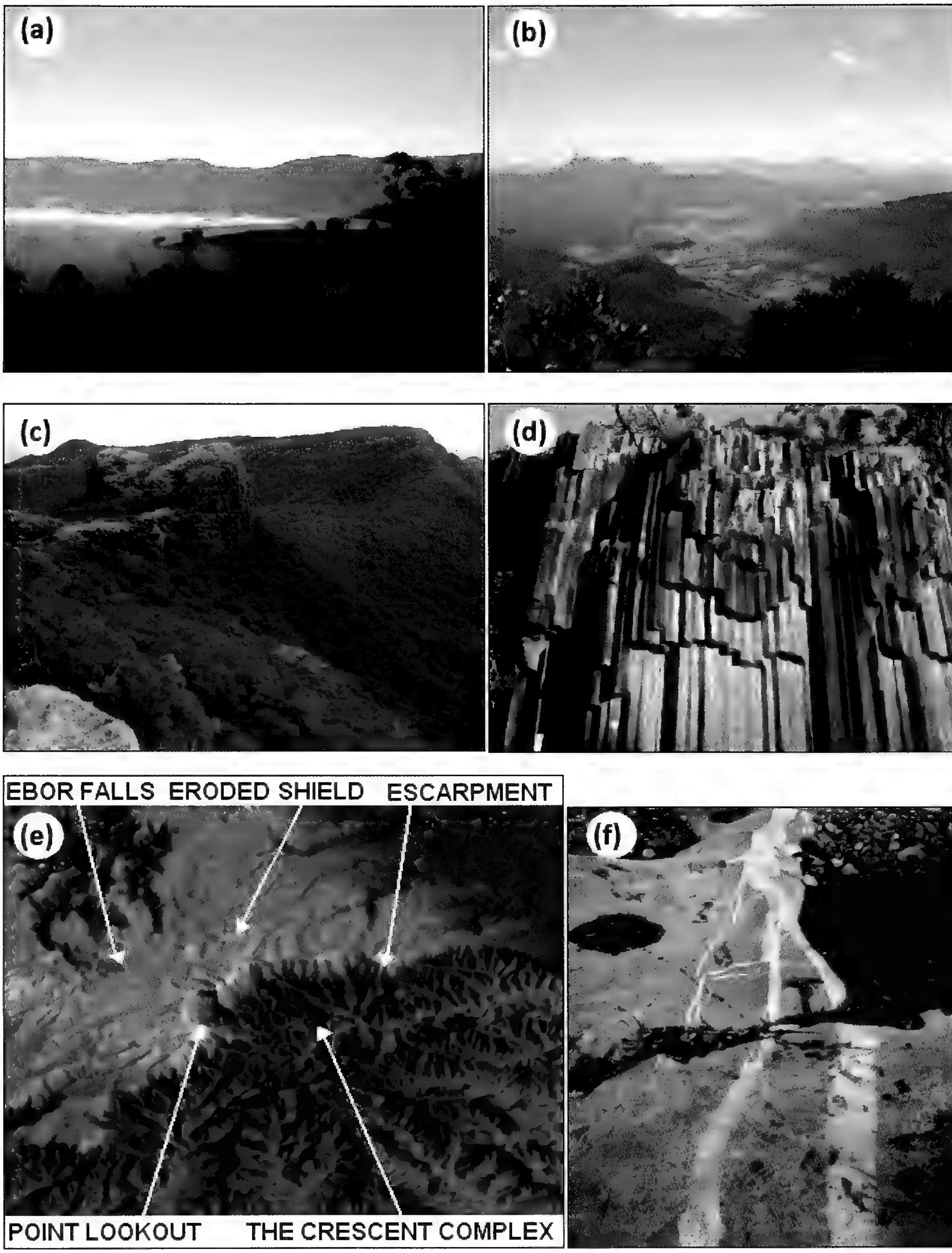

Figure 4. Erosional features developed on older central volcanoes. (a) Border Ranges escarpment, Tweed Volcano. (b) The Mount Warning intrusive complex, from south western lava apron. (c) Governor Bluff, Nandewar Volcano. (d) Sawn Rocks (with columnar jointing), Nandewar Volcano. (e) High altitude perspective of Ebor Volcano partially eroded on the eastern side, forming escarpment (modified from Cohen 2007). (f) Silicic dykes (light coloured) of the Ebor Crescent Complex. Photos: Benjamin Cohen.

for a wide range of threatened wallaby, potoroo, bettong, owl and lyrebird species.

Belmore Volcano

This small central volcano (15 x 20 km), north east of the Clarence River and east of the escarpment, is predominantly silicic in nature without significant remnants of a main basaltic apron (Sutherland et al. 2005b). The lack of basalts is unlikely to represent an erosional event, as only one basalt dyke (post-silicic) was found in the eroded interior. Three silicic rocks are dated at 20.8 ± 0.8 to 21.2 ± 0.3 mya (Ar-Ar dating; Knessel et al. 2008). The highest summit lies at 516 m asl and the lowest remnants lie at c. 200 m asl. Mount Neville NR (www.environment.nsw.gov.au) overlaps an outlying flow ridge from a peripheral vent of the volcano and protects plants such as spike-rush and cabbage tree species at the limits of their geographic ranges.

Nandewar Volcano

This central volcano (30 x 50 km) is exposed in the Mount Kapatur NP (Dawson et al. 2004) and has received detailed petrologic investigations and comment (Duggan et al. 1993; Nekvasil et al. 2004). Limited Ar-Ar dating gives ages of c. 18.5–19.0 mya for the main complex (Cohen et al. 2008). In contrast to the Tweed volcano, much of the central silicic eruptive super structure remains, reaching 1510 m asl (Fig. 3c,d), although the shield is partly dissected by radial drainage which descends through the basalt lavas at plains level (Bob and Nancy's Geotourism site, 2010). The volcanic landforms include outstanding examples of tiered lava terraces, such as Lindsay Rocks, a spectacular set of circular dykes at Mount Yalludundida and a superb example of cooling joints in silicic lava at Sawn Rocks (3d).

Mount Kapatur NP is foremost among Australian conservation areas for the range of vegetation climes that ascend its volcanic slopes over such a short distance. The varied habitats protect a diverse range of plant communities and threatened species of bats, birds, wallabies, quolls and a unique pink slug. The preserved biological communities exhibit both western slopes and tableland affinities within the area and overlaps between both northern and southern species distributions.

Ebor-Dorrigo Volcano

This volcano (40 x 60 km) straddles the present escarpment, producing striking topographic differences across its eroded structure from its high point at 1562 m (Fig. 3e). The volcano formed between 19–20 mya (Ar-Ar dating; Ashley et al. 1995; Knessel et al. 2008). Only the western and northern basaltic aprons show substantial preservation, leaving a decapitated intrusive complex in its eroded centre (Fig. 3f) and a few residual lava caps to the south. A basalt cap at Andersons Sugarloaf (c. 850 m asl), 35 km south of the intrusive core is probably a remnant lava flow from the volcano as it is geochemically similar to analysed Ebor basalts (F.L.Sutherland and I.T. Graham, unpublished analyses). This prominent peak marked a sacred aboriginal initiation site (Kempsey Heritage Inventory; www.kempsey.nsw.gov.au).

The New England NP encompasses volcanic relicts left by escarpment retreat under erosion by the developing Bellingen, Nambucca and Macleay river systems. Guy Fawkes NP includes the west flowing plateau drainage, now entrenched in the basalt apron at Ebor Falls. Dorrigo NP includes some of the basalt apron on its northeastern side and with New England NP they form part of the World-Heritage listed Gondwana Forests of Australia designed to protect stands of Antarctic Beech. The rich basalt soils and wet climate support an exceptional biodiversity. Snow gum woodland, forest and heath on the high plateau pass into towering eucalypt forests and lush rainforest on the slopes.

Warrumbungle Volcano

A central intrusive complex features in this volcano (50 x 80 km), where erosion has exposed spectacular examples of flows, dykes, plugs and domes (Fig. 5 a, b). These showcase a wide spectrum of alkaline rocks (Duggan and Knutson 1993; Duggan et al. 1993; Ghorbani, 1999, 2003). Several Ar-Ar dates indicate that the structure developed from 18 to 15 mya (Cohen et al. 2008). Studies of minerals in the rocks reveal a complex evolution of subsilicic to silicic lavas tapped from deeper mantle and higher crustal chambers (Duggan 1990; Ghorbani and Middlemost 2000). The capping flows reach a high point at 1206 m asl and the eroded intrusive complex is readily accessible in Warrumbungle NP (Whitehead 2009). Peripheral basalt flows mark former radial drainages and descend onto the surrounding plains. "Warrumbungle' is the name given to these peaks by the Gilmaroi aboriginal people, meaning 'crooked mountains'.

Warrumbungle NP, although containing similar volcanic rocks and features to Kaputar NP, shows subtle differences in its landforms and biodiversity to its northern counterpart. The complex incisions within the volcanic edifice produce many diverse microclimates and habitats. Marsupial species abound and include the threatened brush-tailed wallaby,

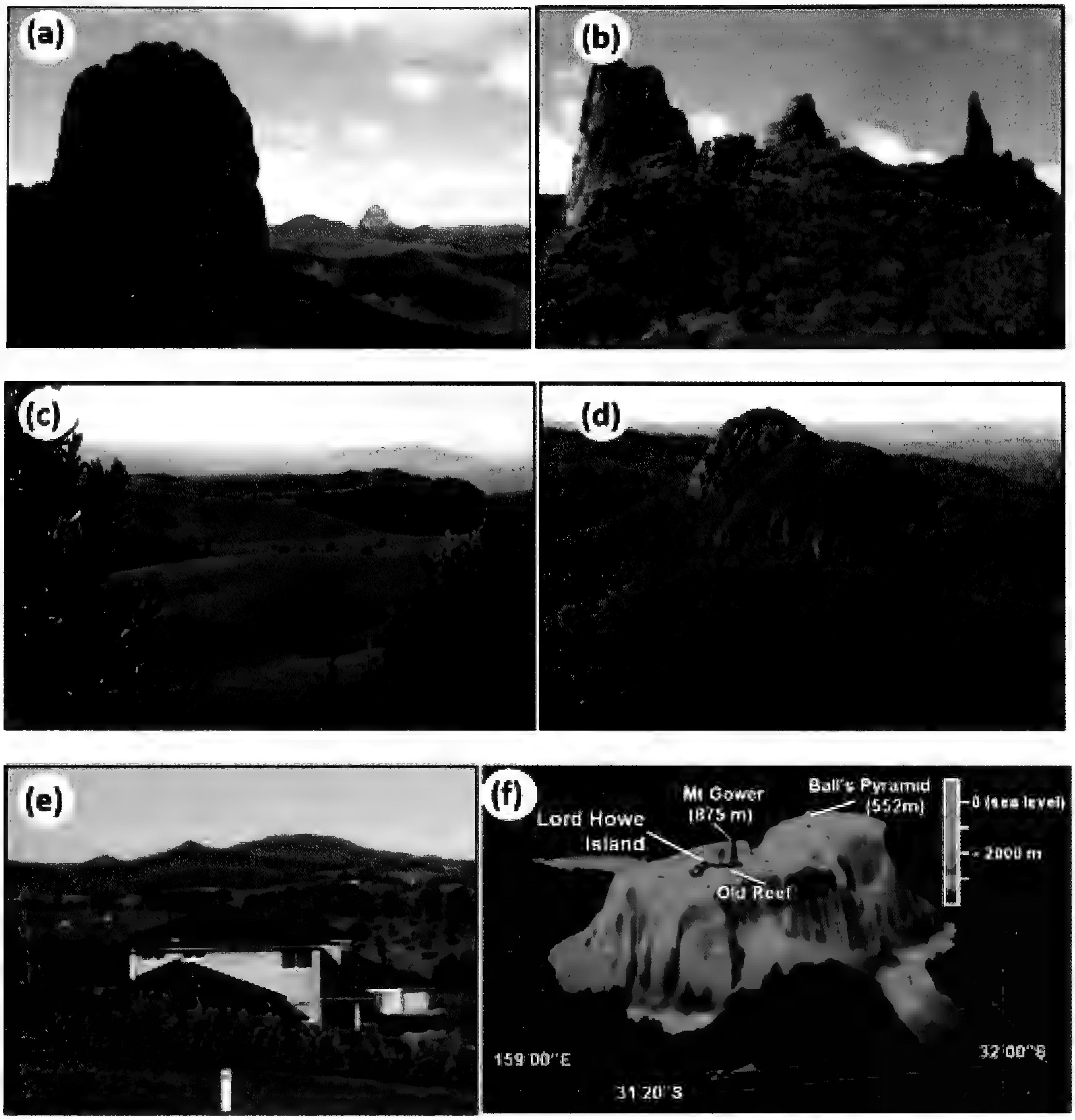

Figure 5. Erosional features developed on younger central volcanoes. (a) View across eroded intrusive core, Warrumbungle Volcano. (b) Silicic plugs and dykes, Warrumbungle Volcano. (c) Basalt Plateau, Comboyne Volcano. (d) Big Nellie silicic plug, Comboyne Volcano. (e) Silicic summit from edge of basalt apron, Canobolas Volcano. Photos: Benjamin Cohen. (f) Submerged basalt pedestal, reef growth and island peaks, Lord Howe Volcano (adapted from Hill et al. 2001).

bird species flourish, including a remarkable range of parrots and many lizard and snake species dwell among the rocky exposures.

Comboyne Volcano

This volcano (25 x 35 km) is preserved as a dissected plateau beside the main escarpment, centred near the town of Comboyne (Pain and Ollier 1986). Lower basalt flows are capped by silicic flows between c. 400–700 m asl (Fig. 5 c) and scattered silicic intrusives up to 865 m asl (Fig. 5 d) mostly rise through basement exposures (Knutson 1989). To the southeast, lower basalts and a trachyte outcrop at Mount Juhle and further south silicic intrusives continue as far as Wingham down to c. 10 m asl. Silicic units give Ar-Ar dates from 16.5–18.1 mya (Knessel et al. 2008; F. L. Sutherland, I. T. Graham and H. Zwingmann, unpublished data). Silicic peaks at Mount Coxcomb, Mount Goonuk and at Big Nellie, Flat Nellie and Little Nellie feature at Mount Coxcomb NR, Mount Goonuk NR and Killabakh NR and Corrabakh NP (Evans 2001; Westerman 2004), while basalt flows on Camboyne plateau feature in Boorganna NR. The name Comboyne is derived from an aboriginal word for kangaroo.

The plateau-escarpment connection in this volcanic area provides complex habitats. Corrabakh NP is an important area for many rare, threatened and endangered plant species, with some lying at their southern limits, while the plugs at Big Nellie support eucalypt species at unusually low altitudes. Endangered animals include the bush curlew and the giant barred frog.

Canobolas Volcano

This small shield (30 x 50 km) largely retains a compact cone-like profile (Fig. 5 e), rising from c.900 m to a summit at 1395 m asl. Its geomorphic features, ranges in basaltic and silicic rocks and the soils are described by Pogson and Watkins (1998) and Chan (2003). Some Ar-Ar dating suggests construction from 13.3 to 11.5 mya (Cohen et al. 2008). The main edifice lies within Mount Canobolas SCA. The mountain name comes from the Wirudyri aboriginal words 'Gaahna Bulla' meaning two shoulders, which describes the two main peaks of 'Old Man Canobolas' and 'Young Man Canobolas' in the eroded volcano.

Mount Canobolas SCA, located on an isolated rocky 'island' rising from surrounding plains, forms an important moist micro-climate habitat for plant and animal communities. Its outcrops host a variety of mosses and lichens, including endangered lichen communities. The mountain supports snow gum sub-alpine woodlands, including the threatened endemic *Eucalyptus canobolas*.

Lord Howe Volcano

This oceanic volcanic island, with its satellite Balls Pyramid to the south, falls under NSW jurisdiction and UNESCO World Heritage listing (Hutton 2008; UNESCO 2010). It is described here with the central volcanoes as part of an age-progressive oceanic volcanic chain (Mortimer et al. 2010), which has a similar, but not contemporaneous, origin to those along the eastern Australian seaboard (Duncan and McDougall 1989). It is largely basaltic, without observed silicic components, but most of the structure (Fig. 5f) forms a large, hidden submarine pedestal (30 x 80 km). Only part of its former caldera lava-filling now stands above sea level and reaches up to 875 asl (Thompson et al. 1987; Hill et al. 2001). The K-Ar dating suggests a 6.5–7 mya construction age.

The Lord Howe Island State MP, gazetted in 1999, and the Lord Howe Island (Commonwealth Waters) NP, proclaimed in 2000, cover several specific areas on the bevelled submarine platform on the volcano, which are presently under revised management arrangements (www.mpa.nsw.gov.au; www.environment.gov.au). Studies of the offshore marine platform recently revealed that a much larger fringing coral reef existed around the Island prior to growth of the present reef since 7 kya (Woodroffe et al. 2010).

BASALT LAVA FIELD COMPONENT

Significant basalt-only lava fields extend throughout eastern NSW and their soil types and vegetation show differences related to their regional climates (Jenkins and Morand 2002). The basalts range from alkaline (nephelinites, basanites, alkali basalts, hawaiites, mugearites) into subalkaline (transitional basalts, olivine tholeiites, quartz tholeiites) types (O'Reilly and Zhang 1995; Vickery et al. 2007). The central New England and Walcha fields occupy significant areas of the New England Tablelands. Voluminous basalts form the Liverpool Range between the Tablelands and the Hunter Valley, while the Barrington province extends through the Mount Royal Range into the Barrington Tops plateau. Lavas in the central New England field (70 x 240 km) reach elevations over 1370 m asl, show a wide age range (14–40 mya) and include alkaline and subalkaline basalts (Vickery et al. 2007). The exposures are largely devoted to pastoral and gem mining pursuits (sapphires and zircon) and only support limited nature reserves (Glen Innes-Guyra basalts, www.environment.gov.au).

A feature of some basalt fields is their growth by repeated eruptions over an extended period, e.g. for over 55 my in the Barrington province. This aspect of 'hydra-head' growth through progressive cut back of earlier volcanoes and subsequent replacement during the eruptive history is illustrated for the North Barrington-Barrington Tops fields in Fig. 6.

Walcha field

Basalts extend over 60 x 60 km and descend from 1200 m to 950 m asl. Alkaline to subalkaline types range in age from 35–73 mya and include gem-bearing types (Sutherland and Barron 2003; Sutherland et al. 2005; Gibson 2007; F.L. Sutherland, I.T. Graham and H. Zwingmann, unpublished data). Deep incision of flows feature in Mummel Gulf NP and basalts extend through Riamukka SF to the west and Einfield SF to the east. Further basalt areas lie

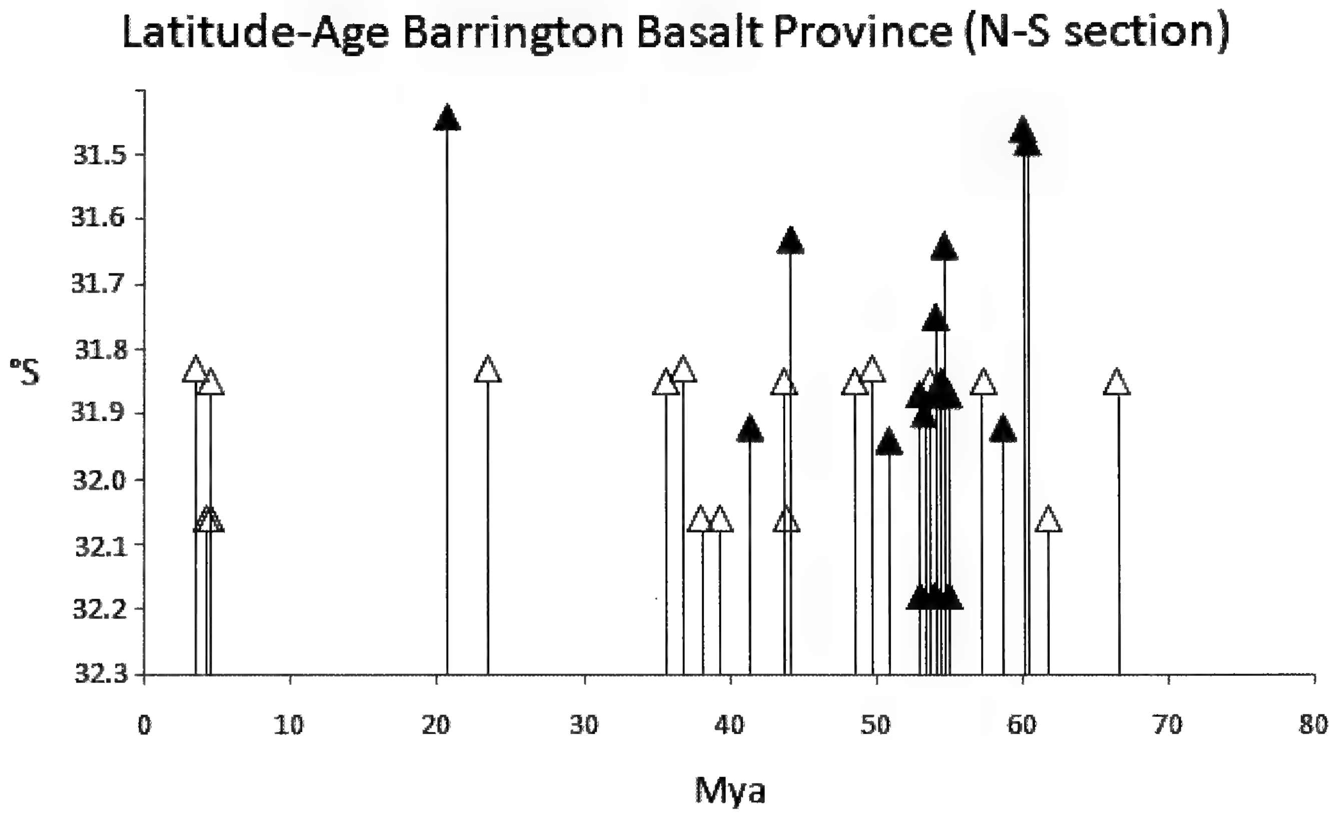

Figure 6. Latitude (°S)–Age (mya) diagram for eruptive centres across a N-S section , Barrington basalt province, including Mount Royal Range and Barrington Tops Plateau, with lava-dominant volcanic centres (K-Ar, solid triangles) and zircon-ages (FT, open triangles). Age data come from Sutherland and Fanning (2001), Roberts et al. (2004), Sutherland et al. (2005a) and Gibson (2007).

in Nowendoc NP and Ngulin NR. Mummel Gulf NP protects extensive old growth forests, which support a large range of bird species, forest bats and small mammals, such as the brown antechinus.

Liverpool Range field

This large basalt field (50 x 120 km) lies between 650–1400 m asl and its dating and petrology is summarised in Schön (1989). Older more alkaline lavas occur to the east (32–35mya) and younger alkaline to transitional subalkaline lavas (38–40mya) form the western sequence. Wallabadah Rock is an unusual isolated rhyolite plug chemically similar to, but older than, the rhyolites in other central volcanoes, as it gave a 46 mya age (Gibson 2007).

Coolah Tops NP extends across the main erosional crest of the western basalts; it forms an isolated basalt plateau that preserves tall open forest communities that differ from the forests on other basalt reserves in the district (Binns 1996). Towarri NP on the southern basalt slopes overlaps three biogeographical regions, the NSW northern Tablelands, Briglow black soil country and Sydney Basin sandstone exposures; these habitats along with Hunter Valley acting as a conduit for migrating species hold considerable biodiversity (Hill et al. 2001). Ben Hall Gap NP lies on the eastern basalt plateau across a drainage divide and has outstanding tall old growth eucalypt forests developed on the thick, nutrient-rich basalt soil (Mitchell 1990); it marks the northern limit of the southern cold temperature rain forests and overlaps the eastern and western distributions of many bird species.

Barrington field

These basalts extend east of the Hunter Valley (Chambers 1995; Sutherland and Graham 2003). The volcanoes show a wide age range (21–61 mya; Gibson 2007), with evidence of limited late activity extending to < 4 mya (Sutherland et al. 2005a) and the basalts are largely alkaline with minor subalkaline types (Sutherland and Fanning 2001). Many Barrington Tops eruptive events carried up gemstones (ruby, sapphire and zircon), which were concentrated in alluvial deposits (Roberts et al. 2004). The main basalt regions lie within the Mount Royal NP, Barrington Tops NP and Barrington Tops SCA in areas which are monitored using vegetation surveys (Zoete 2000). At Barrington Tops, the plateau basalts (Fig. 7 a) reach up to 1576 m asl, and radial drainage has developed

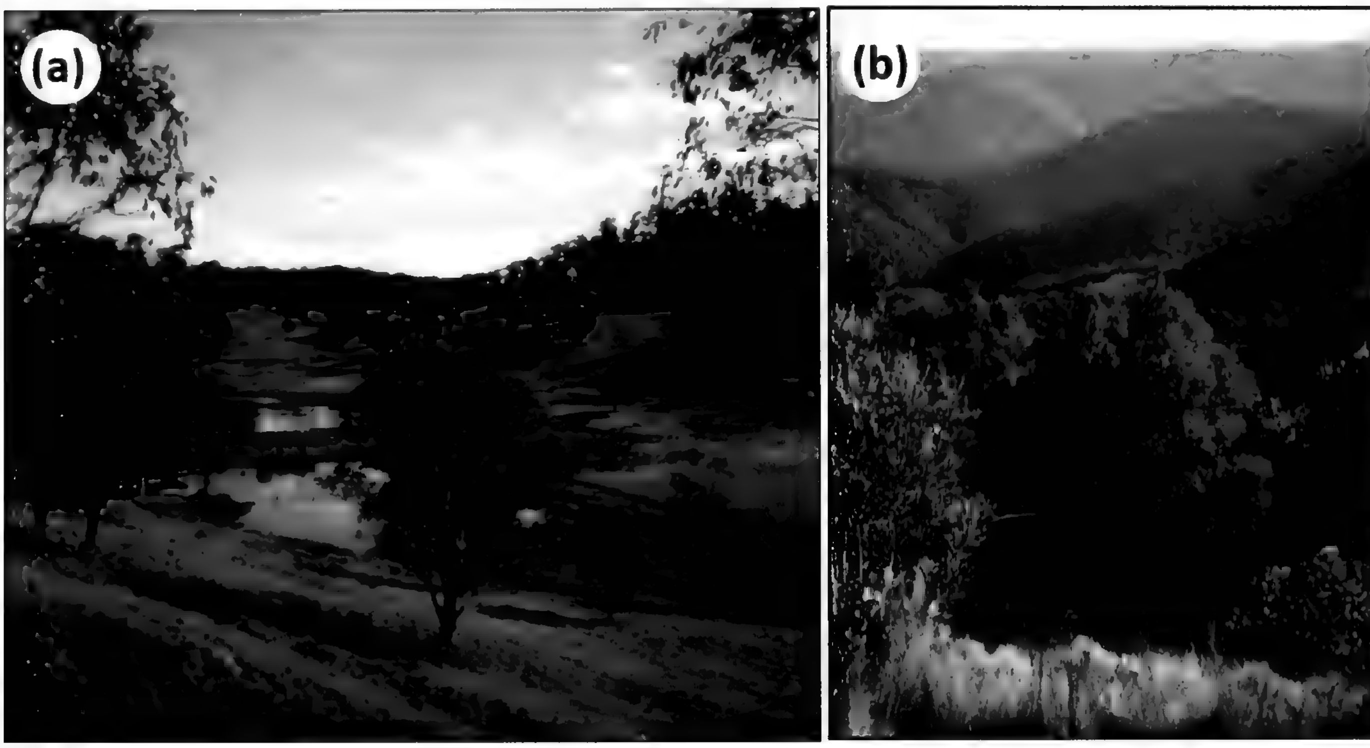

Figure 7. Barrington Tops basalt field, showing erosional features. (a) Plateau surface with drainage headwaters between older 59 mya basalts (left) and younger 50–55 mya basalts (right), Hunter Springs. (b) Dissected plateau scarp, northeastern Barrington Tops Plateau, looking from Moppys Lookout. Photos: F.L. Sutherland.

peripheral escarpments and deep valleys (Fig. 7 b) that cut through the basalts into basement rocks between 600–900 m asl.

Barrington Tops NP and Mount Royal NP include segments of the World Heritage-listed Gondwana Rainforest of Australia for their subtropical rainforests that occupy valleys in the basalt plateaus (UNESCO 2010). The diverse habitats provide refuge for threatened animal species such as the Hastings River mouse.

Mid-NSW basalt fields

Scattered remnants extend through the Sydney-central coast area and westwards into the Oberon and Bathurst areas. Basalt dykes intrude coastal sections between Newcastle and Wollongong and some are Cenozoic, such as those at Era Beach in Royal NP south of Sydney, which gave a 51 mya K-Ar age (Och et al. 2009). Younger alkaline basalts (14–21 mya), such as at Mount Banks, fall within Blue Mountains NP (Alder and Pickett, 1997; Van der Beek et al. 2001) and Mount Yengo NP (Mount Warrenga, Gibson 2007). Older basalts (34–57 mya) extend through Mount Yengo NP, Wollemi NP and Nullo Mountain SF. They rise to 1154 m asl at Tayan Pic, a designated significant geological site, and include Mounts Coricudgy, Pomany, Corriday, Mondilla, Coorangoola and Kerry and Nullo Mountains (Gibson 2007). Mount Yengo formed a significant mythological feature for surrounding aboriginal tribes as a Creator God, Biamie. These basalt peaks and soils influence local habitats within the wide range of eucalypt species developed across the sandstone platforms of the Greater Blue Mountains World Heritage area (UNESCO 2010).

Basalt and dolerite remnants in Abercrombie River NP represent former lavas that extended into headwaters of west-flowing paleodrainage systems, while other basalts entered former Lachlan and Macquarie River courses downstream as far west as the Dubbo-Orange area (Bishop and Brown 1992; Tomkins and Hesse 2004).

Southern NSW fields

The Southern Highlands (100 x 110 km) and Grabben Gullen fields (30 x 40km) southwest of Sydney contain scattered basalt patches with diverse ages (20–60mya; Gibson 2007) and are mostly alkali basalts with confined flow extents (O'Reilly and Zhang 1995). Minor remnants lie within Tarlo NP and rainforest on basalt is preserved in Robertson NR. Further south, alkaline and subalkaline basalts form flows (40–50mya) within the Shoalhaven catchment area and were used to demonstrate the relative antiquity of the plateau surface (Nott et al. 1996). Some flows are found in Morton NP and

Budawang NP. Along south coastal NSW, similar basalt types show younger ages (27–34 mya; Brown 2000), but have induced differing interpretations of their geomorphic relationships with highland development. The northern part of Eurobodalla NP is dominated by basalts, but the largest basalt body forms Mount Durass within the bounds of Greater Murramarang NP (Wright 1996).

To the southwest, basalts in the Snowy field (60 x 80 km) are mostly alkaline types that remain as valley filling ridges and plateaus of Miocene flows (18–24 mya) that range in their elevations from 450 m to summit sources up to 1784 m asl (Sutherland et al. 2002; Sharp 2004). These basalts have engendered considerable discussion on their relationships to the age and uplift history of the surrounding uplands (Young and McDougall 2004). Many of the higher basalts are included in Kosciuszko NP and the Tabletop wilderness area while lower plateau basalts lie within Bago SF. The largest southern field (45 x 110 km) is the Monaro field, where alkaline and some subalkaline sequences (34–58 mya; Gibson 2007) preserve important evidence of early vegetation and climatic records (Taylor et al. 1990; Brown 1994; Roach et al. 1994; Taylor and Roach 2003; Sharp 2004). Although some basalts are located in South East Forests NP and some central-northern reserves (Conartha NR, Myall NR), the bulk of the basaltic soils support grasslands that include a number of preservation areas for endemic species (Garden et al. 2001; Benson 2003).

DISCUSSION

New South Wales is well-endowed with national parks and ancillary reservations, containing over 380 listed sites covering 7% of the State's area (NSW Government websites). Among some sixty national parks, most lie on the eastern side of the state (Explore Australia 2010), where some 30 of them cited in this survey contain exposures of Cenozoic volcanic rocks. This highlights the important role that this unit occupies within the geodiversity on offer in NSW reservations. The most diverse range of rocks and landforms appear in the central volcano shields, where contrasts between basaltic and silicic lithologies lead to more pronounced differences in erosional forms and soil developments. This translates into greater variations in vegetation make up and habitats for fauna. Rainforests tend to develop on nutrient-rich basalt areas while eucalypt sclerophyll stands tend to colonise nutrient-deficient soils on silicic rocks. Nightcap NP, which has the highest annual rainfall in NSW, supports subtropical rainforest on its basalt soils and warm-temperate rainforest on its rhyolite-based soils. The lithological nature and topography in the volcanic areas also dictates land use. Areas with rich basalt soils on flatter, accessible terrains with favourable hydrological characteristics encourage agricultural use (Brodie and Green, 2002), whereas rugged scarps are often too steep for cultivation. Juxtaposed lithological contrasts in the central volcanoes provide scenic appeal for visitors and with their biodiversity factors has led to their prevalent inclusion within parks and reservations.

Systematic geodiversity

The NSW central volcanoes show a general change in their ages (from 25 to 12 mya) and size (from 80 x 100 to 30 x 50 km across) with latitude southwards (28.2 to 33.4°S). This change provides a systematic base to study their geological and habitat variations, related to climate and variable length of erosion and weathering time. This general rule, however, excludes Belmore Volcano. Here, the absence of basalts led to a reduced shield area and a different erosional history and land use. The older northern volcanoes (Main Range-Tweed) provide examples of more extreme erosional relief and habitat ranges than the younger southern Canobolas Volcano, where its remaining profile lacks marked internal topographic disruptions. Habitats are largely limited by basaltic/silicic soil distribution, altitude and hydrological changes from the surrounding plains to the mountain summit.

Two separate central volcano chains formed during their progressive development southwards, giving eastern (Qld-NSW border volcanoes, Belmore, Ebor, Comboyne) and western (Nandewar, Warrumbungle, Canobolas) lines. This brought another systematic erosional factor into play, the intersections of some volcanoes by escarpment retreat towards the east Australian divide during drainage development (Ollier and Pain 2000). The Tweed and Belmore volcanoes grew onto the coastal margin so that the escarpment retreat had intersected their positions by 24–20 mya respectively, but not those of the Main Range and Ebor volcano, which are only now half removed by the escarpment inroads. The Comboyne volcano remains almost connected to the escarpment and the western centres lack the extreme division of habitats caused by escarpment intersections.

Among the basalt fields, systematic differences in habitats can appear where adjoining fields show significant age differences. In southeast NSW, the older Monaro field with more deeply developed soil profiles supports natural grasslands and forests that contrast with less deeply weathered plateau and flow caps that remain in alpine and foothill settings in the Snowy field.

Geodiversity platforms

Variations in volcanic rock types, their ages, landforms and weathering characteristics all feature within this one Cenozoic unit, within the overall geological diversity in NSW. This range in lithology, soil types and dissected features, at different altitudes and geographic locations, both inland and coastal has developed a multitude of diverse habitats. This linkage provides an important platform for promoting the role of geodiversity in the environment. It provides opportunities for multidisciplinary scientific studies, geo-heritage assessments, geo-education and geo-tourism. Examples of multidisciplinary studies that use NSW Cenozoic volcanic components include landform ecological analysis (Mitchell 2003), hydro-geomorphic comparisons (Gibson 2008), aboriginal stone tool analysis (Bowdler 2005; Corkhill 2005), and archaeological appraisals (McIntyre-Tamwoy 2008). Geo-heritage listings range from individual rocks (Nimbin rhyolite, Osborne et al. 1998) to clusters of sites (basalt ridges of the Liverpool and Mount Royal Ranges, Schön 1984) and also large-scale features (Warrumbungle Volcano; Australian Heritage Commission 2010).

Geo-education utilises the NSW volcanic features in varied ways, including inclusion in explanatory books and guides for recreational visitors (Blanch and Kean 1995; Alder and Pickett 1997; Gold and Prineas 1997; Ferret 2005; Whitehead 2008), more specialised visitors (Duggan and Knutson 1993; Sutherland and Graham 2003) or even extending to fanciful stories for children's (Hutchison 2010). Educational slide sets that feature Australian volcanoes include NSW examples (Lewis et al. 1998), while documentary video films feature NSW volcanic backgrounds, particularly the Tweed Volcano, in integrations of landforms and ecology (Sutherland 2008; Warth 2009). An interactive website for school students on Australian volcanoes is maintained by Uni Serve-Science (2001). Geo-tourism is catered for by a range of web sites which list NSW volcanic attractions (www.bigvolcano.com.au) and includes special self-operating tours (Bob and Nancy's Geo-tours 2010).

Although many avenues exist to explore the Cenozoic volcanic features in NSW, there is further scope for promoting their importance both for assisting in their preservation and for exploiting their explanatory role in illustrating geological processes. The systematic differences, within and between the large central volcanoes and basalt fields, provide considerable capacity for developing overarching themes that link their individual features into a grander picture. For example, although each central volcano has its own geological history as a group they can be linked to Australia's plate motion movement away from Antarctica and the concepts of global 'hot spot' volcanic traces elsewhere. Likewise, individual basalt fields can be related to their place within the long evolution of volcanic activity along the Tasman margin, to concepts of landscape inversion or to how they preserve records of former biodiversity during Australia's natural history evolution. Many of the volcanic fields can be linked into preservation of 'Gondwana' rainforest reserves (United Nations Environment Program-Wo 2008).

Unfinished story

The NSW Cenozoic volcanic record developed through to its present landscapes over a 100 my period and volcanism still remains dormant in far northern Queensland, western Victoria and SE South Australia (Johnson 2004). The NSW landforms discussed here only acquired minor, mostly explosive additions in the last 10 my, while erosion further dissected the lavas. Nevertheless, the rocks remain as valuable assets to further decipher their genesis while still generating scientific debate as to the exact causes. Increasing use of more precise dating, high-quality geochemical and isotopic analysis and well-controlled geodynamic modelling continues to furnish new insights into the origin of the volcanism (Vasconcelos et al. 2008; Di Caprio et al. 2009).

The onset of extensive basaltic lava field activity, as found in eastern Australia, is correlated by some workers with global mantle warming effects without other extraneous causes (Coltice et al. 2007), whereas other workers look to additional factors such as buoyant rise of hot mantle wedges when subduction ceased as important mechanisms (Rey and Muller 2010). For progressive central volcano activity on moving plates, fixed deep mantle thermal plumes are commonly invoked, but such activity can also be explained by other means (Reitsma and Allen 2003; Finn et al. 2005). For the eastern Australian central volcanoes different interpretations of their tracks include plumes deflected by mantle processes (Sutherland 2003), plumes deflected by thick subcontinental roots (Manglik and Christensen 2006) or plumes that directly record changes in Australian plate motion (Knessel et al. 2008), but resolution of these views needs further scientific testing. Thus, the intrinsic geodiversity revealed among the NSW Cenozoic volcanic areas continues to be updated and refreshed for presentation to scientific, recreational and geo-tourist audiences. This volcanic heritage can be continually worked into new concepts, such as the new approaches to geodiversity and ecosystem services (Gordon and Brown 2010).

CONCLUSIONS

Cenozoic volcanic remnants form significant contributions to National Parks and reserves in eastern NSW. The large central volcano sites decrease in age and size from the northern border to central NSW, causing corresponding variations in landforms and habitats. The basalt lava fields show a greater age range, lack the silicic attributes within central volcanoes, and develop wider latitudinal and altitudinal habitats. The geodiversity just within this volcanic unit provides exceptional opportunities to study detailed geological, biological and human interactions.

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Geodiversity of the Southern Barrington Tops Lava Field, New South Wales: A Study in Petrology and Geochemistry

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The Barrington Tops lava field lies within the Barrington Tops National Park and State Forests north of the Hunter River Valley and west of Gloucester in eastern NSW. Mapping in the southern lava field has identified 33 basaltic flows each 10-20m thick and separated by agglomerate or by sub-horizontal palaeosols. Petrography and whole-rock geochemistry indicate basanites dominate the stratigraphic sequence, with subsidiary alkali basalts, pyroxene-phyric basalts (ankaramites) and tholeiites. Alkali gabbros form intrusions high in the sequence and represent conduits for surface lavas. Modelling of major and trace elements from the alkaline rocks reveal a co-genetic relationship, chiefly controlled by a low pressure olivine + plagioclase mineral assemblage. Incompatible trace elements suggest low degree melting of an enriched mantle source with entrained amphibole-enriched sub-continental lithospheric mantle. A more depleted mantle component may have contributed to the tholeiites. These southern findings are consistent with observations in the northern lava field, and help to model evolution of the Barrington Tops volcano. Topographic inversion has contributed to geomorphological features which support diverse floral and faunal communities. Such diversity is underpinned by the geology and in particular the lava field, which shaped the natural landscape, provides fertile soils and releases gem-quality sapphires, zircons and rubies.

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KEYWORDS: Barrington Tops, basalt, geochemistry, geodiversity, lava field, New South Wales, petrology,

INTRODUCTION

Barrington Tops is located approximately 100km north-northwest of Newcastle, New South Wales (Fig. 1; inset). The region is dominated by a plateau of average elevation approximately 1500m above sea level with a relief of over 1100m to the valley floors. Barrington Tops is rugged, heavily vegetated and incorporates the Barrington Tops National Park and several surrounding State Forests. Both the National Park and State Forests are well known for recreational purposes that derive from the environmental diversity and geomorphology – both dependent on the underlying geology – of this remarkable region.

The Barrington Tops lava field has a K-Ar age of 59 to 44 Ma (Wellman et al. 1969; Sutherland and Fanning 2001), although more recent fission track and U-Pb dating of zircons suggests that parts of the field were active for over 55 million years, until 4 Ma (Roberts et al. 2004). The volcanic field consists predominately of alkali basaltic rocks, with some olivine tholeiites at the base of the sequence (Mason 1982). Following Mason's (1982) interpretation of the basalts as flows, Pain (1983) envisaged that they were derived from a shield volcano, an idea supported by subsequent authors (O'Reilly and Zhang 1995; Sutherland and Fanning 2001; Sutherland and Graham 2003). The Cenozoic lavas in part overlie Late Permian granitoids which were emplaced at high crustal levels (3-7 km: Eggins 1984) and partly within low grade metamorphosed Carboniferous and Devonian sediments (Mason and Kavalieris 1984) of the New England Orogen that the granites intrude.

In this paper, I present data (collected in 1995 during my Honours thesis) from the southern part of the volcanic field (Fig. 1), an important addition to the literature as most data for these Paleocene/ Eocene (51 to 59 Ma) basalts come from the northern side (Wellman et al. 1969; Mason 1982; Pain 1983; O'Reilly and Zhang 1995; Sutherland and Fanning 2001). The southern lavas range from SiO_2 -deficient basanites, akali basalts and rare trachybasalts to SiO_2

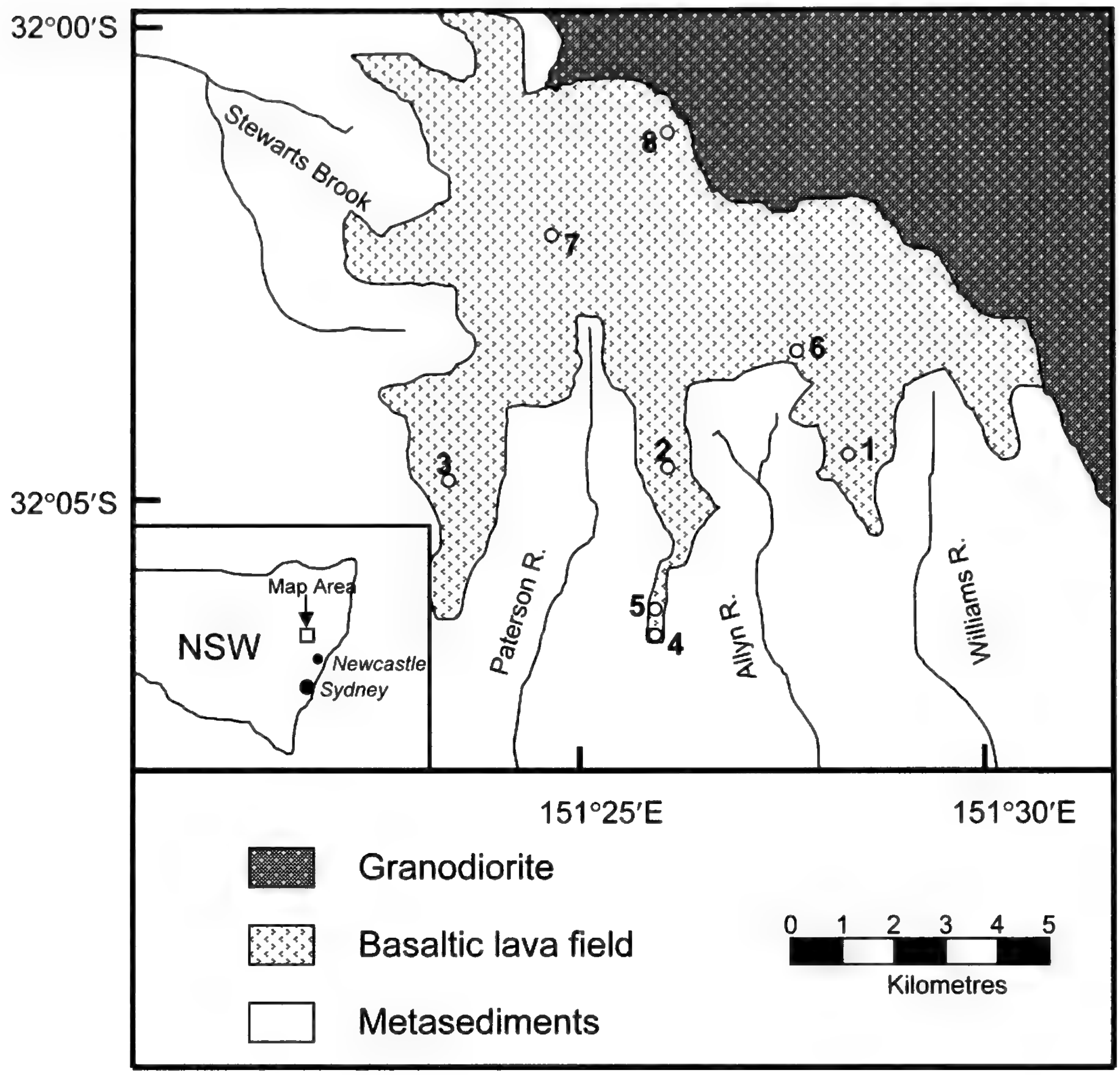

Figure 1. Simplified geological map of the southern Barrington Tops lava field. Numbered points refer to localities mentioned in the text: 1, Williams Range (Careys Peak Trail); 2, Allyn Range; 3, Mount Royal Range; 4, Mt Allyn; 5, Mt Lumeah; 6, Careys Peak; 7, Mt Barrington; 8, Barrington Falls. Inset indicates the map area within NSW.

saturated tholeiites, interspersed with pyroxene-phyric flows (ankaramites) and alkali gabbros.

STRATIGRAPHY

Local stratigraphy in the southern Barrington Tops basaltic field has been determined from detailed petrological study of individual lava flows from type sections exposed in several localities along the Careys Peak Trail, Mounts Allyn, and Lumeah and the Barrington Tops plateau (Fig. 1). Correlations between sites were carried out topographically because of the sub-horizontal nature of the basalt and a similar topographic height of the basalt-metasediment contact. This contact occurs at approximately 920m above sea level.

Fig. 2 is a stratigraphic sequence of the lavas differentiated on petrological and chemical criteria rather than on individual flows. The base of the sequence consists of a thin layer of alkali basalts (~20m thick) and tholeiites (~110m thick), with basanites dominating the middle section (> 200m thick). Interrupting the continuity of the basanites is a relatively thin succession of trachybasalts (~30 m thick). The upper part of the sequence comprises

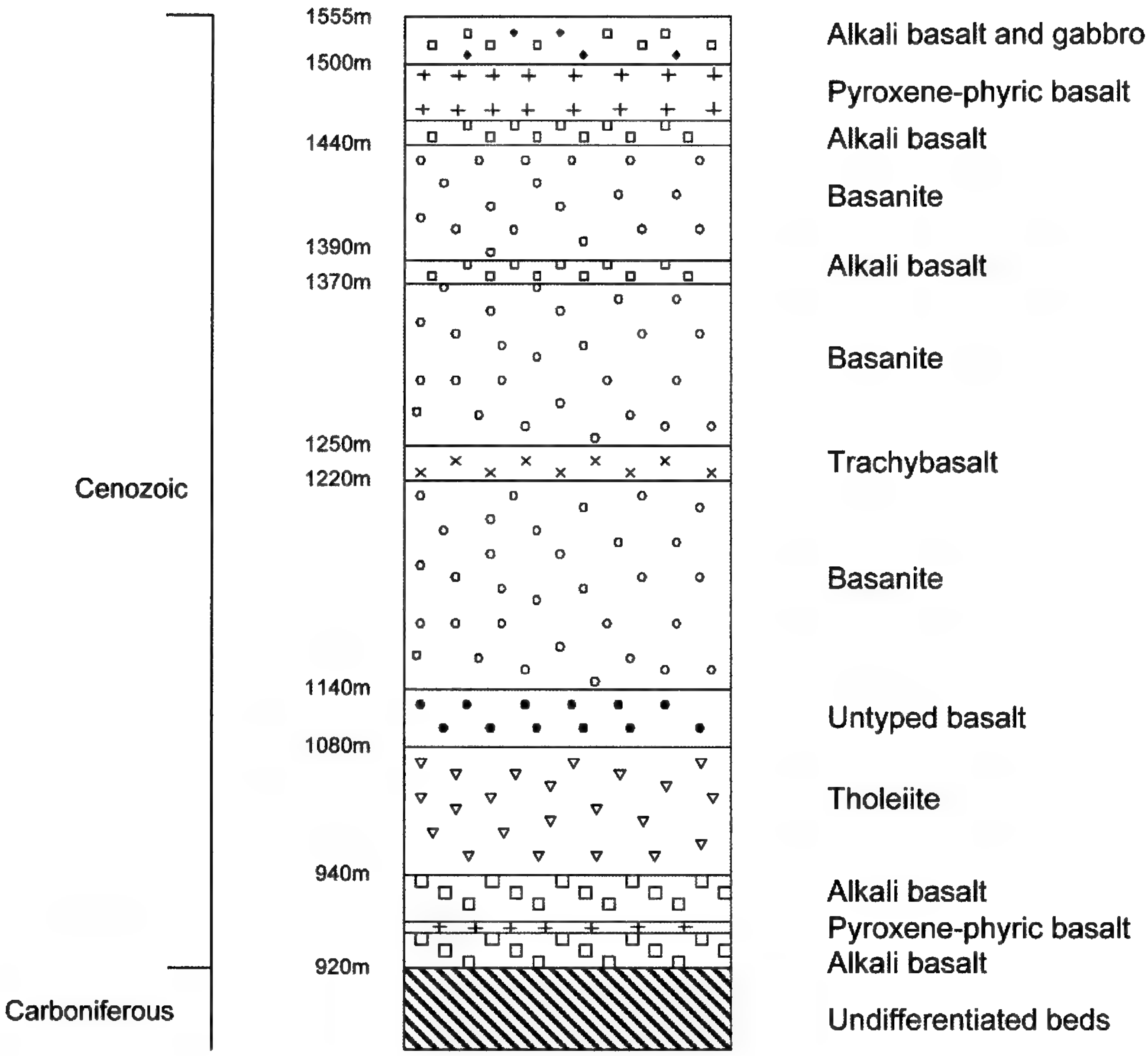

Figure 2. Volcanic stratigraphy for the southern part of the lava field.
Delineations are based on changes in rock-type rather then individual flows. In all 33 flows are exposed through 630m of topographic relief. Numbers refer to elevation above sea level.

alternating successions of alkali basalt and basanite (~185m thick). Pyroxene-phyric basalt (ankaramite) occurs as thin layers both at the base and the top of the sequence in close association with the alkali basalts.

In all 33 individual flows are found to make up the sequence exposed through 630m of relief. Most volcanic flows are identified by the presence of an agglomerate/breccia up to 3 metres thick, which – given its regular occurrence every 10 to 20 metres in the succession – is interpreted to represent either the top or base of individual flows. Some volcanic flows, however, are conspicuous by the absence of the agglomerate. These flows are usually the most vesicular (due to passively expelled volatiles) and are commonly separated by sub-horizontal palaeosols, indicating a temporary cessation of volcanism with weathering and erosion.

Alkali gabbro (teschenite) is also present on the Barrington Tops plateau at Careys Peak and to the south of Mount Barrington above an apparent magma chamber (Wellman 1989). The alkali gabbro was originally noted by Benson (1912) and interpreted as intrusive dykes or sills. Measurement of magnetic anisotropy from one basanite (Barrington Falls) and one tholeiite (Williams Range) indicates that the dominant lineation in these samples strikes approximately north-south and northwest-southeast respectively. Projection of these directional lines intersects on the alkali gabbro to the south of Mount Barrington (Bruce 1995), suggesting that this intrusive body represents remnant vents from which the lava was extruded.

PETROGRAPHY AND MINERAL CHEMISTRY

Analytical Techniques

Minerals were analysed for major elements using a Cameca SX50 Electron Microprobe calibrated with natural and synthetic materials with a general precision ≤ 1%. Analytical conditions were optimised for a standard silicate run using a 15kV accelerating voltage and a 20nA focussed electron beam for all elements, with the exception of K and Na for which a broader (10nA) beam was used. Routine analyses were obtained by counting 30s at peak and 5s on background.

Alkali Basalt (Fig. 3a)

The alkali basalts are fine-grained in hand specimen with scattered phenocrysts of greenish olivine up to 5mm in size. In thin section, the fine-

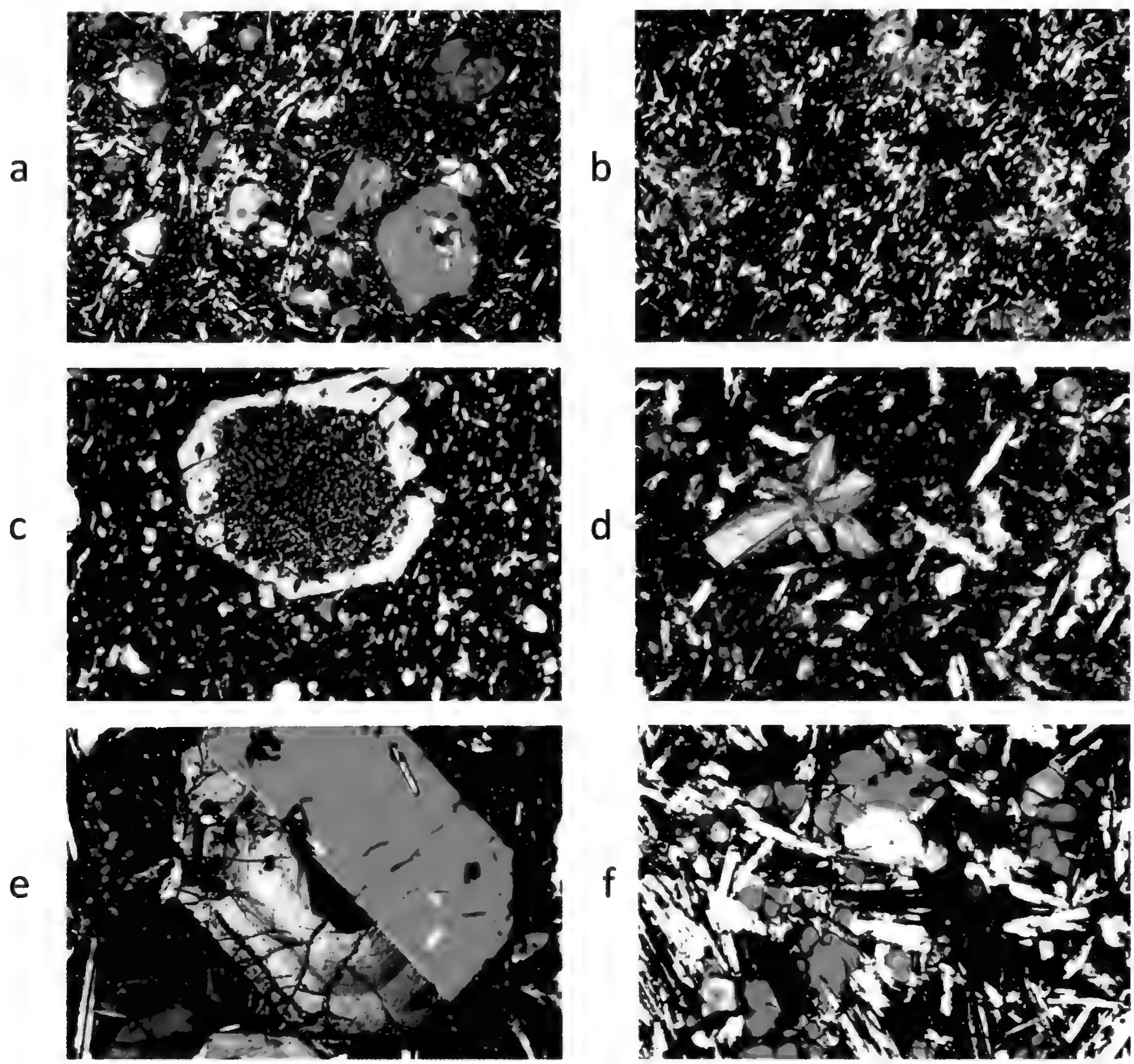

Fig. 3, (a). Photomicrograph (cross polarisation) of an alkali basalt illustrating olivine phenocrysts scattered throughout the groundmass with abundant plagioclase laths. Magnification x 2.5. (b). Photomicrograph (cross polarisation) of a tholeiite displaying ophitic texture defined by plagioclase laths embedded in clinopyroxene. Magnification x 2.5. (c). and (d). Photomicrographs (plane polarisation) from basanites demonstrating three different clinopyroxene textures. Top photo illustrates a sieve-textured proxene (top centre). Bottom photo shows pyroxene crystals in a radiating texture (left centre) and small euhedral phenocrysts (pinkish tinge). Magnification x 6.3. (e). Oscillatory zoning in a twinned Ti-rich diopside phenocryst from a pyroxene-phyric basalt. Cross polarisation. Magnification x 6.3. (f). Photomicrograph of a holocrystalline alkali gabbro dominated by plagioclase laths, olivine and clinopyroxene crystals. Cross polarisation.

grained groundmass is composed of intergranular olivine, clinopyroxene, plagioclase, Fe-Ti oxides and intersertal glass. Subhedral phenocrysts and microphenocrysts of olivine are present (0.1-2mm) as are abundant calcic plagioclase laths (0.2mm). The larger olivine phenocrysts are commonly zoned from a relatively Mg-rich core (Fo_{72}) to more Fe-rich rims (Fo_{63}). Clinopyroxene is notable in its absence as a phenocryst phase and is restricted to the groundmass where it is of diopside composition ($En_{38}Fs_{14}Wo_{48}$). Zeolites are also present as a minor secondary phase and occur as amygdules (0.2mm).

Tholeiite (Fig. 3b)

The tholeiites are very fine-grained and dark grey in hand specimen. In outcrop they are horizontally (?flow) layered. In thin section they are ophitic to subophitic in texture and consist of clinopyroxene and olivine phenocrysts in a groundmass of plagioclase laths, clinopyroxene and Fe-Ti oxides. Rare, prism-shaped plagioclase phenocrysts (~0.4mm) are also present. The plagioclase laths with an average length of 0.1mm are embedded in augite crystals which average 0.7mm in size. Olivine microphenocrysts, however, do not contain any plagioclase inclusions. Intersertal glass and chlorite is evident in the groundmass.

Basanite (Figs 3c and 3d)

The basanites are very fine-grained in hand specimen with small phenocrysts (medium 0.5mm) of olivine and clinopyroxene. In thin section, olivine (Fo_{84-90}) is the most abundant phenocryst, averaging 0.5mm with a maximum of 2mm. Olivine microphenocrysts (0.2mm) and similar sized calcic plagioclase laths (An_{60-71}) are dominant in a fine-grained groundmass of intergranular and interstitial clinopyroxene, olivine, magnetite, calcic plagioclase and mesostasis feldspar. Zeolites usually occur as small amygdules but are also observed as large crystals up to 2mm in size. Glomeroporphrytic aggregates of olivine are common in some samples.

Three types of clinopyroxene phenocrysts occur within the basanites: 1. euhedral pyroxene phenocrysts (average 0.8mm) in which the cores are sieve-textured consisting of probable glass and clinopyroxene, which could not satisfactorily be analysed, and rims that are glass free and composed of diopside ($En_{39}Fs_{10}Wo_{51}$); 2. small (0.3mm) radiating crystals that are zoned from a diopside core ($En_{38}Fs_{13}Wo_{49}$) to a Ti-rich aluminium diopside rim ($En_{32}Fs_{16}Wo_{52}$); 3. large (up to 0.9mm) subhedral to euhedral clinopyroxene phenocrysts zoned from cores of $En_{39}Fs_{13}Wo_{48}$ to rims of Ti-rich aluminium diopside ($En_{33}Fs_{15}Wo_{52}$). The first type of phenocryst is interpreted to represent slow growth of clinopyroxene in which the core has trapped melt before crystallising the outer margin probably during quenching. The second type represents a snapshot of the early stages of pyroxene growth. Further growth of this type has resulted in the third type.

In addition, clinopyroxene xenocrysts are evident in some samples. These are commonly large in size (up to 9mm) and sub-rounded in shape. A gabbroic enclave (5mm) that occurs in one sample consists of clinopyroxene ($En_{37}Fs_{16}Wo47$), orthopyroxene ($En_{59}Fs_{41}$) and calcic plagioclase ($An_{80}Ab_{20}$). The presence of orthopyroxene in apparent equilibrium with clinopyroxene suggests that the enclave was formed under high pressure and transported to the surface rapidly to prevent resorption during ascent (T. Green pers. comm. 1995). This is supported by aluminium stoichiometry in the clinopyroxenes where $Al^4:Al^6 = 1.8$, suggesting crystallisation pressures >1 GPa (Thompson 1974; Wass 1979) or >35 km in depth. However, the relatively low Al_2O_3 content of the co-existing orthopyroxenes (2.2 wt%) is not consistent with an upper mantle origin (Binns et al. 1970) and therefore probably crystallised at crustal pressures.

Pyroxene-phyric Basalt (Fig. 3e)

These basalts (ankaramites) are conspicuous in hand specimen due to an estimated 30-40 percent of large (up to 10mm) clinopyroxene megacrysts. In thin section, the megacrysts are diopside in composition and display strong oscillatory zoning with Mg-rich cores ($En_{40}Fs_{12}Wo_{48}$) and Fe-Ca-rich rims ($En_{34}Fs_{15}Wo_{51}$). They are also Ti-rich with 2-3 wt% TiO_2. The megacrysts contain various inclusions of diopside ($En_{40}Fs_{11}Wo_{49}$), olivine (Fo_{74}), plagioclase ($An_{66}Ab_{34}$) and Ti-rich magnetite. Olivine phenocrysts (1-2mm) zoned from cores of Fo_{74} to rims of Fo_{64} and plagioclase laths ($An_{66}Ab_{34}$) up to 2mm, are abundant and embedded in a fine hypocrystalline groundmass of clinopyroxene ($En_{35}Fs_{18}Wo_{47}$), olivine (Fo_{62}), calcic plagioclase and magnetite - ulvöspinel.

Both zoning in the phenocrysts and megacrysts and inclusions in the megacrysts would suggest variable crystal growth rates, typical of cumulative textures.

Alkali Gabbro (Fig. 3f)

The alkali gabbros are holocrystalline and consist of Ti-rich diopsides up to 5mm in size and 2mm olivine phenocrysts. The diopsides are zoned from $En_{42}Fs_{11}Wo_{47}$ to $En_{37}Fs_{16}Wo_{47}$ with entrained plagioclase (An_{62}) and magnetite - ulvöspinel inclusions. Olivine phenocrysts commonly form a glomeroporphrytic texture and can be strongly zoned from Fo_{71} cores to more Fe-rich (Fo_{58}) rims. Large plagioclase (An_{60}) laths up to 3mm are abundant and set in a coarse (>0.5mm) groundmass of clinopyroxene ($En_{35}Fs_{18}Wo_{47}$), forsterite, mesostasis feldspar, magnetite - ulvöspinel, analcime and apatite needles.

WHOLE-ROCK COMPOSITIONS

Analytical Techniques

Samples were crushed in a TEMA tungsten carbide mill. Major elements were determined using glass fusion discs (Norrish and Hutton 1969) by X-ray Fluorescence (XRF). The instrument used was a Siemen's SRS-1. Calibration was by means of international rock standards and well-calibrated internal standards. All samples were run in duplicate. Trace elements were analysed by XRF using pressed-powder pellets. Mass absorption corrections were applied (Norrish and Chappell 1977). All samples were analysed in duplicate, using international rock standards. FeO was determined by HF digestion and titration with Ceric sulphate. Estimates of precision based on USGS standards BCR-1 and GSP-1, and NIM standard NIM-G are: Major elements; < ±1% relative at > 10 wt% levels; Mn, P, Mg, Na ≤ 2% relative for BCR-1: Trace elements; ≤ 1% relative at 100ppm levels; ± 10ppm for < 100ppm.

Results

Selected bulk-rock data representing each described rock-type are presented in Table 1. The results for all samples analysed are tabulated in the Appendix (Table A1).

Major Elements

The majority of sampled basalts are undersaturated basanites and alkali basalts according to the classification of Le Bas et al. (1986), although one tholeiite and one trachybasalt has also been sampled (Fig. 4). The pyroxene-phyric basalt and the alkali gabbro when considered as plutonites plot as monzogabbro and gabbro respectively using the scheme of Middlemost (1985; not shown). Major elements versus Mg# [100Mg/(Mg + Fe^{2+})] are plotted in Fig. 5 for all samples except the tholeiite. Although some diagrams show substantial scattering, both Al_2O_3 and MgO display strong, coherent trends. This would suggest that all alkaline magmas are related petrogenetically via processes dominated by compositions that concentrate the elements Al_2O_3 and MgO (fractionation/accumulation, partial melting, mixing). Overall there is an increase in TiO_2, Al_2O_3, FeOt (total iron) and K_2O and a decrease in MgO and CaO with increasing fractionation (decrease in Mg#). A positive correlation between CaO/Al_2O_3 and Mg# for the basanites and alkali basalts with Mg# <70 would indicate clinopyroxene fractionation in these rocks.

Trace Elements

Plots of the compatible elements Ni and Cr versus Mg# (Fig. 6) define a strong, positive correlation for the former but a more scattered relationship for the latter. This, combined with a similar MgO trend, suggests that olivine fractionation was the dominant process by which the alkaline magmas were related. Clinopyroxene may not have been a significant fractionating phase in controlling magma composition in the basanites and alkali basalts given the reasonably constant Cr concentrations; although it could have been important in the evolution of the trachybasalts, pyroxene-phyric basalts and alkali gabbros.

Zr/Nb values are virtually constant within a magmatic suite as crystal fractionation and wall rock reaction have little effect on this ratio (Green 1992). This ratio does, however, increase with increasing degrees of partial melting, from values around 3-6 for oceanic island basalts (OIB) to > 30 for normal mid ocean ridge basalts (N-MORB) (Crawford et al. 1997). The alkaline magmas in the southern Barrington Tops lava field have Zr/Nb = 2-3, whereas the sampled tholeiite has a Zr/Nb value > 4. The higher ratio in the tholeiite could indicate either a different, or a heterogeneous, magma source. Furthermore, the source(s) for both magma lineages have Zr/Nb ratios typical of OIB. Multi-element diagrams for both the alkaline magmatic suite and the tholeiite are presented in Fig. 7. These plots are normalised to the average OIB values of Sun and McDonough (1989). Overall, the alkaline magmas have patterns and element concentrations similar to OIB. However, relative to the average OIB, the rocks are depleted in Rb, K, Zr, Ti and Y and enriched in Ba, Nb, Sr and P. The tholeiite follows a similar pattern but has concentrations more akin to enriched mid ocean ridge basalt (E-MORB) suggesting a slightly more depleted component in its source.

PETROGENESIS

Major and trace elements indicate that the alkaline magmas were strongly controlled by the fractionation of a phase dominated by MgO and Ni content and accumulation of a phase dominated by

Table 1 Selected major and trace element XRF analyses, southern Barrington lava field.

Sample	MU55361	MU55372	MU55418	MU55365	MU55369	MU55397
Barrington Tops 1:25k 9133-1-N	GR.492538	GR.553522	GR.560480	GR.500539	GR.502533	GR.555490
Rock type	Alkali basalt	Basanite	Tholeiite	Pyroxene-phyric basalt	Alkali gabbro	Trachybasalt
wt%						
SiO_2	47.44	44.16	49.15	45.25	48.9	46.1
TiO_2	1.97	2.53	1.49	2.55	2.3	2.65
Al_2O_3	14.49	14.54	16.42	16.01	16.38	15.97
Fe_2O_3	1.93	1.91	2.09	1.85	1.85	1.9
FeO	9.63	9.55	10.44	9.28	9.23	9.49
MnO	0.17	0.19	0.16	0.18	0.16	0.18
MgO	10.44	10.95	6.33	7.31	6.28	7.99
CaO	9.8	11.5	10.03	11.73	9.67	9.19
Na_2O	2.72	2.98	2.77	3.32	3.28	3.32
K_2O	1.11	0.85	0.52	1.77	1.24	1.78
P_2O_5	0.39	1.07	0.32	0.96	0.5	0.88
Total	100.09	100.23	99.74	100.21	99.79	99.45
CIPW norms						
Or	6.56	5.02	3.08	10.45	7.35	10.59
Ab	20.75	11.24	23.48	9.5	27.78	18.8
An	23.99	23.7	30.88	23.46	26.32	23.5
Ne	1.2	7.53	0	10.03	0	5.1
Di	18.06	21.75	14.17	23.64	15.42	13.96
Hy	0	0	15.28	0	1	0
Ol	22.06	20.88	6.54	13.33	13.96	18.29
Mt	2.8	2.76	3.04	2.68	2.69	2.77
Il	3.74	4.8	2.84	4.83	4.38	5.06
Ap	0.85	2.33	0.7	2.09	1.09	1.93
An/An+Ab	0.536	0.678	0.568	0.712	0.487	0.556
$Mg/Mg+Fe^{2+}$	0.659	0.672	0.519	0.584	0.548	0.600
ppm						
Ba	409	580	146	712	381	606
Rb	20	22	6	33	17	22
Sr	634	1146	412	1017	666	1328
Y	20	23	22	27	25	27
Zr	122	246	80	226	158	324
Nb	46	103	19	115	53	121
Th	1	6	0	7	1	3
Pb	5	3	3	3	5	2
Ga	19	20	21	23	24	19
Zn	90	80	80	76	84	83
Cu	43	51	71	62	43	33
Ni	171	177	208	82	52	107
V	228	243	192	240	219	195
Cr	351	337	294	112	84	115

Al_2O_3. In a basaltic system, the two phases likely to be involved are olivine and plagioclase respectively. However, Harker-style plots cannot preclude the importance of clinopyroxene as a fractionating phase. Therefore the mineral assemblages; olivine + plagioclase and olivine + plagioclase + clinopyroxene (amongst others) are tested below using the model of Pearce (1968). In this model, element ratios are used instead of oxide-oxide wt% diagrams as the latter may produce spurious correlations (Russell and Nicholls 1988; Rollinson 1993). These ratios are referred to as Pearce Element Ratios (PER) and are based on stoichiometry of the end-members of the mineral phases. The data almost always falls on a straight line (within analytical errors) and by applying a least squares linear regression technique, the slope

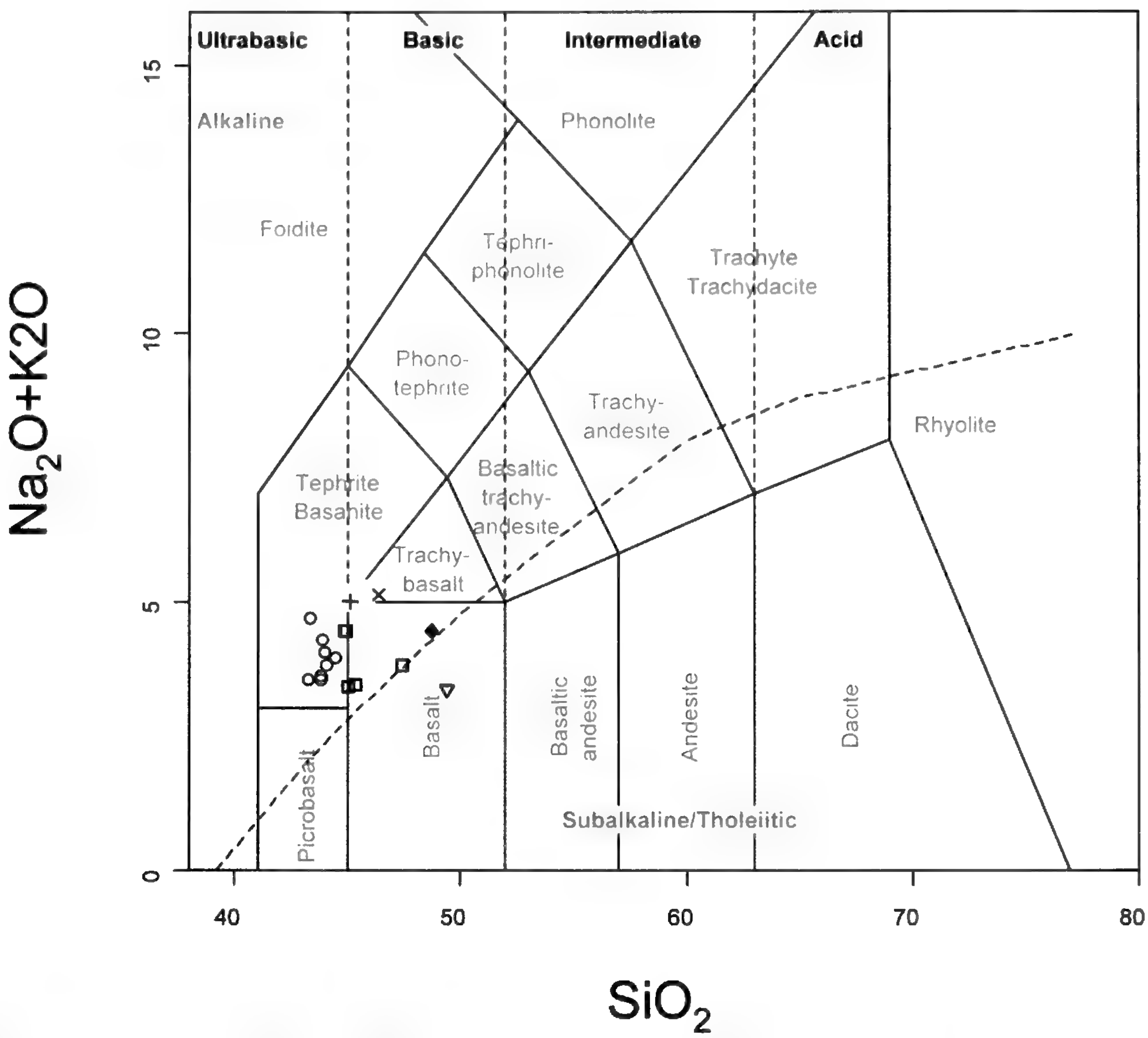

Figure 4. Rock classification diagram of Le Bas et al. (1986). Plotted are the various basaltic lithologies from the southern part of the lava field. Symbols: ○ = basanite; □ = alkali basalt; × = trachybasalt; + = pyroxene-phyric basalt; ◆ = alkali gabbro; ▿ = tholeiite.

of the line can be calculated. This slope reflects the stoichiometry of the minerals, which should equal one (2σ error) if the minerals tested for are in fact the phases involved in the differentiation of the magma. Fig. 8 presents PER diagrams for the following mineral assemblages within a basaltic system; olivine, clinopyroxene, plagioclase, olivine + clinopyroxene, olivine + plagioclase, olivine + clinopyroxene + plagioclase. The pyroxene-phyric basalt and the alkali gabbro have been removed from the model because of the abundance of large crystals that are highly likely to be cumulates from the magmas. The mineral assemblage olivine + plagioclase is the only assemblage that produces a slope of one (0.97) within the 95% confidence limit. Thus, the PER model validates the linear trends of MgO and Al_2O_3 observed in the Harker-style diagrams as fractionation/accumulation controlled. Despite the dominant assemblage of olivine + plagioclase, clinopyroxene must still have been involved in the fractionation process as phenocrysts of this mineral do occur in the basanites, trachybasalts, ankaramites and alkali gabbros.

The mantle reservoir for the alkaline magmas has been established as an OIB-type source. Greater enrichment in Nb, Sr and P coupled with depletions in Ti and Y than the average OIB can be explained by smaller degrees of partial melting of a fertile mantle source. However, simple melting models alone cannot explain the lower than expected depletions of Rb, K and Zr. O'Reilly and Zhang (1995) attributed similar Rb and K depletions from the western Barrington Tops lava field to the melting of metasomatised mantle in which residual amphibole was retained in the source. This explanation is also appropriate to the southern part of the lava field. The low Zr anomalies

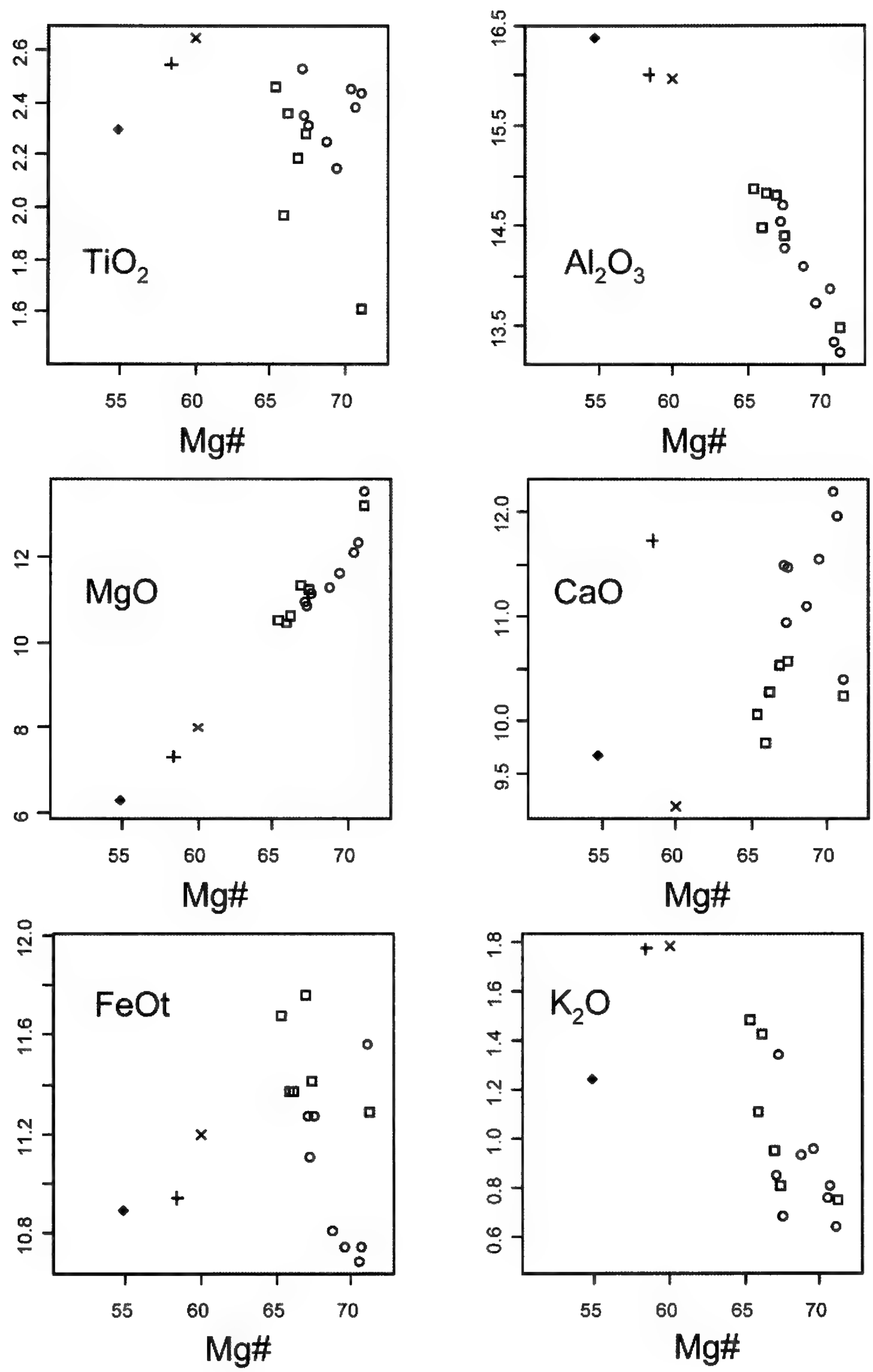

Fig. 5 Major elements (wt%) versus Mg# {100Mg/(Mg+Fe^{2+})}. Same symbols used as in Figure 4. Nb. Tholeiite is not plotted.

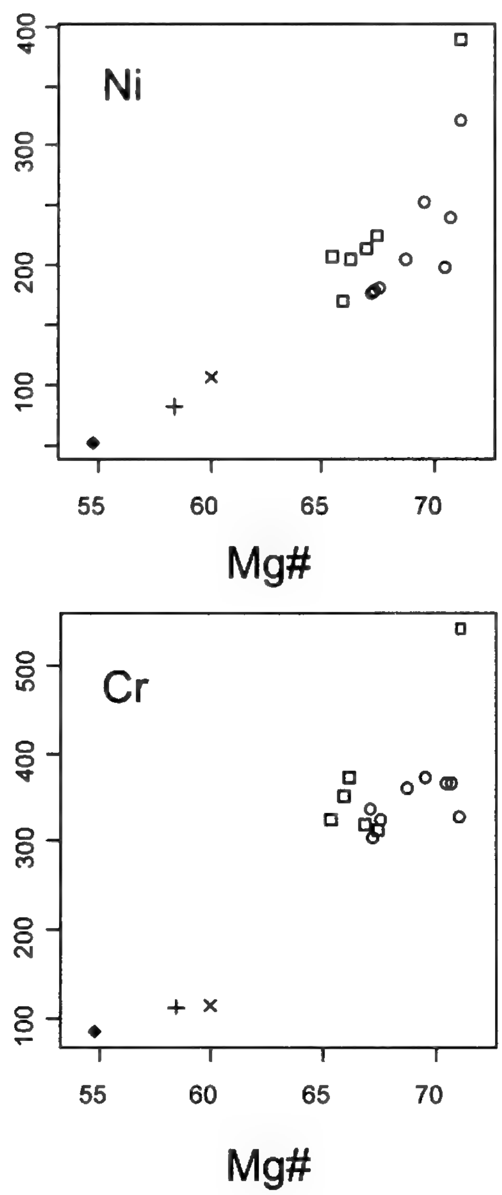

Figure 6 The compatible elements Ni and Cr (ppm) versus Mg#. Note that the alkali basalt with Ni > 300ppm and Cr > 500ppm has petrographic features indicative of cumulative olivine. Same symbols used as in Figure 4. Nb. Tholeiite is not plotted.

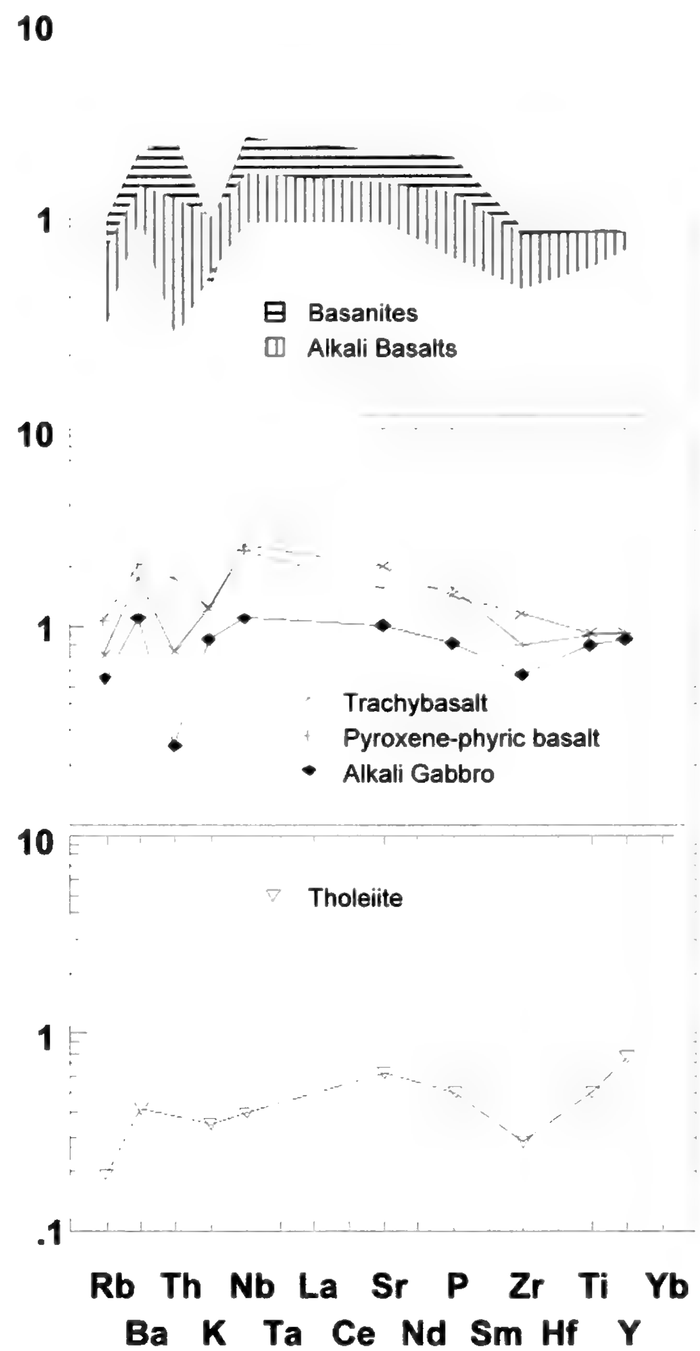

Figure 7 OIB-normalised multi-element plots of the various basaltic lithologies from the southern lava field. Normalisation values after Sun and Mc-Donough (1989).

could be due to plagioclase accumulation in these rocks as Zr is incompatible in this phase with respect to basaltic melts (Kd = 0.048; Rollinson 1993). Thus, the presence of excess plagioclase in the lavas may have diluted the bulk-rock Zr concentrations, hence the depletions.

TOWARDS A GENETIC MODEL

Mantle upwelling resulting in lithospheric melting via adiabatic decompression (eg. Hoernle et.al. 2006) is generally accepted as a likely mechanism for the generation of basaltic magmas in continental settings. Such a scenario (Fig. 9) is envisaged for the southern Barrington Tops lava field, where once formed, some of the magma ascended directly to the surface as evidenced by high-pressure (>1Gpa) gabbroic enclaves and reported mantle xenoliths (Powell and O'Reilly 2007). The majority of the magma, however, was stored in high crustal-level reservoirs conducive to the crystal fractionation of olivine + plagioclase, an assemblage characteristic of low pressure crystallisation. An internal build-up of water in the

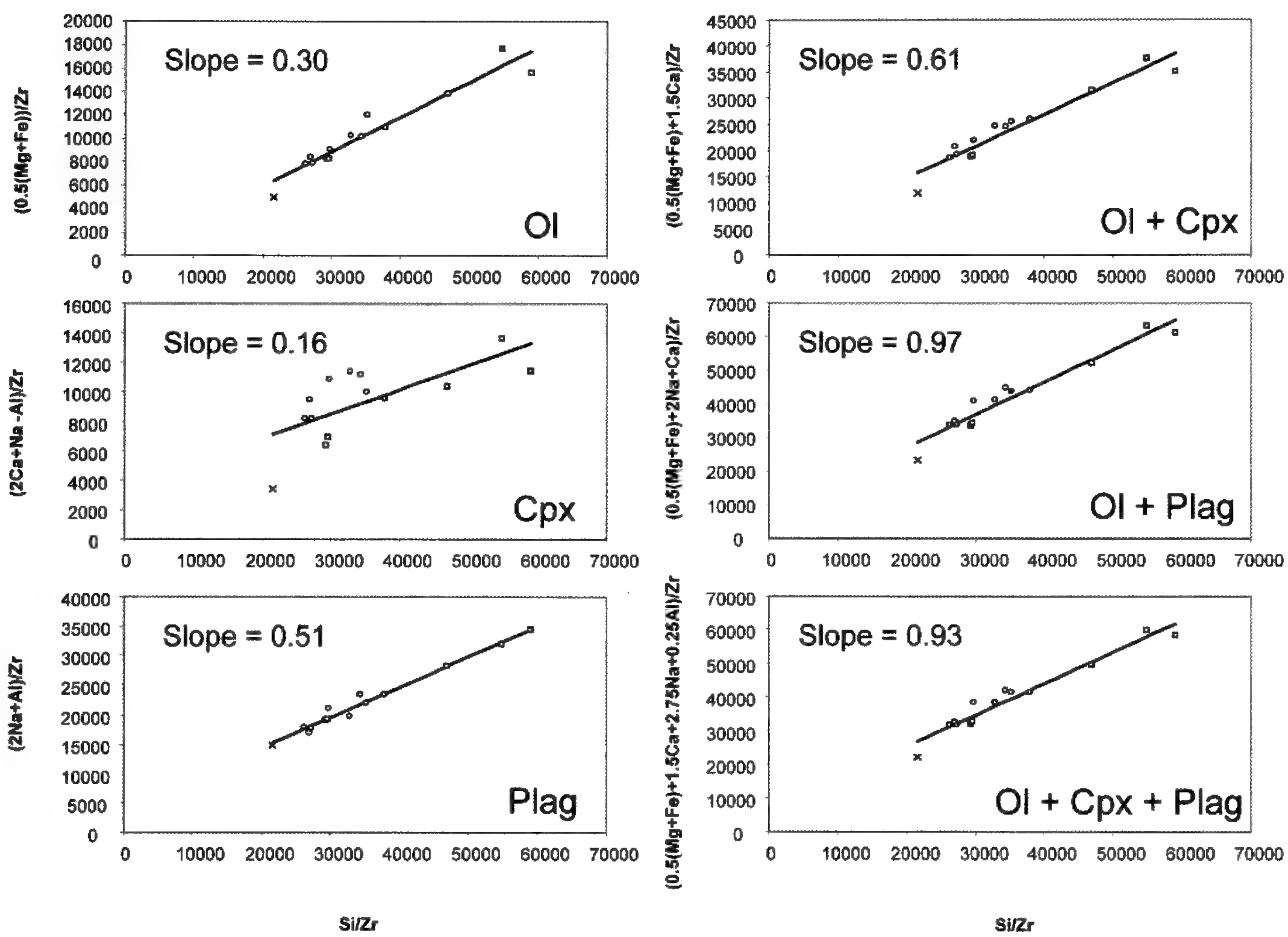

Figure 8. Pearce element ratio diagrams testing for various fractionation/accumulation controlled basaltic mineral assemblages. Note that Ol = Olivine; Cpx = Clinopyroxene; Plag = Plagioclase. Same symbols used as in Figure 4

system 'pushed' the cotectic into the clinopyroxene field. The late crystallisation of clinopyroxene may account for the observed phenocrysts in the rocks while obscuring it in the fractionation models. The alkali basalts, whilst free of clinopyroxene phenocrysts, also fractionated the mineral but in this case the pyroxene phenocrysts dropped completely out of the magma and accumulated on the floors and walls of the magma chambers where they continued to grow. Mason (1985) concluded in his study from the northern part of the field that the cores of these phenocrysts possibly crystallised as deep as the core/mantle boundary based on aluminium stoichiometry. Although similar polybaric crystallisation of pyroxene from ankaramites of the southern lava field (Bruce 1995) suggests shallower depths than this, it certainly does not preclude the existence of deeper level magma chambers, possibly feeding the upper crustal reservoirs. Eruption of these cumulates resulted in the proxene-phyric basalts, which in the field are stratigraphically associated with the alkali basalts. Stratigraphic relationships, magnetic anisotropy and chemical data are consistent with the genesis of the alkali gabbro as remnant dykes/plugs which necessitated the movement of the magma towards the surface.

GEODIVERSITY

The southern area of the Barrington Tops lava field has a topographic relief of about 1500m a.s.l whereas the floor of the incised valleys of the Allyn and Williams Rivers has an average elevation of 430m a.s.l. An escarpment marks the southern edge of the plateau. South of the plateau the region is dominated by the Mount Royal, Allyn and Williams Ranges. These ranges are partially capped with basalt while the valleys separating them are not and consist of folded Carboniferous sediments which form the bedrock for the Patterson, Allyn and Williams Rivers. Within these sedimentary units is a conglomerate that crops out along the Allyn River comprised of rounded pebble to boulder-sized granitoids, diorite, siltstones

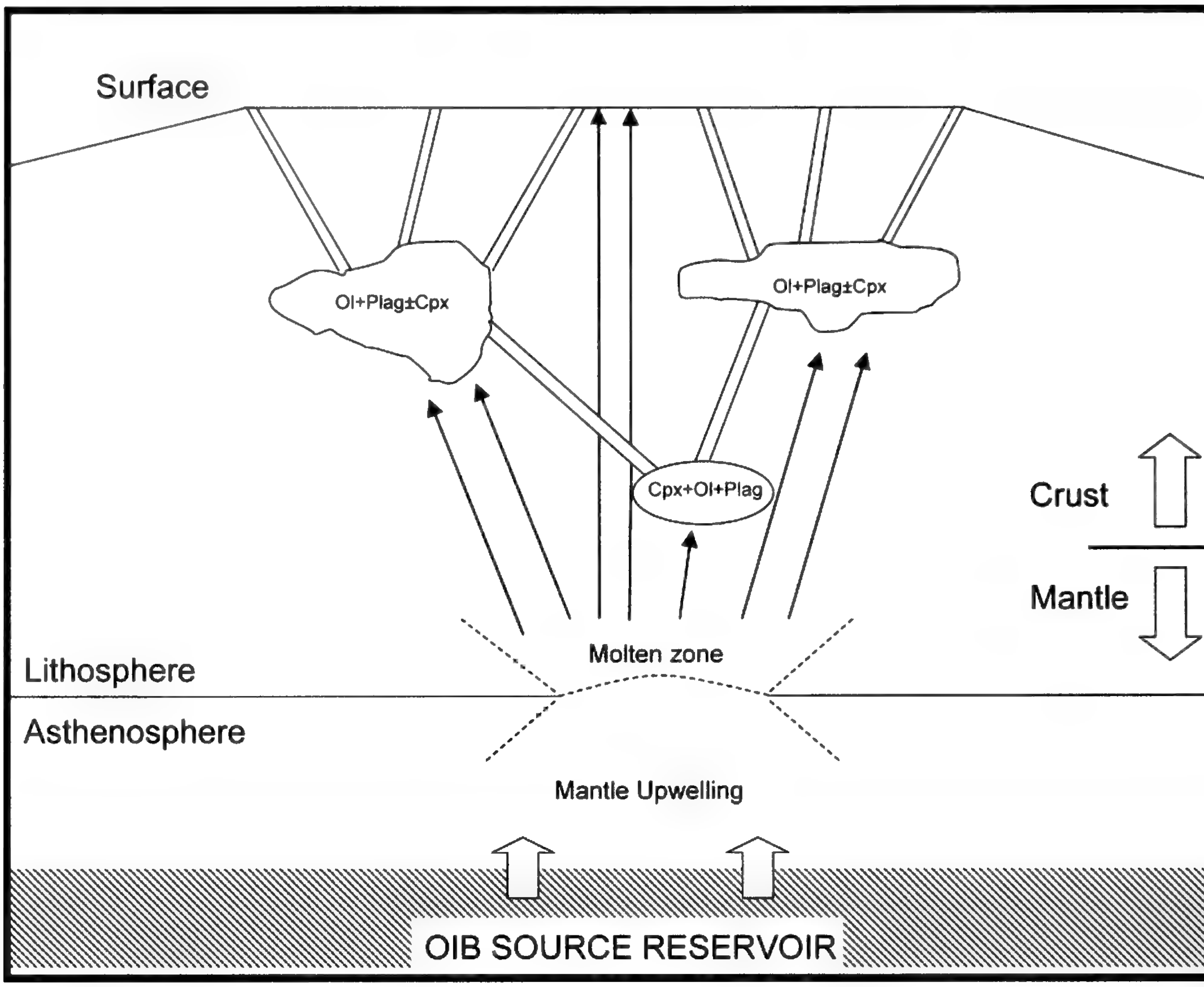

Figure 9. Schematic diagram illustrating the petrogenesis of the basaltic lavas. See text for details.

and quartzites cemented in a sandy matrix. Of particular note is the occurrence of an S-type granite clast similar in composition to parts of the Bathurst Batholith (S. Shaw pers. comm.). Rb/Sr dating on muscovite has returned an age of 325 ± 3.2 Ma (Bruce 1995), suggesting it may have been sourced from ~300 km to the south-west.

Basalt is present from the highest peak (Mount Barrington) down to an altitude of ~920m a.s.l. The resultant volcanic pile is thus ~630m thick. The basaltic flows are sub-horizontal based on the nature of palaeosols which would suggest that the pre-basalt surface consisted of a gently sloping topography. Pain (1983) envisaged a shield volcano for the lava field, an interpretation favoured by most authors (O'Reilly and Zhang 1995; Sutherland and Fanning 2001; Sutherland and Graham 2003). Nevertheless, there is evidence of some localised relief for the pre-basalt surface. Alignment of ferromagnetic minerals, defining lineations or foliations, in individual samples have dips of 20 degrees or more (Bruce 1995). A feature of the basalt today is that it is seen to cover the plateau and ridge tops and is absent in the deeply dissected valleys. This is the opposite of what would be expected had the flows formed on the current topography. It implies that subsequent to the eruption of the basalt, which filled up gently sloping valleys leaving ridges untouched, topographic inversion may have occurred due to a high rate of sedimentary erosion. The previously uncovered ridge tops, consisting of softer Carboniferous sediments, have eroded away to form valleys while the basalt filled valleys have resisted erosion to form the ridge tops. Evidence supporting this model includes the occurrence of a Cenozoic gravel deposit underlying basalt on the Williams Range (Bruce 1995). Such deposits (or deep leads) are indicative of buried valleys. Similar Cenozoic gravel deposits now situated on ridges have been reported by Mason (1982) from beneath the basalt from the western part of the lava field.

Erosion has dramatically altered the Barrington landscape since the Paleocene/Eocene basaltic eruptions in the southern part of the lava field. This has led to some impressive rock formations such as columnar basalt to be found on and around places like Mount Allyn and Mount Lumeah. The plateau and all its distinctive natural features is a post basalt erosional surface (Galloway 1967) and possibly represents remnants of scarp retreat of the Great Dividing Range (Ollier 1982). Rubies, sapphires and zircons of gem quality and rare secondary minerals are associated with the lava field (Sutherland and Graham 2003).

CONCLUSIONS

Geological mapping in the southern Barrington Tops lava field has identified 33 basaltic flows correlated from several localities over 630m of topographic relief. This matches the number of flows recorded by Mason (1982) albeit over only 430m of relief, in the Prospero Trigonometric station sequence in the north-western lava field. In the southern region, flows 10-20m thick are separated by either an agglomerate or sub-horizontal palaeosols. Petrography and whole-rock geochemistry reveal basanites dominate the lava sequence interspersed with alkali basalts, pyroxene-phyric basalts (ankaramites) and tholeiites. Alkali gabbros form intrusions near the top of the sequence and represent conduits for surface lavas. Major and trace elements of the alkaline magmas along with fractionation/accumulation controlled modelling are consistent with the magmas being co-genetic and chiefly controlled by a low pressure olivine + plagioclase mineral assemblage. Clinopyroxene did fractionate without greatly affecting magma compositions. Incompatible trace elements are consistent with low degree melting of an enriched mantle source (OIB-type), although there is evidence of entrained amphibole-enriched sub-continental lithospheric mantle. A third, more depleted mantle component, may have contributed to the tholeiites. These conclusions are consistent with alkali basalts analysed from the northern part of the lava field (O'Reilly and Zhang 1995; Sutherland and Fanning 2001) where basalt generation was linked to thermal anomalies in the mantle causing low degree asthenospheric and lithospheric melting. These melts rose up relatively quickly where they largely pooled in high crustal level magma chambers, fractionated olivine ± clinopyroxene and accumulated plagioclase before venting. The presence of peridotite xenoliths (Powell and O'Reilly 2007) suggests that at least some of the magma ascended directly from the upper mantle, sampling lower crustal material (gabbroic enclave) enroute to the surface.

ACKNOWLEDGEMENTS

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Table A1 Major and trace element XRF analyses, southern Barrington lava field.

Sample	MU55361	MU55365	MU55366	MU55369	MU55372	MU55378	MU55381	MU55382	MU55383
Barrington Tops 1:25k 9133-1-N	GR.492538	GR.500539	GR.553660	GR.502533	GR.553522	GR.528540	GR.520553	GR.524550	GR.553518
Rock type	Alkali basalt	Pyroxene-phyric basalt	Basanite	Alkali gabbro	Basanite	Basanite	Alkali basalt	Alkali basalt	Basanite
wt%									
SiO2	47.44	45.25	43.92	48.9	44.16	43.63	45.02	44.95	44.15
TiO2	1.97	2.55	2.31	2.3	2.53	2.44	2.36	2.46	2.35
Al2O3	14.49	16.01	14.27	16.38	14.54	13.25	14.82	14.87	14.7
Fe2O3	1.93	1.85	1.91	1.85	1.91	1.96	1.92	1.98	1.88
FeO	9.63	9.28	9.55	9.23	9.55	9.8	9.64	9.9	9.42
MnO	0.17	0.18	0.19	0.16	0.19	0.19	0.18	0.18	0.2
MgO	10.44	7.31	11.14	6.28	10.95	13.53	10.59	10.49	10.86
CaO	9.8	11.73	11.47	9.67	11.5	10.39	10.29	10.06	10.94
Na2O	2.72	3.32	3.38	3.28	2.98	2.97	3.05	3	2.6
K2O	1.11	1.77	0.68	1.24	0.85	0.64	1.42	1.48	1.34
P2O5	0.39	0.96	0.99	0.5	1.07	0.73	0.82	0.82	0.85
Total	100.09	100.21	99.81	99.79	100.23	99.53	100.11	100.19	99.29
ppm									
Ba	409	712	567	381	580	427	417	430	681
Rb	20	33	10	17	22	16	20	22	31
Sr	634	1017	1450	666	1146	917	889	989	1141
Y	20	27	24	25	23	22	24	25	23
Zr	122	226	194	158	246	188	231	233	177
Nb	46	115	79	53	103	85	79	81	79
Th	1	7	4	1	6	2	5	4	5
Pb	5	3	4	5	3	6	6	4	5
Ga	19	23	19	24	20	17	20	19	20
Zn	90	76	80	84	80	84	78	81	58
Cu	43	62	54	43	51	39	61	62	47
Ni	171	82	181	52	177	320	204	208	178
V	228	240	245	219	243	248	245	233	238
Cr	351	112	325	84	337	327	372	326	303

Sample	MU55385	MU55386	MU55393	MU55397	MU55401	MU55409	MU55411	MU55418	MU55424
Barrington Tops 1:25k 9133-1-N	GR.563513	GR.555492	GR.565516	GR.555490	GR.519466	GR.518458	GR.518444	GR.560480	GR.526441
Rock type	Basanite	Alkali basalt	Basanite	Trachybasalt	Basanite	Basanite	Basanite	Tholeiite	Alkali basalt
wt%									
SiO2	44.85	45.01	42.87	46.1	43.33	43.01	43.59	49.15	45.17
TiO2	2.28	2.19	2.15	2.65	2.25	2.45	2.38	1.49	1.61
Al2O3	14.41	14.8	13.73	15.97	14.1	13.87	13.35	16.42	13.49
Fe2O3	1.93	1.99	1.82	1.9	1.84	1.81	1.82	2.09	1.92
FeO	9.67	9.97	9.1	9.49	9.15	9.06	9.1	10.44	9.56
MnO	0.17	0.18	0.19	0.18	0.18	0.19	0.18	0.16	0.2
MgO	11.23	11.31	11.64	7.99	11.28	12.12	12.32	6.33	13.22
CaO	10.58	10.53	11.56	9.19	11.1	12.19	11.96	10.03	10.24
Na2O	2.59	2.5	3.67	3.32	3.31	2.78	2.72	2.77	2.69
K2O	0.81	0.95	0.96	1.78	0.93	0.76	0.81	0.52	0.75
P2O5	0.66	0.6	1.23	0.88	1.25	1.22	1.2	0.32	0.75
Total	99.18	100.03	98.92	99.45	98.72	99.46	99.43	99.74	99.6
ppm									
Ba	442	355	771	606	687	663	680	146	517
Rb	9	11	12	22	15	13	16	6	12
Sr	843	768	1322	1328	1330	1292	1413	412	776
Y	23	20	24	27	23	25	24	22	23
Zr	165	146	219	324	251	242	202	80	125
Nb	62	55	109	121	100	123	98	19	51
Th	3	2	10	3	6	4	4	0	5
Pb	4	5	6	2	3	5	5	3	4
Ga	18	19	17	19	15	15	16	21	14
Zn	75	80	77	83	74	73	73	80	78
Cu	64	67	45	33	43	53	42	71	65
Ni	224	213	252	107	206	198	239	208	388
V	212	222	225	195	205	256	245	192	210
Cr	312	318	372	115	361	367	366	294	542

Geodiversity of the Lightning Ridge Area and Implications for Geotourism

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Meakin, S. (2011). Geodiversity of the Lightning Ridge Area and Implications for Geotourism. *Proceedings of the Linnean Society of New South Wales* **132**, 71-82.

The Lightning Ridge region displays rich geodiversity. Though best known for its valuable black opal, it is also world-renowned for yielding a diversity of opalised fossils, including invertebrates, reptiles, dinosaurs and some of the earliest known monotreme mammals. Cenozoic silcrete preserves impressions of fossil plants in great detail at several sites. At Cuddie Springs, 100 km SSW of Lightning Ridge, remains of extinct Pleistocene megafauna are found in association with Aboriginal tools. Numerous Aboriginal sites are also scattered around the ridges and along waterways. Over 100 years of mostly small-scale opal mining at Lightning Ridge is evidenced by historic workings and equipment that are unique to this area or rarely seen elsewhere. This valuable record of geoheritage is of interest to tourists, historians, scientists and artists. Geotourism is intimately linked with opal-mining and is a growing source of income to the region, on par with documented sales of opal itself. Managing such a diverse region presents a challenge, as diverse stakeholders can have conflicting objectives. Tourism has the potential to unite stakeholders and ensure the prosperity of the region long after the opal resources are exhausted. A whole-of-government approach is vital in ensuring sustainable development and prosperity of the region.

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KEYWORDS: Aborigines, Cretaceous, geodiversity, geoheritage, geotourism, Lightning Ridge, mining heritage, opal, palaeontology, prehistory, small-scale mining

INTRODUCTION

Lightning Ridge lies 770 km northwest of Sydney, in northern New South Wales (Fig. 1). The remote town in Walgett Shire is best known for opal, Australia's national gemstone and the mineral emblem of New South Wales. The town also supports rich living cultural and industrial traditions which are related to opal mining and Aboriginal occupation. Its population of about 2600 (2006 census, Australian Bureau of Statistics) is highly variable due to transient miners and residents. Walgett Shire is bolstered by up to 70 000 visitors a year (Tourism Research Australia 2008) who come to try opal fossicking or to explore an outback mining town.

Opal was first discovered at Lightning Ridge in the 1880s but the importance of the discovery was not immediately realised. In about 1901 or 1902, local boundary rider, Jack Murray put down a shaft at Lightning Ridge and was soon joined by Charles Nettleton, who commenced a shaft and then sold the opals he found, thus attracting attention to the field (NSW Department of Mineral Resources 2000).

Governance of the area has been a challenge since. Opal mining in and around Lightning Ridge is generally small scale and there are currently about 3500 small claims registered. Due to the geographical isolation of the area, government regulation and management is often difficult. Theft of opal from claims ('ratting') and social problems occur in these remote and sometimes basic conditions. Conflict between miners and other local stakeholders is common. Whilst many, including farmers, environmentalists and safety regulators, would prefer that land be fully rehabilitated after mining, others (e.g. Smith 2007) argue that some workings should be left accessible or preserved for future exploration, research and geotourism.

GEODIVERSITY

Lightning Ridge is situated on the southern margin of the Great Australian Basin, one of the

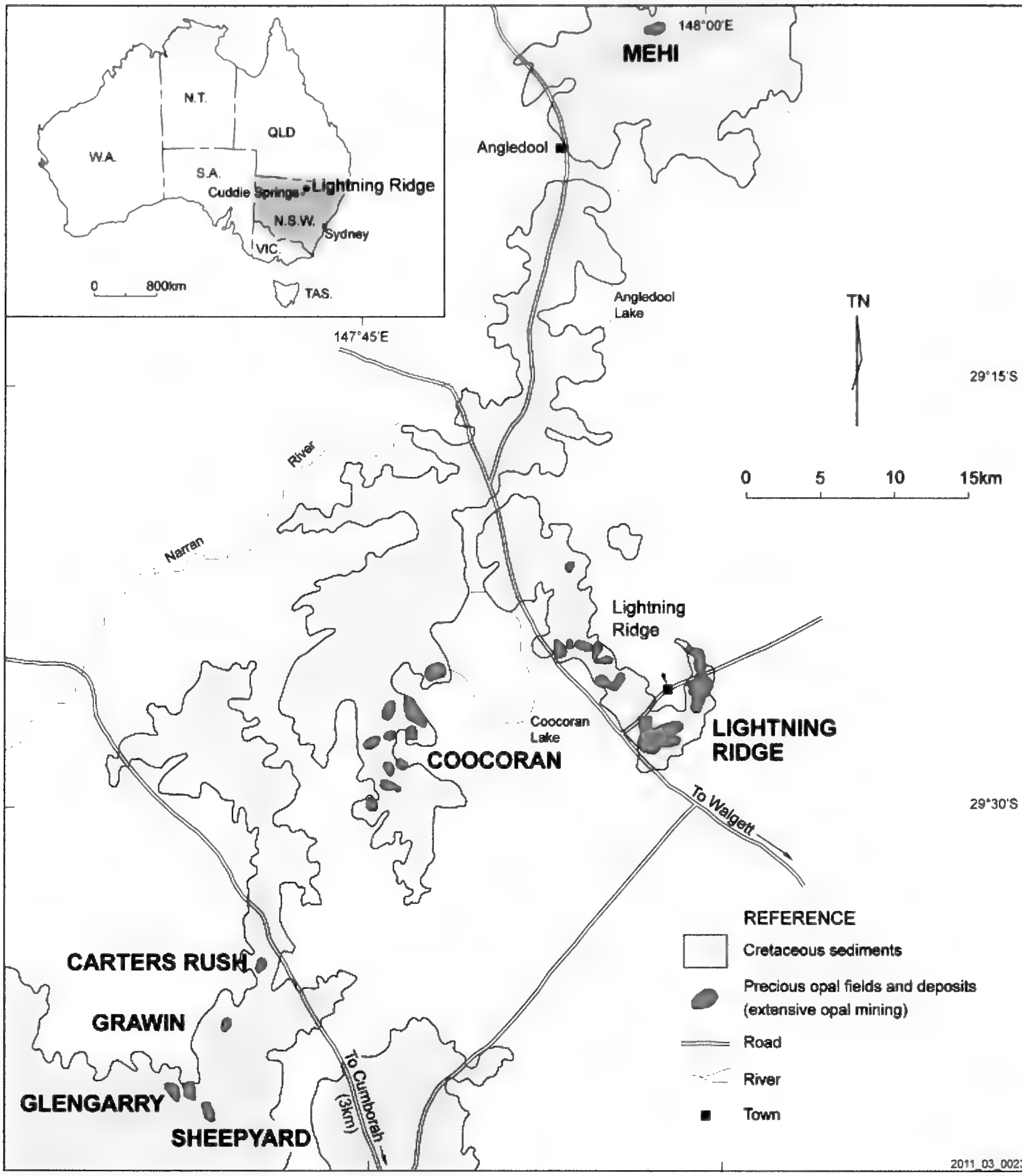

Figure 1. Locality map showing major opal fields in the Lightning Ridge area and simplified geology.

world's largest artesian groundwater basins, which contains Jurassic and Cretaceous fluvio-estuarine to marine sedimentary rocks and includes aquifers that provide a local water supply. The oldest exposed rocks in the area are Cretaceous, and they form north–northeasterly-trending low ridges. They are capped and protected by resistant plateaux of Miocene quartz-rich gravel and silcrete (Burton, in press). The ridges support scrubland and remnant native woodland and are flanked by broad colluvial slopes and grassy alluvial floodplains, which include lakes and aeolian features of Quaternary age.

The region exhibits unique and exceptional geodiversity and landscapes, shaped by over 100 million years of geological history. It is also the only place in the world to produce commercial quantities of extremely valuable black opal. Low ridges of weathered Cretaceous rocks of the Rolling Downs Group stand proud of an extensive Cenozoic floodplain, forming distinctive landscapes that exert strong influence on faunal and floral distribution, and have been appreciated by the Aborigines for thousands of years. The traditional lands of the Yuwalaraay or Euahlayi people extend from Angledool in the north, to Walgett in the south, to the Birree and Bohkara rivers in the west (Narran Lakes Ecosystem Project factsheet undated). Many Aboriginal sites including shell middens, hearth sites with clay ovens, quarries, rock wells, fishing traps, scarred trees and burial sites remain around the region (Predavec et al. 2004).

Cretaceous stratigraphy and palaeontology

During the Cretaceous, Gondwana was at high latitudes, and continental fragmentation generated a series of rift and passive-margin basins that today preserve an impressive record of Mesozoic animal and plant remains (Dettman et al. 1992; McLoughlin and Kear 2010), such as those seen at Lightning Ridge.

The Cretaceous stratigraphy at Lightning Ridge was described by Byrnes (1977), Watkins (1985), and Smith and Smith (1999). The Lower Cretaceous Griman Creek Formation of the Rolling Downs Group is economically significant as it contains the opal fields of the Lightning Ridge area (Fig. 1). Based on palynology, the unit has been assigned an early to middle Albian age (Burger 1980; Morgan 1984). Following on from the work of Byrnes (1977), the Griman Creek Formation has been divided into two members; the uppermost Coocoran Claystone Member and the underlying Wallangulla Sandstone Member, including lenses of the 'clay facies'. The Coocoran Claystone Member (or 'shincracker') consists of white to cream claystone, which is commonly silicified to porcellanite. The Wallangulla Sandstone Member comprises fine- to medium-grained, pale, kaolinitic sandstone that is, in places, cross-bedded and iron-stained. Included lenses of 'Finch clay facies' generally consist of soft, grey to buff claystone. Opal occurs in the top 30 m of the Cretaceous rocks of the ridge country, generally in the top metre of the 'Finch clay facies' and beneath sandstone beds. It typically occurs as irregular nodules ('nobbies') as thin seams along vertical or horizontal joint planes, and as replacements and cast fillings after fossils. Surface structures appear to have influenced the distribution of some known opal occurrences, though conditions required for opal formation are not fully understood and still a topic of some debate. Burton (in press) summarises three main models for opal formation as: weathering processes with passive structural control (e.g. Darragh et al. 1976; Watkins 1985); upwelling fluids with active structural control (Pecover 1996, 1999; Rey et al. 2003); and biological processes. Behr et al. (2000) suggest that microbes may have played a role in opal formation.

Cretaceous rocks of the region are renowned for their diversity of rare opalised fossils (Fig. 2), which are summarised by Smith and Smith (1999). Lightning Ridge is unique among Australian opal fields in producing opalised fossils of predominantly freshwater and terrestrial plants and animals (Smith 2007; 2009) and is the only significant dinosaur locality in New South Wales. Many workers have described fossils from the area, including monotremes (Archer et al. 1985, Flannery et al.1995, Musser 2005), crocodiles (Molnar 1980, Molnar and Willis 2001), bivalves (Hocknull 2000; Kear 2006), gastropods (Hamilton-Bruce et al. 2002; Hamilton-Bruce and Kear 2010), echinoderms, crustaceans, cartilaginous and bony fishes and lungfish (Smith and Smith 1999; Kemp and Molnar 1981), plesiosaurs, dinosaurs (Molnar and Galton 1986; Rich and Vickers-Rich 1994; Molnar 2010), pterosaurs, birds (Molnar 1999), turtles (Smith 2009; 2010), foraminifera (Scheibnerova 1974; 1984), plants (White 1986) and pollen (Morgan 1984). Appendix 1 lists over 60 fossil taxa that have been found as a by-product of mining operations.

Paleogene to Neogene deposits and fossils

Early Cretaceous rocks are unconformably overlain by Paleogene to Neogene gravels and pebbly to granule-bearing quartz-rich sands. Gravels include quartz, chert, jasper, petrified wood, topaz and agate. Palynological dating of Tertiary sediments from the Namoi River and Gwyder River valleys (Martin 1980) and the Castlereagh River valley (Martin 1981) indicated that Cainozoic deposition did not begin until the Middle to Late Miocene, and so Burton (in press) has interpreted the local gravels to be Miocene.

Much of the sediment has been silicified to silcrete, which Burton (in press) interprets as largely obscured by colluvium derived from the ridges. The timing of silicification events within the Cenozoic is problematic. Silcrete was used for tool-making by the Aboriginal population and tools and quarry sites are preserved in the region, as documented by Predavec et al. (2004).

Silcrete at Grawin has yielded a diverse macroflora assemblage of interpreted ?Oligocene to ?mid-Miocene age (Carpenter et al., in litt.). At Cumborah, approximately 40 km southwest of Lightning Ridge, fossil angiosperm leaf impressions in silicified very fine-grained sandstone (Fig. 3) were collected by the author and Burton (Burton, in press)

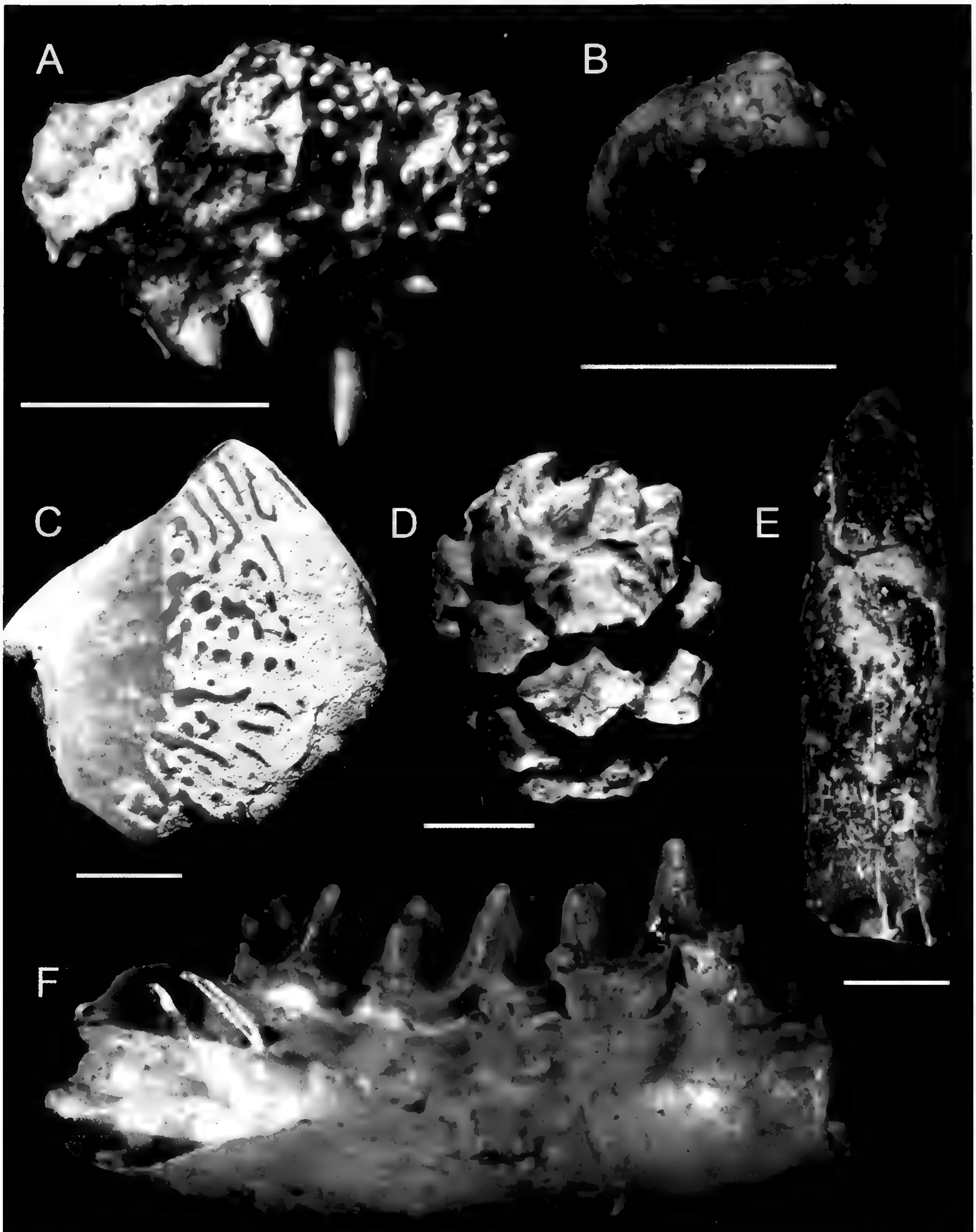

Figure 2. Early Cretaceous opalised fossils recovered from discarded surface dirt at Lightning Ridge. Fossils are from the collection of the Australian Opal Centre except C and F from the collection of the Australian Museum. A. Fish palate with finely-preserved, sharply-pointed teeth. B. Corbiculid bivalve, one of the smallest and most rare bivalve taxa in the Lightning Ridge fauna. C. Turtle shell fragment with ornamentation. D. Pine cone with scales dessicated prior to fossilisation.E. Sauropod dinosaur tooth. F. Lower jaw fragment of the monotreme mammal *Steropodon galmani,* one of the most significant fossils ever found in Australia, featured on the cover of the journal Nature. Scale bar = 5mm. Photographer Robert A. Smith. Photographs and caption courtesy of the Australian Opal Centre.

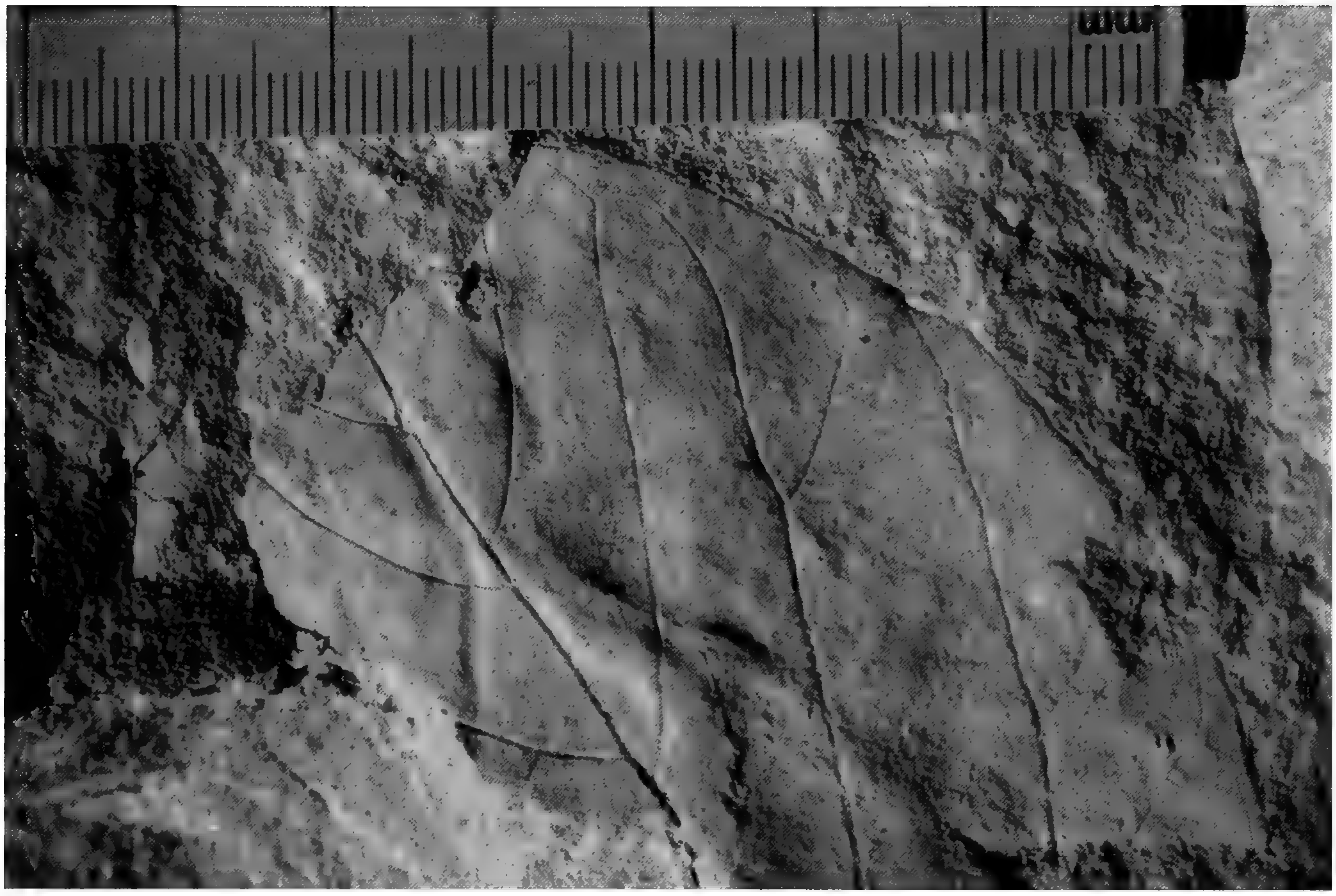

Figure 3. Angiosperm leaf impression — a broad-leaved dicot showing pinnate semi-craspedodromous venation. (Photographer: Simone Meakin).

from the base of a gravel pit. The fossils are difficult to date and could be Cenomanian or younger, but an age of Paleocene to Miocene age is likely and they are suggestive of vine forest (pers. comm., David Greenwood, Brandon University, Manitoba, Canada). Taylor (1978) estimated the age of the gravels at Cumborah to be Late Miocene.

Quaternary features

Adjacent to the ridges, broad floodplains have been built up through the Cenozoic by evolving fluvial systems that are described by Taylor (1976, 1978), Watkins and Meakin (1996) and Burton (2010). Aeolian redistribution of sediments has formed lunettes on the eastern margin of ephemeral water bodies, and source-bordering dunes (Watkins and Meakin 1996; Burton 2010). The history of fluvial deposition and associated geological, geomorphic and vegetative features in the Walgett region are described by Watkins and Meakin (1996). Following on from that work, the late Pleistocene to Holocene fluvial sequence on the plains surrounding the ridge country has been mapped by Burton (in press) as the Bugwah Formation and Marra Creek Formation. The Bugwah Formation preserves wide, slightly elevated meander plains and sinuous channels and has an estimated age of 13400 to 6400 years BP (Watkins and Meakin 1996). The Marra Creek Formation contains narrow channels and meander belts that are not elevated, and the unit represents deposition from 6400 years BP to the present day.

The Narran Lakes Nature Reserve, centred 60 km northwest of Walgett, was listed as a UNESCO 'Ramsar' Wetland of International Importance in June 1999 as it is considered an excellent example of a relatively undisturbed terminal lake system (listed as Site 5AU053 at www.wetlands.org/RSIS). It contains many Aboriginal sites including shell middens, hearth sites with clay ovens, quarries, rock wells, scarred trees and burial sites (Narran Ecosystem Project, undated fact sheet). Springs, waterholes and bends in the Narran River feature in local Aboriginal lore as part of the dreaming path of Baayami, a creation being who created the landscape's natural features.

Angledool Aboriginal Reserve and Cemetery are included in the Australian Heritage Database maintained by the Commonwealth Department of Sustainability, Environment, Water, Population and Communities (http://www.environment.gov.au/heritage/ahdb/index.html). An artesian bore bath at Lightning Ridge, one of three in Walgett Shire, is also listed in the Australian Heritage Database(http://

Figure 4. Aerial shot taken in 1994 showing opal workings in the Preserved Opal Fields. Underground mining is evidenced by mullock heaps stored on the ground surface, and part of the historic Western Fall open cut mine can be seen at the top of the photograph. (Photographer: Dave Barnes; Industry & Investment NSW photographic library).

www.environment.gov.au/heritage/ahdb/index.html). The bore was sunk to a depth of over 1 km in 1962 and taps geothermally heated artesian water that is confined and pressurised within aquifers of the Great Australian Basin and flows freely to the surface at a temperature of about 41.5°C.

At Cuddie Springs, approximately 100 km south–southwest of Lighting Ridge, a diversity of megafauna bones, including marsupials (e.g. *Diprotodon*), birds and reptiles, is preserved in an ephemeral lake, along with Aboriginal stone tools, charcoal and pollen. The deposit is interpreted by some (e.g. Field and Dodson 1999; Field, Wroe and Fullagar 2006) to indicate the local coexistence of megafauna and humans at the site, whereas others (e.g. Brook, Gillespie and Martin 2006) argue that humans caused the extinction of the megafauna and suggest that the deposit has been at least partly sourced from further afield during flooding. Regardless, the site remains an important focus for research into the extinction of Australian megafauna.

GEOTOURISM

Apart from the landscape and geological features described above, the small-scale mining culture, technology and the miners themselves are unique and of great interest to tourists. Popular tourist attractions include the historic Lunatic Hill open cut mine, underground mine tours, an opal and fossil centre, opal field tours, a self-guided tour of the opal fields which uses car doors as signposts, a fossicking site at the tourist office, opal and fossil shops, art galleries, quaint buildings made of local stone and numerous historic and cultural mining sites and buildings. Hot artesian bore baths also attract visitors to the town, and the prehistoric Cuddie Springs site occasionally has open days organised by researchers and the Walgett Shire Council.

The Australian Opal Centre (AOC) attracts thousands of visitors to its showroom each year and is involved in ongoing research. The ARC Linkage Grant project 'Mesozoic Austral Biodiversity: Research and Regional Museum Applications' involves museums and universities in NSW, Victoria, Queensland, South Australia and Sweden in partnership with the AOC. The research focuses on Mesozoic biodiversity, palaeoenvironments, palaeoclimate, and fossil-based tourism. The AOC also produces the newsletter *Harold Hodges' Opal Teeth* to promote geoscience and tourism in the region. Such ecologically sustainable development should be a vital component of the management of the opal fields.

Geoheritage

Opal mining landscapes (Fig. 4) include many features of heritage and cultural interest. Brammall and Smith (2007) describe local examples of hand-dug shafts, puddling dams, tailing heaps, silt tanks, hand-made camps and historic or unique machinery such as agitators, dry rumblers and hoists. Nettleton's Shaft, sunk in Lightning Ridge in 1903, is in the Australian Heritage Database. Mining methods have gradually evolved in the opal fields to adapt to local mining conditions but have generally changed very little over the last hundred years (Figs 5 a,b). Idriess (1944) gives a vivid historic account of the mining lifestyle.

The Preserved Opal Fields around Lightning Ridge have been gazetted in recognition of the heritage and scientific significance of those areas. Covering approximately 63 sq km based over 5 non-contiguous zones, including the Three Mile Opal Field and Lunatic Hill open cut, they contain relics from a century of small-scale mining activity and have yielded an abundance of opal and fossils. These areas

Figure 5. Top: Historical opal working. Miners who were down on their luck were allowed to fossick on other miners' tailings, using devices such as the 'snippers' held by the man on the left. Bottom: Using a dry rumbler in 1994 to search for opal in top dirt dumped by miners in earlier times. (Industry & Investment NSW photographic library).

are now the only remaining areas where miners are allowed to reside permanently in camps on their 20 year Western Lands leases. The Preserved Opal Fields concept has been endorsed by a range of stakeholders as it allows sustainable, low-impact geotourism. However, conflicts exist between mining heritage and rehabilitation and safety objectives, as many old workings pose risks. Moreover, numerous important heritage and scientific sites lie outside these areas. A Crown Reserve was created in 2009 over parts of the Preserved Opal Fields for opal mining and residential purposes and is to be administered by a trust.

DISCUSSION

Local geological features and associated mining activity are clearly prime tourist attractions in the Lightning Ridge area (Table 1). Together, mining and tourism significantly support the local economy (along with agriculture) and supply employment for almost a quarter of the local population, as supported by data from the Australian Bureau of Statistics (2006). Tourism brings opal buyers and wealth to the region, and mining activity supplies the minerals, fossils, characters and landscapes that attract them. Palaeontologists consult with opal miners to see what they have found, or to access spoil heaps and opal mines. Without the assistance of miners, many fossils would never have been recognised and smaller and less spectacular fossils would tend to end up in tailings and silt tanks (Smith 2007). Hence, collaboration between miners and researchers is vital for fossil discovery.

Over the last decade, mining activity and the estimated value of opal recovered have declined (Fig. 6), whereas tourist visitation to the town has increased (Fig. 7). The relationship between tourism and opal mining has evolved into a symbiotic relationship. If these trends continue, it is vital for the town's prosperity that both tourism and opal mining be sustained. The establishment of a 'Geopark' at Lightning Ridge was suggested by Turner (2006a) and also investigated by the Australian Opal Centre. Turner (2006b) cautioned that the boundary would have to be well drawn to accommodate Geopark rules regarding the buying and selling of the material that they wish to promote. The concept of a 'Geopark', as discussed by Turner (2006b) could provide a framework in which the local community, including the Aboriginal population, could sustainably manage and promote their geological and cultural heritage, thus boosting the local economy. The Australian Government has however expressed concern about the application of the UNESCO Geopark concept in Australia and concluded that existing mechanisms

Table 1. A summary of geotourism features of the Lightning Ridge region

- Black opal and the opal-mining industry
- An authentic outback mining town surrounded by opal-mining landscapes
- Small-scale mining methods in use, living heritage
- A huge diversity of opalised Cretaceous fossils, especially vertebrates
- Prehistoric sites (e.g. Aboriginal, megafauna)
- Historic sites (e.g. buildings, camps, machinery, signposts, hand-dug shafts)
- Artesian baths
- Underground and surface tours, community fossicking heap, self-guided car door tour, opal and fossil displays and shops, galleries and studios

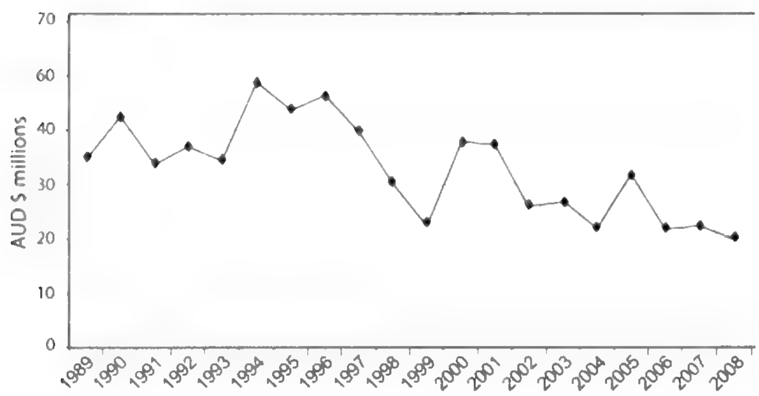

Figure 6. Value of opal exports from NSW, 1989–2008. (Source: DFAT STARS Database; consistent with ABS Cat No 5368.0, September 2009 data).

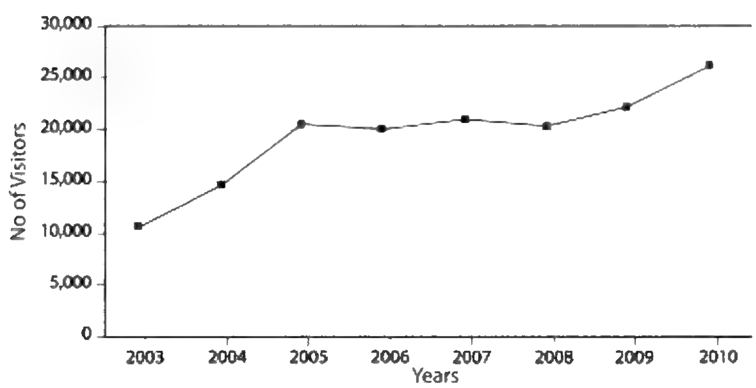

Figure 7. Visitor numbers to Lightning Ridge Visitor Information Centre.

are sufficient to protect geoheritage in Australia (Environmental Protection and Heritage Council, 2009). It has requested that UNESCO take no further action to recognise potential Australian Geoparks unless the formal agreement of the Australian Government has been provided first.

Geotourism, particularly the controlled access to fields by tourists, offers a possible solution to some of the region's problems by providing common ground that has the support of many stakeholders. It benefits all the community by providing income and jobs, and results in improved services and facilities. It educates and encourages commercial and research partnerships. A healthy tourist industry ensures prosperity of the region in hard times, such as drought and flood. Together with mining, tourism can promote ecologically sustainable development by respecting cultures, contributing to conservation of biodiversity, influencing land-use planning, communicating, educating, and contributing to the social and economic development of the community.

CONCLUSIONS

Lightning Ridge is unique in many respects but most notably for its remarkable opal and fossils. Its diverse geological features provide a rare insight into Australia's Cretaceous palaeogeography, palaeoclimate and extreme biodiversity. The fossils contribute greatly to our understanding of Early Cretaceous freshwater and terrestrial biota and environments. To enable continued discovery and research, palaeontologists must continue to work in close collaboration with opal miners, and also provide support to local geotourism initiatives.

Promoting regional development is seen as an important target by government. Given their symbiotic relationship, the tourism and opal mining industries must both be sustained to ensure the future prosperity of the area. A sustainable, low-impact, high-yield growth in tourism is necessary to support the region's development and to counteract a potential decline in opal discovery. A Whole-of-Government approach to the management of this diverse area, involving many state and federal agencies, is vital to ensure its long-term environmental, economic and social sustainability.

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APPENDIX. List of Cretaceous fossil fauna of the Griman Creek Formation, Lightning Ridge, from Smith (2007, 2009, 2010), with contributions from other sources (p.c. = pers. comm.).

		Taxon	Source
Chlorophyceae	Charophyta	indet. taxon	Dr Adriana Garcia p.c; Henk Godthelp p.c.
Foraminifera		*Hyperammina* sp	Scheibnerova 1984
		Ramulina tetrahedralis Ludbrook 1966	Scheibnerova 1984
Radiolaria		? radiolarian	Scheibnerova 1984
Polychaeta		indet. taxon	
Mollusca	Pelecypoda	*Alaythyria jaqueti* Newton 1915	
		Megalovirgus wintonensis Hocknull 1997	
		Hyridella macmichaeli Hocknull 1997	
		Hyridella (Protohyridella) goondiwindiensis Hocknull 1997	
		Palaeohyridella godthelpi Hocknull 2000	
		Coocrania hamiltonbrucei Kear 2006	
		large ?hyriid	
		sphaeriid	
		'tellen' or nut shell	
		corbiculid – river pea shell	
		strongly ridged, subcircular unioid	
		clam with spines, narrow rippled margins	
	Gastropoda	*Albianopalin benkeari* Hamilton-Bruce et al. 2002	
		Albianopalin lizsmithae Hamilton-Bruce et al. 2002	
		Notopala sp. Hamilton-Bruce et al. 2002	
		Melanoides godthelpi Hamilton-Bruce et al. 2004	
		Fretacaeles gautae Hamilton-Bruce and Kear 2006	
		Suratia marilynae Hamilton-Bruce and Kear 2010	
Crustacea	Decapoda	freshwater crayfish – indet. taxon	
Anura		frog – indet. taxon	Dr Mike Tyler and Henk Godthelp p.c.
Pisces	Chondrichthyes	small shark cf *Isurus* or *Cretolamna*	small shark cf *Isurus* or \ *Cretolamna*
	Actinopterygia – Teleostei	indet. taxa x 4	Dr Sue Turner pers. comm.
		aspidorhynchid cf *Richmondichthys sweeti* Etheridge and Smith Woodward 1891	

		Taxon	Source
		freshwater eel – indet. taxon	Dr Peter Forey and Dr Tom Rich p.c..
	Dipnoi – lungfish	*Ceratodus wollastoni* Chapman 1914	Kemp and Molnar 1981
		Ceratodus diutinus Kemp 1993	Kemp 1993
		Neoceratodus forsteri Krefft 1870	Kemp and Molnar 1981
Ichthyosauria		ichthyosaur - indet. taxon	Dr Benjamin Kear p.c.
Sauropterygia	Pliosauria	?Leptocleidid pliosaur	Dr Benjamin Kear p.c.
	Plesiosauria	elamosaurid plesiosaur - indet. taxon	Dr Benjamin Kear p.c.
Testudines - turtles	Chelidae	indeterminate chelid pleurodires x 2 taxa	Smith 2010
	Testudines indet.	meiolaniid-like taxon 1 - 'Spook's Turtle'	Smith 2009
		meiolaniid-like taxon 2 - 'Sunflash Turtle'	Smith 2009
Crocodilia		*Crocodylus selaslophensis* Etheridge 1917	
		crocodile – ziphodont	Molnar and Willis 2001
		crocodile – conical tooth form	Molnar and Willis 2001
Pterosauria		pterosaur - indet. taxon	Henk Godthelp p.c.
Dinosauria	Ornithopoda	stegosaurid	Dr Benjamin Kear p.c.
		Muttaburrasaurus sp	Molnar 1991, 1996
		Fulgurotherium australe von Huene 1932 (Molnar and Galton 1986)	
		Atlascopcosaurus loadsi Rich and Rich 1989	
		Leallynasaurus sp? Rich and Rich 1989	
		very large hypsilophodontid	very large hypsilophodontid
	Sauropodo-morpha	indeterminate sauropods x 2 - 'spoon tooth' form, 'sharp tooth' form	
		small ?prosauropod	
	Theropoda	*Rapator ornitholestoides* von Huene 1932	
		? alvarezsaurid or ceratosaurid - very large form	
		dromaeosaurid cf. *Velociraptor*	Henk Godthelp p.c.
		ornithomimosaurid	Henk Godthelp p.c.
		? spinosaurid	Dr Benjamin Kear p.c.
	Aves	unidentified ornithoracines - two taxa	Molnar 1999
Mammalia	Synapsida	unidentified ?synapsid	Clemens et al. 2003
	Monotremata	Steropodontidae - *Steropodon galmani* Archer et al. 1985	
		Kollikodontidae - *Kollikodon ritchiei* Flannery et al. 1995	
		?Ornithorhynchidae - up to 3 unidentified taxa	Smith 2009

Wee Jasper–Lake Burrinjuck Fossil Fish Sites: Scientific Background to National Heritage Nomination

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The ~5 km thick Burrinjuck Devonian sedimentary sequence records environmental change from a volcanic terrain with deep lake deposits (oldest), through a tropical reef marine ecosystem, to river and lake deposits (youngest). Numerous fossil horizons document evolutionary change through the final stage of terrestrialization of the earth's biota. Exceptional exposures of Devonian tropical reefs in the Wee Jasper valley, with limestones washed completely clean by the waters of Lake Burrinjuck, have produced the world's oldest known coral reef fish assemblage. Including associated invertebrates, the faunal list stands at some 266 fossil genera.

Burrinjuck produced five key fossil fish specimens used in the 1940s in London to develop the acetic acid technique for extracting bone from calcareous rock (now standard in laboratories throughout the world). Recognizing the uniquely preserved early vertebrate braincase structures, the British Museum (Natural History) mounted two collecting expeditions to Burrinjuck (1955, 1963), when some 560 specimens were removed to London. Repatriation of type specimens is a future issue. The largest collection of Burrinjuck early vertebrate braincase material is housed at the Australian National University in Canberra; at least 70 fossil fish species represents biodiversity unequalled at any other Devonian fossil fish locality. Fossil site protection for the Burrinjuck area was the basis for a recent nomination for National Heritage listing. Long-term protection of natural history collections in the National Capital as part of Australia's scientific heritage is a related issue of concern.

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KEYWORDS: Burrinjuck, Cavan, coral reefs, Devonian fishes, vertebrate braincase, Wee Jasper.

INTRODUCTION

The Devonian Period (~418-360 million years ago), known as the 'Age of Fishes', was the geological period when the early jawed vertebrates underwent their first great evolutionary radiation. This included not only abundant and diverse fishes in all habitable aquatic environments, but also an evolutionary expansion of our ancestors (the first four-legged land animals) into an entirely new terrestrial environment, made habitable by the rise of land plants including the first forests during the Devonian Period. One of the NSW geological heritage sites (Taemas-Cavan) described by Percival (1985, pp. 30-33) represents the Devonian Period, and occupies the southeastern arm of Lake Burrinjuck, about 50 km NW of the National Capital in southeastern Australia (Fig. 1). In that area, Early Devonian marine limestones display spectacular folding, and richly fossiliferous shell beds such as are exposed at the 'Shearsby's Wallpaper' protected site.

Taemas-Cavan is the easternmost of two main areas of outcrop of Devonian limestones around Burrinjuck Dam (Fig. 1B). The western outcrop, surrounding the village of Wee Jasper in the valley of the Goodradigbee River, is separated by the Narrangullen anticline, where underlying older units (Mountain Creek Volcanics; Kirawin Formation; Sugarloaf Creek Formation) are exposed. Research on the geology and especially the vertebrate palaeontology of the Burrinjuck area has given it national and international significance. In March, 2010 the author lodged a nomination for part of the western outcrop of the Burrinjuck limestones to be included on the National Heritage List (areas labelled (I), Fig. 1C). Significant cave and karst structures documented by A. Spate form part of that nomination but are not dealt with further here (for details contact A. Spate, Optimum Karst Management). In this paper I summarise the geological and palaeontological significance of the Devonian sequence, with special

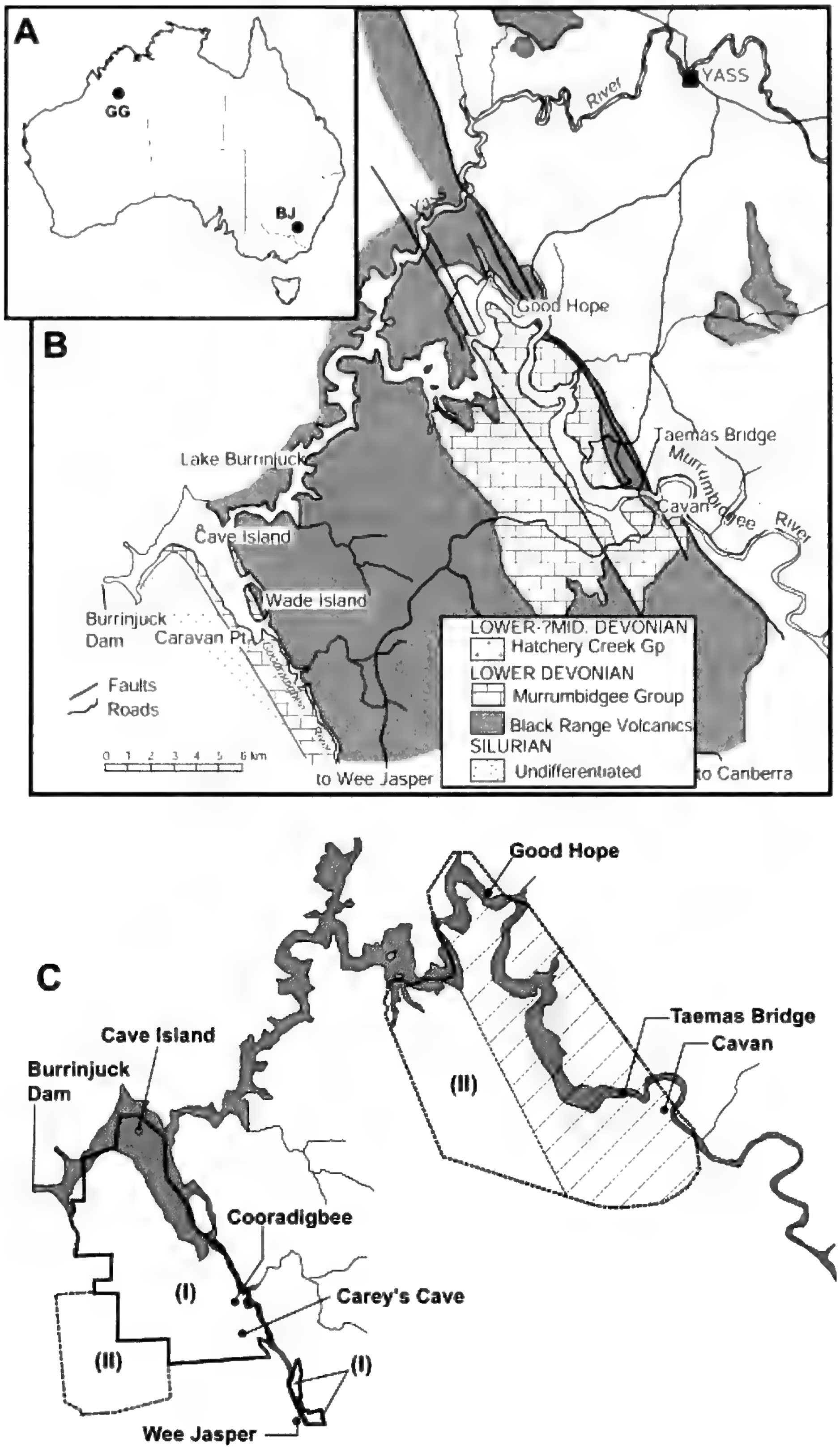

Figure 1. A. General localities for the two Australian limestone reef fossil fish assemblages from the Devonian Period (~418-360 million years ago): Gogo, WA (GG) and Burrinjuck, NSW (BJ). B. Geological map of the Burrinjuck area showing the two outcrops of Murrumbidgee Group limestones: Good Hope – Taemas - Cavan in the east, valley of the Goodradigbee River in the west. C. Lake Burrinjuck (shaded) on the Murrumbidgee River, with location of the area nominated for heritage listing in March 2010 (labelled (I), indicated by solid outline). Proposed future Stage II nomination (labelled (II)) indicated by dashed outline, including the NSW geological heritage area of Percival (1985, map 9) indicated by cross-hatching. Other localities mentioned in the text also labelled ('Cave Island = pre-dam 'Cave Flat').

reference to the remarkable fossil vertebrate remains that have been extracted from the Burrinjuck limestones. A brief summary of recent results of ongoing research is presented.

HISTORY OF SCIENTIFIC INVESTIGATION

The limestones of the Goodradigbee and Murrumbidgee valleys were doubtless well known to the indigenous population for many thousands of years, because of their interesting rock formations and caves. The limestone outcrops were first noted by Europeans as early as 1824 (by Hume and Hovell), and in 1836 fossil corals were collected from the area by the explorer Thomas Mitchell (Mitchell 1838). From 1848, the 'Father of Australian geology' Rev. W.B. Clarke made many collections in the area (Clarke 1860, 1878), which he sent overseas for expert determination (de Koninck 1877) to confirm the Devonian age for the limestones. Bennett (1860, p. 158) mentioned visits to the 'Gudarigby Caverns', apparently the limestone caves at Cave Flat near the junction of the Murrumbidgee and Goodradigbee rivers. Etheridge (1889) reported on a visit to these caves, where a spectacular *Thylacinus* skull was collected, and displayed for many years in the fossil gallery of the Australian Museum, Sydney (see Fig. 4A).

Etheridge recognized the exceptional fossil content of the limestones, which he described in the following terms (1889, p. 36): 'The Murrumbidgee limestone is … crammed with fossils, especially corals. As a display of these beautiful organisms in natural section I have never seen its equal. Large faces of limestone … may be seen, with the weathered corals … standing out in relief and in section also. Many of these masses of coral, particularly those of *Stromatopora* and *Favosites*, are as much as 4 feet in diameter.'

A few years later Etheridge also visited the 'caves at Goodravale, Goodradigbee River' (now Carey's Cave, Wee Jasper valley, included in the heritage nominated area; see Fig. 1C), where cave deposits produced jaw remains of the marsupial lion *Thylacoleo* (Etheridge 1892). Etheridge (1906) then reported the first discovery of a Devonian lungfish from Burrinjuck, at that time the oldest known representative of the Dipnoi (see below). Harper (1909) conducted a geological mapping survey preliminary to the proposal to dam the Murrumbidgee River in the Burrinjuck area.

After construction of Burrinjuck Dam (1912-17), the area became more widely visited, and was a regular destination for geology student excursions from the University of Sydney. The subject matter of Professor T.W. Edgeworth David's first Australian publication (1882) was the geology and palaeontology of this area, and Dr Ida Browne did detailed stratigraphy and produced the first geological maps (Browne 1954, 1959). Her 1959 paper, including her widely used geological map of the Taemas area, was part of a publication to mark the centenary of the birth of Professor Edgeworth David. In recent decades Burrinjuck has been a focus for geology student excursions from many universities, and especially the ANU in Canberra, because of proximity and research interest. With more frequent droughts in recent years the rock exposures and fossil sites along the shores and on the bed of Lake Burrinjuck are now often accessible for extended periods.

BURRINJUCK DEVONIAN SEQUENCE

The Devonian Period lasted for some 60 million years. However, the exceptionally thick Burrinjuck Devonian sequence, comprising some 5 km of sedimentary strata overlying an equivalent or greater thickness of volcanics (Fig. 2), was mainly deposited during the early part of the Devonian Period (see below). A general observation is a strong cyclicity evident on a larger scale through some 3 km of stratigraphic thickness comprising the uppermost Hatchery Creek Group, and the Murrumbidgee Group limestones. In the limestones this is manifested as more recessive units comprising shale/limestone interbeds alternating with more massive limestones as constituent members of the Taemas Limestone (Browne 1959, Young 1969, Pedder et al. 1970). In the Hatchery Creek Group fining-upward cycles occur throughout the succession, but with generally finer and less thick cycles higher in the sequence (Hunt and Young 2010). Google images to the east of Wee Jasper suggest a downward continuation of this cyclicity into the underlying Sugarloaf Creek Formation. The phenomenon could relate to orbital forcing causing regularity in climatic fluctuations (Hunt and Young, submitted). Elsewhere (e.g. Middle Devonian of Scotland, Late Devonian Munster Basin of southwest Ireland) smaller scale (36, 55 m) and larger scale (130 m) sedimentary cycles have been attributed to 100 Ka and 412 Ka Milankovitch Cycles respectively, with somewhat lesser thicknesses (8, 40 m sedimentary cycles) attributed to 21 Ka and 100 Ka Milankovitch Cycles in the largely lacustrine Orcadian Basin (Kelly 1992, Kelly and Sadler 1995, Marshall et al. 2007). This aspect of the Burrinjuck Devonian sequence has not been researched in any detail.

The last comprehensive accounts of the Devonian stratigraphy were by Owen and Wyborn (1979) for the Brindabella 1:100 000 geological map, and by Cramsie et al. (1978) for the northern part of the outcrop on the Yass 1:100 000 geological map. The following stratigraphic summary (oldest to youngest) relies heavily on Owen and Wyborn's (1979) explanatory notes (microfiche portion, now converted to pdf).

Mountain Creek Volcanics

The name was first published by Joplin et al. (1953). Some authors grouped this unit with the overlying Kirawin and Sugarloaf Creek Formations as the 'Black Range Group', but Owen and Wyborn (1979) considered these three units too dissimilar to be grouped together. The upper part of the Mountain Creek Volcanics in the Cavan area comprises rhyolites and tuffs deposited in a terrestrial environment. Estimated total thickness farther south is 5000-8000 m (Owen and Wyborn 1979, p. M190). The Mountain Creek Volcanics are considered to be entirely Devonian (probably mostly Lochkovian) in age, on the assumption that rhyolites at Mount Bowning on the Yass 1:100 000 sheet are equivalent (Link 1970). These rhyolites overlie lowermost Devonian strata containing the early Lochkovian conodont *Icriodus woschmidti* (Link and Druce 1972; see Pogson 2009 for updated comment on the conodonts).

Kirawin Formation

This black shale/mudstone deposit forms a poorly exposed outcrop 0.5 to 4 km wide, in an arcuate 35 km belt across the Narrangullen anticline. The outcrop thins

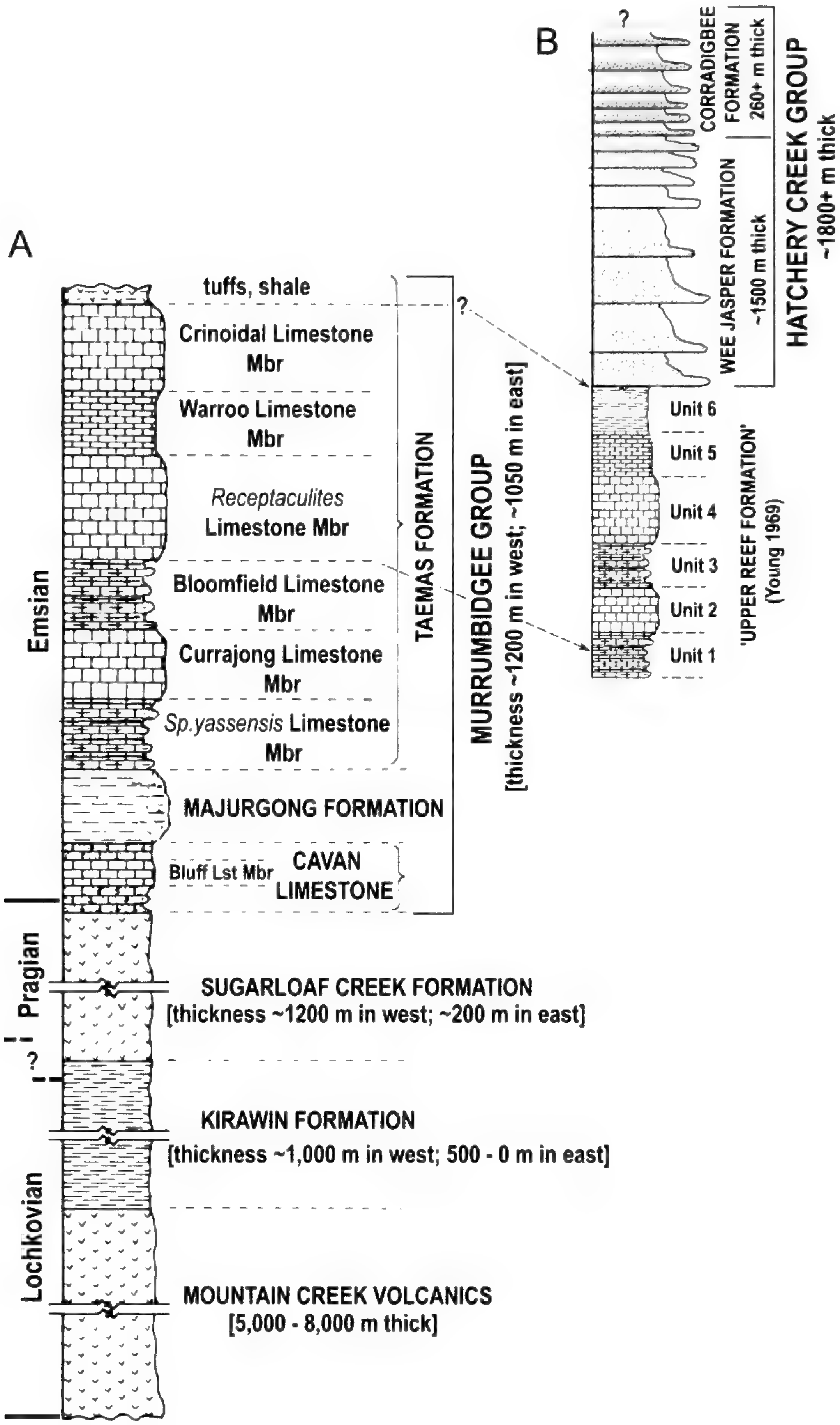

Figure 2. Summary stratigraphic sections (not to scale) for the Devonian sequence of the Burrinjuck area. A. Complete section beneath and through the eastern limestone outcrop (Good Hope – Taemas – Cavan); stratigraphic thicknesses from Owen and Wyborn (1979). B. Upper part of the Murrumbidgee Group and overlying Hatchery Creek Group in the Wee Jasper area; stratigraphy from Young (1969) and Hunt and Young (2010).

dramatically to the east, partly or entirely due to faulting, and is very thin or absent in the Cavan area. The Kirawin Formation is some 500 m thick in its central exposure (including the designated type section, a road cutting on the Yass-Wee Jasper Road near the valley of Narrangullen Creek; Owen and Wyborn 1979, p. M304). Thickness increases to the west to about 1 km towards Wee Jasper. The Kirawin Formation has conformable and gradational boundaries with both the Mountain Creek Volcanics and Sugarloaf Creek Formation. The lower boundary comprises thin rhyolite and tuff interbedded with black mudstone over several tens of metres (Owen and Wyborn 1979, p. M305).

A fossil locality of the probably terrestrial arthropod (?myriapod) *Maldybulakia* (see Edgecombe 1998a, b), found by Nazer (1970) near 'Brooklyn' Homestead along Sawyers Gully Road, occurs at the lower boundary with the Mountain Creek Volcanics. Owen and Wyborn (1979, p. M305) erroneously referred to these as 'unidentified trilobites', and therefore incorrectly suggested a marine environment for part of the Kirawin Formation.

Sugarloaf Creek Formation

The name 'Sugarloaf Creek Tuff' was first used by Edgell (1949) for the unit underlying the limestones at Wee Jasper. The designated type section (Owen and Wyborn 1979, p. M306) follows the Yass-Wee Jasper Road to the east of Wee Jasper. They interpreted the lithology as derived from erosion of volcanic rocks, mainly coarse, poorly sorted arenite with a series of mudflows in a subaerial environment in the west, changing to better sorted arenite, siltstone and shale with predominantly fluviatile deposition in the east. The thickness varies from about 1200 m near Wee Jasper to about 200 m in the Cavan area, where underlying rhyolites are interpreted to indicate terrestrial deposition.

An important fossil locality in the Cavan area discovered by ANU geology students in the late 1960's produced remains of the millipede-like arthropod *Maldybulakia angusi*, described as the oldest land animal known from the Gondwana supercontinent (Edgecombe 1998a). The outcrop, attributed to the Sugarloaf Creek Formation, lies to the east of Mountain Creek Road, about 3 km to the north of 'Kirawin' Homestead. Geological maps of the area show one or more fault contacts against the underlying Mountain Creek Volcanics (Owen and Wyborn 1979; Prihardjo 1989). Another arthropod locality found by Nazer (1970) is better constrained stratigraphically, and clearly much lower in the sequence (base of Kirawin Formation; see above), suggesting that the stratigraphy and/or structure of the eastern arthropod locality may have been misinterpreted.

Edgecombe (1998b, p. 294) noted the exceptional preservation of the arthropods from the eastern locality, which occurred 'in an abundance rivalled by few fossil myriapod sites'. Recently some vertebrate remains (an incomplete acanthodian fish, and the lower jaw cartilage of a primitive shark) were identified in material from this locality, inviting comparison with similar remains from sediments within the Boyd Volcanic Complex on the NSW South coast (see Young 2007), from which a different species of the same arthropod genus was described by Edgecombe (1998a, b). The shark lower jaw closely resembles that of *Antarctilamna* Young, 1982 from the Bunga Beds, a black shale lithology (associated with volcanics) which has also produced articulated acanthodians (Burrow 1996). Apart from isolated teeth and scales, the likely Lochkovian age of the Mountain Creek Road locality makes this shark jaw the oldest known fossil preservation in the world of the chondrichthyans (cartilaginous fishes – sharks, rays and chimaeras of the modern fauna).

MURRUMBIDGEE GROUP

Cavan Limestone

The three-fold subdivision of the 'Cavan Stage' described by Browne (1959) comprised a lower 48 m of flaggy limestone, shale, etc., a middle massive 'Bluff limestone' (48 m), and an upper 32 m of thin-bedded limestone. Owen and Wyborn (1979) formalised the name 'Cavan Limestone' because the 'Cavan Bluff Limestone' of other authors could be confused with the more restricted usage of the term 'Bluff Limestone' by previous workers (e.g. Harper 1909, Browne 1959). The nominated type section is under the power lines at Clear Hill in the Cavan area.

Detailed information on the Cavan Limestone in the Cavan area is held in unpublished ANU theses by Koluzs (1972) and Wu (1983). Koluzs (1972) separated off an underlying sequence 44-70 m thick of interbedded siltstones, fine sandstones and shales as the 'Fifeshire Formation', which was incorrectly included by Cramsie et al. (1978) in the upper part of the Sugarloaf Creek Formation. Young (1969) documented a section to the east of Wee Jasper, but named the lower bedded limestones (beneath the 'Bluff Limestone member') the 'Fifeshire member'. Young (1969) defined the base of the formation at Wee Jasper as the first limestone band, a definition followed by Owen and Wyborn (1979) and Mawson et al. (1992, p. 25). Mawson et al. (1992) documented conodont assemblages through a measured section

177 m thick just south of the section of Young (1969). They identified the Pragian-Emsian boundary at about 35 m below their 'Cavan Bluff Limestone', and 50-60 m above the base of the formation in the Wee Jasper section.

The tripartite subdivision of the Cavan Limestone encompasses a transgression, highstand, and regression, the whole sequence being deposited in a near shore (shallow subtidal to intertidal) environment. Young (1969) recognised detailed similarities at Wee Jasper to the sequence in the Taemas-Cavan area, suggesting either a broad tidal flat, or preservation parallel to a coastline (or both). Owen and Wyborn (1979) commented on the surprising lateral consistency of these lithologies between Taemas and Wee Jasper.

Majurgong Formation

This non-calcareous unit comprises mainly shales and lithic sandstones. Sedimentary structures include cross-bedding and ripple marks. Most of the formation is unfossiliferous, but lingulid brachiopods and gastropods occur in the lower horizons (e.g. bedding planes in the road cutting immediately east of the eastern end of Wee Jasper bridge; lingulids in growth position in shales interbedded with thin limestones in the road cutting opposite the entrance to the Good Hope camping area). These may indicate brackish water conditions, and the Majurgong Formation is interpreted as a non-marine interlude within the predominantly shallow marine Murrumbidgee Group, perhaps deposited in an estuarine environment (Chatterton 1973). Turiniid thelodont fish (agnathans) documented by Basden (1999) were perhaps also restricted to this marginal or non-marine facies.

In the Wee Jasper area the Majurgong Formation is about 120 m thick. It forms a resistant row of hills along the western bank of the Goodradigbee River running north from Wee Jasper village.

Taemas Formation

The Majurgong Formation grades up into the lower fossiliferous beds of the *Spirifer yassensis* Limestone Member, the lowest of six members of the Taemas Formation as recognized and mapped by Browne (1959) in the eastern limestone outcrop (Good Hope – Taemas – Cavan area). Like the Bloomfield Limestone Member, the *Spirifer yassensis* Member comprises interbedded limestones and calcareous shales, and tends to have recessive outcrop compared with the more massive limestones of the overlying Currajong and *Receptaculites* Limestone Members, which both display small reefal bodies in the Goodradigbee valley. Similar massive beds of the *Receptaculites* Limestone Member occur in the eastern limestone outcrop near Taemas-Good Hope (Chatterton 1973).

The Taemas Formation in the Goodradigbee valley is somewhat thicker (1000-1100 m) than in the east (~800 m). Young (1969) only recognized equivalent members up to the Bloomfield Limestone, the *Receptaculites* Limestone and higher members being much more massive, and designated as the 'Upper Reef Formation', which was subdivided into six units (Fig. 2B). Subsequently, a distinct band of *Receptaculites australis* was mapped by Basden (2001) and Lindley (2002), indicating equivalence in part to the *Receptaculites* Limestone Member as identified by Browne (1959). Overlying massive beds composed largely of crinoid ossicles, some showing faint cross-bedding, presumably correspond in part to the Crinoidal Limestone Member of the eastern outcrop.

The uppermost Unit 6 of the 'Upper Reef Formation' of Young (1969) comprises finely laminated unfossiliferous limestones grading through calcareous shale into coarser lithologies of the non-marine Hatchery Creek Group. Campbell and Barwick (1999) measured a section through the contact, and interpreted the uppermost 110 m of thin-bedded limestones and shales 'as an intertidal zone carbonate deposit consistent with the fact that the overlying unit is the fresh water Hatchery Creek Formation' (p. 125). Lindley (2002, fig. 4) presented a revised version of this section, and Campbell et al. (2009, p. 62) noted that the top of carbonate sequence with shallow marine algal mats was 'transitional into the overlying fresh water Hatchery Creek Formation'.

HATCHERY CREEK GROUP

The 'Hatchery Creek Conglomerate', first named by Joplin et al. (1953), was originally assumed to be Upper Devonian, by lithological comparison with the Hervey Group of central NSW, and thus unconformably overlying the Lower Devonian limestones. The lower conglomerates, sandstones and mudstones form fining-upward cycles which are laterally extensive and traceable over several kilometres along the length of the western escarpment of the Goodradigbee Valley (Young 1969).

A new fossil fish assemblage, discovered during geological mapping by Owen and Wyborn (1979), included such forms as the placoderm *Sherbonaspis hillsi*, which closely resembled the 'winged fish' first documented by Hugh Miller (1841) from classic Middle Devonian Old Red Sandstone fish faunas of Scotland. The assemblage was described by Young and Gorter (1981) as demonstrating a probable Eifelian (Middle Devonian) age, rather than Late Devonian as previously assumed. It was suggested that any disconformity with the underlying limestones was of short duration (Owen and Wyborn 1979; Young and Gorter 1981). Previously, Edgell (1949) had interpreted a conformable boundary between the Hatchery Creek sequence and the underlying limestones, whereas Young (1969) and Pedder et al. (1970) had interpreted a disconformable boundary. As noted above, measured sections through new exposures now clearly indicate a gradational boundary at the northern end of the Wee Jasper valley (Campbell and Barwick 1999, Hunt and Young 2010).

Owen and Wyborn's (1979) estimated total thickness of at least 2900 m erroneously included repetition of beds on both sides of the axis of a broad syncline. The revised stratigraphy of Hunt and Young (2010) has elevated the 'Hatchery Creek Conglomerate' to stratigraphic group status, with two constituent formations, the lower Wee Jasper Formation with an estimated thickness based on air photos (at an average dip 40°) of about 1500 m, and an upper Corradigbee Formation at least 260 m thick.

For non-marine basins in various tectonic settings, sedimentation rate has been estimated to vary in the range 0.1-0.6 mm/year (averaged over 10^6 years; Miall 1978). For a total thickness of about 1800 m, the entire Hatchery Creek sequence could have been deposited in about 4.5 Ma using an average sedimentation rate of 0.4 mm/year, or about 5.4 Ma given a slower rate (0.335 mm/year) as documented in some humid fan alluvial systems. This is less than the duration of the *serotinus* conodont zone based on the latest Devonian timescale calibrations of Kaufmann (2006). Thus, it is possible that the Hatchery Creek sequence could have been deposited mostly or entirely within the Emsian stage of the Early Devonian, particularly when there is some evidence that the highest conodont occurrences in the underlying limestone may be low in the *serotinus* zone (Basden 2001; discussed by Young 2004a, pp. 47-48).

Wee Jasper Formation

Owen and Wyborn (1979, p. M314-M320) designated a 1200 m type section of cycles of 'conglomerate, sandstone and siltstone typical of the lower part of the formation' along Cave Creek Road. Hunt and Young (2010) defined an additional type section along 'Windy Top Trail' to include the upper part of the formation. At least 12 major fining upward cycles have been mapped, decreasing in thickness and sediment coarseness up the sequence.

The depositional environment was interpreted by Owen and Wyborn (1979) as a meandering stream deposit, with coarse basal beds probably indicating a high-energy environment and steep gradient. Extensive development of soil profiles suggested that areas were quiescent for long periods before later deposition, with well-developed vegetation being extensively churned in the sediments. Recently discovered are soil horizons with deep root traces (~1.4 m) that are significantly older than recorded elsewhere. In Northern Hemisphere Devonian sequences of this age only low vegetation occurred, and deep root systems did not appear until the Late Devonian after the first forests had evolved (Algeo and Scheckler 1998). However forests may have evolved much earlier on the Gondwana supercontinent (e.g. Retallack 1997).

Corradigbee Formation

Named after the property (*Corradigbee*) that encompasses most of its outcrop (Hunt and Young 2010), the predominant grey-black mudstones of the Corradigbee Formation indicate a change from a well drained to swampy (rather than lacustrine) conditions. Fifteen fining-upward sedimentary cycles are identified in a thickness of at least 260 m (uppermost beds obscured by Tertiary basalt). Numerous new fossil fish localities were identified throughout the Corradigbee Formation (Hunt 2005, 2008), including several new taxa (Young et al. 2010, Hunt and Young 2011), in addition to significant plant remains (lycopsids, stems, early leaves much older than elsewhere; Beerling et al. 2001, Osborne et al. 2004), possible arthropods, and the oldest freshwater gastropod recorded from the Australian fossil record.

EXCEPTIONAL FOSSIL FISH PRESERVATION – THE LONDON CONNECTION

The Rev. W.B. Clarke (1878) was the first to record fossil fish remains from the Burrinjuck area (a bone in limestone collected by Hamilton Hume, and a fish spine sent to Sir Philip Egerton in Britain; see Moyal 2003, p. 1138). The discovery of a fossil lungfish skull near old Taemas Bridge on the Murrumbidgee River (by C.A. Sussmilch of Sydney Technical College) was reported by Etheridge (1906), being the oldest known example at the time of this major group (represented in the modern fauna by only three genera, one of which is the Australian lungfish *Neoceratodus*). The significance of the Taemas skull resulted in it becoming the holotype of a new genus *Dipnorhynchus*, erected by the German authority Prof. Otto Jaekel (1927), and described in

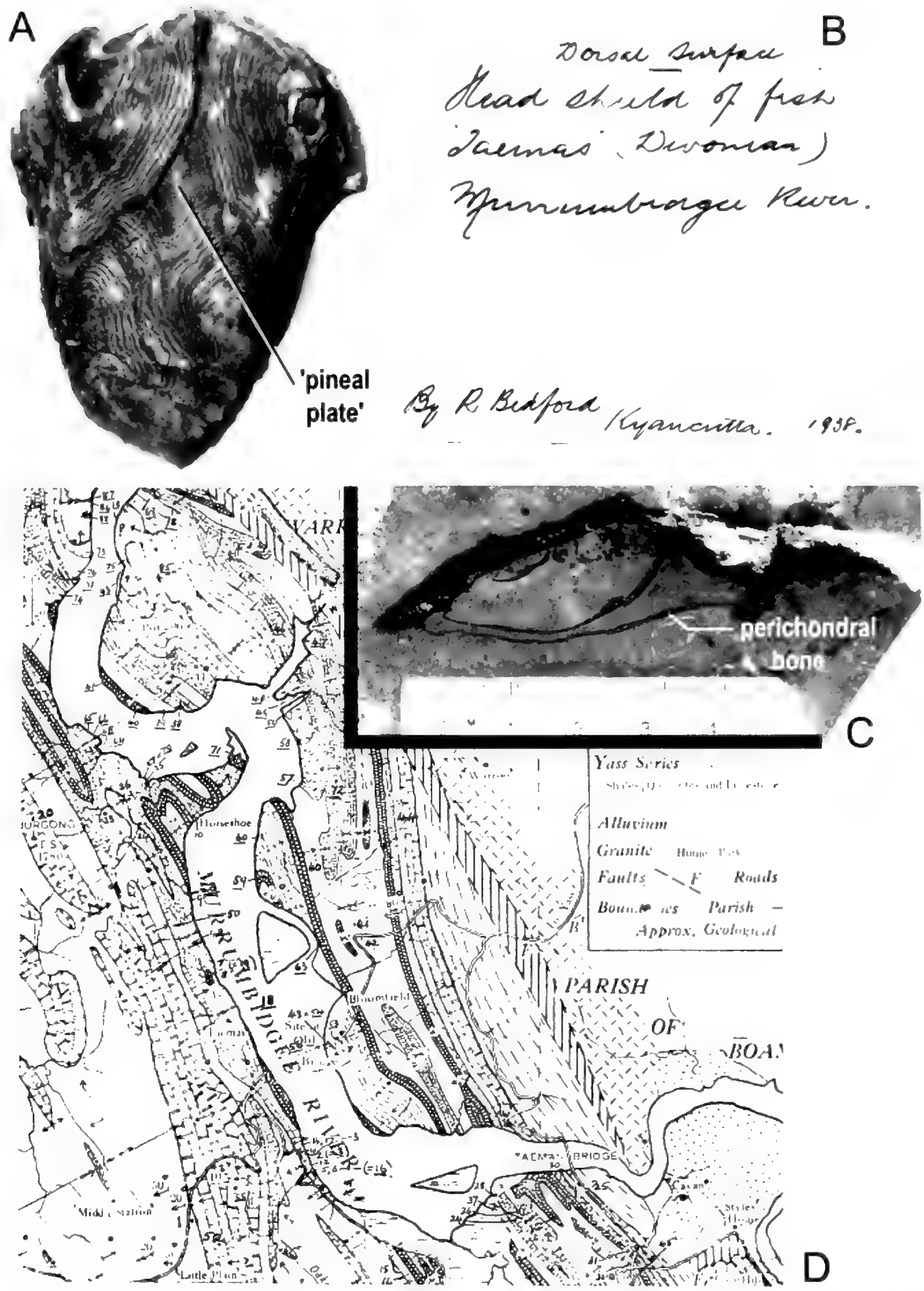

Figure 3. A. 1938 photograph of a presumed Devonian fish skull with a central 'pineal plate' sent by Robert Bedford, Director of the Kyancutta Museum, SA (covering letter dated October 21, 1938) to the collector, Mr W.E. Williams of Cootamundra, NSW. B. Annotation on the back of the photograph. The original of this letter, accompanying sketches and photograph, are held in the ANU Palaeontological Collection with a cast of the specimen – now BM P27073, the holotype of *Williamsaspis bedfordi* White, 1952 housed in the Natural History Museum, London. C. Bone (dark colour) weathering out of clean limestone, observed in the outcrop near Cooradigbee Homestead (see Fig. 1C). The lower thin black lines represent surface ossification of internal cartilage (perichondral bone), an exceptionally rare preservation type that motivated the British Museum to spend over 4 months of intense fossil collecting in the Burrinjuck area (1955, 1963). D, portion of the draft geological map provided by Dr Ida Browne for use by Mr H.A. Toombs in the 1955 and 1963 British Museum collecting expeditions, with his fossil fish localities marked.

more detail by Hills (1933, 1941). Harper (1909) also recorded some 'fish plates' in the limestones, and a Burrinjuck fossil fish skull collected by Mr J.A. Watt, a student at Sydney University, was sent by the NSW Government Geologist to London for examination by the leading British fossil fish expert (Sir) Arthur Smith Woodward. This was exhibited in 1916 to the Geological Society in London, and described 25 years later as *Notopetalichthys hillsi* Woodward, the first formal description of a placoderm fish from Burrinjuck (Woodward 1916, 1941; holotype returned to the Australian Museum, AM F45251).

The key event for international recognition of the Burrinjuck fossil fishes was the transmittal to London in 1939 by Robert Bedford (or Buddicom, 1874-1951), Director of the Kyancutta Museum, S.A., of five fossil fish specimens found in the Burrinjuck area by local collectors A.J. Shearsby (Yass) and W.E. Williams (Cootamundra). They came from two localities (White 1952): 'Barber's ... on the Goodradigbee River' (now the 'Cooradigbee' property; the area nominated for heritage listing), and 'Taemas on the Murrumbidgee River'. These specimens (see Fig. 3A) were used in the laboratories of the British Museum (Natural History) by Mr H.A. Toombs to develop a method of extracting fossil bone from limestone using acetic acid (Toombs 1948). This is now a standard technique used throughout the world, for example to extract fossil mammals from limestones at the World Heritage Riversleigh site in Queensland.

The five Burrinjuck specimens sent to London were described in a 53 page monograph by White (1952), only the second scientific publication describing fossil bones extracted by this new technique. White noted that the Burrinjuck specimens were 'even more interesting and important than first supposed', because braincase structures were preserved (see Fig. 3C), which could be acid-extracted for the first time. These uniquely preserved type specimens remain in the British Museum in London (now called the Natural History Museum).

As a direct result of White's (1952) publication, the British Museum (Natural History) sent H.A. Toombs to Australia on two expeditions (1955, 1963) specifically to collect more fossil fish from the Burrinjuck area. Some 560 fossil fish samples collected from 139 different sites (Fig. 3D) were transported back to London, where they remain in the research collections of that major institution. In his internal reports (Toombs 1955, 1964) Toombs noted for the 1955 expedition that the area needed protection, and he wrote that he had advised the 'Australian authorities ... to discourage casual collecting', but there was no action to effect this in the ensuing fifty-five years. The heritage application lodged in March, 2010 should partly address the need for protection of this unique type of fossil vertebrate preservation.

In his 1963 report Toombs recorded visits to universities in Sydney and Canberra, noting that neither university had any fossil fish specimens, which 'boosted the morale' because the London museum thus had the only substantial collection. He visited the new ANU Geology Department in Canberra only after the bulk of collected samples had already been consigned to London (Prof. K.S.W. Campbell, *pers. comm.*). ANU Foundation Professor of Geology D.A. Brown was extremely concerned that so much fossil material had been removed without local knowledge. Prof. E.S. Hills FRS (University of Melbourne) sent a letter of protest to Dr Errol White, a Fellow of the Royal Society and Keeper of Palaeontology at the British Museum. The best specimens were eventually described many years later (White and Toombs 1972; White 1978). At the time of collection there had been no consultation with local scientists, and hence no agreement about repatriation of Burrinjuck type specimens, in contrast to later collecting by the Natural History Museum at Gogo, WA (see Long 2006).

The discovery of an excellent new specimen of the lungfish *Dipnorhynchus* near the Shearsby's Wallpaper site in the Taemas area initiated a research program on early vertebrates at the Australian National University in Canberra (Campbell 1965; Thomson and Campbell 1971). Numerous subsequent papers and monographs, by Campbell and Barwick (1982-2007) and others, document some of the oldest known and best preserved fossil specimens of the Dipnoi (lungfishes; see Fig. 4F). In addition, a large collection of placoderm fish specimens was obtained by ANU from Cave Flat during the 1968 drought, and since then, regular search of outcrops whenever low water levels produced exceptional exposures of clean limestone (see Kellett 2010, p. 37), has resulted in the unequalled collection of such material at the ANU. The placoderms have been documented by Young (1969-81, 1985-86, 2003-05, 2008-10), Long and Young (1988), Findlay (1996), Goujet and Young (2004), Mark-Kurik and Young (2003), and Young et al. (2001a, b, 2010). Other fish groups (osteichthyans, acanthodians, microvertebrate remains etc.) are documented by Basden (1999, 2001), Basden et al. (2000a, b), Basden and Young (2001), Burrow (2002), Burrow et al. (2010), Giffin (1980), Long (1986), Lindley (2000-2002), Ørvig (1969) and Schultze (1968).

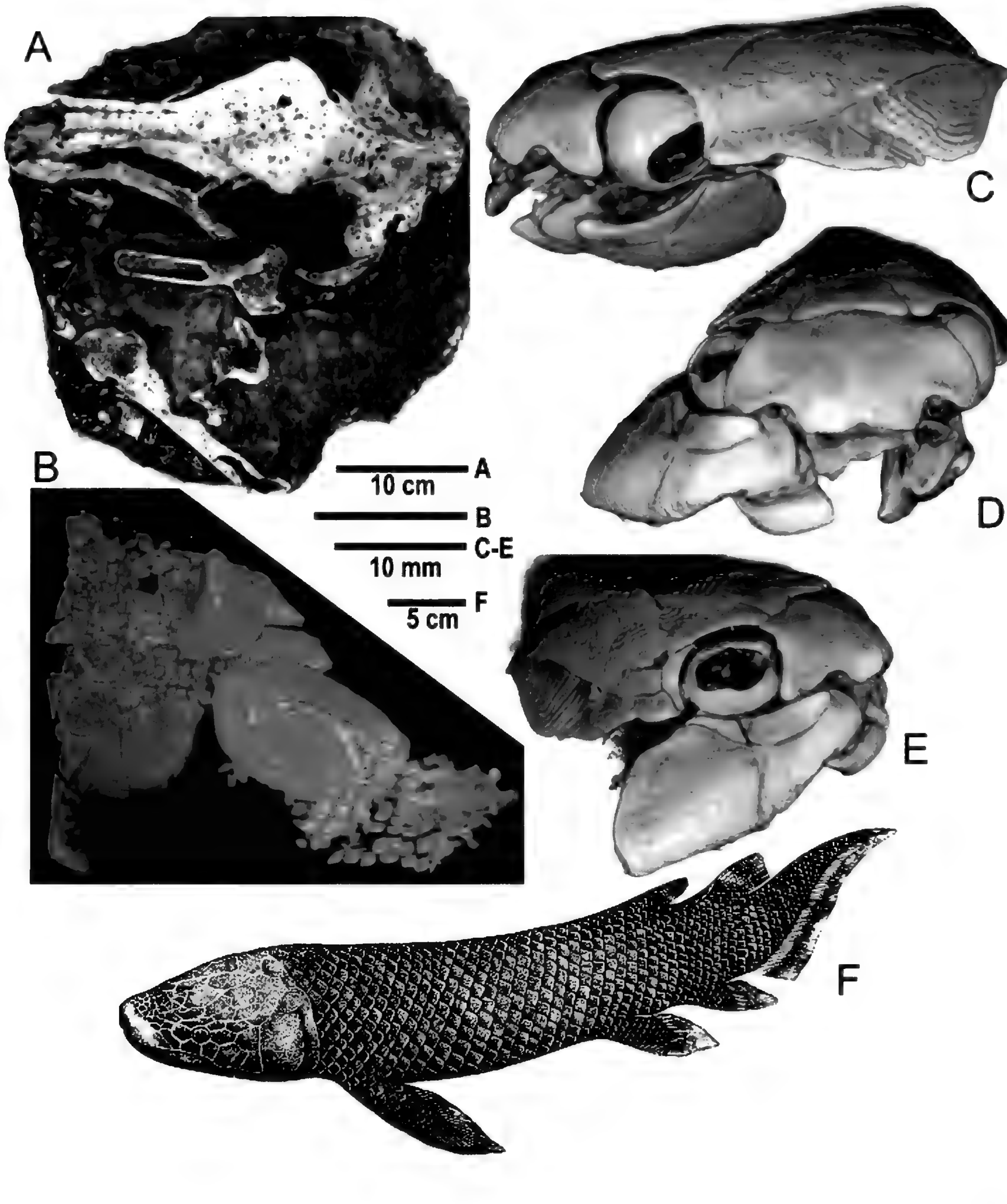

Figure 4. A. An enormous skull of *Thylacinus cynocephalus* (AM F340) collected from cave deposits at Cave Flat by R. Etheridge Jnr in 1888, said to be the largest known (Etheridge 1889, 1892). B-E, CT scanning images of new genus and species of Early Devonian arthrodire placoderm, ANU 49384, showing portion of the tail (B), and complete skull, rostral capsule, both eye capsules, jaw cartilages and toothplates in approximate life position (C, left anterolateral view; D, anterior view; E, right lateral view). F, Generalised reconstruction (by Dr R.E. Barwick) of a primitive lungfish from the Burrinjuck limestones.

The extinct placoderms, which lacked true teeth (Young 2003), are perhaps the most primitive of all the jawed vertebrates, and were by far the most diverse and widespread Devonian fish group (Young 2010). They provide unique insights into braincase structure at the time jaws first evolved. No other fossil locality in the world compares with Burrinjuck regarding the diversity of forms with the braincase preserved (see Faunal List; Appendix). Exceptional specimens include a perfectly preserved 'eye capsule' (Fig. 5A) that completely enclosed and surrounded the soft tissues of the eye, revealing intricate internal details including nerves and muscle attachments controlling eye movement, and tubules connecting the optic nerve and associated blood vessels to the retina (Young 2008a, b). No comparable specimen exists in any other museum collection, and the XCT scanned image of this specimen has been displayed at various international venues including London (Optometry and Vision Science Research Symposium, College of Optometrists), the Horizon Planetarium in Perth, and the Fels Planetarium, Franklin Institute, Philadelphia. Many tens of thousands of Devonian placoderm specimens are held in museum collections all over the world, but only a very few examples display the entirely extracted skull and braincase, eye capsules, jaw cartilages and toothplates. All such specimens come from the Burrinjuck area, and are housed at the Australian National University in Canberra (see Fig. 4C-E, 5B).

ANCIENT REEF EXPOSURES IN THE GOODRADIGBEE VALLEY

During Late Silurian – Early Devonian time much of eastern Australia was a shallow tropical sea, as indicated by widespread coralline limestone deposits. However, in most areas the rocks are folded or otherwise deformed, and poorly exposed, so actual coral reefs generally cannot be seen. Where exposed, their fossil content can be studied by acid cleaning one metre square 'windows' of typically weathered limestone surfaces in a grid across the outcrop, to attempt a reconstruction of the different facies of a fossil reef system.

Following construction of Burrinjuck Dam, large areas of limestone were submerged, and washed completely clean and slightly etched by the lake water. Extreme fluctuations of water level during droughts associated with climate change in recent decades have produced exceptional exposures of ancient coral reefs in the lower Goodradigbee valley (Fig. 6). The integrity of the reef structures is enhanced by the fact that the limestone strata are relatively undeformed compared to the folded strata of the Taemas-Cavan area.

At least seven reefal structures up to 1 km long and 80-100 m thick were identified by Young (1969). Away from the lake to the south (e.g. in the vicinity of Cooradigbee homestead and Carey's Cave; see Fig. 6A) the reefs form massive grey limestones with weathered surfaces in which little structure is seen (Fig. 6D). In contrast, spectacular exposures on the lake foreshore like Cathedral Rock and Currajong Reef (Fig. 6B-C) display back-reef deposits of crinoid gardens, colonies of stromatoporoids and corals within the reef in growth position (Fig. 6F), and a fore-reef of rolled coral blocks and debris that accumulated in storms over the ancient reef front (Fig. 6E).

It is acknowledged that the better known 'Great Devonian Barrier Reef' of the Canning Basin in the Kimberley area, WA, is a much larger structure, with spectacular cliff exposures that cannot be matched by the Burrinjuck reefs (see Playford et al. 2009). However, this reefal system is of Late Devonian age, whereas the Burrinjuck reefs represent a significantly earlier episode of reef development. Differential weathering of relatively flat-lying strata in the Kimberley has produced a topography simulating an exhumed reef system, but much of the stratigraphy is hidden in the subsurface, in contrast to the folded stratigraphic sections that are well exposed at Burrinjuck. In addition, rock outcrops generally need to be acid-cleaned in small areas to examine fossil content (see Playford et al. 2009, p. 97), so the various animal associations on the reef system cannot be observed in detail across an entire reef exposure, as can be done at Wee Jasper. All of these features make the Devonian reefs in the lower Goodradigbee valley amongst the most spectacular and scientifically significant ancient reef exposures known.

OLDEST KNOWN CORAL REEF FISH FAUNA

Australia's renowned World Heritage Great Barrier Reef is notable for its exceptional tropical fish diversity. It is relevant therefore that the exceptionally diverse Burrinjuck fossil fish fauna is also the world's oldest known coral reef fish assemblage. A much younger fossil fish occurrence (Molte Bolca, Italy, ~50 million years old) was claimed in the journal *Coral Reefs* as the oldest (Bellwood 1996), but this was challenged because there was no 'direct evidence that a coral reef existed in the immediate vicinity of the soft sediments in which the fossils were buried' (Robertson 1998, p. 184-85). In the Wee

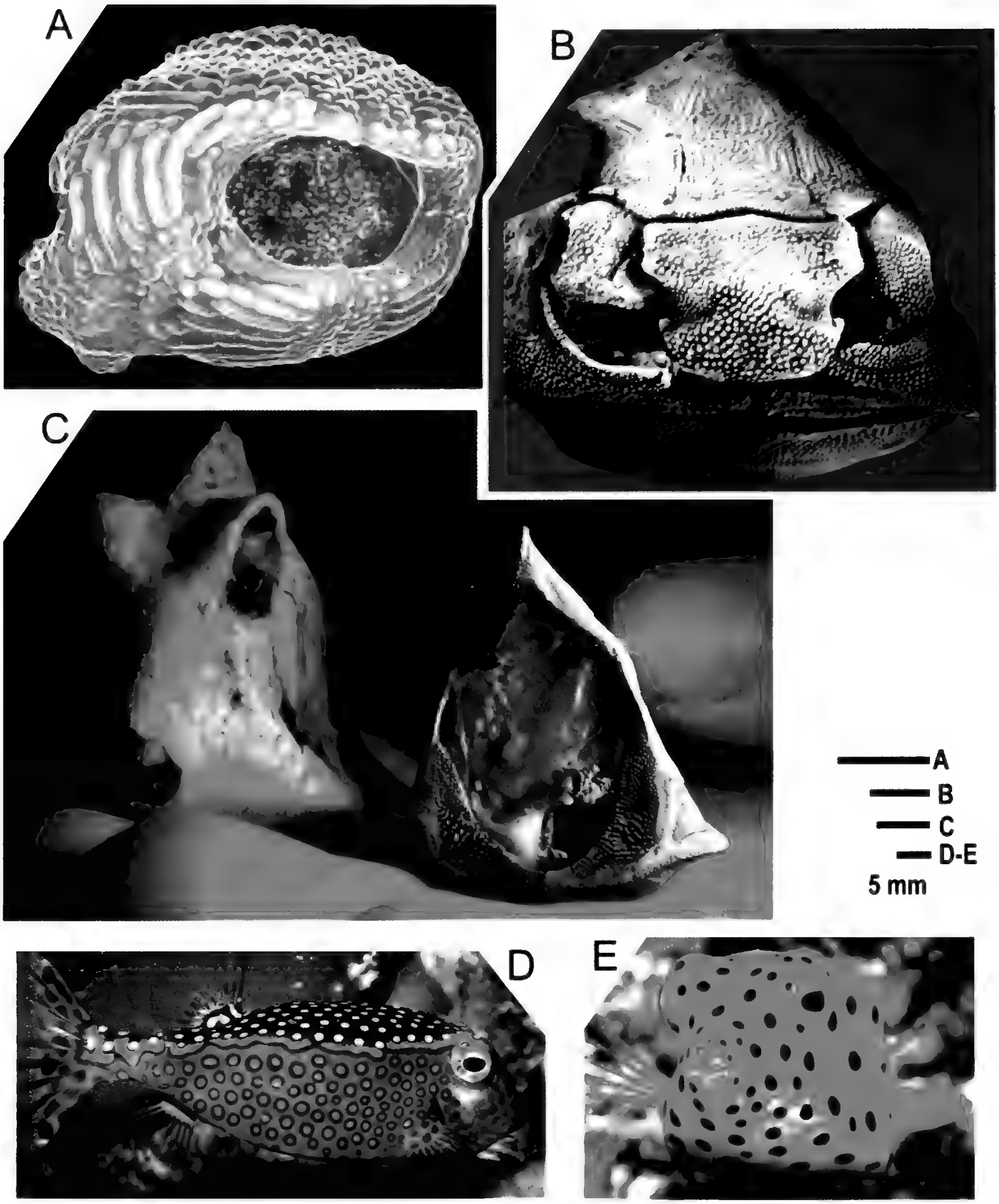

Figure 5. A. CT scanning image of the isolated left eye capsule of the placoderm *Murrindalaspis* (specimen found near Taemas bridge), the oldest known perfected preserved vertebrate eye capsule (specimen in ANU collection; described by Long and Young 1988, Young 2008a, b). B. Completely preserved arthrodire skull, braincase, and jaws in anterior view (from 'Shearsby's Wallpaper' near Taemas; ANU V244, described by Young et al. 2001b). C. Holotype of the williamsaspid arthrodire *Elvaspis tuberculata* Young, 2009 compared (on the right side) with a juvenile turretfish *Tetrasomus* sp. (family Ostraciidae), and two species of Ostracion from the Great Barrier Reef (D, *O. meleagris*; E, *O. cubicus*). D, E, reproduced with permission from Randall et al. (1990).

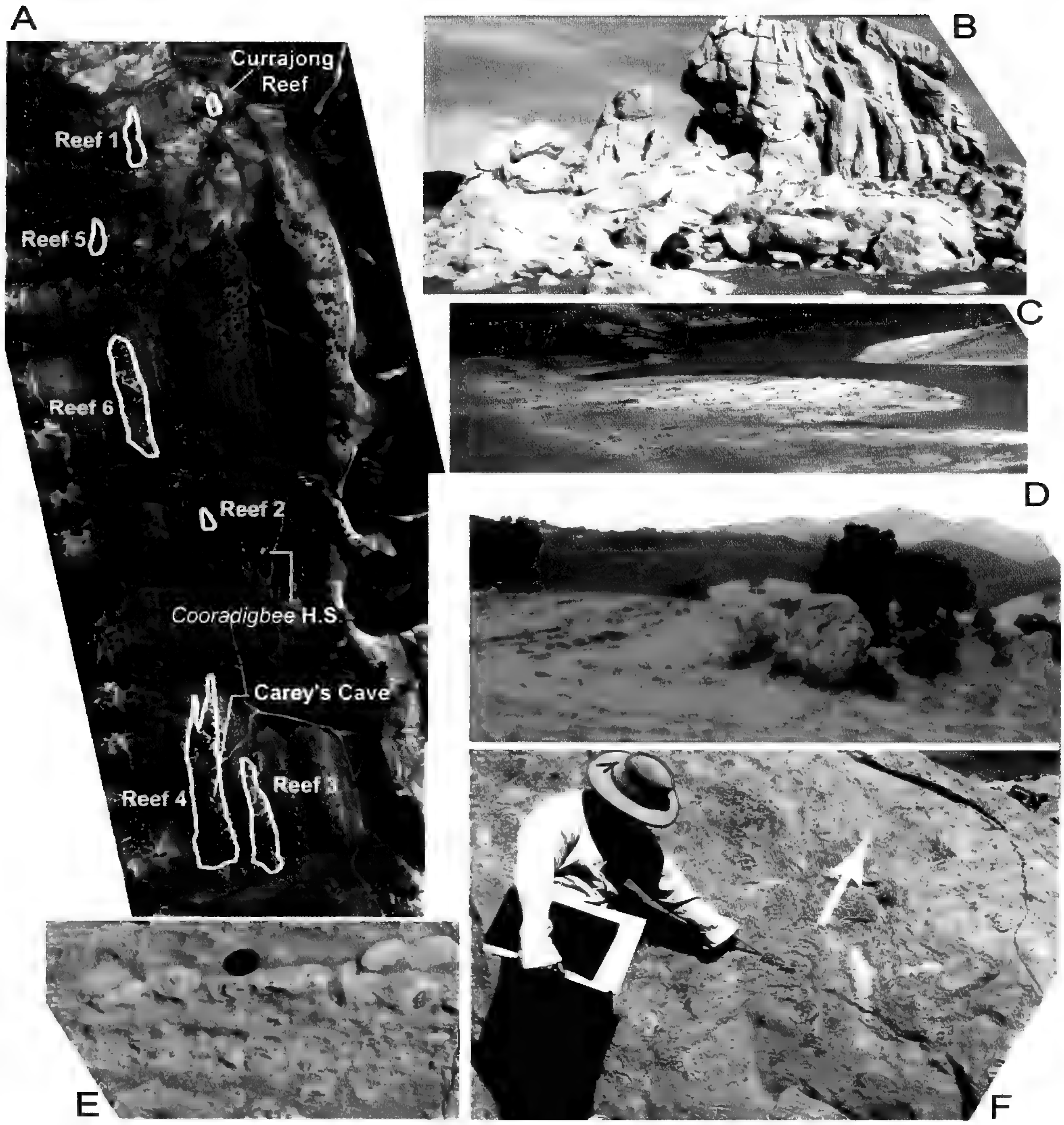

Figure 6. A. Location of some reef structures identified by Young (1969) from the vicinity of Carey's Cave north to the bed of Lake Burrinjuck (Currajong Reef). Base map a composite of Google Earth images. Reefs 1-3 occur in Unit 2, Reefs 4, 6 in Unit 4, and Reef 5 in Unit 5 of the 'Upper Reef Formation' of Young (1969). B, 'Cathedral Rock', a massive reef limestone washed completely clean by the waters of Lake Burrinjuck (Dr A. Basden, Macquarie University, in foreground). Cave deposits of uncertain age in some of the rock crevices have produced skeletal remains including *Thylacinus* (J. Caton, I. Cathles, pers. comm.). This outlier (completely submerged at high water level) is about 200 m along strike to the north from Reef 1. C, view from northwest to Currajong Reef on the lakebed at low water level, March 2010. D, Reef 2, immediately north-west of 'Cooradigbee' homestead, represented by massive limestone (right side of image), with bedded limestone (left side of image) wrapped around the reef by compaction of the sedimentary sequence. The limestone shows normal dark grey weathering, in which few structures are visible without special treatment by acid or thin sectioning of rock samples. E. Bedded limestone outcrop adjacent to F, showing numerous rolled corals with random growth orientations (talus that accumulated off the reef front due to wave action or storms). F, Dr A. Basden, Macquarie University, demonstrating upward growth of massive coral colonies (white arrow), in situ within the massive limestone forming the core of Currajong Reef.

Jasper valley, the evidence that the fish preserved as fossils lived in and around coral reefs is unequivocal. In the Currajong Reef, fossil bones are associated with diverse coral colonies within the reef structure; sometimes bones are observed in outcrop forming the site of growth for coral colonies (Fig. 7A). The ANU collection of acid-etched specimens has numerous examples where bones and skulls show small corals still attached that grew from their surfaces (Fig. 7B). At the time of deposition the limestone was soft calcareous mud, and the disarticulated skeletons of dead fish provided very localised hard substrates on which coral larvae could settle. In some specimens the original orientation of the bone, and how deep it was buried in the mud, can be reconstructed from the pattern of small corals encrusting its surface.

BIODIVERSITY HOTSPOTS IN TROPICAL REEF FISHES - DEVONIAN vs RECENT

It is well documented that peaks in modern tropical fish diversity are associated with coral-rich areas. That this also applied in the Palaeozoic is evidenced by ongoing research revealing many new forms with different body shapes to occupy a variety

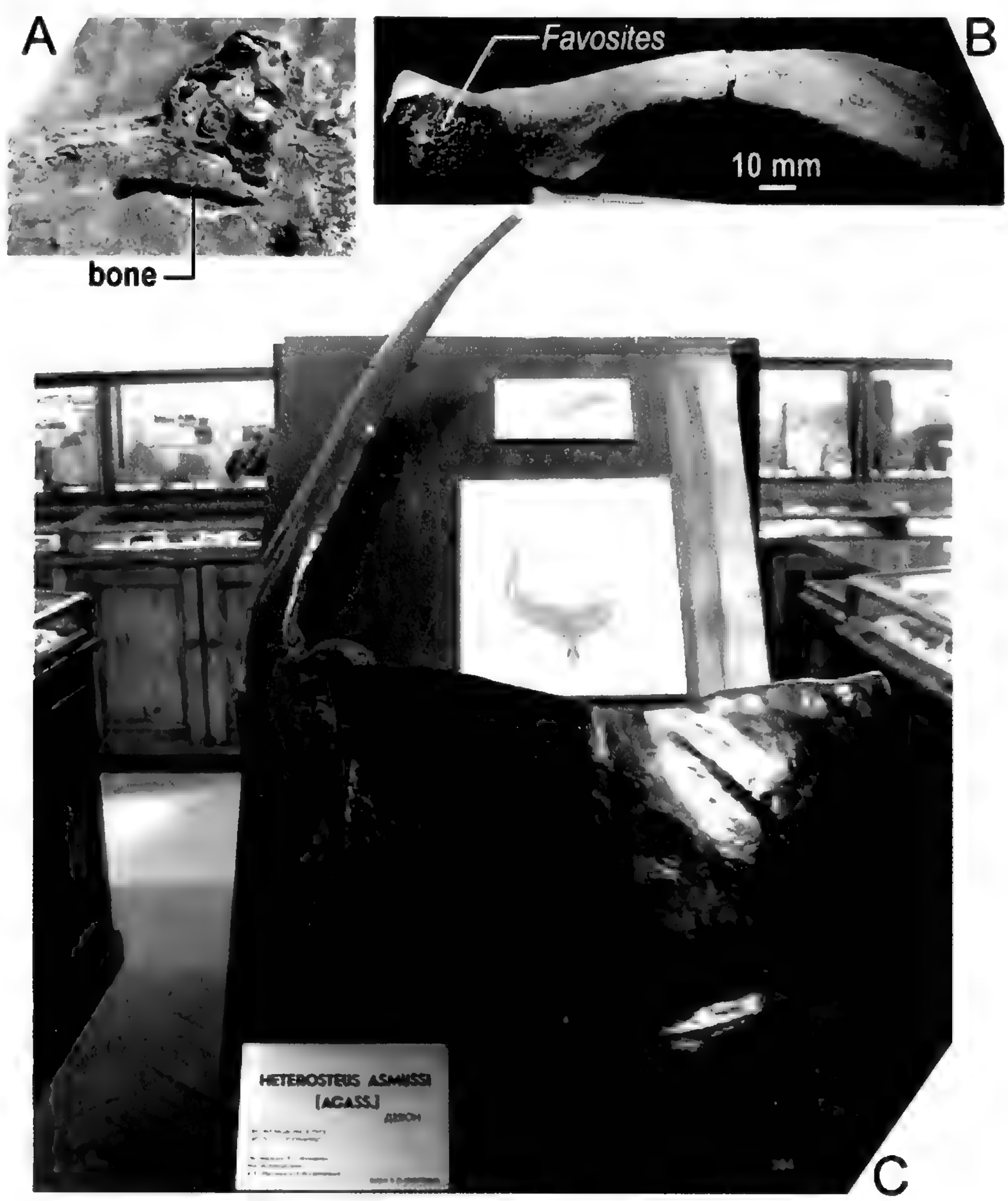

Figure 7. A. Placoderm bone (dark colour) projecting from the limestone outcrop at Currajong Reef, on which coral/algal encrustations show upward growth patterns (at the time of deposition the rock was soft calcareous mud, and the bone a hard surface on the sea bottom on which coral larvae could settle). B. lower toothplate (infragnathal bone, ANU V3081) of a filter- feeding homostiid arthrodire (cf. *Cavanosteus* Young, 2004). C. Display in the Geological Museum of St. Petersburg University, Russia, of the giant arthrodire *Heterostius* from the early Middle Devonian of the Baltic sequence (bones exceeding 1 metre in width).

of ecological niches on the Burrinjuck tropical reef system (Young 2009). Unpublished data from many new specimens (Appendix) demonstrates that the Burrinjuck fish fauna (at least 70 species) is more diverse than any other Devonian fossil fish site in the world. Direct comparisons can be made with reef fish diversity (also mainly placoderms and lungfish) at the famous Gogo fossil locality, also one of the most diverse known Devonian fish assemblages (some 55 species; Long and Trinajstic 2010).

Two issues concerning tropical reef fish diversity in the Devonian compared to modern reefs have been discussed in the recent scientific literature. Anderson (2008) analysed lower jaw elements to compare the diversity of 'coccosteomorph' arthrodire placoderms from the Gogo reef assemblage with 'pachyosteomorph' arthrodires from the younger (Famennian) Cleveland Shale assemblage (Ohio USA). He found the former to show less diversity than the latter, and concluded that in Devonian oceans highest diversity levels may have occurred in open basin fish faunas, the complete opposite of modern oceans where greatest biodiversity occurs on reefs.

Two problems with Anderson's comparison concern the different age of the Gogo (Frasnian) and Cleveland (Famennian) assemblages, and the fact that palaeogeography was not considered. Many of the giant Cleveland fish taxa also occur in limestones in Morocco (e.g. Lehman 1956, 1976, 1977), evidently deposited on a shallow shelf close to a reef environment, and north Africa was much closer to eastern North America than today (the Atlantic Ocean did not open until the Mesozoic).

To reliably assess 'basin' versus 'reef' fish diversity in Devonian oceans the compared localities should be the same age, and clearly representing completely different facies. Thus, the Burrinjuck coral reef fossil fish fauna can be compared with the famous Early Devonian fossil assemblage from the Hunsrückschiefer of Germany, a marine black shale deposit also of Pragian-Emsian age. The Hunsrückschiefer has produced numerous invertebrate fossils including *Receptaculites*, which gives its name to the *Receptaculites* Member of the Taemas Limestone at Burrinjuck. The Hunsrückschiefer fish fauna includes one lungfish species originally assigned to the Australian genus *Dipnorhynchus*, and later provisionally referred to the closely related *Speonesydrion* from Burrinjuck (Campbell and Barwick 1984a). More preparation of the holotype specimen has led to its placement in a new but closely similar genus *Westollrhynchus* by Schultze (2001). *Lunaspis* is a well-known petalichthyid placoderm from the Hunsrückschiefer (e.g. Young 2010, fig. 3e-f) that is also recorded from Burrinjuck (Young 1985). The largest arthrodire from the Hunsrückschiefer is *Tityosteus rieversi*, probably a member of the family Homostiidae, also represented at Burrinjuck by *Cavanosteus* (e.g. Young 2004). These faunal similarities validate a biodiversity comparison between the two localities.

The total fish diversity recorded so far from the Hunsrückschiefer is 14 genera and 15 species, dramatically less than at Burrinjuck, even though fossils from the famous German deposit have been collected and studied scientifically for about 150 years (Bartels et al. 1998). There are nine placoderm genera and 10 species known from the Hunsrückschiefer, of which only three genera and species are arthrodires. This compares with at least 40 genera and 45 species at Burrinjuck, including some 30 arthrodire species (Appendix). These data strongly suggest, in contrast to the conclusion of Anderson (2008), that in Devonian oceans the peaks in fish biodiversity were associated with tropical reef environments, just as in modern oceans.

Young (2009, 2010) discussed the fact that the highly diverse Devonian placoderms could be compared with the dominant teleosts of the modern fish fauna. Taking taphonomic factors into account, there is no evidence to indicate lower diversity of reef fishes on Devonian compared to modern reefs as far as supraspecific taxa are concerned. Anderson (2008, p. 967) suggested no fish on modern reefs of comparable size to the giant Devonian predator *Dunkleosteus*, but very large sharks, both predatory (e.g. 6-7 m tiger shark *Galeocerdo cuvier*) and filter feeders (12+ m whale shark *Rincodon typus*) occur on and around modern tropical reefs. The very large arthrodires of the latest Devonian are consistent with 'Cope's rule' of evolutionary size increase, and even the largest known Early Devonian arthrodires (e.g. *Tityosteus* from Germany, *Dhanguura* from Burrinjuck) probably attained only several metres total length (Young 2004). But by the early Middle Devonian enormous arthrodires including probable filter-feeders such as members of the family Homostiidae had evolved, with earlier representatives known from Burrinjuck (Fig. 7B-C).

Regarding species diversity, many modern fish species can be readily distinguished by differences in surface colour and pattern, and many reef teleosts are brightly coloured. The williamsaspid arthrodires from Burrinjuck have similar body shape to modern boxfishes (family Ostraciidae), interpreted by Randall et al. (1990) to comprise nine species in four genera, most of which are instantly recognisable by their bright colours (Fig. 5D-E). Even amongst the generally drab sharks and rays, numerous similarly-shaped species are easily distinguished by different colours or distinctive surface markings or patterns (see Last and Stevens 1994). Such information is unavailable for fossil fish, even with exceptional whole body preservation such as occurs in the Hunsrückschiefer of Germany. For these reasons, fish diversity at the species level in the fossil record is probably greatly underestimated (Young 2010, p. 542).

The highly diverse Burrinjuck fossil fish assemblage can be compared with some other noteworthy Devonian fossil fish sites. Miguasha National Park in Quebec is a World Heritage listed Devonian fish locality. Many thousands of exquisite fossil fish have been collected, but they are preserved as partly compressed whole bodies in siltstones, and can only be extracted by manual preparation. Numerous Miguasha specimens are held in museums throughout the world, including such famous forms as the lobe-fin *Eusthenopteron*. Even so, Miguasha has produced no more than 21 fish genera in total (Schultze and Cloutier 1996). Similarly, the well known Canowindra fossil fish site in central NSW has produced several thousand fossil fish specimens, but only eight fish genera and species are known. In addition, although generally preserved as relatively complete impressions in sandstone, their internal structure is largely unknown. Gogo, WA, is the only other site in the world producing acid-extracted fossil fish specimens in a comparable diversity to Burrinjuck (~51 genera; Long and Trinajstic 2010). Gogo, Canowindra and Miguasha are all of similar age, and the fossil fish from all three sites are more highly evolved than at Burrinjuck which is 20-30 million years older. In particular, the most diverse component of these faunas (placoderms) have lost much of their internal ossification in the Gogo species. Thus, braincase preservation is a very special attribute of the many primitive forms known only from Burrinjuck. It should be noted that in the first monograph describing placoderms from Gogo (Miles 1971), a Burrinjuck specimen was essential for interpretation of placoderm nasal structure, even though there were numerous exquisitely preserved remains of a new Gogo species of the genus *Holonema* (see Miles 1971, figs. 104, 105).

SOME OUTSTANDING ISSUES

Site protection vs. agricultural activities

Heritage protection of a nominated area only relates specifically to the heritage values of that area, but landowners may still have concerns about possible restrictive impacts on agricultural and other activities. A statement of 'principles of engagement for Heritage Listing', prepared by Helen and Ian Cathles (owners of *Cooradigbee* and *Cookmundoon* stations in the Wee Jasper valley) to clarify rights of landowners, was submitted with the 2010 Heritage Nomination. The four main points may be summarized:

i) the nomination specifically included only fossiliferous outcrops and caves within the nominated area;

ii) the opportunity to integrate successfully conservation with agriculture was recognized, but 'without fear of loss of enterprise and personal infrastructure' where the heritage nominated area (as in this case) includes landowners' paddocks containing fossiliferous outcrops. In such agricultural areas surrounding these outcrops the continuation of essential agricultural activities such as 'bushfire hazard, weed control, feral animal control' would need to be guaranteed.

iii) past practice for the 'identification and preservation of these fossil outcrops' of national significance to be continued;

iv) differences from 'significant impact guidelines' (clause 1.1, Environmental Protection and Biodiversity Conservation Act 1999, p. 21) were noted – specifically, the fact that fossil specimens identified as significant would gradually deteriorate and disappear without intervention. Hence there is a special requirement for expert removal and preparation of fossil specimens, and their subsequent responsible care and housing in appropriate storage to ensure their preservation for posterity.

Collections support and protection

The point just stated focuses on potential incompatibility between protection of actual outcrops, and removal of fossils by various extractive processes that could be considered to damage such outcrops. In this case the scientific significance of specimens (and their enhanced heritage value) can be realized only after their removal for scientific preparation and study. This process greatly increases their information content, but in the case of acid-prepared Burrinjuck braincase material also produces scientific specimens of exceptional fragility, requiring adequate curation, and special care and long-term protection from damage (e.g. Russell and Winkworth 2009).

In these requirements the Burrinjuck fossil vertebrate material can be compared with the Riversleigh-Naracoorte linked World Heritage fossil mammal sites, which have produced some 118 vertebrate species (although from separate limestone and cave deposits of two completely different time periods). The Riversleigh specimens are also particularly fragile after acid extraction, and are permanently curated in the Queensland Museum, Brisbane, a recognized collecting institution, with both the tradition and a legal requirement for long-term preservation of its collections.

In contrast, the largest existing collection of Burrinjuck fossil fish material is a university collection housed on the ANU campus in Canberra. University collections in the state capitals all have a state museum or institutional equivalent where collections can be accessioned for permanent protection and preservation. This is not the case in the National Capital, where there is no museum that takes responsibility for natural history collections (among countries of the developed world Australia is probably unique in this respect). Accordingly, there is a university policy covering long term management, storage and conservation of significant collections, but minimal funding under current circumstances to achieve this. Unlike some famous universities overseas (Sedgwick Museum, Cambridge; Oxford, Harvard, Yale, University of California; numerous European and Russian universities; see Fig. 7C), there is no museum catering for relevant research materials and collections in any scientific field at the Australian National University. Although the ANU palaeontological collection contains numerous type specimens, is does not currently comply with requirements of some international journals regarding lodgement of types in accordance with requirements of the International Code of Zoological Nomenclature ('in an appropriate permanent institution, with staff and facilities capable of ensuring their conservation and availability for future reference in perpetuity'; quoted from 'Notes for Authors' of The Palaeontological Association, London, publishers of the international journals *Palaeontology* and *Special Papers in Palaeontology*). The geological curator position at the Australian National University was abolished 10 years ago, since when no person has had responsibility to maintain the general fossil collections.

Relevant to this issue is the observation that many other internationally recognized fossil localities, such as the Miguasha (Canada) and Naracoorte (S.A.) fossil World Heritage sites, the Canowindra Devonian fish site in NSW, and numerous examples in Europe, have established Visitor Centres with well-maintained displays and collections. A 'Wee Jasper Visitor Center', including interactive displays, and properly housed and curated on-site fossil collections, is envisaged as an essential future development to make more widely known the scientific significance of the Burrinjuck area. Of course, this would not diminish the scientific requirement that type and figured specimens be properly housed and curated in a recognized institution, to ensure their preservation in perpetuity as part of Australia's scientific and cultural heritage.

Stage II nomination

Negotiation with land-owners covering the eastern limestone outcrop [Taemas-Cavan] to support a 'Stage II' nomination is proposed, based on a successful outcome for the current nomination. The eastern area includes the stratigraphic type sections of all Murrumbidgee Group formations and members, the protected 'Shearsby's Wallpaper' fossil brachiopod exposure, and is historically and scientifically significant for fossil vertebrates, producing the first lungfish skull (the holotype of *Dipnorhynchus sussmilchi* Etheridge), and also holotypes of the placoderms *Taemasosteus novaustrocambricus* White, *Parabuchanosteus murrumbidgeensis* White, and *Shearsbyaspis oepiki* Young. Numerous fossil fish sites within the area were collected by H.A. Toombs in 1955 and 1963 (Fig. 3D). The Stage II nomination would also include the main area of outcrop and type sections for the Hatchery Creek Group to the west of Wee Jasper (areas labelled (II), Fig. 1C).

Repatriation of types from London

As noted above, when the 1955 and 1963 British Museum expeditions removed so much fossil vertebrate material from the Burrinjuck area without local knowledge, it caused great concern amongst Australian palaeontologists, and at least one letter of protest was sent to the British Museum. Probably to make amends, and with the necessity of negotiating with the then director of the Western Australian Museum (Dr David Ride), the 1967 joint British Museum-W.A. Museum expedition to the Gogo fossil fish site in the Kimberley region included an agreement to return type specimens and representative material to Australia. This is now a normal arrangement for scientific palaeontological collecting in most countries that restrict export of significant fossil specimens, as does Australia under the Moveable Cultural Heritage Act.

Repatriation from London of type specimens and representative material of Burrinjuck Devonian fossil fish held by the British Natural History Museum must be placed on the agenda, once the issues of long term protection of existing Australian collections is resolved.

SUMMARY

The Burrinjuck area has both national and international significance, from the fossil vertebrate perspective in the same class as some comparable World Heritage listed sites both in Australia and overseas. Main points of significance include:

i) a unique sequence of sedimentary strata some 5 km thick containing numerous fossil horizons encompassing the final terrestrialization of the earth's biota during the Devonian Period (~418-360 million years ago);

ii) the area has produced (and continues producing) uniquely preserved braincase structures of early vertebrates from ~400 million years ago, in a diversity of forms unequalled in any other fossil site in the world. Their significance remains undiminished in the modern era of molecular biology, the 'notable outstanding specimens ... from the Early Devonian of Taemas-Wee Jasper ... and ... Gogo' (Ahlberg et al. 2006, p. 338) still playing a key role in evolutionary studies (e.g. Friedman and Brazeau 2010).

iii) exceptionally exposed Early Devonian tropical reefs occur in the lower Goodradigbee valley, the massive reef limestones also containing significant karst and cave structures;

iv) Burrinjuck fossil fish represent the world's oldest known coral reef fish assemblage, and also the most diverse vertebrate fauna recorded from any Devonian fossil site in the world (the period called the 'Age of Fishes'); associated are numerous invertebrates including corals, bryozoans, stromatoporoids, brachiopods, gastropods, nautiloids and trilobites, giving a total of some 266 genera of vertebrate and invertebrate fossils documented so far;

v) the area produced five key specimens used in the 1940's in London to develop the acetic acid preparation technique, now standard in laboratories throughout the world for extracting fossil vertebrates from calcareous rock matrix, and it was the target of two collecting expeditions by the British Museum (Natural History) in 1955 and 1963, when some 560 specimens were removed to London.

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APPENDIX

Faunal list for Devonian fossil vertebrates from the Murrumbidgee Group limestones at Burrinjuck, updated from Young (2009, table 1) with additional taxa represented by newly prepared specimens (indicated by ANU V number).

AGNATHA
Thelodontida
1. *Turinia* sp. cf. *T. australiensis* Basden, 1999

GNATHOSTOMATA
ACANTHODII
2. *Cheiracanthoides comptus* Giffin, 1980
3. *Cheiracanthoides* sp. cf. *C. wangi* [Basden, 2001]
4. *Taemasacanthus erroli* Long, 1986
5. *Taemasacanthus porca* Lindley, 2000
6. *Taemasacanthus narrengullenensis* Lindley, 2002a
7. *Taemasacanthus cooradigbeensis* Lindley, 2002a
8. *Cavanacanthus warrooensis* Lindley, 2000
9. *Cambaracanthus goodhopensis* Lindley, 2000
10. *Nostolepis guangxiensis* Wang, 1992 [Basden, 2001]
11. *Nostolepoides platymarginata* Burrow, 1997 [Basden, 2001]
12. *Trundlelepis cervicostulata* Burrow, 1997 [Basden, 2001]
13. *Gomphonchus? bogongensis* Burrow, 1997 [Basden, 2001]

OSTEICHTHYES
Actinopterygii
14. *Ligulalepis toombsi* Schultze, 1968

Sarcopterygii
15. *Onychodus yassensis* Lindley, 2002b
16. ?osteolepid indet. Lindley, 2002b
17. porolepiform indet. Young, 1985

Dipnoi
Dipnorhynchidae
18. *Dipnorhynchus sussmilchi* (Etheridge) Hills, 1941
19. *D. kurikae* Campbell and Barwick, 1985, 2000
20. *D.(Placorhynchus) cathlesae* Campbell and Barwick, 1999; Campbell *et al., 2*009
21. *Speonesydrion iani* Campbell and Barwick, 1983
22. *Cathlorhynchus trismodipterus* Campbell, Barwick and Senden, 2009

CHONDRICHTHYES
23. *Ohiolepis* sp. Ørvig, 1969
24. *Skamolepis fragilis* Giffin, 1980

PLACODERMI
Arthrodira
25. *Buchanosteus confertituberculatus* Young, 1979
26. *Parabuchanosteus murrumbidgeensis* White and Toombs, 1972
27. buchanosteid n. sp. [ridged ornament] ANU 49387 [skull, braincase]
28. buchanosteid n. sp. [anterior nasal openings] ANU V2418 [rostral capsule]
29. *Burrinjucosteus asymmetricus* White, 1978
30. *Goodradigbeeon australianum* White, 1978
31. *Taemasosteus novaustrocambricus* White, 1952
32. *Toombsosteus denisoni* White, 1978
33. *Arenipiscis westolli* Young, 1981
34. *Errolosteus goodradigbeensis* Young, 1981
35. *Williamsaspis bedfordi* White, 1952
36. *Cavanosteus australis* (McCoy) Young, 2004a
37. *Cathlesichthys weejasperensis* Young, 2004b
38. *Dhanguura johnstoni* Young, 2004b
39. *Bimbianga burrinjuckensis* Young, 2005
40. ?holonematid n. g. [?*Bimbianga* sp. 2] ANU V2933 [SO plate]
41. *Elvaspis tuberculata* Young, 2009

42. *Elvaspis whitei* Young, 2009
43. small brachythoracid n. g. ANU 49384 [complete skeletons]
44. brachythoracid n.g. 1 'highly arched' (Young, 2009, p. 76) ANU V114 [PNu plate]
45. brachythoracid n.g. 2 [long para-articular process] ANU V156 [PNu plate]
46. brachythoracid n.g. 3 [MD contacts vertebral column] ANU V3118 [MD plate]
47. brachythoracid n.g. 4 [MD rounded carinal process; ANU V1059, 2386, 2403, 35332]
48. ?heterostiid n.g. [long cheek] ANU V79 [SO plate]
49. ?*Antineosteus* n.sp. ANU V1970 [SO plate]
50. ?*Atlantidosteus* n.sp. ANU V2946 [SO plate]
51. 'coccosteid' [lacking median spine] ANU V2899 [MD plate]
52. 'coccosteid' [posterior median spine] sp. 1 ANU V124, 1209, 2447 [MD plates]
53. 'coccosteid' [smooth posterior median spine] sp. 2 ANU V 3244 [MD]
54. 'coccosteid' [no spine; posterior carinal process] ANU V1863 [MD]

Acanthothoraci

55. *Weejasperaspis gavini* White, 1978
56. weejasperaspid n.g. [long spinal] ANU V38 [shoulder girdle]
57. *Brindabellaspis stensioi* Young, 1980
58. brindabellaspid n.g. [with spines] ANU V1062, 1264, 1883, 2925 [shoulder girdles, spines]
59. *Murrindalaspis wallacei* Long and Young, 1988

Rhenanida

60. rhenanid n.g. ANU V1077 [skull and braincase]

Petalichthyida

61. *Notopetalichthys hillsi* Woodward, 1941
62. *Wijdeaspis warrooensis* Young, 1978
63. *Shearsbyaspis oepiki* Young, 1985
64. *Lunaspis* sp. Young, 1985
65. petalichthyid n.g. ANU V2859 [skull and braincase]

Ptyctodontida

66. ptyctodontid n.g. Young, 1976
67. ?ptyctodontid n. g. ANU V2902 [skull and braincase]

Placodermi *incertae sedis*

68. placoderm n.g. [reverse neckjoint articulation] ANU V2392 [ADL plate]
69. placoderm n.g. [indet. bone] ANU V3123 [shoulder girdle plate]

Gnathostomata *incertae sedis*

70. new genus and species ['fish vertebrae'; Zapaznik and Johnston, 1984]

Incertae Sedis

71. *Ohioaspis tumulosa* Giffin, 1980

Preservation of the Rocky Beach Blueschist-Eclogite Outcrop, Port Macquarie, NSW as a Geoheritage Reserve

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Och, D.J. and Graham, I.T. (2011). Preservation of the Rocky Beach blueschist-eclogite outcrop, Port Macquarie, NSW as a geoheritage reserve. *Proceedings of the Linnean Society of New South Wales* **132**, 109-114.

Small outcrops of blueschist and eclogite occur at Rocky Beach, Port Macquarie, on the NSW mid north coast. These are geologically significant as they represent a unique *insitu* exposure of a rare high-pressure - low-temperature metamorphic sequence not seen elsewhere in Australia. They are also of great educational value to universities, school groups and the general public as they illustrate the effects and consequences of subduction zone processes at depth, now exposed on the surface. Being relatively easily accessible, the site is in danger of destruction by removal of samples and hence should be protected by being listed as a national geoheritage site or included within the nearby Sea Acres National Park.

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KEYWORDS: blueschist, geoheritage, lawsonite eclogite, Port Macquarie, Watonga Formation.

INTRODUCTION

The Rocky Beach Metamorphic Melange is located at Port Macquarie on the mid north coast of New South Wales, approximately 400 km north of Sydney (Figure 1a). It covers an area of just under 1 hectare and is locally bound by the Pacific Ocean to the east, Oxley Beach to the north, Flynns Point headland to the south, and a steep densely vegetated slope to the west, up to the sealed road which provides a buffer from the surrounding residential development on the western side of the road (Figure 1b, 2 and 3).

GEOLOGICAL SETTING

The Rocky Beach Metmorphic Melange forms part of the Port Macquarie Block (Och 2007), located in the eastern part of the southern New England Fold Belt (Figure 1c). It is notable for the presence of well-exposed (?) Early Cambrian to mid-Silurian high-pressure – low-temperature metamorphic rocks juxtaposed against Late Ordovician ribbon chert, siltstone, sandstone and pillow basalts of the Watonga Formation (Och et al. 2005, 2007) embedded in lenses of mid-Silurian serpentinite melange. Elsewhere along the coastal exposure, to the north and south of Rocky Beach, these rocks are intruded by minor mafic and intermediate calc-alkaline dykes and plutons (Och et al. 2005, 2007).

Similar rocks occur elsewhere in the New England Fold Belt associated with the disrupted boundary between Palaeozoic arc basinal rocks and accretionary subduction zone units. Radiometric dating from scattered localities suggests that the ultramafic protolith of the serpentinites has an age of ~ 530Ma (Aitchison and Ireland 1995). One eclogite phacoid is c.536 Ma (Fanning et al. 2002) and at Port Macquarie, the blueschists were dated by Fukui et al. (1995) using K-Ar at 469 Ma. Recent K-Ar dating of fuchsite from the chlorite-actinolite rind of the Rocky Beach Metamorphic Melange (a reaction rind between the blueschist and eclogite) indicates crystallisation at 427± 8 Ma, therefore defining a hydration age of the ultramafic rock (Och et al. 2010).

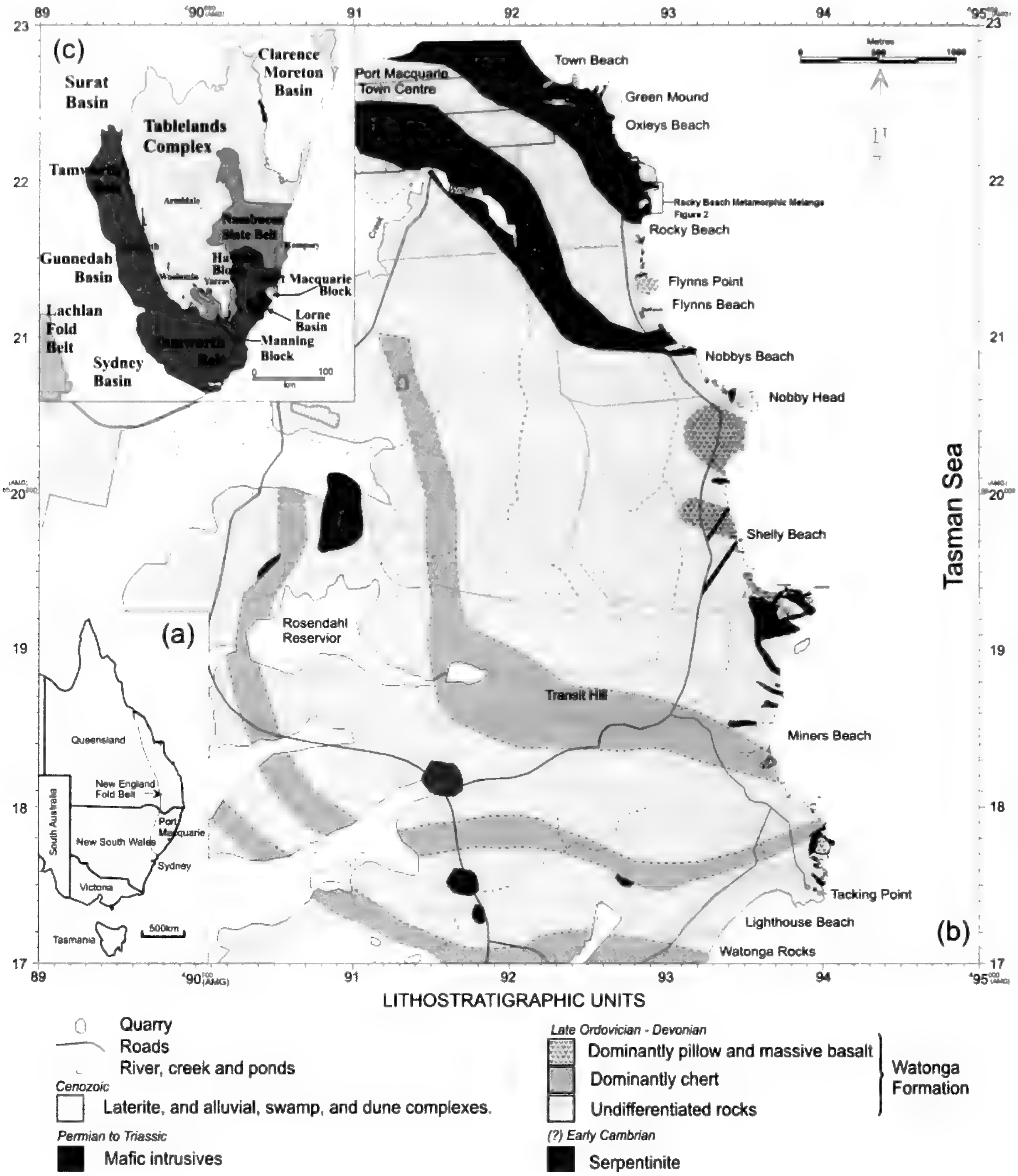

Figure 1 (a) Location of Port Macquarie in the eastern part of the southern New England Fold Belt. (b) Geological map of the northeast corner of the Port Macquarie Block. Map grid is AMG-66. (after Och et al. 2007). (c) The Port Macquarie Block and adjacent tectonic assemblages of the southern New England Fold Belt. Pale grey (Tablelands Complex) is mostly accretionary – subduction complex terranes, grey (Manning Block and Nambucca Slate Belt) Early Permian overlap sequences, and dark grey (Tamworth Belt) Palaeozoic arc and forearc deposits. Widespread latest Carboniferous-Triassic granite bodies omitted.

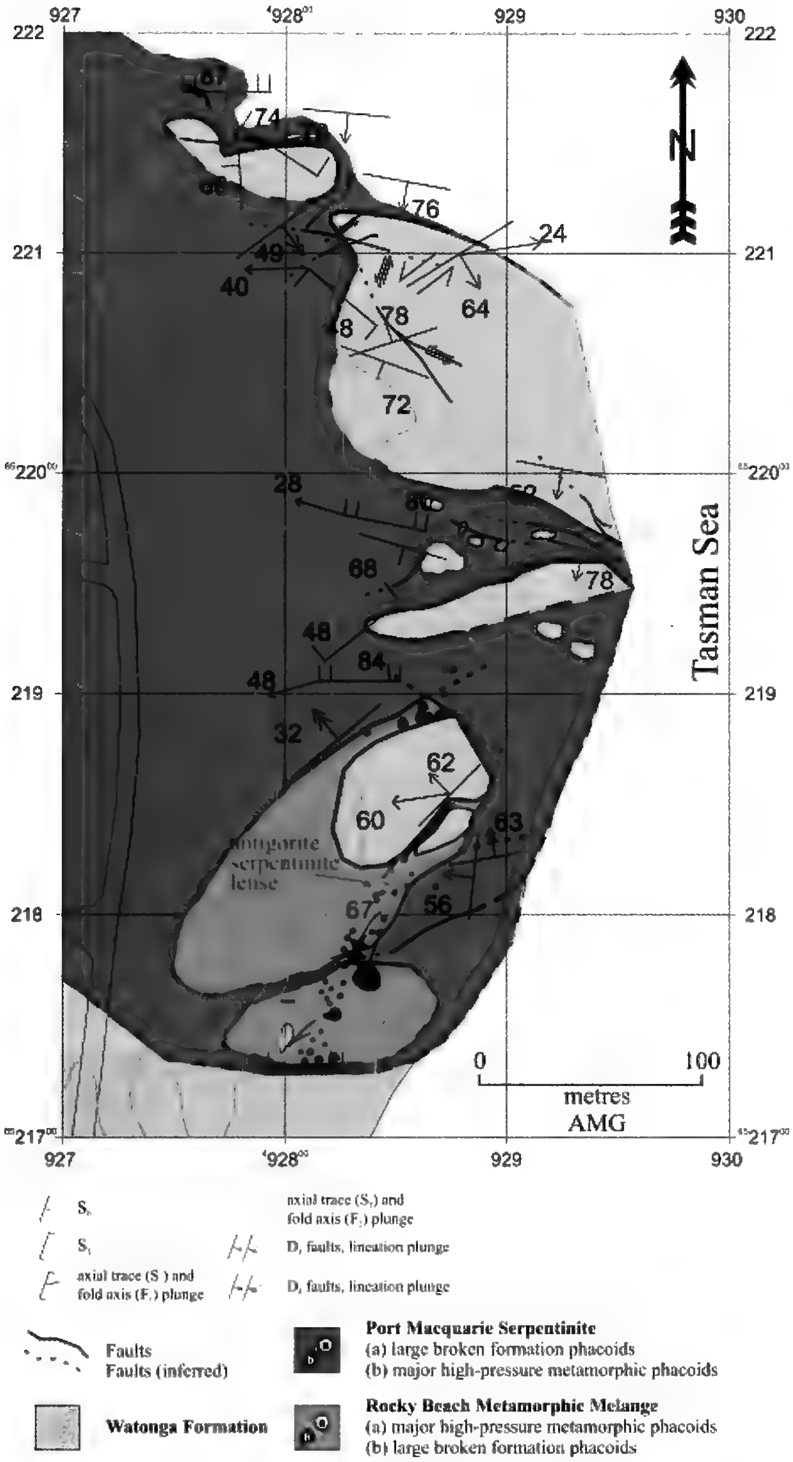

Figure 2 Geological map of the Rocky Beach Coastal outcrop.

LOCAL GEOLOGY

At Rocky Beach (Figure 2 and 3) a 'melange-in-melange' structure is preserved and consists of a serpentinite mass that has invaded the Watonga Formation, enveloping two lenses of high-pressure – low-temperature metamorphic rocks that consist of metre-scale phacoids of lawsonite eclogite (Figure 4a and 4b), omphacitite (Figure 5) and glaucophane schist embedded in a chlorite-actinolite schist matrix (Och et al. 2003, 2005, 2007; Och 2007). This exposure has excellent formational contacts (Figure 5) that demonstrate age relationships that are not observable for similar rock types elsewhere in Australia. The importance of this coastal exposure is the occurrence of a rare high-pressure - low-temperature metamorphic sequence.

DISCUSSION AND CONCLUSION

Geological significance of the Rocky Beach Metamorphic Melange:

- Globally, there are only 10 recorded occurrences of lawsonite eclogite in Phanerozoic orogenic belts (Tsujimori et al. 2006).
- This is possibly the oldest known occurrence, along with a similar occurrence in Spitsbergen in the Arctic.
- Formation and preservation of this sequence requires cold subduction to mantle depths and rapid exhumation.
- The lawsonite eclogite and omphacitite at Rocky Beach are the only occurrences documented in Australia for these rock types.

Social Significance of the Rocky Beach Metamorphic Melange:

- The variety of ancient rocks and excellent exposures along this coastline provide a scientific interest for visitors.
- Ready accessibility of the coastal outcrops have attracted numerous geological visitors, including university undergraduate groups, geological conference excursions, and research scientists from around the world.

Allocating a geoheritage reserve status to this sequence at Rocky Beach would help preserve it for future geology students, researchers and geotourists. As the rocks are very limited in distribution and rare, protection would be achieved with a declaration as an Australian geoheritage site. This would require anyone who requires samples for analysis to obtain necessary permission from the relevant authority (e.g. NSW National Parks and Wildlife Service). To allow for easy access to this site, a staircase and a walkway would need to be constructed from the coastal walk to the beach below with a possible exit staircase at Flynns Point, also along the coastal walk. Plaques describing distinctive geological units and specific rock types would allow the coastal walk to become a

Figure 3 The Rocky Beach coastal section looking north at low tide.

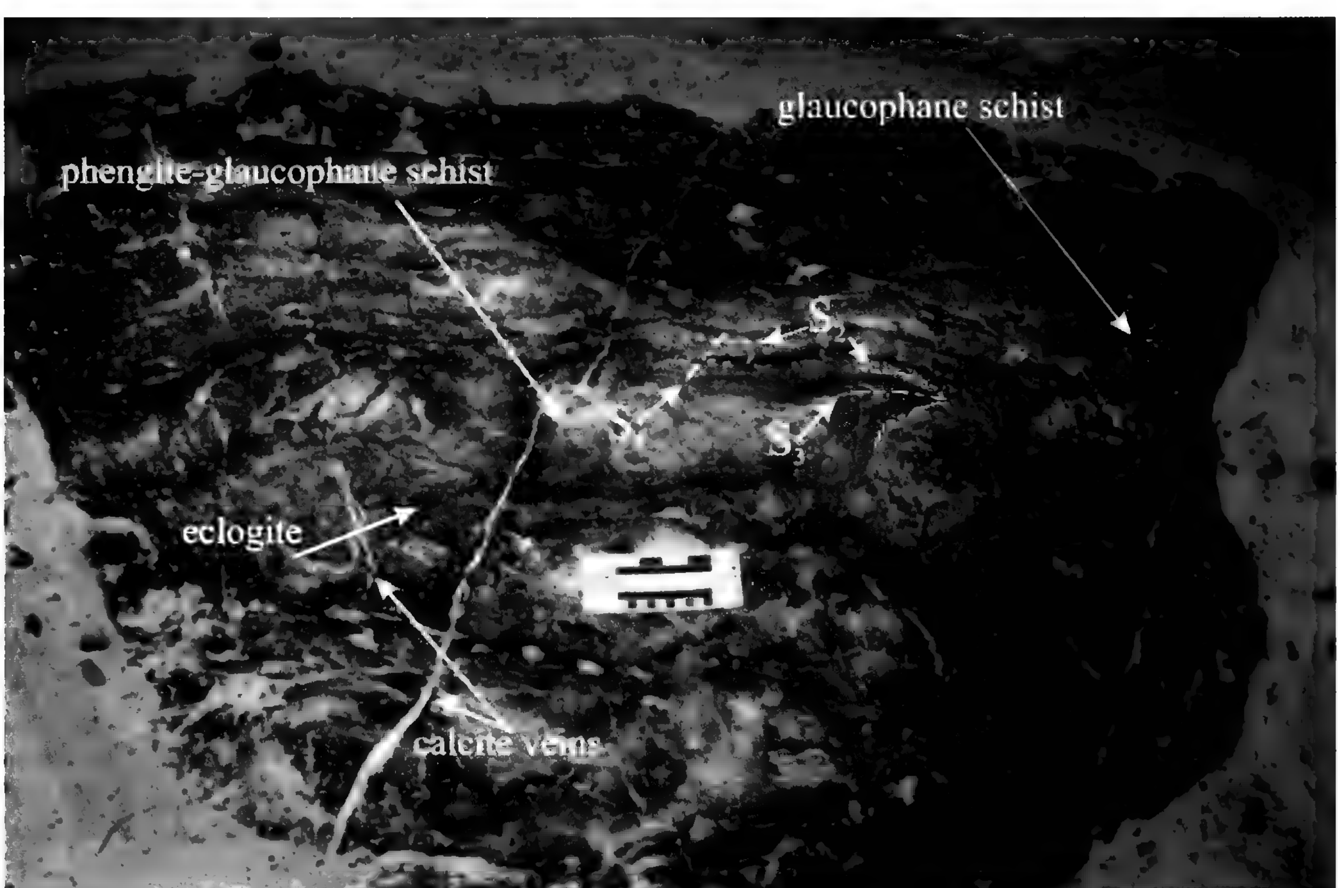

Figure 4A Eclogite phacoid with annotated structural elements (Och 2007), surrounded by sand in the intertidal zone at Rocky Beach (GR 92792178).

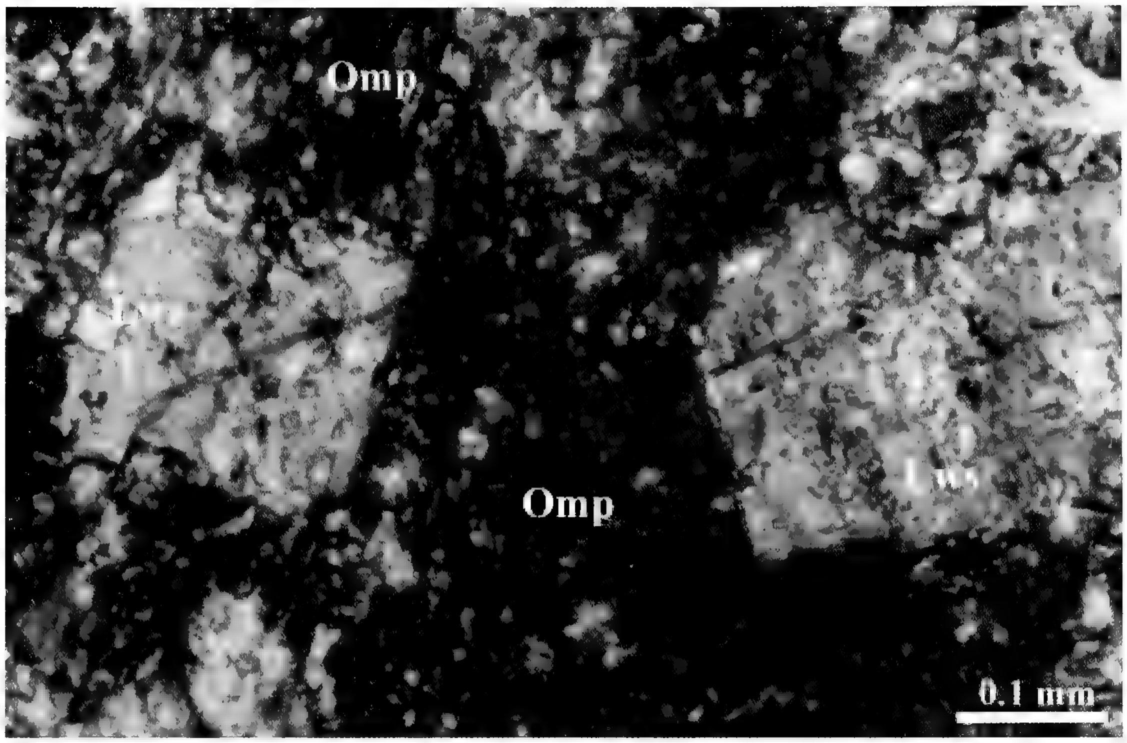

Figure 4B Straight and corroded grain boundaries between omphacite (Omp) and lawsonite (Lws) from eclogite (sample Ptmk432).

geological tourist trail (ie. Town beach, Rocky Beach, Miners Beach and Tacking Point) additionally helping to promote geotourism in the Port Macquarie region.

We believe that allowing access through this area would have a positive impact on the preservation of these rare rock types. The volume of people that would view the geology and detailed signage prohibiting sampling of the outcrops would help stop collectors. The significance of this site to our understanding of the geological evolution of eastern Australia and the extremely rare occurrence of some of these rock types on a global scale would also warrant it being included within an expanded Sea Acres National Park.

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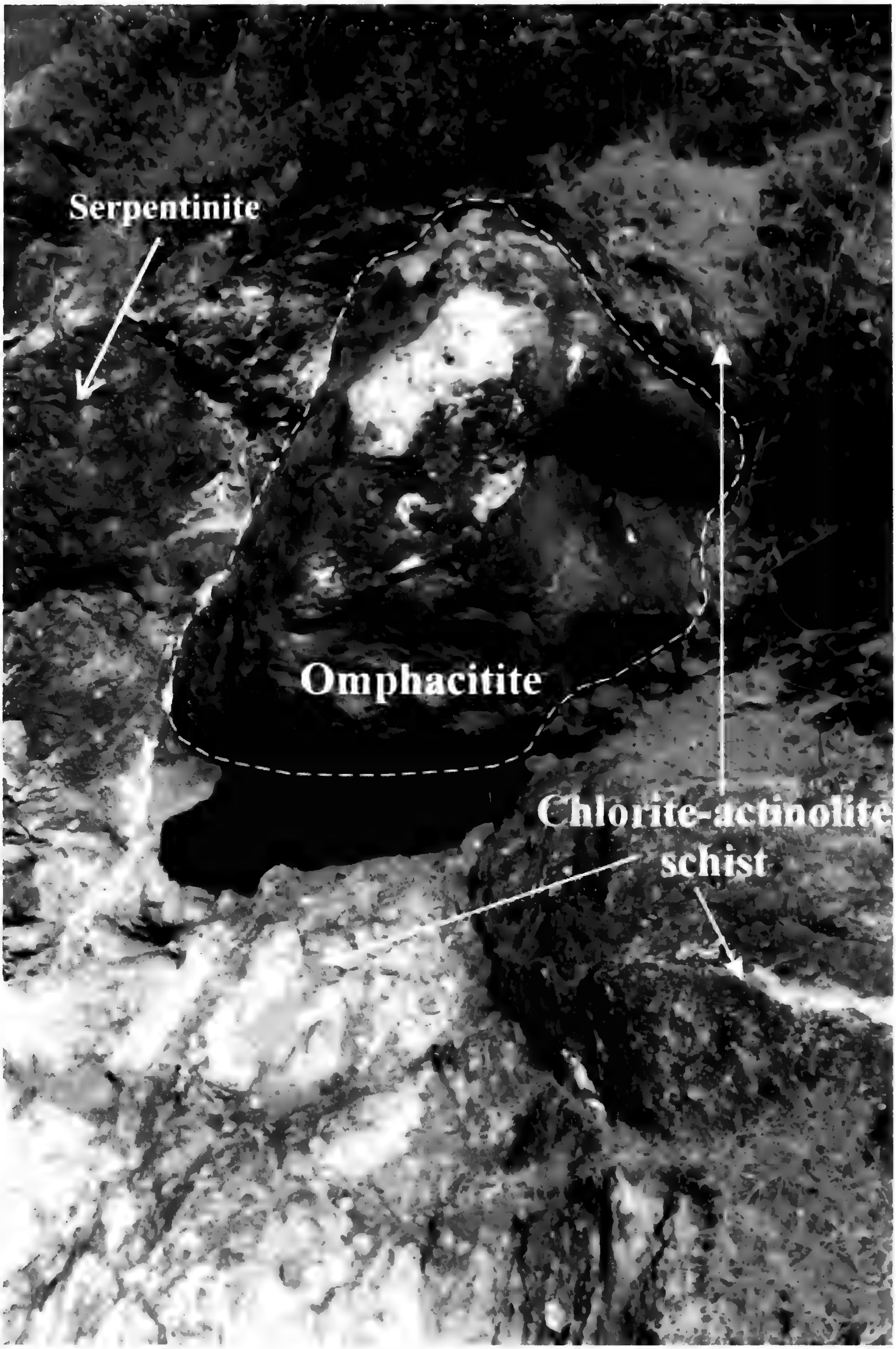

Figure 5 Omphacitite phacoid (outlined) embedded in chlorite-actinolite schist matrix, Rocky Beach Metamorphic Mélange, Rocky Beach (GR. 92812147). Diameter of phacoid is ~ 1.4 m.

Assessing Geoheritage Values: a Case Study Using the Leschenault Peninsula and its Leeward Estuarine Lagoon, South-western Australia

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Brocx, M. and Semeniuk, V. (2011). Assessing geoheritage values: a case study using the Leschenault Peninsula and its Leeward Estuarine Lagoon, south-western Australia. *Proceedings of the Linnean Society of New South Wales* 132, 115-130.

To further the disciplines of geoheritage and geoconservation, a Geoheritage "tool-kit" has been developed to systematically compile an inventory at various scales of geological and geomorphological features in a given area, assess their levels of significance, and address whether geoheritage features are treated in isolation or as inter-related suites that should be conserved as an ensemble. The Leschenault Peninsula, a retrograding Holocene dune barrier in south-western Australia, and its leeward estuarine lagoon, provide a case study of the application of this tool-kit. The barrier-and-lagoon is unique in Western Australia and comprises a wide variety of geological and geomorphological features, from large to fine scale, and varying in significance from International to State-wide to Regional. Some key features include: active parabolic dunes; an interface between dunes and estuary that is the most complex sedimentologically, hydrologically, and ecologically in Western Australia; a stratigraphy recording a complex Holocene sea level history; barrier retreat marked by parallel bands of submerged beach rock; and a sheet of calcrete above the water table. In terms of geoconservation, addressing the various features of geoheritage value in this area is best achieved by viewing the system as an integrated geopark of interactive processes, geology, and geomorphology.

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Keywords: dune barrier, estuarine lagoon, geoconservation, geoheritage, geoheritage tool-kit, Holocene, Leschenault Peninsula, south-western Australia.

INTRODUCTION

Geoheritage and geoconservation have become significant endeavours in the conservation of important geological features. Within a broadly defined scope of geoheritage of Brocx and Semeniuk (2007), and building on Brocx (2008), a Geoheritage "tool-kit" has been developed to assess geological and geomorphological features that should be encompassed under the umbrella of geoheritage. In a given area, geoheritage features of geoconservation significance can range from large scale to fine scale, from international to local in significance, can encompass a wide range of geological/geomorphological features, and can occur in isolation, or as an inter-related suite that should be conserved as an ensemble. This Geoheritage tool kit has been designed to systematically address and assess this diversity.

This paper outlines the concepts underpinning the approach adopted for use in geoheritage and geoconservation, and describes the Geoheritage tool-kit. It provides a case study of Leschenault Peninsula and its leeward estuarine lagoon, where the tool-kit has been applied to identify sites and features therein, and evaluate their significance. This tool-kit aims to address the classification and assessment challenges for land managers and geoheritage practitioners.

SCOPE, SCALE, AND LEVELS OF SIGNIFICANCE OF GEOHERITAGE FEATURES

The term geoheritage is used as follows (after Brocx and Semeniuk 2007):

Globally, nationally, state-wide, to local features of geology, such as its igneous, metamorphic, sedimentary, stratigraphic, structural, geochemical, mineralogic, palaeontologic, *geomorphic, pedologic, and hydrologic attributes, at all scales, that are intrinsically important sites, or culturally important sites, that offer information or insights into the formation or evolution of the Earth, or into the history of science, or that can be used for research, teaching, or reference.*

This perspective definitively places many aspects of geology, previously perhaps not recognised as part of the spectrum of geoheritage, firmly under its umbrella.

While geoheritage relates to features of a geological nature, geoconservation is the action that works towards the preservation of sites of geoheritage significance once their level of significance has been determined.

Following Brocx and Semeniuk (2007), sites of geoheritage significance can be assigned to one of four conceptual categories (Figure 1): 1. as reference sites and/or type locations; 2. as sites of cultural or historical significance; 3. as geohistorical sites showing ancient sequences where the history of the earth can be determined; and 4. modern landscapes and setting where Earth processes are still active.

Scale is important to consider in geoheritage and geoconservation since geoheritage sites can range from landscapes and geological phenomena at montane-scale, to that of outcrops, beddings planes, or a crystal (for examples, see Brocx and Semeniuk, 2007). Formal application of scale to describe or denote geological features for assessing geoheritage and for geoconservation follows Brocx and Semeniuk (2007):

Regional scale (or megascale): geological/geomorphological features encompassed by a frame of reference of 100 km x 100 km or larger; examples include mountain range scale, or drainage basins;

Large scale (or macroscale): geological/geomorphological features encompassed by a frame of reference of 10 km x 10 km; examples large outcrop scale features, or barrier islands;

Medium scale (or mesoscale): geological/geomorphological features encompassed by a frame of reference of 1 km x 1 km or larger; examples include small mesas and their adjoining plain;

Small scale (or microscale): geological/geomorphological features encompassed by a frame of reference of 10-100 m x 10-100 m; examples include local cliff exposures;

Fine scale (or leptoscale): geological/geomorphological features encompassed by a frame of reference of 1 m x 1 m; examples include bedding scale features such as fossil beds and animal tracks;

Very fine scale: geological/geomorphological features encompassed by a frame of reference of 1 mm x 1 mm or smaller; examples include small crystals.

Levels of significance assigned to geoheritage sites have been defined for Western Australia in Brocx and Semeniuk (2007), but the principles are applicable worldwide. While various levels of significance have been used globally, nationally in Australia, and within Western Australia (viz., International, National, State-wide/Regional, and Local), there generally have not been definitions of these terms until recently (as discussed in Brocx 2008). The criteria adopted here for levels of significance are (Brocx and Semeniuk 2007):

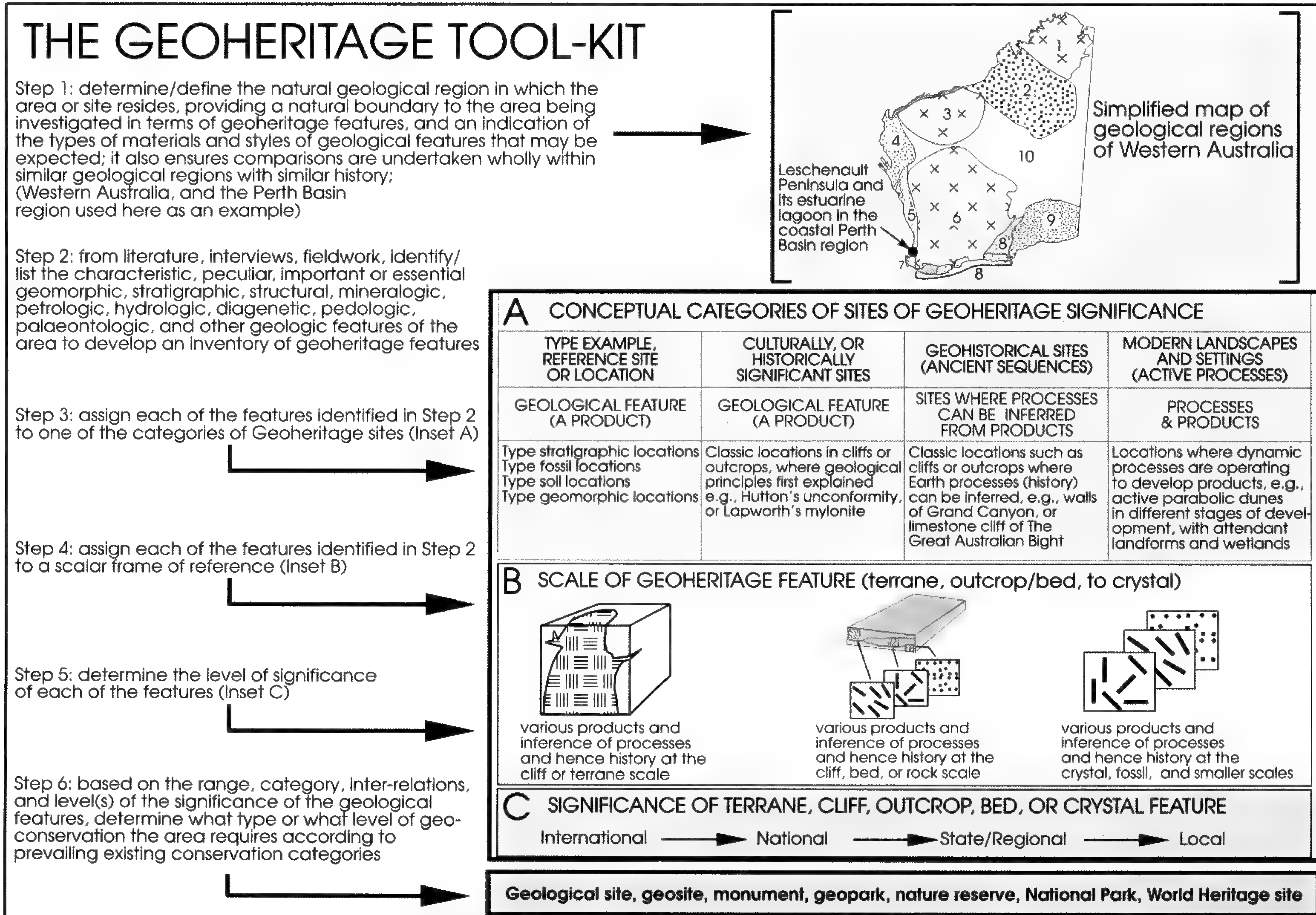
International: one of, or a few, or the best of a given feature globally;

National: though globally relatively common, one of, or a few, or the best of a given feature Nationally;

State-wide/Regionally: though globally relatively common, and occurring throughout a Nation, one of, or a few, or the best of a given feature State-wide or Regionally;

Local: occurring commonly through the world, as well as Nationally to Regionally, but especially important to local communities.

Figure 1 OPPOSITE: The elements of the Geoheritage tool-kit showing the six steps in its application leading to assessment of types of geoconservation. The map of Western Australia in Step 1 also shows the location of the Study Area. The simplified geological regions of Western Australia are (from Brocx and Semeniuk 2010, modified from the Geological Survey of Western Australia 1990): 1. Precambrian Kimberley Region; 2. Phanerozoic Canning Basin; 3. Pilbara Region (with three Precambrian units, and a coastal fringe of Cainozoic sediments); 4. Phanerozoic Carnarvon Basin; 5. Phanerozoic Perth Basin; 6. Precambrian Yilgarn Craton; 7. Precambrian Leeuwin-Naturaliste Orogen; 8. Precambrian Fraser-Albany Orogen and Tertiary Bremer Basin; 9. Tertiary Eucla Basin; and 10. undifferentiated regions. The diagram showing the scope of geoheritage in terms of its conceptual categories (A), its scales of application (B), and potential levels of significance (C) for Steps 3-5 is adapted from Brocx (2008).


THE GEOHERITAGE TOOL-KIT
Step 1: determine/define the natural geological region in which the area or site resides, providing a natural boundary to the area being investigated in terms of geoheritage features, and an indication of the types of materials and styles of geological features that may be expected; it also ensures comparisons are undertaken wholly within similar geological regions with similar history; (Western Australia, and the Perth Basin region used here as an example)
Simplified map of geological regions of Western Australia
Leschenault Peninsula and its estuarine lagoon in the coastal Perth Basin region
1
2
3
4
5
6
7
8
9
10
Step 2: from literature, interviews, fieldwork, identify/list the characteristic, peculiar, important or essential geomorphic, stratigraphic, structural, mineralogic, petrologic, hydrologic, diagenetic, pedologic, palaeontologic, and other geologic features of the area to develop an inventory of geoheritage features
Step 3: assign each of the features identified in Step 2 to one of the categories of Geoheritage sites (Inset A)
Step 4: assign each of the features identified in Step 2 to a scalar frame of reference (Inset B)
Step 5: determine the level of significance of each of the features (Inset C)
Step 6: based on the range, category, inter-relations, and level(s) of the significance of the geological features, determine what type or what level of geo-conservation the area requires according to prevailing existing conservation categories
A CONCEPTUAL CATEGORIES OF SITES OF GEOHERITAGE SIGNIFICANCE
TYPE EXAMPLE, REFERENCE SITE OR LOCATION
GEOLOGICAL FEATURE (A PRODUCT)
Type stratigraphic locations
Type fossil locations
Type soil locations
Type geomorphic locations
CULTURALLY, OR HISTORICALLY SIGNIFICANT SITES
GEOLOGICAL FEATURE (A PRODUCT)
Classic locations in cliffs or outcrops, where geological principles first explained e.g., Hutton's unconformity, or Lapworth's mylonite
GEOHISTORICAL SITES (ANCIENT SEQUENCES)
SITES WHERE PROCESSES CAN BE INFERRED FROM PRODUCTS
Classic locations such as cliffs or outcrops where Earth processes (history) can be inferred, e.g., walls of Grand Canyon, or limestone cliff of The Great Australian Bight
MODERN LANDSCAPES AND SETTINGS (ACTIVE PROCESSES)
PROCESSES & PRODUCTS
Locations where dynamic processes are operating to develop products, e.g., active parabolic dunes in different stages of development, with attendant landforms and wetlands
B SCALE OF GEOHERITAGE FEATURE (terrane, outcrop/bed, to crystal)
various products and inference of processes and hence history at the cliff or terrane scale
various products and inference of processes and hence history at the cliff, bed, or rock scale
various products and inference of processes and hence history at the crystal, fossil, and smaller scales
C SIGNIFICANCE OF TERRANE, CLIFF, OUTCROP, BED, OR CRYSTAL FEATURE
International → National → State/Regional → Local
Geological site, geosite, monument, geopark, nature reserve, National Park, World Heritage site

The boxed text and illustrations labelled A, B, C, in Figure 1 summarise the scope of geoheritage in terms of its conceptual categories, its scales of application, and potential levels of significance that can be assigned to sites.

IDENTIFYING SITES OF GEOHERITAGE SIGNIFICANCE

There are a number of ways that sites of geoheritage significance may/can be identified. The British and European literature provides a history of how this has been achieved, with the final outcome being an inventory-based approach (Doyle et al 1994; Wimbledon et al. 1995, 1996; for discussion see Brocx 2008). For instance, since 1949, the assessment and subsequent selection of sites in the United Kingdom has been undertaken on the basis of a series of blocks which may be based on time, subject or regional divisions, or combinations thereof. In 2001-2002 ProGEO contributed to a number of important geoconservation initiatives that included the incorporation of a policy statement relating to the importance of geology and physical landscapes in the Pan-European Biological and Landscape Diversity Strategy, and an alliance with the International Union of Geological Sciences and UNESCO for the purpose of compiling a European inventory for the Geosites project (ProGEO 2002).

A systematic inventory-based approach to geoheritage and geoconservation requires a procedure. Identifying geological regions and the geological essentials of those regions provides the first step to developing such a procedure in order to identify the fundamental geological features for geoheritage of a given region (Brocx and Semeniuk 2010). Clearly not all aspects of geology of the Earth are present in the one region, and clearly not all aspects of the geology of a region may be of geoheritage significance - the former, for instance, recognises the unique occurrence, rarity, or representativeness of some geological features, and the latter requires some measure of assessment of significance. The Chalk, for example, well exposed along the southern coast of England, along the Cliffs of Dover is an essential feature of geoheritage significance of the south-eastern and southern coast of England (Gallois 1965; Melville and Freshney 1982; Brocx and Semeniuk 2010). Similarly, the Grand Canyon in Arizona (Holmes 1966; Shelton 1966) is a feature of international heritage significance not found outside of its area of occurrence. In Australia, Shark Bay is a World Heritage site not replicated elsewhere globally, and some of its essential features of international significance include its large scale stratigraphy, the deep-embayed limestone coastal morphology, seagrass banks, the coquina deposits, stromatolites, high-tidal crusts, high-tidal gypsum crystals, gypsum-filled birradas, modern ooid sand banks, Pleistocene oolite, and high cliffs cut into Pleistocene limestone (Logan 1970, 1974; Brocx and Semeniuk 2010). In each of these world class examples cited above, the geoheritage essentials of a given area tend to be unique to that area.

Identifying the geological essentials of a region requires recognising those geological features that *characterise*, or are *peculiar*, to a given natural geological region. This was the approach adopted in Western Australia as part of the Regional Forests Agreement where sites of geoheritage significance were determined within a framework in which the *geological essentials* of the region were identified (Semeniuk 1998). In the Yilgarn Craton, the Precambrian rock types, features that illustrate their structural and metamorphic history, the laterite, and the landscape comprise the geological essentials of that region. On the Nullarbor Plain, the Tertiary limestone, the coastal cliffs, the karst, the cave sedimentary deposits, the late Cainozoic surficial aeolian sand sheet, and wetlands would be identified.

The geological essentials of a region can be identified using a staged three-pronged approach to compile an information database on the geology of an area and at the same time potentially identifying sites of geoheritage significance. The first draws on the experience of geologists as published in the literature. The second seeks the views of geologists still practising in the field (through questionnaires/ interviews); this approach provides information and personal insights about the geoheritage potential of an area. The third, after identifying gaps in information seeks to systematically obtain further information based on regional geology. For all three approaches, there will be some degree of overlap in information and outcomes.

Identifying the various geological regions, and their contained/intrinsic features, therefore, is the first stage of a systematic inventory-based approach to developing a database for sites of geoheritage significance. This does not necessarily translate to just listing isolated sites of geoheritage significance but also attempts to identify ensembles of features where they are inter-related. The next stage would be to locate good examples, regardless of scale, of these features or of inter-related ensembles of features, and assess them according to the significance criteria outlined above.

THE GEOHERITAGE TOOL-KIT: A SYSTEMATIC PROCEDURE TO IDENTIFY AND ASSESS SITES OF GEOHERITAGE SIGNIFICANCE

The Geoheritage tool-kit provides the procedure to identify geological components across various geological sub-disciplines and at various scales, to assign geological sites to various conceptual categories of geoheritage, and to assess the levels of significance of the various geological features (Figure 1). The procedures outlined in Steps 1-6 below assume that the wider definition of what constitutes 'geoheritage', as discussed in Brocx and Semeniuk (2007), is being applied.

Step 6 of the procedure, after an assessment of the range, categories, inter-relationships, and level of significance of the geological features, determines what type and what level of geoconservation the area requires – Regional/State, National, or International.

Once the inventory of components and their level of significance are compiled, and enough geological features have ranked as being of significance, or a few rank as being of high significance, Step 6 is used to determine whether the area can be proposed/proffered for geoconservation at a Regional, State, National or International level for one or a few of its components, or for the integrated ensemble of its components. If the latter, the area may qualify to be viewed as a geological park or a geopark (see Discussion later). The area may be proposed/proffered for geoconservation especially if there is a range of inter-related geological features that all ranked highly in assessment of significance.

THE LESCHENAULT PENINSULA AND ITS LEEWARD ESTUARINE LAGOON - A DESCRIPTION

The Leschenault Peninsula and its leeward estuarine lagoon (the Leschenault Inlet estuary) located in south-western Australia (Figure 1), provide an excellent case study of how the Geoheritage tool-kit can be applied, as there is a wide range of geological features that range in scale from large scale to fine scale, cross a wide range of geological phenomena, and range in significance from International, National to State-wide. Selected key features of the stratigraphy, geomorphology, sea level history, diagenesis, and pedology of this area are presented in Figure 2.

The Leschenault Peninsula is the only Holocene linear dune barrier system in Western Australia. Its leeward estuarine lagoon is one of four large estuaries located along the south-western coast of Western Australia (see Semeniuk et al. 2000a, 2010 for comparative detail) developed along the shore of the Swan Coastal Plain, the surface expression of the Perth Basin.

In terms of classification for comparative coastal geoheritage purposes, Brocx and Semeniuk (2010) assign the Leschenault Peninsula and its lagoon to the Perth Basin Geological Region, and assign it to Coastal Type 7 and Coastal Type 11, i.e., a coast constructed by sedimentation with superimposed erosion, and a depositional coast recording Holocene history, respectively.

The text below describing the Leschenault Peninsula and its leeward estuarine lagoon, in terms of its geology, geomorphology and active processes, draws only on the essential patterns of this barrier and estuarine system from the published literature.

The dune barrier is located in a subhumid climate with mean annual rainfall of 880 mm, an annual evaporation of 1300 mm (Bureau of Meteorology 1988), an onshore (sea breeze) and offshore (land breeze) wind system, with winds reaching 15 m/s during summer and mean speeds up to 20 m/s during winter storms (Semeniuk and Meagher 1981a). The barrier coast faces the open Indian Ocean, with swell and wind waves directly impinging on the shore without offshore barriers perturbating, dissipating, or dampening the wave fields; tides are microtidal (Searle and Semeniuk 1985). For winter storms that derive from northwest, the estuarine lagoon has a long fetch to generate storm waves along the length of the estuarine lagoon.

The Leschenault Peninsula is a linear retrograding dune barrier, and is the southern part of the Leschenault-Preston Barrier (Semeniuk 1996) that formed during the post-glacial transgression when sea level reached near its present position in the Holocene ~ 7000 years ago (Semeniuk et al. 2000a). The initial, longer, more extensive, early Holocene barrier (75 km long, and approximately 0.5-1.5 km wide) formed because, unlike the rest of coastal south-western Australia, which is dominated by lines of offshore limestone islands, submerged ridges and reefs, associated onshore cuspate forelands and other sandy accumulations (formed leeward of the discontinuous and perforated offshore aeolian limestone barrier), and limestone rocky shores (Searle and Semeniuk 1985), the coast between Preston and Leschenault Peninsula offshore is shelter-free (i.e. without offshore limestone islands, ridges, and reefs), and subject directly to swell and wind waves (Searle and Semeniuk 1985). As such, instead of discrete

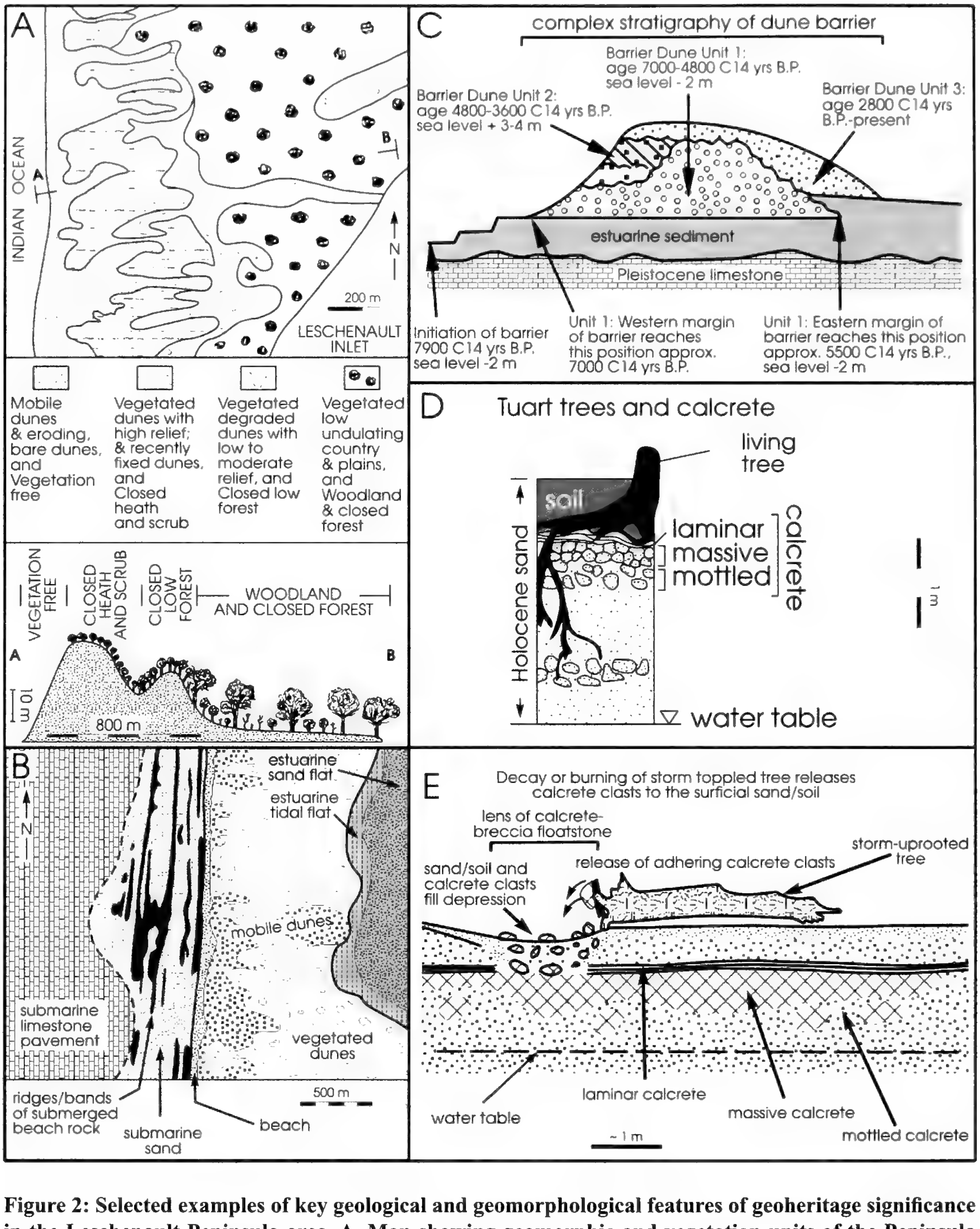


Figure 2: Selected examples of key geological and geomorphological features of geoheritage significance in the Leschenault Peninsula area. A. Map showing geomorphic and vegetation units of the Peninsula and cross section showing the change from west to east from relatively high relief terrain to undulating plains (Semeniuk & Meagher 1981a). B. Map showing ridges and bands of submerged beach rock seaward of the Leschenault Peninsula (Semeniuk & Meagher 1981a). C. The complex stratigraphy of the barrier showing its internal units and their ages relative to MSL (Semeniuk 1985). D. Calcrete forming above the water table by tuart trees (Semeniuk & Meagher 1981b). E. Development of lenses of calcrete breccia floatstone in soils following decay and/or burning of storm-uprooted trees that have ripped up calcrete during their upheaval (Semeniuk 1986b).

cuspate forelands and limestone rocky shores, that typify the rest of south-western Australia's shores, the coast has developed this extensive linear barrier.

The Leschenault Peninsula dune barrier, 15 km long, 15-30 m high, at the southern end of the Leschenault-Preston Barrier, is narrow, generally 0.5-1.0 km wide, and composed of overlapping eastward migrating parabolic dunes in various stages of mobility and fixation (Figures 2A, 2B, 2C and 3B). The gradation in time in landscape-and-vegetation evolution of these dunes are: mobile parabolic dunes, grading to fixed parabolic dunes with heath cover and incipient to weakly developed humic soils, to (naturally) geomorphically degraded parabolic dunes with forest cover and strongly developed but thin humic soils, to (naturally) geomorphically degraded undulating plains and plains with a woodland cover of tuart trees (*Eucalyptus gomphocephala*) and strongly developed thick humic soils (Figure 2A; Semeniuk and Meagher 1981a). The stratigraphy of the barrier is complex (Figure 2C), reflecting a complex Holocene sea level history and barrier development with a sea level –2 m AHD between 7000 and 3500 years BP, a sea level +3-4 m AHD some 3500-2000 years BP, and with a sea level falling to present level from 2000 years BP to the present (Semeniuk 1985), the result of local tectonism (Semeniuk and Searle 1986). A sheet of calcrete is forming in the zone of capillary rise above the modern water table (Figure 2D), induced by plant extraction of groundwater, leaving a residue of fine grained calcite (around the tuart tree root hairs) that accumulates and coalesces to form mottles, and then (coalescing of mottles to form) massive calcrete, capped by laminar calcrete (Semeniuk and Meagher 1981b). Wind excavation of sand in the bowls of the parabolic dunes exposes the calcrete sheet, which forms a floor to the parabolic dune bowl. Plains with tuart woodlands develop sheets of calcrete, while copses of isolated tuart stands develop lenses of calcrete. While this copse *versus* woodland/forest association is present on the Leschenault Peninsula, it is also reflective of a climate gradient: forests and woodlands of tuarts predominate in humid climates and develop sheets of calcrete in the zone of capillary rise, while copses and isolated stands of tuarts in less humid climates develop lenses of calcrete in the zone of capillary rise (Semeniuk 1986a).

Since the level of the water table under Leschenault Peninsula is and has been related to the position of MSL, then calcrete formed earlier in the Holocene under different levels of MSL and different heights of the water table is at lower or higher stratigraphic levels than the modern calcrete sheet. Further, calcrete occurs as lenses at these different stratigraphic levels, indicating that the tuarts earlier in the Holocene formed copse vegetation formations and not woodlands and forests, thus signalling a different climate. These higher or lower stratigraphic level calcrete lenses have been used to reconstruct Holocene climate (Semeniuk and Searle 1985; Semeniuk 1986a).

Periodically, major storms and cyclones impact on the dune barrier, up-rooting the large trees and in the process locally ripping up the calcrete sheet within which their roots are embedded, creating a depression in the soil sheet. Later filling of the depression by sheet wash and fragments of calcrete develops a lens of calcrete breccia floatstone (Semeniuk 1986b). This process, on-going during the later Holocene, has developed isolated lenses of the calcrete breccia floatstone within the soils underlying the woodland plains (Figure 2E).

In the core of the dune barrier there is a "shoestring" or prism of freshwater bordered to the sea and to the estuary by saline water, with an inclined saline water / freshwater interface on both sides. Freshwater discharges by seepage to the sea shore resulting in the formation of beach rock (Semeniuk and Searle 1985), and to the estuary shore resulting in ecological responses (Cresswell 2000; Pen et al. 2000; Semeniuk et al. 2000b), calcitisation of estuarine plant roots by encrustation and permineralisation, and precipitation of calcitic laminae (Semeniuk 2010).

Beach rock, formed at the shoreline of the seaward edge of the barrier with time-staggered coastal retreat during periodic storms and cyclones, is left stranded as a submerged ridge or band of cemented sand (rock) off shore from the barrier (Figure 2B). Successive periods of formation of beach rock, and retreat of the barrier during storms, has left a series of shore-parallel bands and ridges of this rock reflecting the various former position of the shoreline of the retreating dune barrier (Semeniuk and Searle 1987).

The Leschenault Inlet estuary, leeward of the dune barrier, is an elongate shore-parallel, shallow water estuarine lagoon with distinctive patterns of bathymetry and geomorphology, framed to the east by the Mandurah-Eaton Ridge (a Pleistocene quartz sand ridge; Semeniuk 1997), to the west by the Holocene dune barrier, and to the south by two deltas Semeniuk 2000; Semeniuk et al. 2000a). One delta is tide-dominated (the Preston River Delta); the other overall is fluvial-dominated but asymmetric, with the southern part fluvial-dominated, and the northern partly storm-developed (the Collie River Delta). The estuarine lagoon is diurnally microtidal, wave-dominated and wind-current-driven. Estuarine waters are annually poikilosaline, alternating between brackish/marine salinity in winter and marine salinity in summer (Wurm and Semeniuk 2000). At the large scale, stratigraphic relationships within the system are relatively simple (Semeniuk 2000). Estuarine sediments to the east onlap the Pleistocene quartz sand ridge, and Holocene dune barrier sands encroach over estuarine sediments to the west. Sedimentary patterns are underpinned by geomorphology and bathymetry, and linked to the lithologic nature of the dune terrain bordering the lagoon, as well as the nature of shorelines and the reworking of sources and hydrodynamics; with muddy sediments accumulating in deeper water basins and semi-sheltered environments, and sand accumulating on exposed platforms, dune margins, or in deltas (Pen et al. 2000). There are facies changes in the estuary from east to west, dependent on the source of shore sand, the bathymetry, and facies changes from south to north, from delta-dominated in the south to shallow mud flat dominated in the north (where south-westerly winds have carried mud in suspension to north to form in a large accumulation) (Semeniuk 2000). Small scale geomorphology and stratigraphic relationships along the dune barrier margin with the estuary are more complex, with spits, cheniers, pockets of mud in dune finger corridors, aprons of sand around the parabolic dunes that have encroached into the estuary, and interfingering of the dune sand with estuarine sediment (Semeniuk 2000). As noted above, freshwater discharges from the barrier into the estuary form shore seepages, which are important for shore vegetation and fauna (Cresswell 2000). In one case, the freshwater seepage sustains a stand of mangroves, *Avicennia marina* (Semeniuk et al. 2000b).

Leschenault Inlet estuary is unique in south-western Australia for several reasons. Formed behind a shore-parallel dune barrier, and wholly Holocene in age, its estuarine geomorphology and hydrologic structure are different to other local estuaries such as the Swan River Estuary and the Peel-Harvey Estuary (Semeniuk et al. 2000a). The estuary does not represent a classic and simple river-to-sea transition, but has rivers entering at the southern end of the long north-south oriented lagoon that had formed by marine processes rather than fluvial erosion. Leschenault Inlet estuary has also had a complicated Holocene sea level history, resulting in complexity of its shores. Its western shore is further complicated as parabolic dunes encroach into the estuary, producing a varied assemblage of shore types and stratigraphic/ hydrologic situations. The complex of shores and wetland types peripheral to the estuary support a variety of fringing vegetation assemblages as linked to shoreline geomorphology, stratigraphy, hydrology and hydrochemistry (Pen et al. 2000). Consequently, Leschenault Inlet estuary is a classic area for studies of how geodiversity underpins both local alpha biodiversity and beta biodiversity (cf. Whittaker 1972) and the ecology of estuarine peripheral vegetation. In this context, the system ranks as one of the most significant in southern and south-western Australia (Table 4 in Pen et al 2000). Through its proximity to the Leeuwin Current, the estuary also supports the most southern occurrence in Western Australia of the mangrove *Avicennia marina*, and the array of landforms and vegetation in and around the estuary as related to bathymetry, geomorphic setting and habitats, combine to create an important class room for Holocene estuarine shore palynology (Semeniuk et al. 2000c).

Revets (2000) documented a rich (neo) palaeontological assemblage of Holocene foraminifera in the Leschenault Inlet estuary with a Fisher alpha index of 30.47 for the whole estuary. At one location opposite the Collie River delta, on a shallow water muddy sand platform, Revets (2000) found the richest biodiversity of (neo)palaeontological foraminiferal assemblage globally, with a Fisher alpha index of 31.87 – essentially the most species-rich assemblage of foraminifera in any estuary in the world.

THE GEOHERITAGE ESSENTIALS OF THE LESCHENAULT PENINSULA AND ITS ESTUARINE LAGOON

For the Leschenault Peninsula area and its associated estuarine lagoon, there are many features that comprise its geoheritage essentials. Whereas there are linear barriers and linear lagoons elsewhere in Australia (e.g., the Younghusband Peninsula and its lagoon, on The Coorong; (von der Borsch and Lock 1979; Geddes and Butler 1984; Murray-Wallace et al. 1999) this linear retrograding dune barrier sheltering a linear estuarine lagoon is unique in Western Australia. It is wholly Holocene in age. By contrast, the coastal barriers of the Coorong to Mount Gambier Coastal Plain (e.g., the Younghusband Peninsula), though Holocene linear barriers, appear to have a core of Pleistocene limestone (Belperio 1995; Murray-Wallace et al. 1999). Additionally, because of the history of relative MSL, tuart-developed calcrete, and mobile parabolic dunes interfacing with the estuary, the Leschenault Peninsula and its associated lagoon has developed a range of geomorphic, stratigraphic, hydrological, hydrochemical, and digenetic features distinctive and Internationally and/or Nationally unique to this system.

Table 1. Essential features of geoheritage that characterise the Leschenault Peninsula and its associated estuarine lagoon, ordered from dune to estuary

1.	linear retrograding Holocene dune barrier in south-western Australia
2.	active parabolic dunes within the barrier
3.	gradational range of landscapes from active mobile dune to undulating plain
4.	calcrete forming in the modern zone of capillary rise
5.	lenses of calcrete at high stratigraphic levels
6.	calcrete exposed in deflation bowls of parabolic dunes
7.	calcrete breccia floatstone
8.	beach rock forming in the tidal zone
9.	stranded beach rock forming submerged shore-parallel bands and ridges
10.	complex stratigraphy of the dune barrier
11.	Holocene sea level history recorded in the stratigraphy
12.	complex of shorelines and stratigraphy along the dune/estuary interface
13.	freshwater seepage along the dune/estuary interface and complex ecology
14.	a prominent mangrove stand developed along the dune/estuary interface
15.	estuary shore landforms along the western estuary shore, graded south to north
16.	calcite encrustation of sea rush roots in the tidal zone
17.	rich biodiversity of Holocene estuarine foraminifera
18.	well-documented Holocene palynological record as a model for estuaries
19.	north-south and east-west patterns in sediments and stratigraphy of the estuary
20.	an intra-estuarine delta
21.	peripheral wetlands along western and eastern estuary margin
22.	stratigraphic type sections

The Leschenault Peninsula and its leeward estuarine lagoon also have several type locations for Holocene stratigraphic units, viz., members within the Safety Bay Sand (the Burrangenup Member, the Rosamel Member, the Vittoria Member, the Koombana Beach Rock, the Binningup Calcrete), and the estuarine Leschenault Formation (Semeniuk 1983).

The key features of geology and geomorphology, at various scales, that are identified, and that are important and distinctive to the region, are listed in Table 1. The large scale features of the Leschenault Peninsula area and its associated estuarine lagoon are listed only to identify the important geological framework for this region. It is also axiomatic that if features at smaller scales *within* the Leschenault Peninsula area and its associated estuarine lagoon rank as significant at the National or State-wide level, then the system that contains them also should be ranked as significant at the National or State-wide level.

The grading of the essential geoheritage features in the Leschenault Peninsula and the Leschenault Inlet estuary with respect to International, National and State-wide/Regional significance, and the rationale for that assessment are outlined in Table 2. Application of the Geoheritage tool-kit to the Leschenault Peninsula and its leeward estuarine lagoon is illustrated in Figure 3: the categories of sites of geoheritage significance are identified, key selected features at the various scales are provided as examples, and the essential features are graded as to their level of significance.

SUMMARY AND DISCUSSION

This paper has endeavoured to provide a description of the "state of the art" of geoheritage and geoconservation in Western Australia, and a case study of the application of the techniques of identification of features and assessment of features, i.e., the Geoheritage tool-kit. The main objectives of earlier work of Brocx and Semeniuk (2007) and Brocx (2008) were to define geoheritage within a broader context of geology, conceptualise the various categories of what constitutes geoheritage, deal with the issue of scale, and more rigorously define levels of significance. These outcomes are essential foundations to designing classification and assessment systems to

Table 2. Grading of essential features of geoheritage significance in Leschenault Peninsula and its Leschenault Inlet estuary, and the rationale for the assessment.

Geological feature and its scale	Type of site (category of site from Figure 2)	Significance	Rationale for assigning the level of significance
calcrete in zone of capillary rise; small to fine scale feature	modern landscapes and setting (active processes)	International	first and only description to date globally of Holocene calcrete forming in the zone of capillary rise in relationship to plants
calcrete at high/low stratigraphic levels; small to fine scale feature	geohistorical site	International	first use of Holocene calcrete to reconstruct Holocene climate history
calcrete breccia floatstone	modern landscapes and setting (active processes)	International	first description of lenses of Holocene calcrete breccia floatstone in soils, developed as a consequence of tree heave by storms
complex stratigraphy of barrier; medium scale feature	geohistorical site	International	one of the most complex dune barriers stratigraphically in the world because of the local sea level history superimposed on dune barrier development
stranded submerged beach rock forming bands/ridges; medium to small scale feature	modern landscapes and setting (active processes), and geohistorical site	International	first and only description to date globally of stranded beach rock forming submerged shore-parallel bands/ridges with barrier retreat
biodiversity of foraminifera; very fine scale feature	modern landscapes and setting	International	richest biodiversity of Holocene estuarine foraminifera (neo)palaeontologically in the world
linear retrograding barrier; large to medium scale feature	modern landscapes and setting (active processes)	National	the only linear retrograding Holocene dune barrier barring a barrier-parallel linear lagoon in Western Australia, and only one of a few nationally
Holocene sea level history recorded in the stratigraphy; small scale feature	geohistorical site	National	unique Holocene sea level history recorded in the stratigraphy and reflecting local tectonism
complex shorelines/stratigraphy along the dune/estuary interface; large to medium scale feature	modern landscapes and setting (active processes)	National	since the dune barrier is only one of a few occurring Nationally, the complex of shorelines and stratigraphy at the dune/estuary interface in this climate setting are Nationally uncommon
calcite encrustation of sea rush roots; fine to very fine scale feature	modern landscapes and setting (active processes)	National	encrustation (and permineralisation) by calcite. Mg-calcite, and dolomite of sea rush roots in the tidal zone at the dune/estuary interface in this climate setting is Nationally uncommon
well-documented Holocene palynological record as a model for estuaries; very fine scale feature	modern landscapes and setting (active processes)	National	the documented patterns of pollen distribution in the Holocene estuarine sequence provides model to interpret estuarine palynology

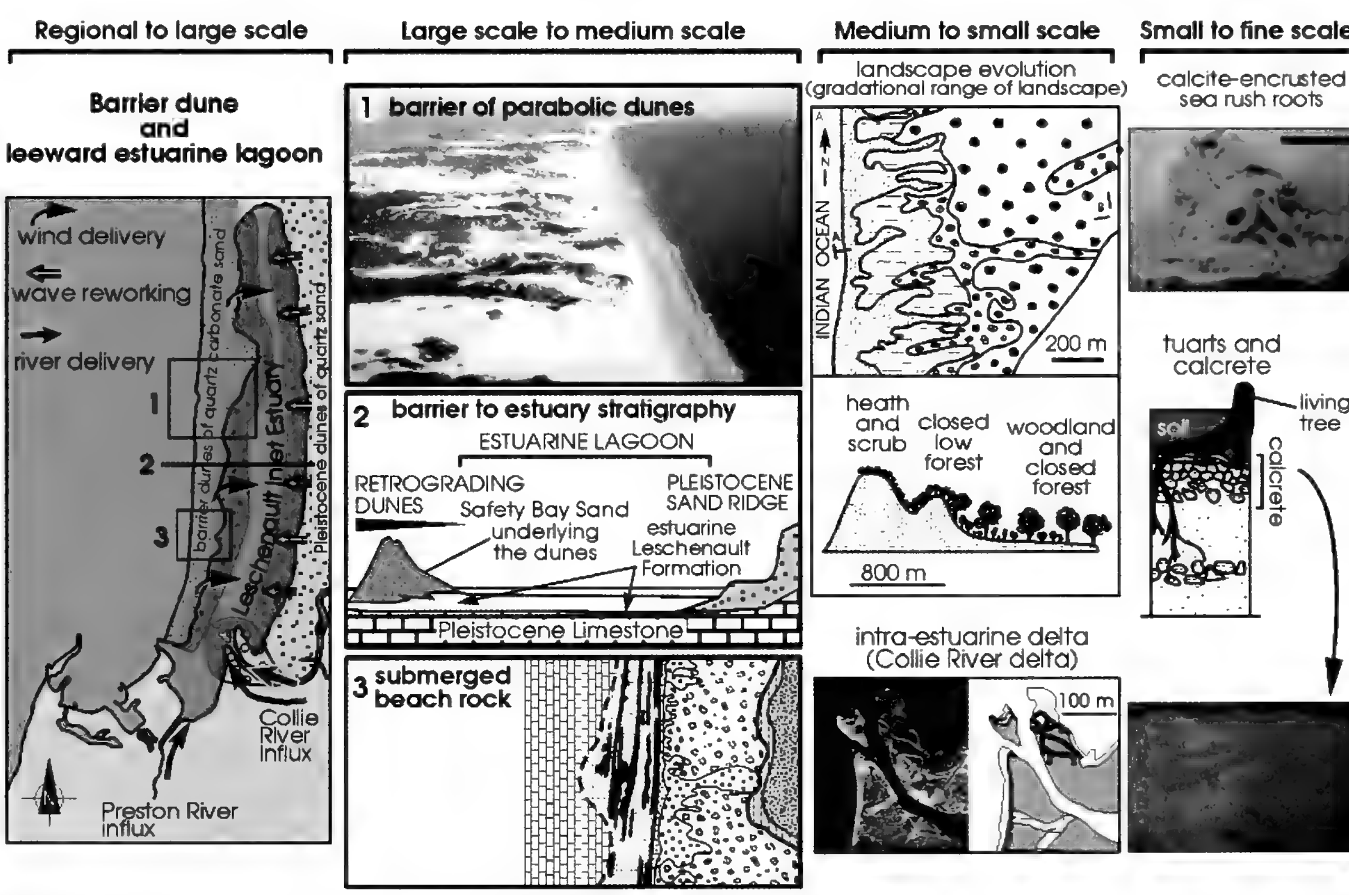
active parabolic dunes in barrier; medium scale feature	modern landscapes and setting (active processes)	State-wide/ Regional	the geometry and style of active parabolic dune development within the barrier is unique in the State; compared with other parabolic dunes that change shape and orientation with respect to progressively changing wind directions and wind speed latitudinally (see Semeniuk et al. 1989)
gradational range of landscapes: mobile dune to undulating plain; large to medium scale feature	modern landscapes and setting (active processes)	State-wide/ Regional	in this climate, with the vegetation contributing organic matter to soils, and the natural geomorphic gradation from mobile dunes to fixed dunes to plains, this transition is unique in Western Australia
calcrete exposed in deflation bowls of parabolic dunes; small scale feature	modern landscapes and setting (active processes)	State-wide/ Regional	normally, dune bowl excavation proceeds to the water table and forms dune slacks, but calcrete arrests this excavation; calcrete exposed in bowls is a unique landscape feature in this calcrete-and-parabolic dune setting in Western Australia
beach rock in the tidal zone	modern landscapes and setting (active processes)	State-wide/ Regional	this type of beach rock is restricted to this part of Western Australia, and reflects the hydrochemical interchange between the freshwater reservoir in the barrier and the marine shore
freshwater seepage at dune/estuary interface; small scale feature	modern landscapes and setting (active processes)	State-wide/ Regional	freshwater seepage along the dune/ estuary interface produces complex ecological responses, and results in the second most complex estuarine shore in Western Australia
mangrove stand at dune/estuary interface; small scale feature	modern landscapes and setting (active processes)	State-wide/ Regional	a prominent mangrove stand is formed at the dune/estuary interface where there is freshwater seepage from the tip of a parabolic dune encroaching into estuary
estuary western shore landforms graded south to north; large scale feature	modern landscapes and setting	State-wide/ Regional	the south to north transition of shore landforms along the western estuary shore reflects the unique nature of the northerly oriented linear lagoon, and its relation to wind and wave dynamics, and is a feature of State significance
north-south and east-west patterns in sediments and stratigraphy of estuary; large to medium scale feature	modern landscapes and setting	State-wide/ Regional	the linear lagoon bordered by distinct landforms and provenances has resulted north-south and east-west patterns in sediments and stratigraphy of the estuary that are unique in Western Australia
an intra-estuarine delta; medium scale feature	modern landscapes and setting (active processes)	State-wide/ Regional	at the southern end of a north-south oriented estuarine lagoon, the Collie Delta is asymmetric reflecting fluvial construction and a storm influenced northern part that faces the long fetch of the lagoon - a feature unique in Western Australia
peripheral wetlands along western and eastern shore of estuary; large scale feature	modern landscapes and setting (active processes)	State-wide/ Regional	the stratigraphy, landforms, and freshwater seepage along the estuarine shores from the dune barrier and the Eaton Ridge has resulted in distinct peripheral wetlands along western and eastern shores of the estuary that are found nowhere else in Western Australia
stratigraphic type sections; small scale feature	reference sites	State-wide/ Regional	the area contains a number of stratigraphic type sections

A CONCEPTUAL CATEGORIES OF SITES OF GEOHERITAGE SIGNIFICANCE

TYPE EXAMPLE, REFERENCE SITE OR LOCATION	CULTURALLY, OR HISTORICALLY SIGNIFICANT SITES	GEOHISTORICAL SITES (ANCIENT SEQUENCES)	MODERN LANDSCAPES AND SETTINGS (ACTIVE PROCESSES)
GEOLOGICAL FEATURE (A PRODUCT)	GEOLOGICAL FEATURE (A PRODUCT)	SITES WHERE PROCESSES CAN BE INFERRED FROM PRODUCTS	PROCESSES & PRODUCTS
Type stratigraphic locations Type fossil locations Type soil locations Type geomorphic locations	Classic locations in cliffs or outcrops, where geological principles were first explained *e.g.*, Hutton's unconformity, or Lapworth's mylonite	Classic locations such as cliffs or outcrops where Earth processes (history) can be inferred, *e.g.*, walls of Grand Canyon, or limestone cliffs of the Great Australian Bight	Locations where dynamic processes are operating to develop products, *e.g.*, active parabolic dunes in different stages of development, with attendant landforms and wetlands

B SCALE OF GEOHERITAGE FEATURE (terrane, outcrop/bed, to crystal)

Decreasing scale of geoheritage features in Leschenault Peninsula and estuary
(a selection of features only shown)



C SIGNIFICANCE OF TERRANE, CLIFF, OUTCROP, BED, OR CRYSTAL FEATURE

International → **National** → **State/Regional**

International
- calcrete in the zone of capillary rise
- calcrete lenses at high stratigraphic level
- calcrete breccia floatstone
- beach rock ridges/bands
- complex stratigraphy of the dune barrier
- biodiversity of estuarine foraminifera

National
- linear retrograding Holocene dune barrier
- Holocene sealevel history in the stratigraphy
- shorelines/stratigraphy, dune/estuary interface
- calcitisation of sea rush roots in tidal zone

State/Regional
- active parabolic dunes within the barrier
- gradational range of landscapes
- calcrete exposed in deflation bowls
- beach rock forming in the tidal zone
- freshwater seeps at dune/estuary interface
- prominent mangrove stand
- estuary shore landforms on western shore
- complex stratigraphy of the estuary shores
- N-S & E-W patterns in estuarine stratigraphy
- an asymmetric intra-estuarine delta
- peripheral wetlands of estuary margin
- stratigraphic type sections

identify sites of geoheritage significance in Western Australia, and elsewhere.

In this case study along the south-western coast of Western Australia, the Geoheritage tool-kit has been applied to identify sites of geoheritage significance, deriving from an inventory-based approach that rigorously assigns a level of significance to geological features regardless of their scale and within a framework of the broadest possible definition of geoscience. While the Leschenault Peninsula and leeward estuarine lagoon was used as a case study because it contains a wide variety of geological and geomorphological features ranging from large scale to fine and very fine scale, and varying in significance from International to State-wide, in fact the Geoheritage tool-kit can applied to any geological site, or region, to determine geoheritage values for conservation and management.

The Geoheritage tool-kit provides a method to give context to a range of inter-related features such as those found in the Leschenault Peninsula and leeward estuarine lagoon because there is a need not only for geoconservation of large scale features but also of significant smaller scale features in this system, and geoconservation of individual features as well as integrated geoconservation system conserving the suite as an inter-related ensemble. Thus in terms of geoconservation, addressing the various features of geoheritage value in the Leschenault Peninsula area and its associated estuarine lagoon, that individually rank from Regionally significant to Nationally to Internationally significant, is best achieved by viewing the system holistically as an integrated (geo)park of interactive processes, geology, and geomorphology. Therefore, given this background and the important and unique nature of the Leschenault Peninsula area, it should be viewed as a National or State geopark, within which there are also features of International significance, thus integrating the many smaller-scale features of geology and geomorphology into a single geoconservation unit. In the UNESCO definition of a geopark, the Leschenault Peninsula and its associated estuarine lagoon qualifies in containing numerous "*geological heritage sites of special scientific importance*". The various components of the geoheritage of the area should be viewed not in isolation, as type locations, or "best example of a given feature", but as the integrated system of geological products and as integrated systems of processes-and-products. Landscape evolution is an example of these principles. Calcrete, intra-estuarine deltas, and their asymmetric nature, the wetlands, the dunes of the barrier dunes, and the distinctive and complex estuarine shore stratigraphy also provide examples. Fine and very fine scale features, such as calcitisation of sea rush roots by encrustation and permineralisation under the high tidal flat, that is dependent on the groundwater seepage from the adjoining dunes, provide another specific example of these principles, in that without the calcite-bearing dune sand, the parabolic dune encroaching into the estuary, and the nature of the dune sand to estuary hydrology, there would not be the calcitisation of the sea rush roots.

While the Leschenault Peninsula and its estuarine lagoon are unique in Western Australia, and has been afforded National significance in that it is 'one or a few of such systems occurring Nationally' (Department of Conservation and Land Management 1998), in fact, it may be unique in Australia. Firstly, though linear barriers are common along the eastern seaboard of Australia, they generally bar digitate embayments and estuaries formed by postglacial marine flooding of riverine drainage patterns such that the lagoons are digitate to circular (Roy and Crawford 1979; Roy 1984; Roy et al. 1994), and as such as not

Figure 3 OPPOSITE: Application of the Geoheritage tool-kit to the Leschenault Peninsula and its leeward estuarine lagoon. In inset A, the categories of geoheritage applicable to this area are highlighted in blue. In inset B, some selected features of geoheritage significance are illustrated, graded in decreasing scale from left to right. Under the column "regional to large scale", the map of the barrier and lagoon shows a boxed inset 1, a transect labelled 2, and a boxed inset 3 – these are shown in detail as (1), (2), and (3) under the column of "large to medium scale". Under "large to medium scale", there is (1) an oblique aerial view of the barrier showing mobile and vegetated dunes, (2) a cross-section of barrier-to-lagoon stratigraphic relationships, and (3) the map of submerged beach rock (whose legend is in Figure 2). Under "medium to small scale" there is map of the landscape setting and associated vegetation, and their cross-section, and a map of the asymmetric Collie River delta. Under "small to fine scale" there is a photograph of the calcitised sea rush roots (from Semeniuk 2010), a diagram of the relationship of calcrete to tuart trees and the water table, and a photograph of a polished vertical slab of the calcrete (details of the calcrete profile are in Figure 2). The bar scale for the calcitised sea rush roots and the calcrete in the column of "small to fine scale" is 2 cm. In inset C. all features listed in Table 1 are allocated to a level of significance to comparatively illustrate the range of features and their significance.

comparable. Linear barriers protecting linear lagoons are not so common. Secondly, the nearest analogue to the Leschenault barrier-and-lagoon system is the Younghusband Peninsula barring The Coorong, however, it appears that ensemble of barriers in the Coorong Coastal Plain region may be founded on a low relief Pleistocene limestone ridge as an earlier barrier of the last interglacial period (Belperio 1995; Harvey 2006). Thirdly, focusing on the lagoons themselves, the geomorphology and sedimentary fill of the estuarine lagoon of Leschenault Inlet estuary and The Coorong are wholly dissimilar, the former comprised of provenance-specific sand platforms and deeper water terrigenous mud, with the sediments still filling the linear depression (Semeniuk 2000), and the latter essentially a carbonate-dominated sedimentary accumulation that has filled the linear depression (Alderman and Skinner 1957; von der Borch and Lock 1979; Harvey 2006).

Calcrete also is significant in the Leschenault Peninsula dune barrier. While calcrete has been recorded from another calcareous barriers (e.g., the Younghusband Peninsula; Warren 1983), these latter types are pedogenic and not related to the water table and tree-induced precipitation. Indeed, the tree responsible for calcrete precipitation is biogeographically unique to south-western Australia, and hence this type of calcrete is restricted to the south-western Australian region. A consequence of the calcrete sheet being related to a shallow water table is that a fluctuating sea level history will result in a sympathetic fluctuation in the water table and hence a history of calcrete development that will reflect the sea level history. Similarly, the unique occurrence of tree-induced precipitation of calcrete will result in lenses of calcrete breccia floatstone in soils where such trees are up-rooted by storms, a stratigraphic and lithologic feature distinct to this region.

Currently 580 ha of the Leschenault Peninsula is in the Conservation Estate as a nature reserve (Leschenault Peninsula Conservation Park) vested in the National Parks and Nature Conservation Authority (Department of Conservation and Land Management 1998), but this is based more on its biological values than its geological attributes. We argue that geological attributes should be added as criteria in identifying terrain for the Conservation Estate in general, criteria that are not currently pursued in Western Australia, and that the Leschenault Peninsula and its leeward estuarine lagoon should be viewed as a geopark with a focus on its important geological features and that these concepts be added to the notion of its existence as conservation park.

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The Geoheritage and Geomorphology of the Sandstone Pagodas of the North-western Blue Mountains Region (NSW)

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The towered 'pagoda' rock formations of the north-western Blue Mountains, west of Sydney, have a heartland of about 600 km^2, mostly at around 1000 metres altitude in Banks Wall and Burra Moko Head Sandstones. The pagodas are of two types: the 'platy pagodas' are generally stepped-cones in shape, with semi-regular ironstone bands, whereas the 'smooth pagodas' display less ironstone bands and are similar to many slickrock slopes found elsewhere. The platy pagodas however are an uncommon and significant geomorphic landscape feature, and are distinguished by the extent and regularity of their ironstone banding. The formation of the ironstone banding has involved the movement of iron in solution and its precipitation to form resistant bands, swirls and pipes. Questions remain as to how the ironstone banding formed, however 'roll fronts' of reaction between reduced Fe^{2+}-rich water and oxygenated water may best explain the amazing ironstone shapes. The geoheritage value of the pagodas is significant, but is threatened by activities such as longwall coal mining. The pagodas and the associated slot canyons of the Blue Mountains are ideal candidates for future geological and geomorphological research.

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KEYWORDS: Blue Mountains sandstones, geoheritage, geomorphology, ironstone banding, ironstone formations, Liesegang banding, pagodas.

INTRODUCTION

The 'pagodas' are a local name for distinctive sandstone formations in the north-western Blue Mountains region of NSW, west of Sydney (Fig. 1). These rocky cones are found in parts of three reserves of the Greater Blue Mountains World Heritage Area; the northern parts of the Blue Mountains NP, along the western edge of Wollemi NP, and in the Gardens of Stone NP. However much of the pagoda heartland is still found outside of reserves, principally on Newnes Plateau, Genowlan and Airly mesas in the Capertee Valley, and in Ben Bullen State Forest. The main concentration of the pagoda country covers around 600 km^2. Pagodas are conical rock formations formed by differential weathering and erosion of the local sandstones. They come in two forms. Smooth pagodas have relatively regular conical-shapes (without terraces), while platy pagodas are stepped and terraced cones that resemble Asian pagodas, ziggurats or step-pyramids. On platy pagodas, erosionally resistant ironstone bands from 1 to several cm thick project from the surface and form the hard surfaces of the terraces. These bands can project laterally from the underlying sandstone for tens of centimetres, and display detailed 3-dimensional forms that can resemble chairs and tables, pipes and pulpits. Pagoda complexes are part of wonderfully intricate, ruin-like, landforms that resemble lost cities and temples, and are also often associated with slot canyons and weathering caves. Their significance only started to be appreciated in the 1980s.

HERITAGE

Large sections of the pagoda region were incorporated into the Greater Blue Mountains World Heritage Area due to their biodiversity significance, particularly eucalypt diversity. However it is of concern that scenic, cultural and geoheritage values of the pagodas landscapes have not been fully appreciated or officially recognised.

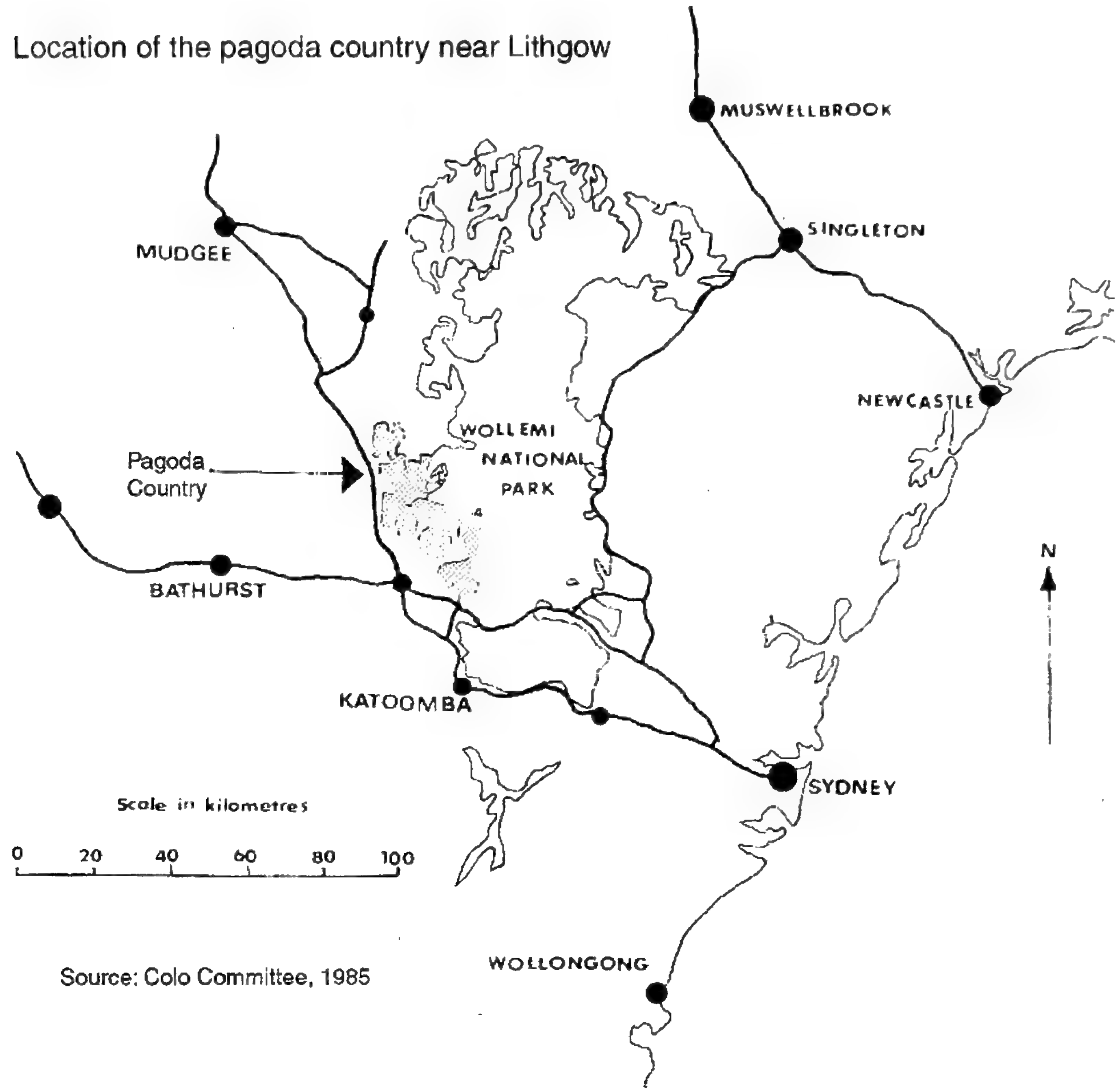


Figure 1. Map of the main distribution of the pagoda country in relation to Sydney, NSW (Washington, 2001a)

Geoheritage

The geoconservation significance of the pagodas has been recently recognised, but only to a partial extent. 'Geoheritage' as a term was originally only applied in Australia to *geological* features, not geomorphological or soil features (Sharples 1998). However, here we apply the broader usage of geoheritage (Washington 2001b), where the pagodas are geoheritage in view of the fact that they are uncommon and significant geomorphic sandstone landscape features.

The National Trust gave the first historical recognition of the visual and aesthetic significance of the pagodas when they proposed a Pinnacles National Park in 1977 (Washington 2001b). At that time these rock formations were called pinnacles, stuppas, beehives or just 'rocky outcrops', as on the 1:100,000 topographic maps. Although their visual beauty had been recognised by the National Trust, nobody had yet begun to appreciate their scientific values, such as geomorphology and botany. In the early 1980s a community non-government organisation the Colo Committee took up the campaign to conserve these rock formations, and along with the Colong Committee and the Federation of Bushwalking Clubs proposed the Gardens of Stone National Park (Colo Committee 1985). They focused on the term 'pagoda', which usage is now accepted for these smooth and stepped cones. At that time the pagodas locally were seen at best as interesting oddities, and at worst as sources of the 'black crinkly' bushrock that was sold on the Sydney market well into the 1980s.

Geodiversity – unlike biodiversity – is not alive, but it may be unique and significant and can be easily destroyed. The major impact on the pagodas has been subsidence due to longwall coal mining, where the ground surface can drop by up to 1.5 metres. While pagodas are quite geologically stable under normal conditions, the stresses of subsidence both crack pagodas and cause extensive cliff collapses. These collapses mostly occur along overhanging cliffs (often Aboriginal sites). This issue was highlighted at the Airly Commission of Inquiry in 1992, which investigated the proposal for coal mining of the Mt. Airly mesa in the then proposed Gardens of Stone National Park. At that time the Department of Mineral Resources (in response to a question by the Colo Committee) stated that in the Baal Bone Colliery area there had been 124 cliff collapses over 2-3 years, while in the adjacent Angus Place Colliery area there were 55 cliff collapses over the same period, some over 1,000 cubic metres (Washington 2001b). Significant cliff collapses have continued since (Muir 2010).

Mining subsidence can also impact on the Temperate Highland Peat Swamps on Sandstone (an endangered ecological community under the Commonwealth EPBC Act) through draining of aquifers and surface streams down strata shattered by subsidence. When the Colo Committee raised concerns in 1992 that the Department of Mineral Resources did not recognise the geomorphological value of these rock formations, the Department replied: 'That is not true, we do value the pergolas (sic)'. The confusion over the name, where 'pagodas' became 'pergolas', demonstrated that the geoheritage value of the pagodas was not being acknowledged at that time.

While Gardens of Stone National Park was proposed in 1985, a park by that name was not created till 1994, and covered only 11,780 Ha, later being extended to 15,080 Ha. The Park gazetted was the area of the pagoda country that did not overlie mineable coal (due to the thinning of the coal seams and 'bad roof' due to jointing). While some pagodas are found in the nearby Wollemi and Blue Mountains National Parks, and others are found in the Gardens of Stone NP, around half the core pagoda country is not protected in reserves. The main pagoda areas not protected are the Genowlan/Airly mesas, Newnes Plateau, and parts of Ben Bullen State Forest. Much of this area is covered by coal leases such as Airly, Baal Bone, Angus Place and Clarence.

The Gardens of Stone Stage 2 proposal of an additional 40,000 Ha was put forward in 2005 by the Colong Foundation for Wilderness, Blue Mountains Conservation Society and the Colo Committee. The proposal sought to form a State Conservation Area (SCA) over most of the area, which would have protected surface features but allows underground mining. Currently, the Department of Environment, Climate Change and Water (DECCW) has been working on a proposal to make the Genowlan and Airly mesas an SCA. This would allow 'bord and pillar' coal mining by Centennial Coal of the Airly Coal lease, but give protection to the surface features, including an extensive complex of pagodas, sometimes known as the 'Three Hundred Sisters'. The nearby Genowlan mountain is part of an area proposed for a future coal lease and contains an endangered ecological community (Genowlan Point Heathland) and a critically endangered plant *Pultenaea sp. Genowlan Point* (under EPBC Act), of which only 39 individuals were known in 2005 (Washington 2005), with only 26 being found in a recent visit in 2011.

The proposal to give SCA status to much of Newnes Plateau seems to have become bogged down due to a perceived conflict with forestry and popular 4WD and trail bike use. However, most of the pagodas on Newnes Plateau could be protected *without* conflict with these activities. There is an ongoing community campaign for the protection of Gardens of Stone II (Muir 2005).

Bioheritage

Given that biodiversity often is dependent on geodiversity, it is not surprising that the pagodas are a biodiversity hotspot for rare and threatened species. Pagoda areas offer many different habitats to species and also offer a refuge from fire and grazing to some plant species. Thus species survive there which may have gone extinct in the rest of the landscape. The rare Pagoda Daisy (*Leucochrysum graminifolium,* Figure 2a) is virtually restricted to pagodas. The rare *Prostanthera hindii* similarly is also mostly found on pagodas. In the northernmost part of the pagoda region, to the west of Nullo Mountain, a new species was found only a decade ago, now named *Leionema scopulinum.* It also is essentially limited to pagodas. Other rare or threatened plants often found on or near pagodas are *Pseudanthus divaricatissimus, Banksia penicillata, Acacia asparagoides, Epacris muelleri* and *Philotheca obovalis* (Washington 2001a). The 'regionally significant' *Eucalyptus oreades* is commonly found on and around pagodas. There are several threatened animals species found in and around pagodas. The Broad-headed Snake (*Hoplocephalus bungaroides*) is found on pagodas (as it lives under loose surface rock), while Glossy Black Cockatoos (*Calyptorhynchus lathami*) feed on *Allocasuarina* species found on and adjacent to pagodas. Raptors such as the endangered Peregrine Falcon (*Falco peregrinus*) use adjacent cliff habitats (e.g. Genowlan Point).

Cultural heritage

A number of Aboriginal art sites are found in sandstone weathering caves among pagodas, with Blackfellows Hand Aboriginal Place being the most famous. There are many other sites found in weathering caves in pagodas near swamps. There is also an extensive European coal and oil shale mining heritage associated with areas near pagodas, which dates from the 1880s (Colo Committee 1992). Oil derived from the kerogen in torbanite was used to replace sperm whale oil for domestic lighting. The western side of Wollemi NP contained narrow but rich bands of torbanite, and these were mined from Mt Airly, Newnes and Glen Davis. Mining heritage can be found at all these now-ruined sites, including steam winches, air shaft chimneys, and miners' cottages built into caves on Airly Mountain (Colo Committee 1992).

GEOMORPHOLOGY OF THE PAGODAS

These pagodas are an unusual landform type, and very little is known about how they form. What is clear is that pagodas are differential weathering formations found in the Banks Wall and Burra Moko Head Sandstones of the Triassic Narrabeen Group. The majority of platy pagodas appear to be found in the Banks Wall Sandstone, though smooth pagodas can be found in the underlying Burra Moko Head Sandstone. Both of these sandstones are fine to course-grained, porous sandstones, often with small pebble bands (Bembrick 1980). They were laid down in a massive river delta flowing from the north-west some 230 to 250 million years ago. Occasionally there are fine claystone bands intercalated amongst the sandstones.

Pagodas come in two forms – 'smooth' and 'platy'. Smooth pagodas (Figure 2 b and c) resemble cones or beehive structures found in the Bungle Bungles, Budawangs and other areas around Australia and the world (Young, Wray and Young 2009), such as the central-west USA where they would be called 'slickrock' slopes (Howard and Kochel 1988). Platy pagodas (Figures 2 d, e, f) however commonly have regular ironstone banding every 20 cm to a metre that can extend up to 60 metres in height. This banding is generally 2-5 cm in thickness and can, because of erosion of the surrounding friable sandstone, often project 20-40 cm from the sandstone (and in exceptional cases can project up to a metre). This ironstone plays a major protective role, and smooth pagodas appear to be eroding far more quickly than platy pagodas (we estimate at least 10 times faster, though this needs further research).

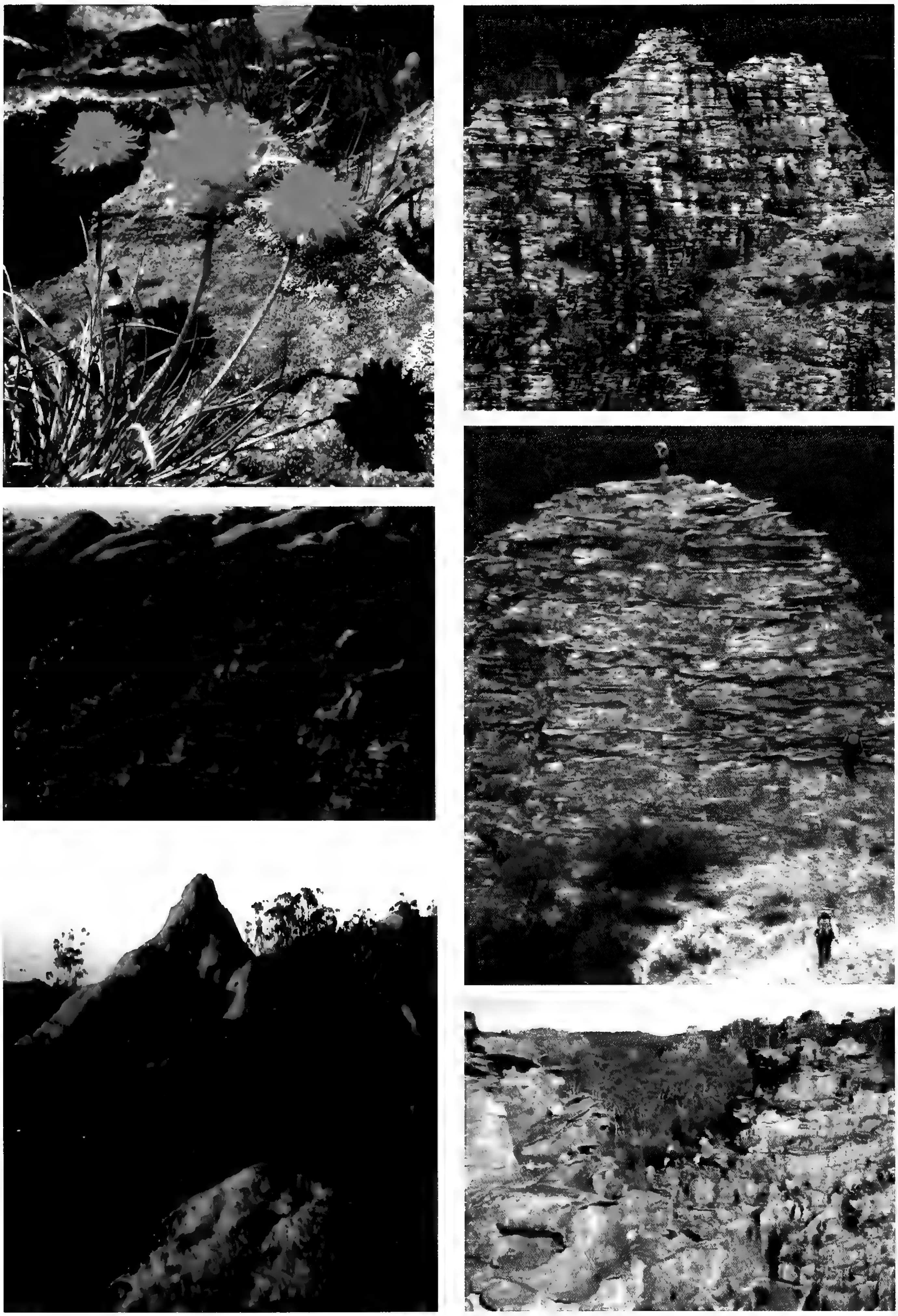
Platy pagodas are in our view distinct and significant features, as we are not aware of any other rock formations in Australia or overseas that mimic the geomorphology of platy pagodas (see Young, Wray and Young 2009). While there are many other rock pinnacles and beehives around the world, and while ironstone formations are found in other places, the regular stepped-cone shape of platy pagodas is a distinct geomorphic feature. The ironstone banding of the platy pagodas is thus significant in degree, not in nature, as ironstone is found throughout the Sydney Basin. However, the development of banding in platy pagodas forms a distinct geomorphic landscape unit. By analogy, limestone caves are significant, even though limestone is common. The reason why platy pagodas are virtually restricted to this area may be due to the friable nature of the porous bedrock itself, the amount of iron present in the sandstone, or aspects of former climate and associated hydrology. The exact formative mechanisms of platy pagodas remain unclear, but several hypothesis and suggestions for further research will be presented.

The erosional formation of the smooth beehive-shaped pagodas and similar 'slickrock slopes' elsewhere is fairly well understood (Howard and Kochel 1988; Young, Wray and Young 2009). Similarly, platy pagodas appear to result from the differential weathering of the resistant ironstone banding and the much softer, friable, surrounding sandstone. However, it is not known how the regular ironstone banding of platy pagodas has formed, and it is noteworthy that until now nobody seems to have asked these questions or published on this issue.

It has been suggested in community discussion over the years that the ironstone was possibly formed during deposition of the sediments. Given that these sediments were laid down in the delta of a large river,

Figure 2 OPPOSITE, a: Pagoda Daisy (*Leucochrysum graminifolium*); b: Smooth pagoda at Pt. Cameron, with platy pagodas in strata below; c: detail of b; d, e: Platy pagodas, Bungleboori Ck, Newnes Plateau; f: Platy pagodas at Gooches Crater.

a b c d e f



it is difficult to see how precipitated iron could have been deposited, which later reformed as ironstone in the 3-dimensional shapes seen within these sandstones. Whilst there is clear evidence that ironstone sheets commonly follow vertical cracks or joints in the sandstone (Figure 3a), the sub-horizontal ironstone layers are clearly not bedding-related features, as the 3-dimensional ironstone layers clearly cut across beds, and there are also ironstone piping (Figure 3b) and multi-dimensional ironstone sculptures (Figure 3c).

The iron thus appears to have reached its location through solutional processes, possibly when reduced Fe^{2+}-rich water precipitated out as ironstone. This was also the conclusion of Beitler et al. (2005) regarding the iron movement and ironstone formation within the Navajo Sandstone in the central US. Another suggestion for smooth pagoda formation has been that they are buried landscapes (e.g. dunes). This is not supported by the evidence, as while smooth pagodas may resemble dunes, they are rapidly eroding erosional landscapes that keep their shape not because they were buried dunes but because they are erosional features. The pagoda formation raises many questions, which are addressed in the following sections.

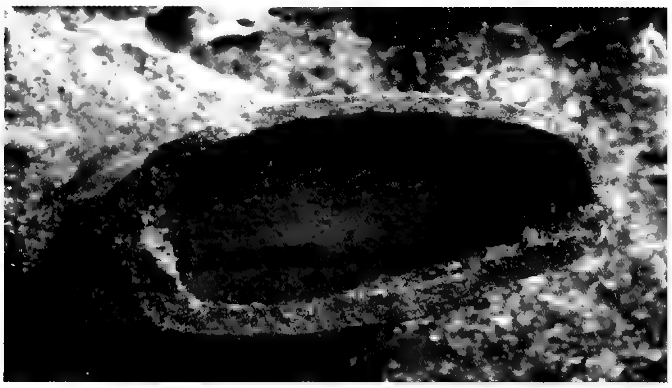
The Source of the Iron

The source of the iron remains a matter of debate. Some geologists suggest it is derived from former overlying basalt (as argued by Dr David Roots of Macquarie University in the 1980s). Remnant Tertiary basalt caps are found on Airly Turret and Mt Cameron in the north of the region, and on Mounts Wilson, Banks, Bell, Irvine, Tomah, Hay, and Tootie in the south, and these show that some small and localised basalt flows did occur near the pagoda region. Weathering of former overlying Tertiary basalt flows may have contributed locally to the iron content of the underlying sandstone. However, there is no definitive proof that basalt once covered the whole (or even significant parts) of this area, as noted by Dr John Pickett of the Geological Survey of NSW.

Others believe it originated from leaching of the iron coatings on sand grains and the iron cement in the sandstone itself (again noted by Dr Pickett). Leaching of 30% of the iron in coatings has been known from bleached zones in the Navajo Sandstones in Utah (Chan et al. 2006), which has then precipitated into ironstone formations that can contain 35% iron (Beitler et al. 2005). We agree with the second interpretation, that the iron comes predominantly from within the sandstone itself (possibly deep weathering during the Tertiary), but this needs further research.

Figure 3: a ABOVE, iron-indurated vertical crack; b OPPOSITE, ironstone tubing; c: ironstone sculpture on Wolgan/Capertee divide; d: Massive ironstone deposition above impermeable Wentworth Falls claystone (e) at Bungleboori Ck; f: 'dragon skin' ironstone nodule sheet (nodules c. 1 cm).

b



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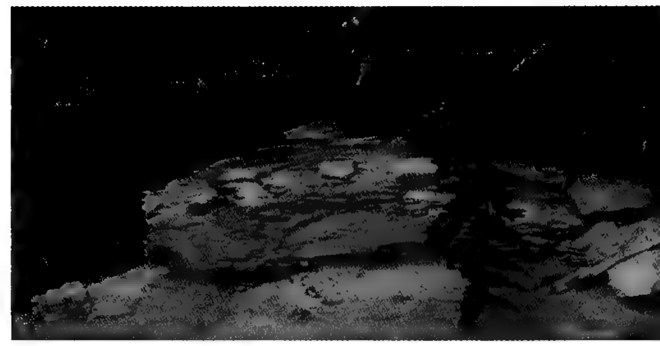

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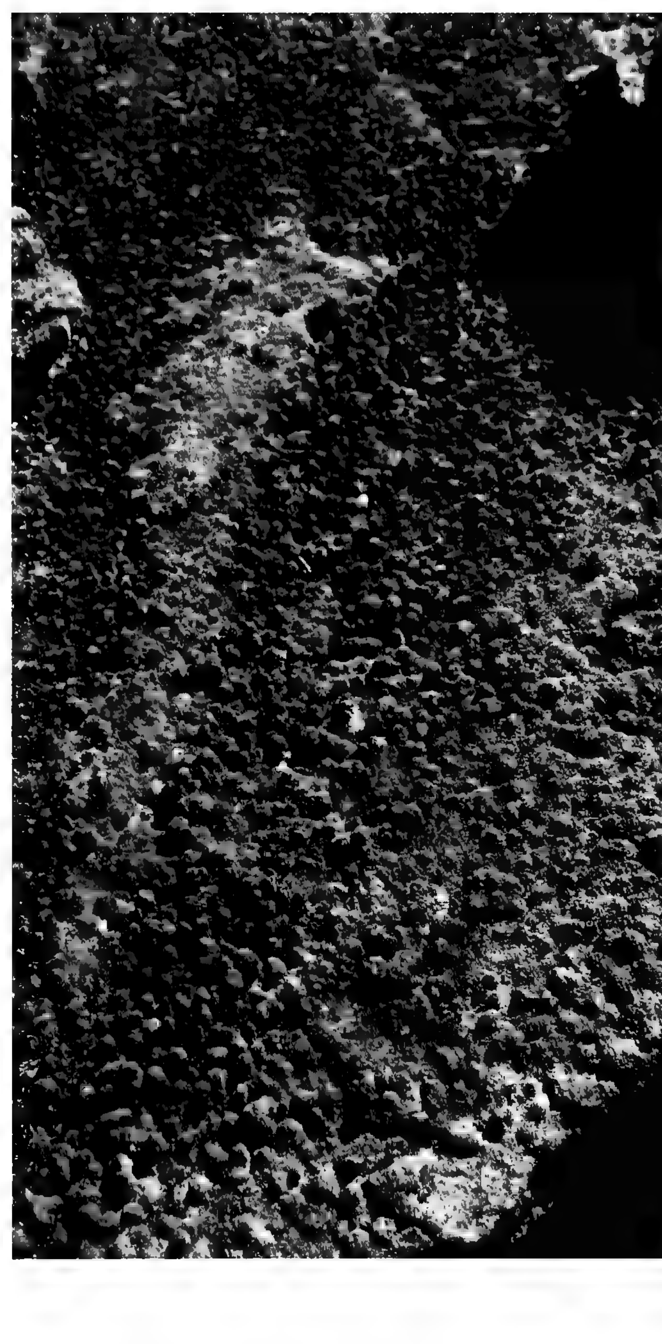

Hydrothermal hypotheses

Did the iron-rich water come from hydrothermal vents from basalt dyke intrusions, such as Varilova (2007) postulated for similar looking ironstone layers within sandstones of the Bohemian Switzerland National Park? While in that area there are nearby basalt dyke intrusions, no such intrusions have been found near the pagoda region. In any case, there is no evidence of how hydrothermal vents might have formed from such possible overlying basalt flows. Given the amount of ironstone present (which in places is rich enough to be an iron ore), evidence of hydrothermal vents should be more obvious.

Timeline of iron precipitation

It would be useful to know *when* the iron precipitated in the sandstone. Was this a single geological event, or were there a sequence of such events? Examination of oxygen isotope fractionation within authigenic clays in the ironstones may clarify this question. Palaeomagnetism of the ironstones may also reveal information as to the timing of ironstone formation. Determining the time of the formation of the ironstone banding may suggest how it was formed (e.g. whether it was associated with events such as volcanic activity in the Tertiary that may have shattered impermeable layers and allowed reduced iron-rich water to mix with oxidised surface water?).

Geochemistry of iron precipitation

It has been noted that oxygenated Fe^{2+} originally precipitates as polynuclear aggregates of Fe^{3+} hydroxides and ferrihydrite (Cornell and Schwertmann 1996), which are converted to a polymorph of FeO(OH) such as goethite, and finally to hematite (Berner 1980). Certainly a transition does occur with ironstone banding within sandstone bedrock on Newnes Plateau, as when uncovered (in sand quarries and road cuttings) the banding is light red and fairly soft. This then changes over a few months to become a deep purple colour and is much harder. Beitler et al. (2005) note that for Navajo Sandstone the presence of both iron oxide phases indicates multiple precipitation events with different geochemical conditions or progressive dehydration of goethite to form hematite. This may explain the change in colour and hardness of ironstone banding newly exposed to the Australian weather. Much more detailed geochemical investigation, including examination of iron-isotopes, may elucidate these aspects.

Three-dimensional ironstone banding

Platy pagodas contain extensive three-dimensional whorls, curves and pipes. While the ironstone formations in places follow cracks and other discontinuities in the sandstone where water might percolate, in the larger majority of instances it passes right *across* bedding planes. What can be responsible for this, to the extent that it can form piping, curves, and complex 3-dimensional sculptures formed by the coalescence of several ironstone bands? We believe the most likely explanation may be due to 'roll fronts' between reduced iron-rich water and oxygenated surface water. This has been postulated by Beitler et al. (2005) for the Navajo Sandstone (Fig. 4). Some concentric banding patterns have been called 'ironstone roses' and have been ascribed to Liesegang rings (Varilova 2007). We believe that the complex three-dimensional structures may reflect both vertical and horizontal movement of iron through the sandstones, leading to a complexity of formations not seen in the simple Liesegang banding in gel experiments in the laboratory.

Chan et al. (2006) note that precipitation of terrestrial concretions is thought to occur when Fe^{2+}-bearing (reduced) fluids intersect oxidizing groundwaters, where oxidation of iron at near-neutral pH would produce immediate precipitation of iron oxide at the mixing interface (Von Gunten and Schneider, 1991). Precipitation of iron oxide would be concentrated within a spatially-limited reaction front corresponding to this mixing interface. Beitler et al. (2005:556) note that 'This combination of advective and diffusive processes could account for the complex mineralization patterns seen in the field'. Interestingly they also note that 'Spatial relationships between bleached zones and iron-rich facies indicate that in some areas iron ions have traveled several kilometers before oxidation'. Concretions that precipitate within such a reaction front are commonly spheroidal in shape (Chan et al. 2006), and this might also assist in explaining the undulating nature of many ironstone bands, and possibly how tubular structures form? We recognise that while 'roll fronts' might explain how the amazing diversity of ironstone shapes could come about, it does not fully explain the process that leads to these formations, especially the regular banding of platy pagodas.

Regular ironstone banding

Apart from the 3-dimensional ironstone structures found in pagodas, there is also the regular sub-horizontal banding at a spacing of 0.2 to 2 metres, which can occur over heights of up to 60 metres. What best explains this? Is the regularity of the layering due to sequential events over geological time? Regular banding was *not* found in the Navajo sandstone, where Beitler et al. (2005:559) noted:

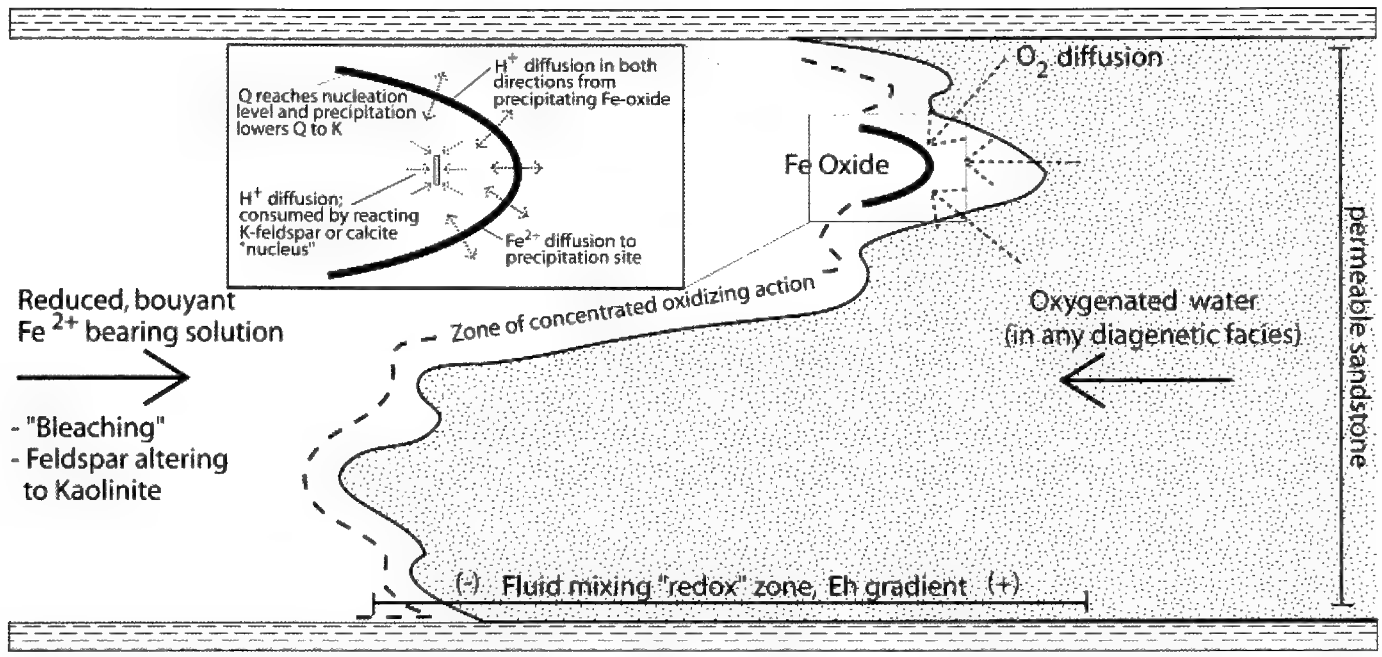

Figure 4 Generalized conceptual model of an oxidation-reduction front with precipitation of ferric oxide near the interface between oxidizing, O2-bearing water and reduced, Fe2+-bearing waters. A reduced, Fe2+-bearing solution moves to the right into a region of porous rock containing oxygenated water. (From Beitler et al. 2005, Fig. 12)

> 'The iron staining is commonly diffuse and permeates the sandstone on one side of the joint, and terminates abruptly on the other side of the joint, indicating directional fluid mixing and diffusion. The joints were likely conduits for oxidizing meteoric groundwater that infiltrated the sandstone and created a local oxidizing environment. If the sandstone was saturated with reducing iron-saturated fluid at the time of joint formation, the influx of this meteoric water would have resulted in precipitation of iron along this increased permeability zone.'

They thus found that joints were an important means of flow for oxidising water, but the ironstone was diffuse and not banded. What then causes the regular banding found in the sandstone of the platy pagodas? One hypothesis we have considered is that they are due to a series of wetting and drying events. It may represent a regular sequence where water moved through the sandstone as an aquifer, and ponded to a certain depth (e.g. on top of a claystone layer), then Fe^{2+} was precipitated out on the top of this water surface (due to higher oxygen levels, possibly due to arrival of oxygenated surface water) to form a new impermeable layer. More water then ponded to a similar depth on the new impermeable layer, which then precipitated Fe^{2+} to lay down another impermeable layer, and so on. This would suggest that under those conditions there was an optimum depth of water pooling in the sediments where the Eh and pH conditions were suitable for Fe^{2+} to precipitate out as Fe^{3+} in iron hydroxides in a horizontal 'roll front', which later formed into goethite (and then upon exposure, hematite). The banding may thus be a function of the properties of the porous sandstone itself, plus the climate and hydrology at the time, and the iron geochemistry associated with this.

As the distance between the bands varies from place to place (from 0.2 metres to 2 metres), this may reflect differences in the sandstone porosity, iron content, local hydrology and geochemical conditions. Field observations lend some support for this hypothesis, in that the most massively iron-indurated sandstone (Figure 3d) is often the layer immediately above a claystone band (Figure 3e). In places it seems these impermeable layers may only need to be quite thin to cause major iron induration. This may mean that the first leaching cycle extracted the greatest amount of iron, which was then indurated in that first layer. The presence of massive amounts of deeply weathered (> 60 metres) sandstone on Newnes Plateau (Peckover 1986) shows this region was subjected to major episodes of leaching and weathering. The question remains as to when this took place, given this area has been exposed to weathering since at least the early to mid-Tertiary (Young, Wray and Young 2009). Pickett and Alder (1997) also believe this leaching probably took place during the Tertiary.

Another explanation that may explain the regular banding is 'periodic precipitation', similar to the phenomenon known as Liesegang banding. This explanation for platy pagodas was suggested by geophysicist Prof. Marjorie Chan of Utah University. Hantz (2006) notes regarding Liesegang banding:

> Although the Liesegang phenomenon has been studied for over a century since its discovery in 1896, the mechanisms responsible for these structures are still under discussion. The models that try to explain the pattern formation can be divided into three main classes: supersaturation, sol coagulation and phase separation theories.
>
> All of these theories can reproduce the most important macroscopic characteristics of the bandings, but none of them is able to explain all the experimental findings. It is reasonable to assume that several mechanisms account for the Liesegang banding.

The complexity of the iron banding (with occasional gaps between banded areas) poses the question as to whether there may have been more than one precipitation event. This has been postulated in regard to small 'Liesegang blocks' in Iran (Shahabpour 1998). For this to occur in the platy pagoda banding however would mean that the bands formed are not immediately impermeable, and allow the reactant (e.g. oxygenated water moving down or reduced Fe^{2+} water moving upwards) to continue to pass through the rock. However, ironstone banding is often now observed to be impermeable, but this impermeability might possibly form later as the iron hydroxides later change to goethite and/or hematite. Horizontal flow of reduced iron-rich water between existing ironstone bands may possibly form other ironstone bands. This may explain the most heavily indurated ironstone areas above aquacludes. The regular ironstone banding of the pagodas remains one of the most difficult aspects of pagoda morphology to explain. Our above discussion details two hypotheses to be considered by future research.

Distribution Patterns and Controls

What determines where platy pagodas form? This may be due to three processes. Firstly, the faster erosion occurring along existing joints and valleys would allow platy pagodas to erode out in these areas. Secondly, the sites where one finds pagodas may be due to the fact that ironstone banding is not distributed uniformly across the strata that give rise to platy pagodas, so that the banding is *thicker* or more prevalent in some places. Certainly from field observation the thickness of bands varies from place to place. Ironstone banding can be seen in some of the friable sandstone quarries and road cuttings on Newnes Plateau, though this can be quite thin in places compared to that seen in pagodas. Thirdly, much of the pagoda country is deeply weathered (which presumably originally mobilised the iron). Newnes Plateau contains half a billion tonnes of friable sandstone (Peckover 1986). The degree of weathering may vary from place to place, so that in some areas the bedrock retains more cement between the grains. The formation of platy pagodas may thus be a function of enough protective ironstone banding, in addition to whether the bedrock between the bands is weathered to a greater or lesser extent. Even with banding present, if the bedrock is so weathered as to erode quickly, the pagoda may collapse and the banding be fragmented into ironstone debris. Such ironstone debris is commonly seen in places on Newnes Plateau, and near other pagodas. At this stage, we do not know which process is dominant in the formation of the platy pagodas we see today. Quite likely all three aspects are operating. Examination of drill cores and the friable sandstone quarries may provide further evidence as to the uniformity of banding, its thickness, the weathering of the sandstone, and whether such sites could form pagodas in the future upon differential weathering.

Impermeable bands

To what extent do claystone and ironstone bands determine water flow and hence where iron precipitates out? Claystone bands of various thicknesses are common within these sandstones, and begs the question whether these function as impermeable layers that have directed groundwater flow and ironstone formation? Claystone and ironstone bands function in the central Blue Mountains as impermeable layers that direct water along strata that feed hanging swamps (Pickett and Alder 1997), and they should function similarly in the north-western Blue Mountains. However, sometimes claystone bands in overhangs in the pagoda region can be seen to have been breached by cracks, and the iron-rich water has passed through to the strata underneath (and formed banding). In other places the impermeable claystone is intact and the ironstone banding is much thicker and more massive on top of these claystone bands (which in some spots may only need to be quite thin). This may account for the massive ironstone 'sculptures' which can be several metres high (Figure 3c) that are found in many places. The action of impermeable claystone bands may also explain why a strata under such a claystone band has extensive ironstone banding and platy pagodas, while the strata above the band is virtually free of ironstone and has only smooth pagodas (as observed at Point Cameron on the Wolgan/Capertee divide). In that location it would seem iron-rich water only had access to the lower strata, but not the upper. Similarly, massive iron-banding can be found in platy pagodas on top of the Wentworth Falls Claystone, while the Burra Moko Head Sandstone underneath contains mostly smooth pagodas (seen in the 'Lost World' on Bungleboori Ck). Claystone bands would thus seem to function as water barriers, where a strata that carries iron-rich water (due to water flow controlled by impermeable layers) forms iron banding, while another does not, as iron-rich water cannot reach it. This needs further research.

Bacterial influence

The role of bacteria in iron dissolution and precipitation needs to be clarified. as it is noted in the literature that bacteria are involved in both the reduction and oxygenation of iron in sandstone. Beitler et al. (2005:559) note in regard to the Navajo Sandstone that 'Bacteria commonly mediate iron mobilization and precipitation and could possibly be an important component of this system (Cornell and Schwertmann 1996)'. However, the complexity involved in the bacterial control of iron precipitation does not seem to have been adequately explained in the literature. Are the amazing ironstone shapes found in pagodas in part due to bacterial colonies in the sandstone changing Eh and pH and thus precipitating Fe^{2+}? Certainly cracks and weaknesses in the sandstone would allow greater water flow and hence may bring more food to bacterial colonies at these sites, hence Fe^{2+} may precipitate to a greater degree along with the higher bacterial density.

There is also the question of whether bacteria are present in nodular ironstone concretions found on ironstone sheets in pagodas, known colloquially as 'dragon skin' (Figure 3f). Nodular iron structures have been noted elsewhere in ironstone formations (Chan et al. 2006; Varilova 2007). However, no detailed study seems to have been carried out to date on the bacterial involvement with iron precipitation in ironstone. Chan et al. (2006) note that ironstone nodules also form on Mars, where bacteria may not be involved, and suggest that nodular sheets may just be a function of reaction fronts in active chemical systems. This is clearly an area in need of further investigation, where the possible application of iron-isotope studies may shed light on the action of bacterially-mediated iron precipitation.

Present day activity

Does ironstone precipitation continue today that will one day weather out to form pagodas? Iron is still being dissolved and is moving in solution across the landscape and precipitating out in swamps such as Long Swamp Creek (headwaters of the Cox's River). In such swamps it might then be reduced in the sediments and then move downwards and sideways through the porous sandstone, within the controls exerted by the impermeable claystone bands. In this regard iron induration of sandstone may still be continuing today, laying further ironstone layers that may form the pagodas of the future. Alternatively, was all the ironstone banding laid down in one key geological event? If it proves possible to date ironstone banding, it may answer this question. If ironstone banding is still forming, then it raises the question of how swamps may have been involved in the past iron induration of the sandstone. A casual examination of pagodas clusters shows a linearity evidenced in many places, but this may just be due to linear jointing and erosion along these joints. However, swamps also form along such joints (e.g. the shrub swamps of Newnes Plateau) where iron could seep into sandstone over many thousands of years. As such, the formation of ironstone banding may still be ongoing. This issue remains a fascinating hypothesis for future research.

CONCLUSION

The pagodas are a case-history of how difficult it can be for something to be recognised as geoheritage. It is also an excellent example of why the concept of geoheritage in NSW needs to be expanded beyond just geological sites to include geomorphological and soil sites. If geodiversity and geoconservation in the literature are seen as applying to all three categories (geology, geomorphology and soils), then so also should geoheritage. The north-western Blue Mountains pagodas were originally appreciated for their scenic grandeur, and only later started to be recognised and understood as 'hotspots' of biodiversity. However, science was slow to appreciate just how distinct and significant pagodas (especially platy pagodas) are as a distinct landform. Iron movement and precipitation within these sandstones seem to have been taken for granted as a process, and scientists have been slow to ask just how pagodas, particularly platy pagodas, actually formed. We conclude that they are distinct and significant geomorphological features, even by world standards.

Despite these significant values, the geoheritage of the pagodas is still under threat, largely due to underground longwall coal mining, but also due to damage by human trampling. There have however been advances over the years as recognition of their geoheritage value has increased. For example, the orientation of some coal mining longwalls have been changed, or terminated earlier, to protect particular pagoda formations (e.g. Oakbridge Colliery stopped a longwall short of the 'Artefact' pagodas in Baal Bone Colliery, Washington 2001b). Protection zones have also been created in coalmine operation plans to protect some areas containing pagodas and swamps. The use of 'bord and pillar' coalmining can reduce subsidence if the pillars are retained (as Centennial Coal has agreed to do in some areas), and hence can protect overlying pagodas. One coal company, Centennial Coal, has been willing to consider the idea of a State Conservation Area being created over their coalmining lease at Mt. Airly.

However, just as Australia has been slow to acknowledge its wealth of biodiversity, the pagodas show that we have been similarly slow to recognise the significance of our geodiversity, and the platy pagodas are certainly a distinct and significant part of Australia's geodiversity. The formation of platy pagodas has yet to be full explained, but their geomorphic significance is not in doubt. We believe that pagodas and their associated sandstone landforms (such as slot canyons) are important and significant parts of the sandstone geodiversity of the Greater Blue Mountains World Heritage Area and adjacent unprotected areas. This is of significance given the Commonwealth Government plans to renominate this World Heritage Area for geodiversity in the future (currently it is listed only for biodiversity). Pagodas deserve full and expanded recognition as a significant part of the geodiversity and geoheritage of the Blue Mountains region. Their natural aesthetic beauty, their biodiversity, and their significant geomorphological values mean they deserve enhanced recognition and conservation into the future.

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Suture Index as an Indicator of Chronological Age in the Male South African Fur Seal, *Arctocephalus pusillus* (Pinnipedia: Otariidae)

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The South African fur seal (*Arctocephalus pusillus pusillus*) is very closely related to the Australian fur seal (*A. pusillus doriferus*). We examine skull suture index (**SI***) as an indicator of chronological age in the male South African fur seal, based on 42 animals of known age ranging from 10 m to 11 y 11 m. Twenty one (21) animals were aged based upon tagging as pups and 21 were aged based on dentine growth layers (1 to 11 y). Age is approximately directly proportional to suture index [Age = $(0.7990 \pm 0.02354) \times$ **SI***, $r = 0.8887$, $n = 42$, valid **SI*** range 0 – 16, useful predictive range 0-≈14 y)]. We describe the sequence of cranial suture closure (n = 11 sutures, 69 animals) and determine whether suture index (**SI***) reliably corresponds to chronological age. Sutures do not close in a definitive order in all individuals and some sutures take longer to close than others. In animals ≤ 12 y, the general sequence of full suture closure was the Basioccipito-basisphenoid, Occipito-parietal, Interparietal, Coronal and finally the Squamosal-jugal. The Maxillary, Squamosal-parietal, Interfrontal, Basisphenoid-presphenoid, Internasal were used in the **SI*** calculation even though none showed any sign of closure in the known-age individuals but did show some closure in very old animals of indeterminate age. Suture closure criteria are useful in classifying males into juveniles, subadults and adults. Multiple linear regression might also prove to be useful to predict chronological age from suture closure data but its utility was limited in the present study by both the size of the data set available and the lack of animals with a known age older than 12y. More data is needed on old animals of known age but the relationship between skull sutures and age found in the present study would be sufficient for aging most male skull material because very few males are likely to reach ages greater than about 12-14 y.

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KEYWORDS: age-determination, asymptotic size, maturity classification, Otariidae, Pinnipeds, skull suture, suture index.

INTRODUCTION

Age determination in pinnipeds is important in many studies of their biology and ecology, particularly those examining development and growth. Various techniques have been used to determine absolute or at least relative age in pinnipeds. Techniques include: examination of tooth structure, the use of incremental structures in nails and bones, suture closure, standard body length, baculum development, eye lens weight, ovarian structure, and pelage characteristics (see Laws 1962; Jonsgard 1969; Morris 1972; McCann 1993; McLaren 1993). Currently, examination of tooth structure is the most precise method of age determination in pinnipeds (Scheffer 1950; Laws 1953; McCann 1993; McLaren 1993) and has been used to successfully age the South African fur seal (*Arctocephalus pusillus pusillus*) (Fletemeyer 1978;

Oosthuizen 1997; Stewardson et al. 1998; Stewardson 2001; Stewardson et al. 2008). In the present study, as in our previous studies (Stewardson et al. 2008, 2009, 2010a,b), age estimates are based on counts of growth layers in the dentine of canines.

The alternative dentition based technique of counting growth layers in the cementum of teeth (premolars) used by Arnould and Warneke (2002) on the Australian fur seal (*Arctocephalus pusillus doriferus*), the New Zealand fur seal (*Arctocephalus forsteri*) (McKenzie et al. 2007) and the Antarctic fur seal (*Arctocephalus gazella*) (Arnbom et al. 1992; Boyd and Roberts 1993) was not used in the present study. Oosthuizen (1997) compared the dentine and cementum techniques for aging South African fur seals of known age based on tagging and concluded that the dentine technique was more reliable and in particular concluded that the cementum techniques was not satisfactory for use on canines (cementum layer is too thin and fragile).

The counting Growth Layer Groups (GLG) in dentine has some significant limitations for aging fur seals. In the South African fur seal, it is not possible to determine chronological age of animals ≥12 y from growth layers in the dentine-GLG because of pulp cavity closure (Oosthuizen 1997; Stewardson 2001; Stewardson et al. 2008). The innermost dentine-GLG is the last layer laid down. There is a significant failure rate: in the present study about 1/3 of animals could not be aged after dentine sectioning because GLGs could not be resolved by microscopy.

The dentine and cementum based aging methods are destructive because teeth of specimens need to be extracted from skulls and sectioned. Sometimes neither the dentine-GLGs or cementum-GLCs can be properly distinguished after tooth sectioning. It might not be possible to get permission to do histological sectioning on the teeth of museum collections and some skulls might be in poor condition with missing, broken and decayed teeth. It appears that the dentine method is more suitable for dry museum skull specimens than the cementum method (Oosthuizen 1997; Stewardson et al. 1998). The cementum method is usually attempted on alcohol or formalin preserved teeth from recently dead or tranquilised animals (Arnbom et al. 1992; Boyd and Roberts 1993; Oosthuizen 1997; Arnould and Warneke 2002; Laws, Baird and Bryden 2002; McKenzie et al. 2007).

The estimated longevity of male South African fur seals in captivity is about 20 y (Wickens 1993) and wild male Australian fur seals live to at least 16 y (Arnould and Warneke 2002). Wild male New Zealand fur seals (*Arctocephalus forsteri*) in southern Australia are known to live to at least 19 y (McKenzie et al. 2007). Male Antarctic fur seals (*Arctocephalus gazella*) are also known to live to at least 16 y based on tag-aged animals (Arnbom et al. 1992; Boyd and Roberts 1993). Here we investigate the usefulness of suture closure criteria as an indicator of chronological age and physiological development in the male South African fur seal. Specific objectives were to: (i) describe the sequence of cranial suture closure and (ii) determine whether suture index corresponds to chronological age. There is no comparable information on development of sutures vs. age in the Australian fur seal, which is very closely related to the South African fur seal (Lento et al. 1997; Brunner 1998a,b; Brunner et al. 2002; Brunner 2004; Brunner et al. 2004; Stewardson et al. 2008, 2009, 2010a,b) and so any information gained on the South African fur seal would be useful for studies of the life history of the Australian fur seal (Arnould and Warneke 2002). Some caution is needed in applying information on South African fur seals to Australian fur seals. Adult male Australian fur seals are known to reach a marginally larger size than the South African variety and grow faster and perhaps live longer (Arnould and Warneke 2002; Stewardson et al. 2008, 2009).

MATERIALS AND METHODS

Abbreviations used in Text

Full Suture Closure (**FSC**), Partial Suture Closure (**PSC**), Suture Index (**SI**), Adjusted Coefficient of Determination (**R^2**).

Collection of specimens and morphometry

Male South African fur seals were collected along the Eastern Cape coast of South Africa between Plettenberg Bay (34° 03'S, 23° 24'E) and East London (33° 03'S, 27° 54'E), from August 1978 to December 1995, and accessioned at the Port Elizabeth Museum (PEM). Collection procedures are described in Stewardson et al. (2008, 2009). From this collection, 48 males had suture index (**SI**) information. Other skull data was available on 44 animals but suture information was missing on PEM2035, 2141, 2151 & 2252.

Thirty one (31) specimens were aged from incremental lines (called Growth Layer Groups, **GLG**) observed in the dentine of upper canines (Oosthuizen 1997; Arnould and Warneke 2002; Stewardson et al. 2008, 2009). Unfortunately, the GLG dentine-based aging method cannot age animals beyond 12 y old because of closure of the pulp cavity and so 10 of the 31 GLG-dentine-aged animals could only be classified as being ≥12 y old. Occasional individuals are found where 13 GLGs can be distinguished (PEM2151) and

Table 1: Suture Indices (SI*) for Male South African fur seals according to chronological age (y) based on tagging (Marine and Coastal Management (MCM collection), Cape Town) or dentition (Port Elizabeth Museum, PEM). Age classes are whole years (x) rounded to the nearest year. The suture scores were coded as ranging from 0-3 (fully open, 0; suture less than half closed, 1; suture more than half-closed, 2; fully closed, 3). Suture numbers (I to XI) are reconciled to those used by Brunner (1998a,b).

Suture & Suture N°	Age Classes (y)											
	Juvenile	Subadults	Adults									
	1	2	3	4	5	6	7	8	9	10	11	12
Basioccipito-basisphenoid (VI)	0,0	1,0	3,3	3,3,2,2,1,2,3	3,3	3,2,3,3,3,3	3,3,3,3,3,3,3,3,3	3,3,3,3,3,3	3,3,3	3	3	3
Occipito-parietal (I)	0,0	0,0	2,2	1,3,2,2,1,1,3	3,2	3,1,3,2,3,3	2,3,3,2,2,3,3,2,3	3,2,3,2,2,3	3,3,2	3	3	3
Coronal (V)	0,0	0,0	1,1	1,1,2,1,0,1,0	1,0	1,2,1,2,1,0	1,1,1,1,2,2,1,1,2	2,2,2,3,2,2	3,2,3	2	2	3
Interparietal (III)	0,0	0,0	0,0	1,1,1,1,0,1,0	1,1	0,2,1,1,0,1	1,1,1,1,1,2,0,1,2	2,1,2,1,0,1	3,1,3	2	1	3
Squamosal-jugal (X)	0,0	0,0	0,0	0,0,0,0,0,0,0	0,0	0,0,0,0,1,0	0,0,1,0,0,0,0,0,0	1,0,0,0,1,0	0,0,1	1	1	3
Premaxillary-maxillary (IX)	0,0	0,0	0,0	0,0,0,0,0,0,0	0,0	0,0,0,0,0,0	0,0,0,0,0,0,0,0,0	0,0,0,0,0,0	0,0,0	0	0	1
Maxillary (VII)	0,0	0,0	0,0	0,0,0,0,0,0,0	0,0	0,0,0,0,0,0	0,0,0,0,0,0,0,0,0	0,0,0,0,0,0	0,0,0	0	0	0
Squamosal-parietal (II)	0,0	0,0	0,0	0,0,0,0,0,0,0	0,0	0,0,0,0,0,0	0,0,0,0,0,0,0,0,0	0,0,0,0,0,0	0,0,0	0	0	0
Interfrontal (IV)	0,0	0,0	0,0	0,0,0,0,0,0,0	0,0	0,0,0,0,0,0	0,0,0,0,0,0,0,0,0	0,0,0,0,0,0	0,0,0	0	0	0
Basisphenoid-presphenoid (VIII)	0,0	0,0	0,0	0,0,0,0,0,0,0	0,0	0,0,0,0,0,0	0,0,0,0,0,0,0,0,0	0,0,0,0,0,0	0,0,0	0	0	0
Internasal (XI)	0,0	0,0	0,0	0,0,0,0,0,0,0	0,0	0,0,0,0,0,0	0,0,0,0,0,0,0,0,0	0,0,0,0,0,0	0,0,0	0	0	0
Suture Index (SI*)	**0,0**	**1,0**	**6,6**	**6,8,7,6,2,5,6**	**8,6**	**7,7,8,8,8,7**	**7,8,9,7,8,10,7,7,10**	**11,8,10,9,8,9**	**12,9,12**	**11**	**10**	**16**
Total N° Skulls = 42	**2**	**2**	**2**	**7**	**2**	**6**	**9**	**6**	**3**	**1**	**1**	**1**

so their minimum age is ≥13 y but such animals are rare. Attempts to age the remaining seventeen (17) animals from tooth sectioning were not successful.

The sample was supplemented with external body and skull measurements from 21 known-age animals (animals tagged as pups) from Marine and Coastal Management (MCM), Cape Town. Most specimens in the MCM collection had very complete data sets with the exception of MCM1809, which had only information on tag-age, suture indices for the skull sutures and condylobasal length (**CBL**). The data set for regression analyses of Age vs. Suture Index was therefore restricted to 42 skulls (21 age-tagged animals plus 21 GLG-dentine-aged animals < 12 y).

Sequence of suture closure

Eleven cranial sutures (Table 1) from 42 skulls with a definitive age, 10 skulls known to be from

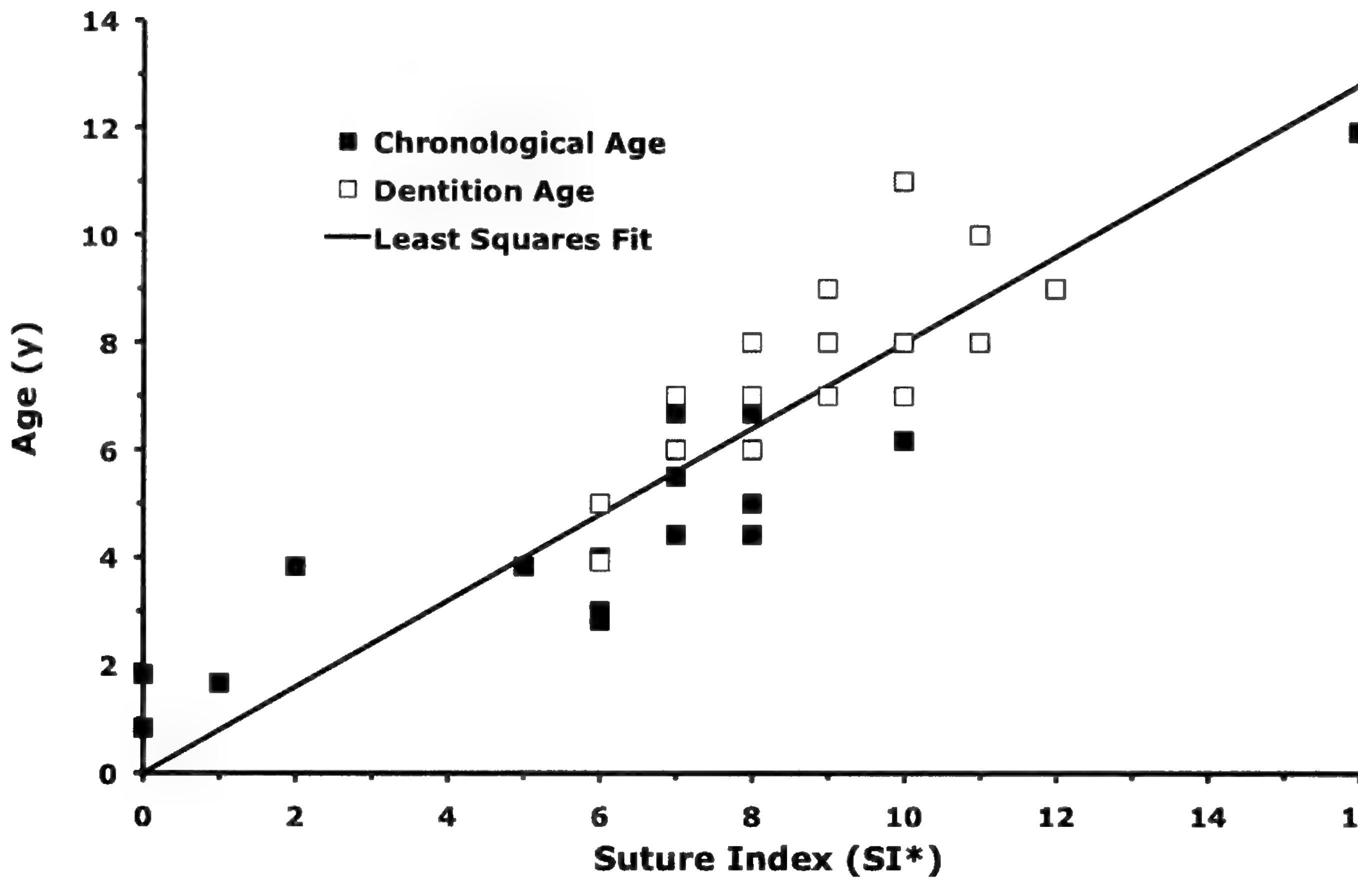

Figure 1. Regression analysis for age (y) of male South African fur seals vs. Suture Index (SI*) of male South African fur seals. Twenty one (21) seals (closed squares) were aged based upon being tagged as pups (with birthdate taken as 1 November). Twenty one (21) seals were aged based upon GLG-dentine (open squares). The fitted line is an ordinary least squares linear regression forced through the origin (0,0) ($m = 0.7990 \pm 0.02354$, $n = 42$, $r = 0.8887$, $p << 0.001$).

males ≥12 y and 17 skulls of unknown age, were examined (n = 69). Sutures are conventionally assigned a value of 1-4, according to the degree of closure (1 = suture fully open; 2 = suture less than half-closed; 3 = suture more than half-closed; and 4 = suture completely closed) (Stewardson 2001; Brunner 1998a,b). Brunner (1998a,b) in her study of skull sutures in South African and Australian fur seals and the New Zealand Fur seal (*Arctocephalus forsteri*) measured nine sutures (did not record development of the Squamosal-jugal or Internasal sutures) and used a different numeration convention for numbering the sutures to those used by Stewardson (2001). For consistency with Brunner's work (Brunner 1998a,b, 2004; Brunner et al. 2002, 2004) her numeration conventions for sutures were adopted in the present study with the Coronal designated as suture (V), Interparietal as suture (III), Maxillary as suture (VII), Squamosal-jugal designated as suture (II) and the Internasal as suture (XI). Sutures were arranged in Table 1 in the approximate order of Partial Suture Closure (**PSC**) and Full Suture Closure (**FSC**).

To make curve fitting easier to interpret in the present study, the suture scores were recoded as ranging from 0-3 (fully open, 0; suture less than half closed, 1; suture more than half-closed, 2; fully closed, 3). These values were added to give a total suture index (**SI***), ranging from 0 (all sutures open) to 33 (all sutures closed). The special form of the suture index used in the present study is designated **SI***. The highest **SI*** on a male of definitive age was **SI*** = 16 for an individual 11 y 11 m old (MCM1809). The highest **SI*** readings were **SI*** = 22 for an animal ≥ 12 y based upon GLG-dentine (PEM1698) and another specimen (PEM1587) of unknown age.

Simple linear regressions were fitted using EXCEL routines and the SOLVER least squares fitting routine in EXCEL (Stewardson et al. 2008, 2009). General linear models and multiple linear regressions were fitted in Minitab15 (Minitab Inc., State College, PA 16801-3008, USA). Asymptotic errors of the fitted parameters were calculated by matrix inversion as previously described (Stewardson et al. 2008, 2009).

RESULTS

Suture Index vs. chronological age

The relationship between suture index (**SI***) and chronological age (Fig. 1, Table 1) was examined

Table 2: Analysis of Variance for a Multiple Linear Regression (MLR) of known age of Male South African Fur Seals on the following suture scores (0-3) for the Occipito-Parietal (OP), Coronal (C), Squamosal-Jugal (SJ) sutures (Equation 1). Based on 21 males with tag based ages and 21 with dentition based ages <12y. The Multiple Linear Regression was fitted as described by Cook and Weisberg (1999). The Students-t statistic and the calculated probability are for the null hypothesis that the value of each of the fitted parameters were zero. The relationship has a predictive range from 1.5542y (all sutures open, score 0) to 12.41y (all sutures closed, score 3).

Anova Table for Multiple Linear Regression

Source	df	SS	MS	F	P
Regression	3	219.541	73.180	52.73	< 0.0005
Residual Error	38	52.735	1.388		
Total	41	272.276			

Statistics on the fitted relationship: y = 1.5542 + 1.0616xOP + 1.4538xC + 1.1033xSJ

Predictor	Coefficients ± SE	Students t	P
Constant	1.5542 ± 0.4680	3.32	0.002
Occipito-Parietal (OP)	1.0616 ± 0.2156	4.92	< 0.0005
Coronal (C)	1.4538 ± 0.2386	6.09	< 0.0005
Squamosal-Jugal (SJ)	1.1033 ± 0.3490	3.16	0.003

using definitively known-age animals, 10 months to 11 y 11 m (n = 42) males. Twenty one (21) seals were aged based upon being tagged as pups (with birthdate taken as 1 November). Twenty one (21) seals were aged (1 to 11 y) based upon GLG-dentine as described previously (Oosthuizen 1997; Stewardson et al. 1998, 2008).

Regression analysis for age (y) of male South African fur seals vs. Suture Index (**SI***) is shown in Fig. 1. The fitted line is an ordinary least squares linear regression forced through the origin (0,0) or y = mx. This was justified because the y-intercept of a regression of the form y = mx + b was not significantly different to zero. The slope m = 0.7990 ± 0.02354, n = 42, r = 0.8887, p << 0.001. The standardized residuals vs. fitted values and the normal probability plot of the standardized residuals showed that the model assumptions held (errors independently and identically distributed according to a Normal distribution with zero mean and constant variance). The normality assumption was justified based upon the appearance of the normal probability plot.

Another way to approach estimating age is to fit a General Linear Model (GLM) to suture scores (Dobson 2001). A general linear model fit was made of age on the suture scores for the Basioccipito-basisphenoid (VI), Occipito-parietal (I), Coronal (V), Interparietal (III) and Squamosal-jugal (X) (five variables) as described by Cook and Weisberg (1999). The suture scores were treated as categorical data (strictly speaking they are ordinal which is ordered categorical). The reason the other suture variables were not included was because they were fully open for all definitively aged animals so provided no useful information for predicting age. The residuals vs. fitted values plot looked like a random scatter about zero so the model was adequate. The normal probability plot of the standardized residuals was approximately linear so the normality assumption held. Plotting the coefficients for each level of the suture considered against level the relationship was roughly linear for each suture so we could treat the sutures as continuous variables even though technically they are ordinal variables. This allowed us to fit a multiple linear regression model to the data with age as the dependent variable and the five suture variables as the independent variables. Not all five sutures were needed in the model. A multiple F-Test showed that we could collapse the model with all five predictors in it to a simpler model (p-value = 0.61) with only 3 suture scores plus a constant. The final multiple linear regression model fitted to the data was;

Predicted Age (y) =
1.5542 + 1.0616xOP + 1.4538xC + 1.1033xSJ
Equation 1

where, OP is the suture score for the Occipito-parietal (I), C is the score for the Coronal (III) and SJ is the score for the Squamosal-jugal (X). The Coefficient of Determination (R^2) was 0.8060 and the Adjusted Coefficient of Determination was 0.7910 (adjusted for fitting 3 parameters, see Cook and Weisberg 1999).

The ANOVA on the multiple linear regression and the asymptotic errors of the fitted parameters calculated by matrix inversion are shown in Table 2. Inference was possible because the residuals vs. fitted values plot looked like a random scatter about zero

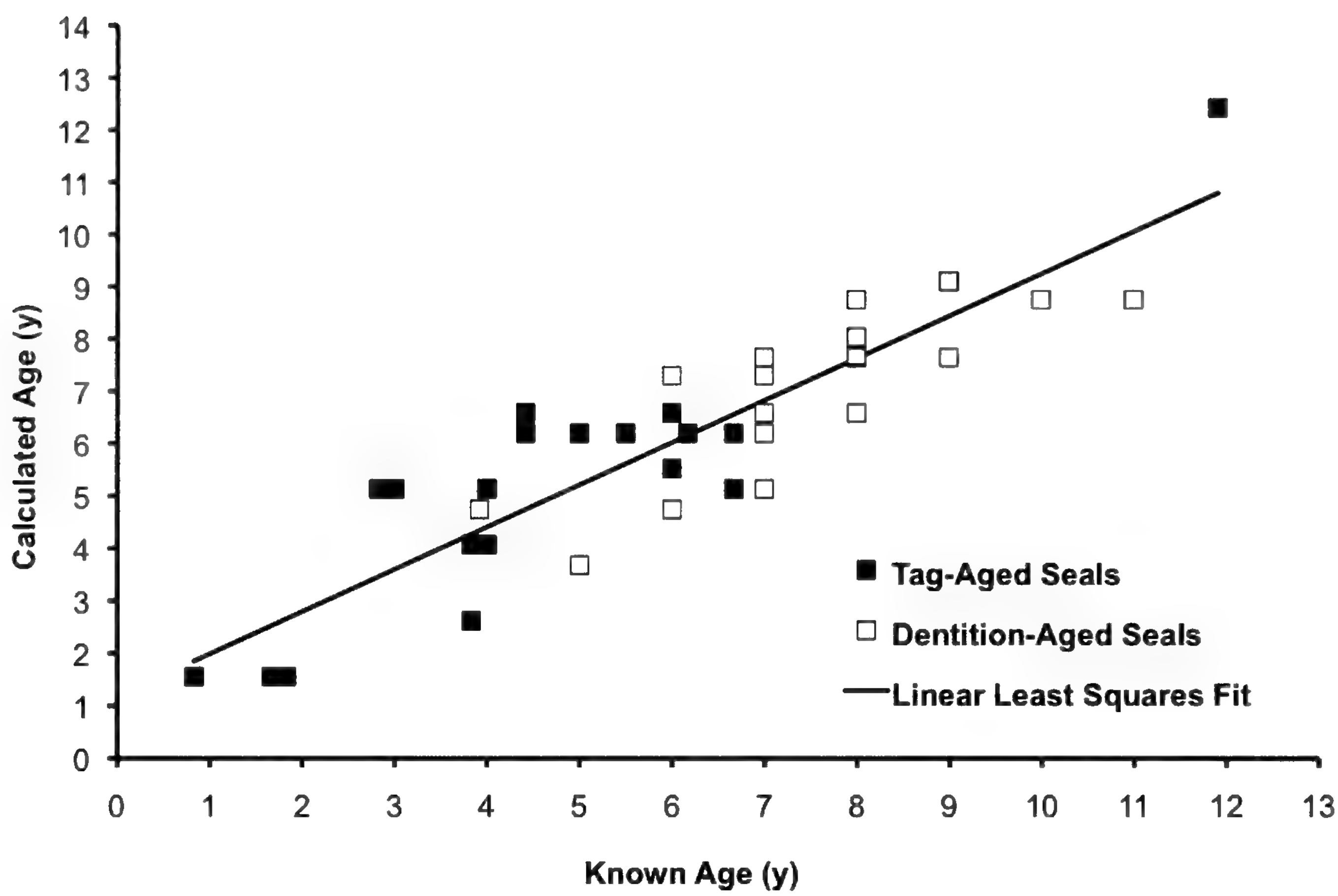

Figure 2. Calculated age using multiple linear regression of suture scores vs. known age (n = 42) of male South African fur seals. Suture scores were graded from 0 to 3 and the predicted age calculated using Equation 1 using data on closure for the Occipito-parietal (I), Coronal (V) and Squamosal-jugal (X) sutures. The minimal possible predicted age was when all sutures had a suture score of zero and maximum when all sutures had a score of 3. The predicted age was within ±1 y in 26 of 42 animals, within ±1.5 y in 34 of 42 animals and all predicted ages were within ±2 y.

and the normal probability plot of the standardized residuals was approximately linear so the normality assumption held. All predictions of age lie between 1.5542 (all sutures with a score of zero) and 12.4103 (all three sutures with a score of 3) so we could use this fitted model to predict the age of subadults and adults. The maximum possible predicted age using Equation 1 is 12.41; inclusion of the 5 suture variables initially used for this analysis only extends the predicted age to 12.65 y.

Fig. 2 shows a plot of predicted age using the multiple linear regression above (Equation 1) vs. known age. The multiple linear regression is able to predict ages within about ± 1 y for individuals 1 to 12 y. There is a good linear relationship between predicted age (y) and known age (y), ($r = 0.8980$, $p << 0.001$). The accuracy of the predicted age varies from 1.9 ± 0.4 y for 1 year-olds to 10.9 ± 0.86 y for 12 y-olds. Predicted age was within ±1 y for 62% of all animals of known age, within ±1.5 y for 81% and within ±2 y for all animals of known age.

Sequence of Suture Closure

The sequence of partial suture closure (**PSC**) differed from the sequence of full suture closure (**FSC**) with fusion beginning at different ages and some sutures taking longer to close than others (Tables 1 and 3).

For the range of available specimens using classification analysis, the sequence of beginnings of **PSC** according to chronological age was Basioccipito-basisphenoid (VI) (**PSC** at 2 y), Coronal (V) (**PSC** at 3 y), Occipito-parietal (I) (**PSC** at 3 y), Interparietal (III) (**PSC** at 4 y), Squamosal-jugal (X) (**PSC** at 6 y) and Premaxillary-maxillary (IX) (**PSC** at 12 y). Considering that the Basioccipito-basisphenoid suture (VII) was fully closed in nearly all animals at 3-4 y, **PSC** would occur at 1 or 2 y, before or at the same time as the Coronal (V). The Squamosal-parietal (II), Interfrontal (IV), Basisphenoid-presphenoid (VIII) (sutures of the brain case), Internasal (XI) and Maxillary (VII) (sutures of the face), showed no signs of partial closure in animals less than 11 y 11 m. Even

Table 3: Standard body length (SBL), Condylobasal length (CBL), SI* and Age Estimations for Male South African fur seals using the Age (y) vs. SI* linear regression relationship (Fig. 1) and the multiple linear regression approach (Equation 1, Fig. 2) which gives an age maximum of 12.4 y. The 17 males with ages marked (*) had no tag or dentition-based age; specimens marked ^{3}12 or ^{3}13 (n = 10) were known to be 12 y or older based upon dentition. Predicted ages based upon SI* values >16 are only provisional because they are extrapolations and are marked (?).

Museum N°	SBL (cm)	CBL (mm)	Suture N° (as for Table 1; those used for multiple linear regression marked in **bold**)											Suture Index (SI*)	Age (y)	Predicted Age (y ± SE)	Age (y) Multiple Linear Regression
			VI	**I**	**V**	III	**X**	IX	VII	II	IV	VIII	XI				
PEM898	200	*	3	**3**	**2**	2	**2**	1	1	0	0	1	1	16	*	12.78 ± 0.38	9.85
PEM916	91	159.5	1	**0**	**1**	0	**0**	0	0	0	0	0	0	2	*	1.60 ± 0.05	3.01
PEM917	104	176.6	1	**0**	**1**	0	**0**	0	0	0	0	0	0	2	*	1.60 ± 0.05	3.01
PEM951	170	226.5	3	**2**	**1**	0	**0**	0	0	0	0	0	0	6	*	4.79 ± 0.14	5.13
PEM958	190	240.9	3	**3**	**1**	1	**1**	0	0	0	0	0	0	9	*	7.19 ± 0.21	7.30
PEM975	172	232.2	3	**3**	**2**	0	**0**	0	0	0	0	0	0	8	*	6.39 ± 0.19	7.65
PEM1453	193	*	3	**3**	**1**	0	**0**	0	0	0	0	0	0	7	*	5.59 ± 0.16	6.19
PEM1560	201	241.3	3	**3**	**1**	3	**0**	0	0	0	0	0	0	10	*	7.99 ± 0.24	6.19
PEM1587	192	265.3	3	**3**	**3**	3	**3**	2	2	2	1	0	0	22	*	17.58?	≥ 12.4
PEM1892	185	242.9	3	**3**	**2**	1	**0**	0	0	0	0	0	0	9	*	7.19 ± 0.21	7.65
PEM2035	*	*	1	**0**	**1**	0	**0**	0	0	0	0	0	0	2	*	1.60 ± 0.05	3.01
PEM2137	118	194.9	1	**1**	**1**	0	**1**	0	0	0	0	0	0	4	*	3.20 ± 0.09	5.17
PEM2198	104.8	186.4	3	**0**	**1**	0	**0**	0	0	0	0	0	0	4	*	3.20 ± 0.09	3.01
PEM2201	103	171.1	2	**0**	**0**	0	**0**	0	0	0	0	0	0	2	*	1.60 ± 0.05	1.55
PEM2238	96	176.5	2	**1**	**0**	0	**0**	0	0	0	0	0	0	3	*	2.40 ± 0.07	2.62
PEM2253	152	230.8	3	**3**	**2**	2	**0**	0	0	0	0	0	0	10	*	7.99 ± 0.24	7.65
PEM2254	146	226.5	3	**3**	**1**	0	**1**	0	0	0	0	0	0	8	*	6.39 ± 0.19	7.30
PEM1507	198	260.7	3	**3**	**2**	3	**2**	2	2	2	1	0	0	20	≥12	15.98?	9.85
PEM1698	190	*	3	**3**	**3**	3	**3**	2	2	2	1	0	0	22	≥12	17.58?	≥ 12.4
PEM1879	200	259.2	3	**3**	**3**	2	**2**	2	1	1	1	0	0	18	≥12	14.38?	11.3
PEM1882	180	248.3	3	**3**	**3**	3	**2**	2	0	0	0	0	0	16	≥12	12.78 ± 0.38	11.3
PEM1890	192	258.5	3	**3**	**3**	2	**2**	1	1	1	1	0	0	17	≥12	13.58?	11.3
PEM1895	188	263.9	3	**3**	**3**	2	**3**	1	2	2	0	0	0	19	≥12	15.18?	≥ 12.4
PEM2049	174	262.7	3	**3**	**3**	3	**1**	1	1	0	1	0	0	16	≥12	12.78 ± 0.38	≥ 12.4
PEM2132	194.8	257.8	3	**3**	**3**	3	**2**	2	2	1	1	0	0	16	≥12	12.78 ± 0.38	10.2
PEM2141	*	250.3	3	**3**	**3**	3	**1**	1	1	1	1	0	0	20	≥12	15.98?	11.31
PEM2151	*	262.7	3	**3**	**3**	3	**3**	0	1	0	0	0	0	17	≥13	13.58?	10.2

in the very old males (≥ 12 y) there were no signs of closure in the Basisphenoid-presphenoid (VIII) or Internasal (XI) (Table 3).

The sequence of **FSC** according to known chronological age was Basioccipito-basisphenoid (VI), Occipito-parietal (I), Coronal (V), Interparietal (III) and finally Squamosal-jugal (X) (Table 1). With the exception of the Squamosal-jugal (X) these are sutures of the brain case. The Basioccipito-basisphenoid (VI) was fully closed at 3-4 y in nearly all animals. The Occipito-parietal (I) was fully closed in some animals as early as 4 y-old class. The Coronal (V) was fully closed in one 8 y-old, two 9 y-olds and one 12 y-old. The Interparietal (III) was fully closed in two 9 y-old animals and one 12 y-old. The Squamosal-jugal (X) was fully closed in the one animal in the 12 y-old class where its age was based upon tagging. All other definitively aged animals had no closure or only partial closure of the Squamosal-jugal (X). The Maxillary (VII), Squamosal-parietal (II), Interfrontal (IV), Basisphenoid-presphenoid (VIII) and Internasal (XI) showed no signs of even partial closure in definitively aged animals (Table 1) but some partial closure of these sutures were observed in very old animals with ages greater than or equal to 12 y (Table 3).

Although the sutures and their pattern of closure were clearly related to each other and to chronological age, the sequence of closure was not sufficiently close to be used as a reliable technique for estimating chronological age (Table 1). Unfortunately, the data set was too small to further develop such a classification system in the present study.

DISCUSSION

Limitations of Dentition-Based Ageing of Skulls

There are two commonly used methods of aging seals using dentition: counting growth layers in the dentine or counting growth layers in the cementum. The geometry of deposition of dentine and cementum is different: dentine is deposited from the outside to the inside of the tooth and hence is limited by closure of the tooth pulp. Once the pulp is closed no further layers of dentine can be deposited and so dentine layering has determinant growth (McCann 1993). Cementum is deposited by the periodontal membrane surrounding the root of the tooth and so the innermost layer is the oldest and the outermost layer is the newest. Its growth is indeterminate.

In the South African fur seal, it is not possible to determine chronological age of animals ≥12 y from growth layers in the dentine (called Growth Layer groups or GLG) because of pulp cavity closure (Oosthuizen 1997; Stewardson 2001; Stewardson et al. 2008) and so cannot be used to estimate ages of animals over the full life-span of these seals (Wickens 1993). Male Australian fur seals up to 16 y old were identified by Arnould and Warneke (2002) using the cementum-ageing method. It is important that Arnould and Warneke (2002) were able to identify very old females up to 26 y old and so it is likely that the technique would be useable for males over their entire lifespan. Arnbom et al. (1992) were able to correctly age Antarctic fur seals (*Arctocephalus gazella*) using the cementum technique on animals with known ages of 16 y and McKenzie et al. (2007) could age male New Zealand fur seals (*Arctocephalus forsteri*) up to 19y.

Lack of awareness of the limitations of dentine-based aging can lead to mistakes in aging animals and hence erroneous life tables. Dickie and Dawson (2003) did not take pulp closure into account in their dentine-based aging of New Zealand fur seals and concluded that the oldest individuals in their study were 12 y old. In an independent study McKenzie et al. (2007) using the cementum method were able to identify males that were 19 y old and so it is probable that some individuals in the study by Dickie and Dawson (2006) aged using the dentine-GLG method were actually older than 12 y. The crucial limitations of the dentine aging method are well illustrated by the example of the crabeater seal (*Lobodon carcinophagus*). In the crabeater seal the dentine method is only useable for animals up to about 10 y old because of pulp cavity closure but the cementum technique can be successfully used to age animals up to 39 y (Laws et al. 2002). The cementum technique needs reassessment in South African fur seals.

Suture closure

Examination of suture index (**SI***) relative to **SBL** supported the sequence of **FSC** derived from chronological age: (i) full closure of the Coronal (V) occurs at about the same time or slightly before that of the Interparietal (III), and (ii) full closure of the Maxillary (VII) occurs after full closure of the Squamosal-jugal (X). The order of closure appears to be, Basioccipito-basisphenoid (VI), Occipito-parietal (I), Coronal (V), Interparietal (III), and then the Squamosal-jugal (X) (suture sequence: 6,1,5,3,10). The Premaxillary-Maxillary (IX) showed no signs of closure in any of the definitively aged animals except for the oldest specimen, which was 11 y 11 m old. In our sample of skulls there were no signs of closure in definitely aged animals (≤12 y) of the Maxillary (VII), Squamosal-parietal (II), Interfrontal (IV), Basisphenoid-presphenoid (VIII) or Internasal (XI) although some animals aged as ≥12 y based upon GLG-dentine did have partial closure of these sutures (Table 3).

With the exception of the Squamosal-parietal (II), our study shows that the sutures of the brain case [Basioccipito-basisphenoid (VI), Occipito-parietal (I), Coronal (V) and Interparietal (III)] close before those of the face [Squamosal-jugal (X) and Premaxillary-maxillary (IX)]. Brunner (1998a) found a similar, but not identical, general pattern in the Australian fur seal (suture sequence: 6,1,3,5,2,7,9,8,4) and the New Zealand fur seal. As with other mammals, the brain case attains full size early in development (neural growth pattern) because early maturation of the brain case is essential for nervous control of the body (Moore 1981).

The sequence of **FSC** reported by Rand (1949) based on male South African fur seals of unknown chronological age was: Basioccipito-basisphenoid (VI), Occipito-parietal (I), Interparietal (III), Coronal (V), Squamosal-parietal (II), Premaxillary-maxillary (IX); Interfrontal (IV) and Basisphenoid-presphenoid (VIII) in fully mature males (**SBL** ≈ 217 cm); and finally the Internasal (XI) in very old emaciated males (SBL ≈ 223 cm). The Maxillary suture (VII) was not examined and so Rand's **FSC** suture sequence was: 6,1,3,5,2,9,4,8,11. This **FSC** sequence is similar to that found by Brunner (1998a) for the Australian fur seal (suture sequence: 6,1,3,5,2,7,9,8,4) but differs from that found in the present study in the order of closure of the Interparietal (II) and Coronal (V). The sequence of **FSC** for the first 4 sutures was supported by the present study, and confirmed that certain sutures do not fully fuse until the animal is ≥12 y (Premaxillary-maxilla (VI), Maxillary (VII), Interfrontal (IV), Basisphenoid-presphenoid (VIII) and Internasal (XI). It is interesting to note that the **PSC** and **FSC** closure sequences found in the present study are similar to but not identical to those found for the Australian fur seal (**PSC**: suture sequence: 1,5,6,2,3,7,9,4,8; **FSC**: suture sequence: 6,1,3,4,2,7,9,8,4) and considerably different to sequences found in the New Zealand fur seal (Brunner 1998a,b) and other fur seals (Brunner 2004; Brunner et al. 2004). Our suture closure sequences are more reliable than most other reported suture closure sequences of fur seals because they are largely based on known-age males.

One major difference between closure patterns of sutures in South African fur seals compared to suture closure patterns in Australian fur seals may be in the maximum degree of closure found in the animals. On the Brunner scale (Brunner 1998a,b) the maximum suture index score was 4 × 9 = 36 when all 9 sutures were closed. Brunner (1998a) recorded several animals with suture scores greater than 34. In the present study on South African fur seals, no animal closely approached **FSC** of all the sutures examined. On Brunner's scale and taking into account only the 9 sutures used in her study, the two animals with the highest suture indices in the present study were PEM1698 (≥12 y) with a Brunner-scale suture index of 26 and PEM1587 (unknown age) with a Brunner-scale suture index of 28. These suture indices are well short of the 36 maximum score for 9 sutures on a 1-4 scoring scale. The data of Arnould and Warneke (2002) shows that male Australian fur seals may be considerably longer-lived than their South African counterparts and their data also supports Brunner (1998a) who contended that Australian fur seals have a slightly different growth pattern to South African fur seals.

Orr et al. (1970) found that in male *Zalophus californianus,* California sea lion, the sequence of **PSC** and **FSC** (n = 9 sutures) differed slightly from that found in the South African fur seal. The sequence of **PSC** was: Basioccipito-basisphenoid (VI), Coronal (V), Squamosal-parietal (II), Occipito-parietal (I), Interfrontal (IV), Interparietal (III), Premaxillary-maxilla (IX), Basisphenoid-presphenoid (VIII) and finally the Maxillary (VII), while the sequence of **FSC** was: Basioccipito-basisphenoid (VI), Occipito-parietal (I), Interparietal (III), Squamosal-parietal (II), Coronal (V), Basisphenoid-presphenoid (VIII) and finally the Interfrontal (IV)/Premaxillary-maxillary (IX)/Maxillary (VII), with all sutures fully closed by 15 y (n = 35 males, 1-15 y). Thus, the suture index (**SI***) of the California sea lion does reach an asymptote, whereas this does not seem to occur in the South African fur seal although it does seem to occur in both the Australian fur seal and the New Zealand fur seal (Brunner 1998a,b). No wild South African fur seal male appears to be recorded where all the skull sutures have been found to be fully closed (present study and Rand 1949). Perhaps so few animals reach ages much beyond 12 y that it would be unlikely to find a tagged animal of such an age. Boyd and Roberts (1993) in their study of the life history of the Antarctic fur seal on South Georgia found that the average age at death of a sample of 724 male seals was only 7.69 ± 1.9 (SD) y and were able to find only two 14 y-olds and one 16 y-old.

In male *Callorhinus ursinus,* Northern fur seal, the age at which the sutures begin to close and the length of time taken for sutures to fully close was slightly different than in the South African fur seal (Scheffer and Wilke 1953; present study). For example, the Basioccipito-basisphenoid (VI) closed between 2 and

6 y; the Occipito-parietal (I) closed between 2 and 6 y; and the Interparietal (III) closed between 4 and 7 y (n = 121 males, 1-7 y). Other sutures were not examined.

Differences in growth rates/patterns and considerable individual variation between animals of similar age, and small sample sizes, would account for observed discrepancies within and between species noted by Brunner (1998a,b), Brunner (2004) and Brunner et al. (2002, 2004).

Suture Index as an indicator of chronological age

We have concluded that in male South African fur seals, suture index (**SI***) cannot be regarded as a highly reliable technique for estimating chronological age. The suture index (**SI***) has been shown to be a useable estimator of the age of male South African fur seals but is not as accurate as GLG-dentine (Oosthuizen 1997; Stewardson et al. 1998, 2008). This is in agreement with comprehensive studies on humans where date of birth and date of death are usually well documented (McKern and Stewart 1957; McKern 1970). No suture index (**SI***) vs. age information appears to be available on Australian or New Zealand fur seals.

The limitations of the plot of **SI*** vs. Age (Fig. 1) are that there is a significant spread of data points around the regression line and the oldest animal in the data set was only 11 y 11 months old. The relationship between **SI*** and Age is not known for animals older than 12 y or only about 1/2 to 2/3 of the estimated lifespan of South African fur seals (Wickens 1993). Nevertheless, Table 3 shows that Age vs. **SI*** does not appear to suddenly reach an asymptote at **SI*** values only slightly beyond the maximum **SI*** value for an animal of definitively known age (Fig. 1, Tables 1 and 2). The linearity of the **SI*** vs. Age regression does not appear to level off in old animals but it would be inappropriate to confidently extrapolate the curve for deducing the age of animals with a **SI*** value much greater than 16. Some very old animals had suture indices as high as 22 (PEM1587 & PEM1698), which by extrapolation implies an age of about 17.5 ± 0.5 y, but such age determinations should be taken as *only provisional*. Orr et al. (1970) found that suture index vs. age was asymptotically curvilinear in old male California sea lions. In most mammals (Morris 1972) and in humans (McKern and Stewart 1957; McKern 1970; Sinclair 1973) it is known that suture closure does not continue at a linear rate in old age. Perhaps a curvilinear model might prove to be more appropriate if **SI*** data on very old animals becomes available.

Table 3 shows a summary of our attempts to use the simple linear regression of age vs. **SI*** to predict the ages of some specimens where no age information was available or where the dentine-GLG technique could only estimate their age as greater than or equal to 12 y. The Age vs. **SI*** regression (Fig.1) is useful for predicting the age of animals of unknown age (n = 17) and some animals with a GLG-dentine-based age of ≥12 y (n = 10). Six (6) of the ten animals known to be at least 12 y (based upon GLG-dentine) had **SI*** values of 16 or 18 and so their ages can be estimated to be about 13 to 15 y old with a reasonable degree of confidence (Table 3). The remaining four (4) males had **SI*** values ranging from 19 to 22, indicating that they must be very old animals. Sixteen of the 17 animals with unknown age have **SI*** values within the range of the regression fit (**SI*** = 0 to 16) and so valid estimates of their ages could be made (Table 3).

Multiple linear regression (Equation 1) appears to give useful estimates of the ages of animals based on closure of three sutures (Fig. 2; Tables 2 and 3). The predictive range of Equation 1 is 1.55 y (all 3 sutures open) to 12.41 y (all 3 sutures closed). There are no pups and only two yearlings (aged 6 to < 18 months) in the data set. All fur seals with ages defined only as being greater than 12 y (based upon GLG-dentine, n = 17) and hence not used to generate Equation 1, were correctly predicted to be adults at least 9.85 y (Table 3). If we had seals older than 12 y that were accurately aged, it should be possible to extend the model using closure of additional sutures to estimate ages greater than the limits imposed by using only 3 sutures. Including later-closing sutures in an extended model it may be possible to reliably predict ages of older males using suture index (**SI***) or a multiple linear method. This would help in life-history and population studies of fur seals.

Suture Information and Age Class

Data on closure of some sutures are useful for classifying animals into pup/juvenile, subadult and adult classes and so is an indicator of age class in male South African fur seals (Table 1). The Basioccipito-basisphenoid suture (VI) located at the base of the skull is open (Suture score = 0) in pups and juveniles and is completely closed (score = 3) or more than 50% closed in all males older than 3 y. The sequence of closure of the Basioccipito-basisphenoid suture (VI) in South African fur seals exhibited little variability, with complete or nearly complete fusion evident at 3 or 4 y. Examination of this suture reveals the following: (i) suture open = male ≥ 3 y old; (ii) suture fully closed = male 3-4 y or older and male has reached puberty (Stewardson et al. 1998). Complete closures of the Basioccipito-basisphenoid (VI) + Occipito-parietal (I) + Coronal (V) + Interparietal (III) sutures only occurs in adult males > 7 y.

CONCLUSIONS

In male South African fur seals the sequence of partial suture closure (**PSC**) is different to the sequence of full suture closure (**FSC**). Sutures of the skull begin to close at different ages and the length of time taken for each suture to fully close is different. The sequence of **FSC** is Basioccipito-basisphenoid (VI), Occipito-parietal (I), Interparietal (III)/Coronal (V) and finally the Squamosal-jugal (X) in males ≥ 12 y. Suture index (**SI***) is not a very accurate indicator of chronological age (error ≈ ± 1-1.5 y), sutures close faster in some individuals than in others and sutures do not close in a definitive order, they close in different orders in different individuals. Thus suture closure statistics shown in Table 1 demonstrate that using suture closure sequences to determine relative ages of fur seals has the underlying flaw that sutures do not close in a definitive order (cf. Rand 1949, 1956; Brunner 1998a,b; Brunner et al. 2004). Based upon the data set currently available, **SI*** can be used to estimate ages of males up to about 14 y. If the average life span of South African fur seals is similar to that of the Antarctic fur seal (Boyd and Roberts 1993; Boyd et al. 1995) then a 0 - 14 y useful age range would be sufficient to be able to age the vast majority of skulls of dead animals. The Basioccipito-basisphenoid (VI) can be used as an indicator of age class for pups/ juveniles and subadults and combined with closure scores of other sutures adults can be distinguished from subadults. In principle, multiple linear regression of age vs. suture scores of several individual sutures can be used to estimate age. Multiple linear regression is likely to give more accurate estimates of age than the cruder suture index (**SI***) but inherently requires a large data set because several independent variables have to be fitted to the data set. Since we know that some sutures only close in very old males (Table 3), the use of suture information does offer a means of estimating the age of very old males but suture data on old males of known age is needed to extend the method to the full lifetime of the seals. However, in order to age very old animals using a multiple linear regression approach more suture variables would have to be added to the 3 suture scores used in Equation 1 and Fig. 2 because in very old animals all of these sutures have completely closed (Table 3). A multiple linear regression equation to predict ages over the full lifespan of male fur seals would probably need 9 to 11 suture scores as variables. Future efforts should be made to develop the cementum-dentition method of determining age in South African fur seals.

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Suture Index and Growth in the Male South African Fur Seal, *Arctocephalus pusillus* (Pinnipedia: Otariidae)

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The South African furs seal (*Arctocephalus pusillus pusillus*) is very closely related to the Australian fur seal (*A. pusillus doriferus*). We examine the relationship between skull suture index (**SI***) and growth parameters in the male South African fur seal, based on 42 animals of known age ranging from 10 m to 11 y 11 m. Twenty one (21) animals were aged based upon tagging as pups and 21 were aged based on dentine growth layers (1 to 11 y). Suture index and morphometric information was available on an additional 27 males; 17 had no age information but 10 were known from their dentition to be ≥12 y. Age has previously been found to be approximately directly proportional to suture index. Here we estimate asymptotic size and growth kinetics from **SI*** using nonlinear growth models [exponential saturation (von Bertalanffy), Logistic, Gompertz] fitted to cross-sectional morphometric data (n = 8 variables). The relationship between the following measurements was examined and suture index are presented in the present study: external body (standard body length, **SBL**; length of front flipper; length of hind flipper), skull (condylobasal length, **CBL**; Bizygomatic breadth; mastoid breadth; length of Mandible or Ramus length) and baculum (bacular length, **BL**). The asymptote values of these parameters are compared to those derived from chronological age and show very good agreement. The growth kinetic parameters calculated in terms of **SI*** when converted into years using the relationship between **SI*** and true Age (y) are also in close agreement with those calculated on tag and dentition aged animals.

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KEYWORDS: age-determination, asymptotic size, body measurements, maturity classification, Otariidae, Pinnipeds, skull suture, suture index.

INTRODUCTION

Skull suture characteristics have been shown to give a good indication of age class or maturity of male South African fur seals (*Arctocephalus pusillus pusillus*) and suture index (**SI***) can give approximate estimates of the age of the animals (Stewardson et al. 2011). Sutures in South African fur seals do not close in a definitive order (Stewardson et al. 2011) and so using order of suture closure to determine relative ages of male seals is only approximate (cf. Rand 1949, 1956; Brunner, 1998a,b; Brunner et al. 2004). The major limitation of the method, however, is that the relationship between suture scores of individual sutures and suture index (**SI***) and age is not known for very old animals (≥12 y). Suture information is available on animals that must be considerably older than the oldest animal of definitively known age. It is therefore useful to investigate the relationship between suture index (**SI***) and growth parameters such as Condylobasal length (**CBL**) of the skull, standard body length (**SBL**) and skeletal measurements.

Examination of growth and development of the skeleton was thought to be one of the more useful methods of estimating relative age in older specimens of fur seals (Rand 1949, 1956; Jonsgard 1969; McCann 1993; McLaren 1993) but statistical studies (Stewardson 2001; Stewardson et al. 2008, 2009, 2010a, b) have shown that skull and skeletal measurements give an indication of "age class" rather than chronological age. Skull, skeletal measurements, Standard Body length (**SBL**) and even baculum measurements can all be successfully used to classify South African fur seals into pups, juveniles, subadults and adults if the sex is known (Stewardson et al. 2008, 2009, 2010a,b). If the sex is not definitely known difficulties would arise in distinguishing a subadult male from a female (Stewardson 2001; Stewardson et al. 2010a).

The specific objective of this study was to estimate asymptotic size inferred from suture index using nonlinear growth models fitted to cross-sectional morphometric data. There is no comparable information on development of body size parameters vs. suture closure parameters in the Australian fur seal (*Arctocephalus pusillus doriferus*), which is very closely related to the South African fur seal (*Arctocephalus pusillus pusillus*) (Lento et al. 1997; Brunner 1998a,b; Brunner et al. 2002; Brunner 2004; Brunner et al. 2004; Stewardson et al. 2008, 2009, 2010a,b, 2011) and so any information gained on the South African fur seal would be useful for studies of the life history of the Australian fur seal (Arnould and Warneke 2002). Adult male Australian fur seals are known to reach a marginally larger size than the South African variety and grow faster and perhaps live longer (Arnould and Warneke 2002; Stewardson et al. 2008, 2009) and so some caution is needed using data on South African fur seals to draw inferences about Australian fur seals.

MATERIALS AND METHODS

Abbreviations used in Text

Full Suture Closure (**FSC**), Partial Suture Closure (**PSC**), Condylobasal length (**CBL**), Standard Body length (**SBL**), Suture Index (**SI**), Coefficient of Determination (**R^2**).

Collection of specimens and morphometry

Male South African fur seals were collected along the Eastern Cape coast of South Africa between Plettenberg Bay (34° 03'S, 23° 24'E) and East London (33° 03'S, 27° 54'E), from August 1978 to December 1995, and accessioned at the Port Elizabeth Museum (PEM). Collection procedures are described in Stewardson et al. (2008, 2009). Forty eight (48) males had suture index (**SI**) information; external body information was available on 43 males (body measurement information missing on PEM 898, 1453, 1698, 2047 & 2258); skull data was available on 44 animals (but suture information was missing on PEM2035, 2141, 2151 & 2252). Matched baculum data and suture index information was available on only 35 animals (13 male specimens with suture data, had no baculum information).

Thirty one (31) specimens were aged from incremental lines (called Growth Layer Groups, **GLG**) observed in the dentine of upper canines (Oosthuizen 1997; Stewardson et al. 1998; Arnould and Warneke 2002; Stewardson et al. 2008, 2009, 2011). Ten (10) of the 31 GLG-dentine-aged animals could only be classified as being ≥12 y old (Stewardson et al. 2011). Occasional individuals are found where 13 GLGs can be distinguished (PEM2151) and so their minimum age is ≥13 y but such animals are rare. Attempts to age the remaining seventeen (17) animals from tooth sectioning were not successful.

The sample was supplemented with external body and skull measurements from 21 known-age animals (animals tagged as pups) from Marine and Coastal Management (MCM), Cape Town. Most specimens in the MCM collection had very complete data sets with the exception of MCM1809, which had only information on tag-age, suture indices for the skull sutures, condylobasal length (**CBL**) and standard body length (**SBL**). No baculum data was available on any of the MCM specimens.

The total number of animals with suture information was 48 + 21 = 69 animals but many animals had incomplete sets of information on other skull and body measurements. For example, the difference in the data set for sutures and **CBL** (n = 65) and sutures and **SBL** (n = 64) is not simply due to a single missing **SBL** measurement. All MCM animals had information on sutures and **CBL** and **SBL.** In the PEM data set in one animal both **CBL** and **SBL** data were missing, in 4 animals **CBL** data was available and **SBL** data was not and in 3 other animals **SBL** data was available and **CBL** was not. Thus, in the case of skull measurements, 65 animals had information on sutures and **CBL** but 4 lacked **CBL** information because of skull damage.

The relationship between the following measurements was examined and suture index are presented in the present study: external body (standard body length, **SBL**; length of front flipper; length of hind flipper), skull (condylobasal length, **CBL**; Bizygomatic breadth; mastoid breadth; length of Mandible or Ramus length) and baculum (bacular length, **BL**). Measurements were recorded according to Stewardson et al. (2008, 2009, 2010a,b). Statistics on Tip of Snout to Genital Opening and Tip of Snout to Anterior Insertion of Front Flipper vs. suture index were investigated by Stewardson (2001) but provided little novel extra information and so have been omitted from the present study.

To make curve fitting easier in the present study, the suture scores were recoded as ranging from 0-3 (fully open, 0; suture less than half closed, 1; suture more than half-closed, 2; fully closed, 3). These values were added to give a total suture index (**SI***), ranging from 0 (all sutures open) to 33 (all sutures closed). The special form of the suture index used in the present study is designated **SI***. The highest **SI*** on a male of definitive age was **SI*** = 16 for an individual 11 y 11 months old (MCM1809). The highest **SI*** readings were **SI*** = 22 for an animal ≥ 12 y based upon GLG-dentine (PEM1698) and another specimen (PEM1587) of unknown age.

Asymptotic size

Asymptotic size, inferred from suture index (**SI***), was estimated by fitting three nonlinear growth curves [Exponential Saturation (sometimes called the von Bertalanffy equation), Logistic and Gompertz curves, Stewardson et al. 2009] to morphometric data (Tables 3 and 4 below). The data on Front and Rear Flipper vs. **SI*** were found to be described very well by simple linear regressions of the form y = mx + b. The nonlinear and linear growth curves were fitted using EXCEL routines and the SOLVER least squares fitting routine in EXCEL (Stewardson et al. 2008, 2009, 2010a,b). Asymptotic errors of the fitted parameters were calculated by matrix inversion as previously described (Stewardson et al. 2008, 2009, 2010a,b).

RESULTS

Suture Closure vs. Condylobasal length (CBL) and Standard Body Length (SBL)

The relationship between **SI*** and **CBL** (Table 1) was examined using animals 80-201 cm **SBL** and ages 10 months to 11y 11 months upon tagging (n = 21) and the animals with a definitive age (< 12 y) based upon GLG-dentine (n = 21). **CBL**s were classed into groups rounded off to the nearest 10 mm (range 160 mm to 240 mm). For the range of available specimens, the sequence of partial suture closure (**PSC**) according to **CBL** was Basioccipito-basisphenoid (VI), Occipito-parietal and Coronal (I & V), Squamosal-jugal (X), Interparietal (III), Premaxillary-maxillary (IX).

Table 2 shows the data on **SI*** vs. **SBL** classed into groups rounded to the nearest 10 cm (range 84.5 to 199 cm). Two males from the Port Elizabeth museum collection (PEM2036 & PEM 2252) had no **SBL** measurements and so the data set consists of 21 animals with ages based on tagging but only 19 animals with GLG-dentine-based ages. For the range of available specimens, the sequence of **PSC** according to **SBL** was Basioccipito-basisphenoid (VI), Occipito-parietal/Coronal (I & V), Squamosal-jugal (X), Interparietal (III) and Premaxillary-maxillary (IX) in the oldest tag-aged animal. The other sutures were partially (**PSC**) or completely closed (Full suture closure, **FSC**) only in animals ≥12 y-old. The order of closure appeared to be Squamosal-parietal/ Interfrontal (II & IV) and then the Maxillary (VII). The Basisphenoid-presphenoid (VIII) and Internasal (XI) showed no signs of closure in the specimens used in the present study but have been reported to close in very old South African fur seal males (Rand 1949).

The sequence of **FSC** (suture score = 3 in the present study) for animals placed in groups according to **SBL** was Basioccipito-basisphenoid (VI), Occipito-parietal (I), Interparietal (III), Coronal (V), Squamosal-jugal (X) and finally the Premaxillary-maxillary (IX). The Basioccipito-basisphenoid (VI) was fully closed in all animals ≥ 150 cm **SBL** and nearly all animals with a **CBL** > 200 mm. **FSC** was evident in some animals in the 120 cm **SBL** and 190 mm **CBL** classes. The Occipito-parietal (I) was fully closed in all animals with an **SBL** greater than 170 cm, with **FSC** evident in some animals in the 130 cm **SBL** class. The Interparietal (III), Coronal (V) and Squamosal-jugal (X) were closed in some animals in the 170 cm **SBL** size class. The Maxillary (VII), Premaxillary-maxillary (IX), Squamosal-parietal (II), Interfrontal (IV), Basisphenoid-presphenoid (VIII) and Internasal (XI) showed no signs of closure in any animals less than 12 y-old. The male PEM2049 (**CBL** 262.7 mm, **SBL** 174 cm) was the smallest animal with any closure of these sutures.

Relationship between Skull and Body Parameters and Suture Index

Estimated asymptotic **SBL** was calculated using animals 80-201 cm, using all the animals with **SI*** information (n = 64). Parameters for the three growth functions are given in Table 3. Inspection of the residuals versus fitted values plots indicated that the three models (Exponential, Logistic and Gompertz) were all adequate for the range of **SI*** values available. In terms of the coefficient of determination (R^2), the models were found to be quite similar and the plotted curves largely overlap so they cannot be distinguished. Most R^2-values are ≈ 0.8 or higher and so fit the data very well. All three of these models adequately described the 'general' growth pattern of the Condylobasal length (**CBL**), Ramus length, Bizygomatic breadth, Mastoid breadth, Standard Body length (**SBL**) and baculum length (**BL**) vs. Suture Index (Table 3). Fig. 1 is a plot of Condylobasal length (**CBL**) vs. **SI*** and Fig. 2 is a plot of Standard Body Length (**SBL**) vs. SI.

Table 1: Suture Scores and Suture Index (SI*) for classes of Condylobasal Length (CBL) for male South African Fur Seals. Suture data for animals with known chronological age (y) based on tagging (Marine and Coastal Management (MCM) collection, Cape Town) and dentition (Port Elizabeth Museum, PEM). Suture number system (I-XI) and suture scores procedure as for Stewardson et al. (2011). Each CBL size class is rounded to the nearest 10 mm.

	Condylobasal Length Class (mm)										
Suture & Suture N°	160	170	180	190	200	210	220	230	240	250	270
Basioccipito-basisphenoid (VI)	0,0	0	1,3	3,1	3,3,2,2	3,3,3,3	3,3,2,3,3,3	3,2,3,3,3,3,3,3,3	3,3,3,3,3,3,3,3	3,3,3	3
Occipito-parietal (I)	0,0	0	0,2	2,1	2,1,2,1	3,2,3,3	3,3,3,3,3,3	2,2,2,3,3,2,3,2,3	3,3,3,2,3,3,2,3	2,2,3	3
Coronal (V)	0,0	0	0,2	1,0	1,1,1,1	1,2,0,2	1,1,2,1,1,2	1,2,0,1,1,1,1,2,2	3,3,2,2,2,2,1,0	3,3,2	2
Interparietal (III)	0,0	0	0,1	0,0	0,1,1,1	1,1,0,1	0,1,2,1,1,2	1,1,1,0,1,1,0,0,2	3,3,2,1,2,1,1,1	1,3,2	1
Squamosal-jugal (X)	0,0	0	0,0	0,0	0,0,0,0	0,0,0,0	0,0,0,0,0,0	0,0,0,1,1,0,0,1,0	0,3,1,0,0,0,0,0	0,1,1	1
Premaxillary-maxillary (IX)	0,0	0	0,0	0,0	0,0,0,0	0,0,0,0	0,0,0,0,0,0	0,0,0,0,0,0,0,0,0	0,1,0,0,0,0,0,0	0,0,0	0
Maxillary (VII)	0,0	0	0,0	0,0	0,0,0,0	0,0,0,0	0,0,0,0,0,0	0,0,0,0,0,0,0,0,0	0,0,0,0,0,0,0,0	0,0,0	0
Squamosal-parietal (II)	0,0	0	0,0	0,0	0,0,0,0	0,0,0,0	0,0,0,0,0,0	0,0,0,0,0,0,0,0,0	0,0,0,0,0,0,0,0	0,0,0	0
Interfrontal (IV)	0,0	0	0,0	0,0	0,0,0,0	0,0,0,0	0,0,0,0,0,0	0,0,0,0,0,0,0,0,0	0,0,0,0,0,0,0,0	0,0,0	0
Basisphenoid-presphenoid (VIII)	0,0	0	0,0	0,0	0,0,0,0	0,0,0,0	0,0,0,0,0,0	0,0,0,0,0,0,0,0,0	0,0,0,0,0,0,0,0	0,0,0	0
Internasal (XI)	0,0	0	0,0	0,0	0,0,0,0	0,0,0,0	0,0,0,0,0,0	0,0,0,0,0,0,0,0,0	0,0,0,0,0,0,0,0	0,0,0	0
Suture Index (SI*)	**0,0**	**0**	**1,7**	**6,2**	**6,6,6,5**	**8,8,6,9**	**7,8,7,8,8,10**	**7,7,6,8,9,7,7,8,10**	**12,16,11,8,10,9,7,7**	**9,12,11**	**9**
Age Class (y)	**1,1**	**2**	**2,8**	**3,4**	**3,4,4,4**	**5,6,4,8**	**6,4,6,6,7,8**	**7,4,5,6,7,7,7,8,7**	**9,12,8,7,7,9,7,6**	**8,9,10**	**11**
Total N° Skulls = 42	**2**	**1**	**2**	**2**	**4**	**4**	**6**	**9**	**8**	**3**	**1**

Table 2: Suture Scores and Suture Index (SI*) for classes of Standard Body Length (SBL) for male South African Fur Seals. Suture data for animals with known chronological age (y) based on tagging (Marine and Coastal Management (MCM) collection, Cape Town) and on dentition for the animals from the Port Elizabeth Museum (PEM). Suture numbers (I-XI) and suture scores procedure as for Stewardson et al. (2011). Each SBL size class rounded to the nearest 10 cm. Roman numerical classification of sutures follows Brunner (1998a,b).

	Standard Body Length Class (cm)												
Suture & Suture Nº	80	90	100	110	120	130	140	150	160	170	180	190	200
Basioccipito-basisphenoid (VI)	0,0	0	1	2	3,3,2,1	3,3	3,3,3,3	2,2,3,3,3,3,3,3	3,3,3,3,3	3,3,3,3,3,3,3,3	3	3,3	3
Occipito-parietal (I)	0,0	0	0	1	2,2,2,1	1,3	3,3,3,3	2,1,3,2,3,2,3,3	2,3,2,2,3	3,3,2,2,2,3,3,3	2	3,3	3
Coronal (V)	0,0	0	0	1	1,1,1,0	1,1	1,1,0,1	2,2,1,2,1,0,1,1	1,2,1,2,2	3,3,1,2,3,2,2,2	3	2,2	2
Interparietal (III)	0,0	0	0	1	0,0,1,0	1,1	0,1,0,1	1,2,1,1,1,1,0,0	1,2,1,0,2	3,3,1,1,1,2,1,1	3	1,2	2
Squamosal-jugal (X)	0,0	0	0	0	0,0,0,0	0,0	0,0,0,1	0,0,0,0,0,0,1,0	0,0,0,1,0	0,3,0,0,0,0,0,0	1	1,1	1
Premaxillary-maxillary (IX)	0,0	0	0	0	0,0,0,0	0,0	0,0,0,0	0,0,0,0,0,0,0,0	0,0,0,0,0	0,1,0,0,0,0,0,0	0	0,0	0
Maxillary (VII)	0,0	0	0	0	0,0,0,0	0,0	0,0,0,0	0,0,0,0,0,0,0,0	0,0,0,0,0	0,0,0,0,0,0,0,0	0	0,0	0
Squamosal-parietal (II)	0,0	0	0	0	0,0,0,0	0,0	0,0,0,0	0,0,0,0,0,0,0,0	0,0,0,0,0	0,0,0,0,0,0,0,0	0	0,0	0
Interfrontal (IV)	0,0	0	0	0	0,0,0,0	0,0	0,0,0,0	0,0,0,0,0,0,0,0	0,0,0,0,0	0,0,0,0,0,0,0,0	0	0,0	0
Basisphenoid-presphenoid (VIII)	0,0	0	0	0	0,0,0,0	0,0	0,0,0,0	0,0,0,0,0,0,0,0	0,0,0,0,0	0,0,0,0,0,0,0,0	0	0,0	0
Internasal (XI)	0,0	0	0	0	0,0,0,0	0,0	0,0,0,0	0,0,0,0,0,0,0,0	0,0,0,0,0	0,0,0,0,0,0,0,0	0	0,0	0
Suture Index (SI*)	**0**	**0**	**1**	**5**	**6,6,6,2**	**6,8**	**7,8,6,9**	**7,7,8,8,8,6,8,7**	**7,10,7,8,10**	**12,16,7,8,9,10,9,9**	**12**	**10,11**	**11**
Age Class (y)	**1,1**	**2**	**2**	**4**	**3,3,4,4**	**4,5**	**6,4,4,7**	**4,6,6,6,7,5,6,7**	**7,8,7,8,7**	**9,12,7,7,8,7,9,8**	**9**	**11,10**	**8**
Total Nº Skulls = 40	**2**	**1**	**1**	**1**	**4**	**2**	**4**	**8**	**5**	**8**	**1**	**2**	**1**

Table 3: Growth Parameters of Male South African Fur Seals Fitted to Suture Index (SI*)

Parameter	Fitting Model	Number of Animals (n)	Pup Size (P)	Exponential Constant (k)	Asymptotic Maximum (E_∞)	Coefficient of Determination (R^2)	Asymptote Max.- Older than 7 y or ≥ 200 cm **SBL**
Skull							
Condylobasal Length (**CBL**), mm Figure 1	Exponential	65	156 ± 4.705	-0.1115 ± 0.007527	276 ± 8.332	0.8400	254 ± 2.6 (n = 14) Max. = 265.3
	Logistic		157 ± 4.242	-0.1719 ± 0.01893	268 ± 5.563	0.8453	
	Gompertz		157 ± 4.570	-0.1413 ± 0.01800	271 ± 6.620	0.8429	
Ramus Length, mm	Exponential	60	99.2 ± 3.861	-0.09730 ± 0.008689	202 ± 8.687	0.8387	192 ± 2.9 (n = 13) Max. = 194
	Logistic		101 ± 3.425	-0.1675 ± 0.01919	192 ± 5.162	0.8433	
	Gompertz		100 ± 3.698	-0.1320 ± 0.01797	196 ± 6.407	0.8413	
Bizygomatic Breadth (Zyg), mm	Exponential	61	85.23 ± 3.368	-0.06495 ± 0.009577	182 ± 15.54	0.8057	149 ± 2.0 (n = 14) Max. = 159
	Logistic		85.87 ± 3.046	-0.1288 ± 0.01995	166 ± 7.368	0.8098	
	Gompertz		85.5 ± 4.274	-0.09658 ± 0.01884	171 ± 9.975	0.8078	
Mastoid Breadth, mm	Exponential	59	74.1 ± 2.940	-0.07436 ± 0.008803	167 ± 10.98	0.8436	138 ± 6.0 (n = 14) Max. = 150
	Logistic		85.87 ± 4.358	-0.1288 ± 0.02903	166 ± 10.98	0.8470	
	Gompertz		74.57 ± 3.159	-0.1103 ± 0.01660	158 ± 7.153	0.8464	
Body							
Standard Body Length (**SBL**), cm Figure 2	Exponential	64	77.1 ± 6.868	-0.1114 ± 0.01387	211 ± 11.73	0.7688	199 ± 3.6 (n = 17) Max. = 201
	Logistic		79.2 ± 5.665	-0.2182 ± 0.02717	198 ± 6.485	0.7815	
	Gompertz		78.0 ± 5.753	-0.1635 ± 0.02407	203 ± 8.160	0.7783	
Length of Front Flipper, cm Figure 3	Exponential	43	21.47± 1.467	-0.07445 ± 0.02306	50.57 ± 10.07	0.6887	47.2 ± 1.9 (n = 8) Max. = 55
	Logistic		21.73 ± 1.355	-0.1576 ± 0.04247	45.12 ± 4.622	0.6901	
	Gompertz		21.60 ± 2.598	-0.1157 ± 0.04094	47.03 ± 6.263	0.6896	
	Linear		23.44 ± 1.100	m = 1.3144 ± 0.1368		r = 0.8322	
Length of Rear Flipper, cm	Linear	43	15.17 ± 0.8823	m = 1.030 ± 0.1096		r = 0.8262	28.7 ± 0.9 (n = 7), Max. = 32
Baculum							
Baculum Length, mm Figure 4	Exponential	35	-12.5 ± 17.05	-0.2695 ± 0.05170	122 ± 3.944	0.7871	112 ± 6.4 (n = 14) Max. = 134.7
	Logistic		21.8 ± 4.660	-0.4653 ± 0.06346	119 ± 2.959	0.8105	
	Gompertz		14.5 ± 5.53	-0.3601 ± 0.05341	120 ± 3.319	0.8012	

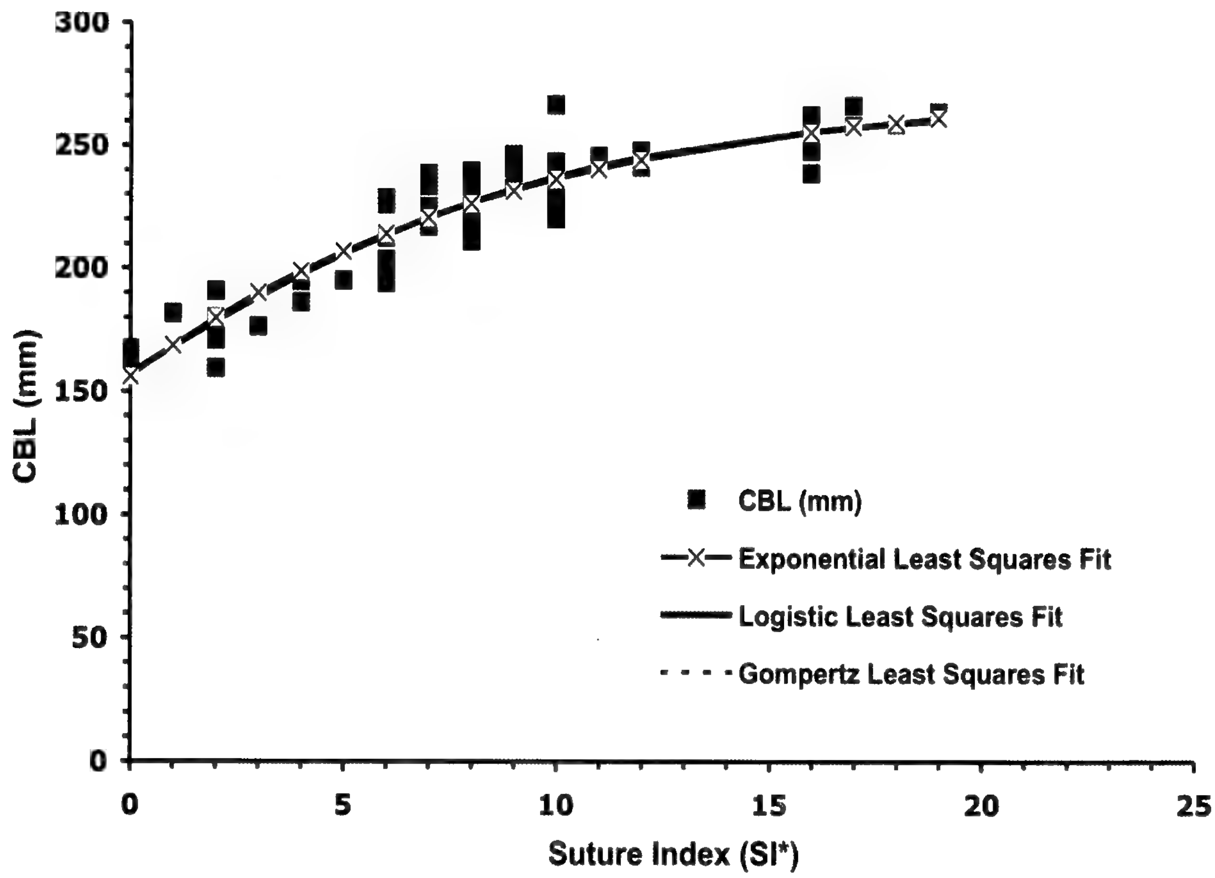

Figure 1. Non-Linear least squares fits to plots of Condylobasal Length (CBL) (mm) vs. Suture Index (SI*) (n = 63). All the fits were good (Coefficients of determination R2 > 0.8) and the model parameters are tabulated in Table 3.

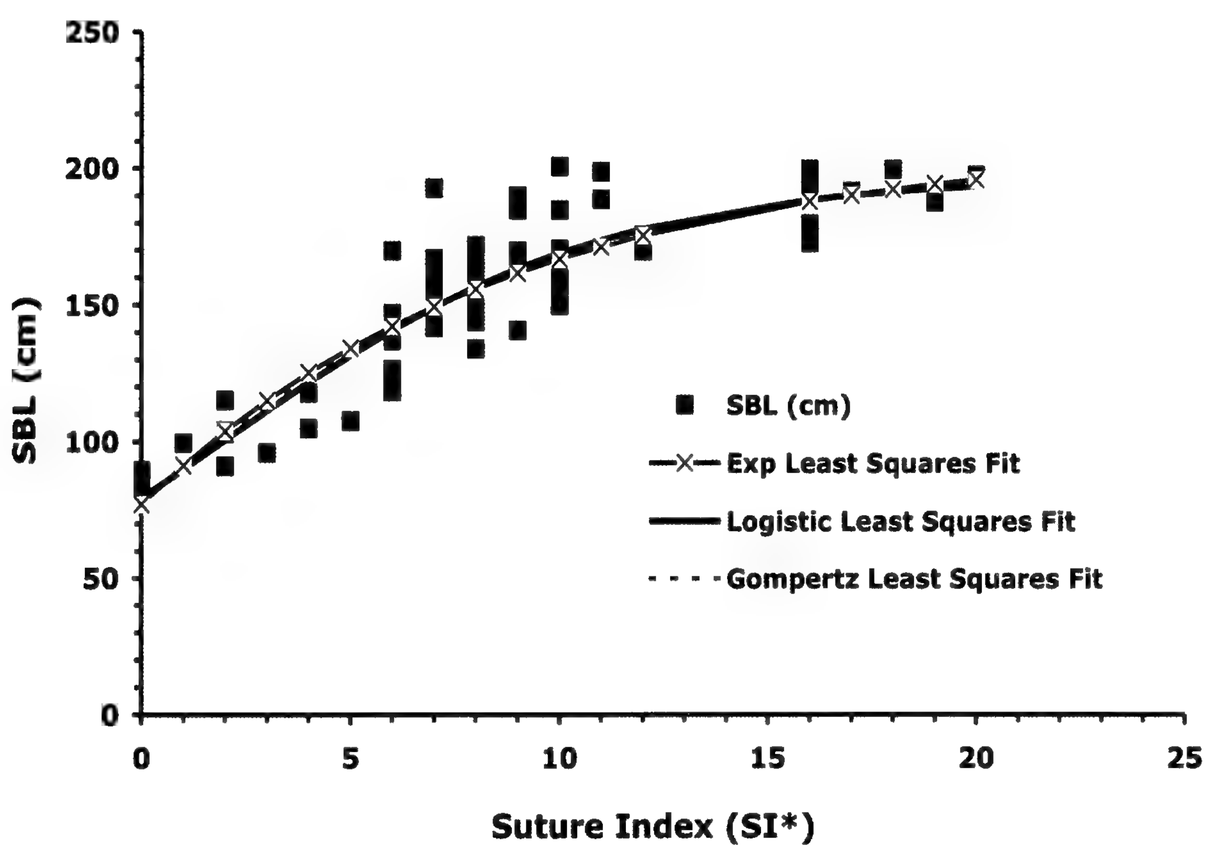

Figure 2. Non-Linear least squares fits to plots of Standard Body Length (SBL) (cm) vs. Suture Index (SI*) (n = 63). As for Fig. 1 all the fits were good (R2 = 0.76) and the model parameters are tabulated in Table 3.

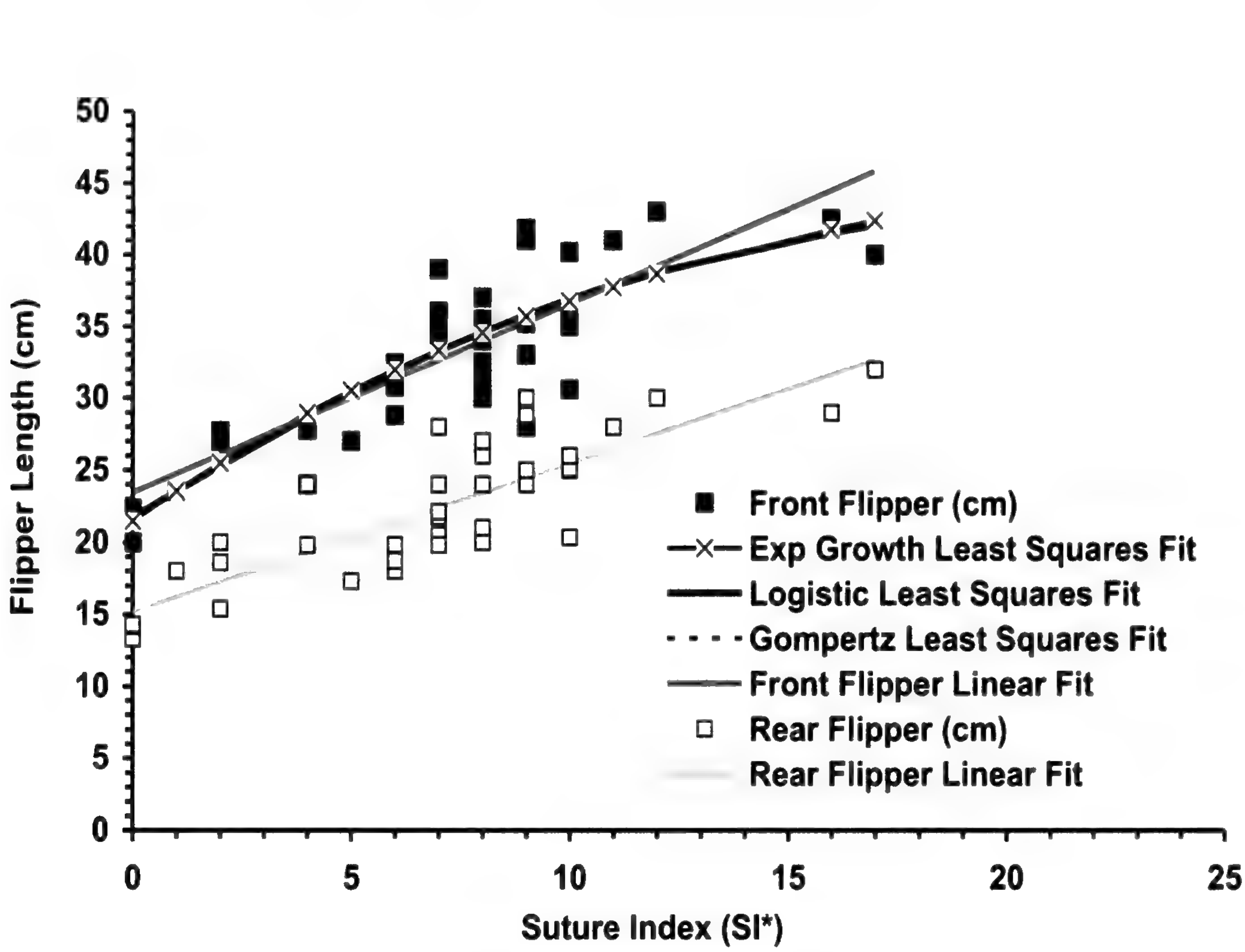

Figure 3. Front and Rear Flipper lengths vs. Suture index (SI*). Non-linear fits (Exponential, Logistic and Gompertz models) of Front Flipper length (cm) vs. SI* and also a linear fit to the same data (n = 42) are shown. A linear fit is shown for Rear Flipper length vs. SI*.

Plots of the three models in Figs. 1 & 2 are virtually identical and almost completely overlap each other. The initial sizes (the 'pupsize') and the asymptotic maximum sizes determined using the three models were consistently not significantly different to one another, regardless of which fitting curve model was used (Table 3).

Plots of Front Flipper Length vs. **SI*** and Rear Flipper Length vs. **SI*** (Fig. 3) are more problematic. Satisfactory fits to the Exponential, Logistic and Gompertz models could be achieved for the Front Flipper vs. **SI*** data, however Fig. 3 clearly shows that fitted lines are very close to linear with very little curvature. The relative errors of the fitted parameters are large even though $R^2 > 0.67$ (Table 3) suggesting that the three parameter models are overly complex for the data available. A simple linear relationship of Flipper Length vs. **SI*** also fits the data very well ($m = 1.3144 \pm 0.1368$, $R^2 = 0.6926$) and is a fundamentally simpler model using only two parameters. The plot of Rear Flipper length vs. **SI*** does not fit the Exponential, Logistic and Gompertz models very well because estimates of the initial size and the asymptotic final size are not very precise and the fitted lines are almost linear. Fitting the simple linear relationship is more realistic (Fig. 3): based on the principle of adopting the simplest model consistent with the data. The linear fit has a correlation coefficient (r) value of 0.8262 and a slope of 1.030 ± 0.1096 ($p << 0.0005$).

Some conclusions can be drawn about the relative growth rates of front vs. rear flippers. Front Flipper and Rear Flipper measurements on the same individual are highly correlated ($r = 0.8288$, $n = 43$) with a slope of 1.05 ± 0.111, indicating that both flippers increase in length by the same amount although from different initial lengths as the animal grows larger.

The exponential kinetic parameter (k) calculated for the Exponential, Logistic and Gompertz models are different to one another but the models show some consistent patterns (Table 3). The k-values for

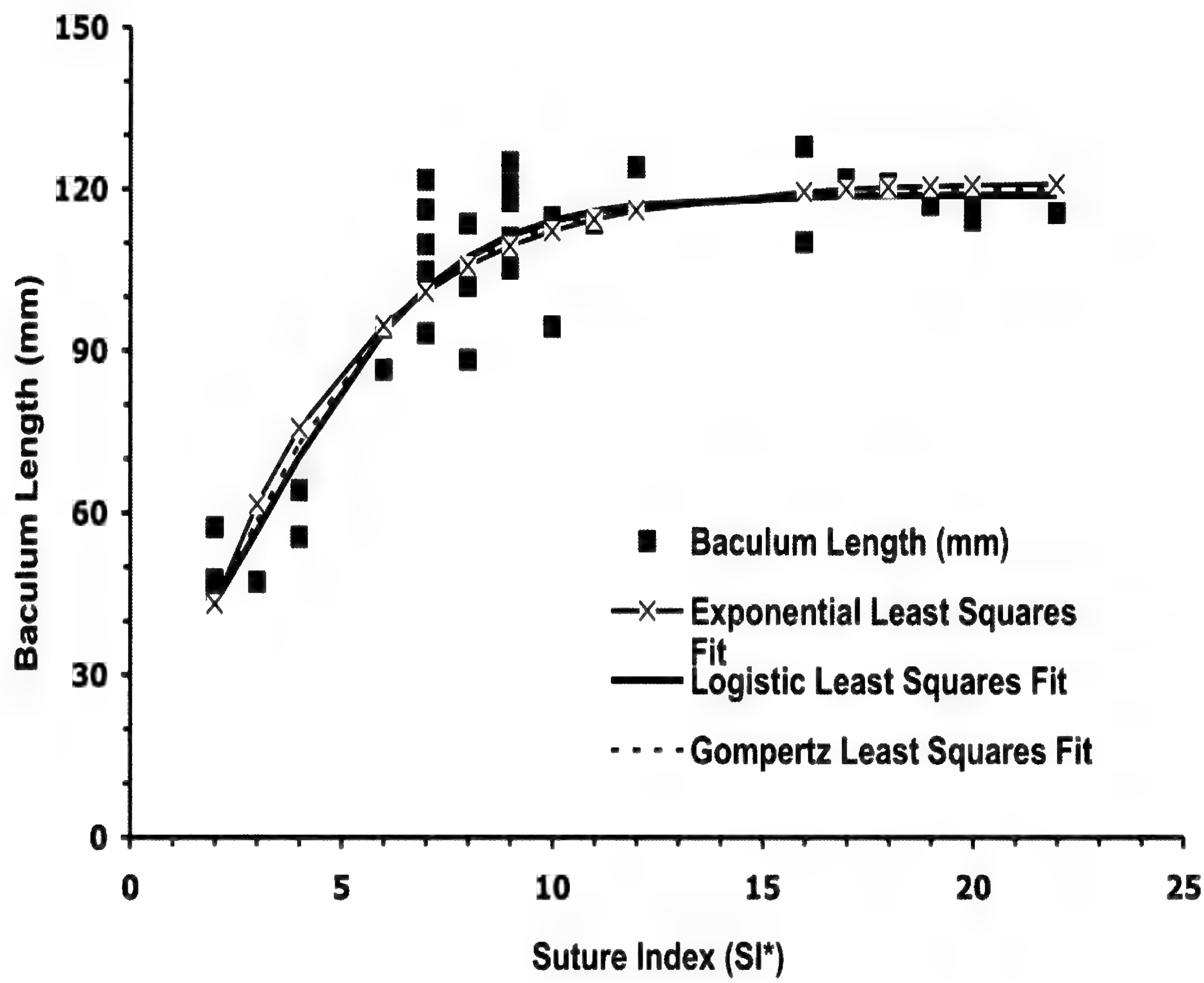

Figure 4. Non-Linear least squares fits to plots of Baculum Length (mm) vs. Suture Index (SI*) (n = 35). As for Figs 1 and 2 all the fits were good (R2 > 0.77). The model parameters are tabulated in Table 3.

the exponential model for length parameters such as **CBL**, Ramus length and **SBL** are all very similar (k ≈ -0.1). Similarly, the Logistic and Gompertz k-values are for **CBL**, Ramus and **SBL** are similar to one another (k ≈ -0.18 for logistic model and k ≈ -0.15 for the Gompertz model). The exponent k-parameters for the three models related to the width of the animal, in the skull (Bizygomatic breadth and Mastoid breadth) and the Front flipper are also similar indicating that increases in the size of these parameters follow similar kinetics.

Growth of the baculum (Fig. 4 and Tables 3 and 4) has conspicuously different kinetics to the skull and body size parameters. Plots of the Exponential, Logistic and Gompertz models are virtually identical and almost completely overlap each other. The three models predict very similar asymptotic maximum sizes (about 120 mm). Estimates of the initial size are plausible for the Logistic and Gompertz models (15 & 22 mm respectively). The Exponential model gives a spurious negative initial value that is not significantly different to zero. All three models show that the asymptotic baculum size is reached very quickly when animals attain an **SI*** of about 7 or at about 5 and a half years old based on the relationship between age and **SI*** (Stewardson et al. 2011b). Thus, the baculum length very rapidly reaches an asymptote much earlier than the skull parameters and the other body measurements.

Biologists generally have a better grasp of growth kinetics expressed as half-times ($t_{0.5}$) rather than exponential constants. Table 4 shows the half-times calculated from the exponential growth model shown in Table 3 for incremental growth of the skull and

Table 4: Incremental Growth and Estimated Time to Reach One Half of Full Incremental Growth of Male South African Fur Seals. Half-times in years were calculated from the relationship of SI* to Age (y) found by Stewardson et al. (2011).

Parameter	Fitting Model	Number of Animals (n)	Incremental Growth Asymptote	Exponential Constant (k)	Half-Time on SI Basis (SI*)	Half-Time (y)
Skull						
Condylobasal Length (**CBL**), mm Figure 1	Exponential	64	120 ± 9.57	-0.1115 ± 0.007527	6.22 ± 0.420	5.02 ± 0.421
Ramus Length, mm	Exponential	60	103 ± 9.51	-0.09730 ± 0.008689	7.12 ± 0.636	5.76 ± 0.549
Bizygomatic Breadth (**Zyg**), mm	Exponential	61	96.4 ± 15.9	-0.06495 ± 0.009577	10.7 ± 1.57	8.63 ± 1.305
Mastoid Breadth, mm	Exponential	59	93.0 ± 11.4	-0.07436 ± 0.008803	9.32 ± 1.10	7.54 ± 0.927
Body						
Standard Body Length (**SBL**), cm Figure 2	Exponential	64	134 ± 13.6	-0.1114 ± 0.01387	6.22 ± 0.775	5.03 ± 0.648
Length of Front Flipper, cm Figure 3	Exponential	43	29.1± 10.2	-0.07445 ± 0.02306	9.31 ± 2.88	7.53 ± 2.35
Length of Rear Flipper, cm	Exponential Model Inappropriate					
Baculum						
Baculum Length, mm Figure 4	Exponential	35	134 ± 17.5	-0.2695 ± 0.05170	2.57 ± 0.493	2.08 ± 0.405

body parameters and for the baculum length. The half time in terms of **SI*** was converted to chronological age using the regression relationship found previously (Stewardson et al. 2011). Parameters related to the 'length' of the animal (**CBL**, Ramus length and **SBL**) all have half times for incremental growth of about 5 years. 'Width' parameters more related to cross-section of the animals (Bizygomatic breadth, mastoid breadth and front flipper length) all have half times of about 8 years. This is consistent with the seals reaching adult body length rather quickly but increase considerably in mass as they mature. Growth of the baculum to adult size is very rapid with a half-time of only about 2 years leading to the completion of growth of the baculum in males at an age of ≈ 5.5 years.

DISCUSSION

As with other polygynous breeding pinnipeds, which exhibit, pronounced size dimorphism, full reproductive status (social maturity) is deferred until full size and competitive vigour are developed (Bartholomew 1970; McLaren 1993) although the baculum rapidly reaches adult size (Fig. 4). Male South African fur seals attain social maturity at 8-10 y (Stewardson et al. 1998, 2008). Although some males may grow to **SBL** = 220 cm or more (Rand 1949), asymptotic **SBL** size is estimated to be between 198 and 220 cm (present study) which agrees well with estimates based on **SBL** vs. known age (Stewardson et al. 2009).

Information on asymptotic size (Table 3) of parameters such as **CBL** and **SBL** are advantageous for comparisons among different species of pinnipeds because average size (including average adult size) may be more influenced by sampling biases, e.g., larger or smaller individuals may be over-represented in certain year/suture classes (McLaren 1993). Estimates of asymptotic size from plots of size vs. **SI*** appear to be of practical value in life history studies of the South African fur seal and may prove to be of value for studies of the Australian fur seal

(*Arctocephalus pusillus doriferus*). Asymptotic size estimates derived from plots of size vs. **SI*** in the present study and asymptotic sizes based upon plots of size vs. chronological age were found to be consistently very similar (Stewardson et al. 2008, 2009). In the case of growth of the baculum vs. age of animals it was not possible to calculate the asymptotic size of the baculum from plots of baculum size vs. age because of a lack of baculum measurements for animals with a definitive age greater than 10 years or for subadult males (2 to 6 y) (Stewardson et al. 2010a). Data for baculum size vs. suture index (**SI***) has allowed us to show that baculum size reaches an asymptote in animals at about 6 y. Baculum size might be of some value in classifying males into juvenile, subadult and adult classes but is of limited value for age determination.

The major advantage of using suture index (**SI***) information as a substitute for chronological age in growth studies is the limited number of animals that have been aged based on tagging or upon dentition (Stewardson et al. 2011a). More information on animals older than 12 y is needed. Tagging is the definitive source of age information. Dentine-GLG methods of aging South African fur seals not only has inherent limitations because of pulp cavity closure (Stewardson et al. 2011a) but also has a significant failure rate. Seventeen out of 48 specimens used in our studies of South African fur seals could not be aged at all because dentine growth lines could not be recognised in prepared sections of canines. Oosthuizen (1997) found that the cementum of canines was too thin for reliable aging. Suture information is relatively easy to obtain on skulls and is non-destructive.

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Aquatic Inventory of Nadgee Lake, Nadgee River and Merrica River Estuaries

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Scanes, P., Dela-Cruz, J., Coade, G., Haine, B., McSorley, A., van den Broek, J., Evans, L., Kobayashi, T. and O'Donnell, M. (2011). Aquatic inventory of Nadgee Lake, Nadgee River and Merrica River estuaries. *Proceedings of the Linnean Society of New South Wales* **132**, 169-186.

Nadgee Lake, Nadgee River and Merrica River in far south NSW are in NSW's only coastal wilderness and have no human habitation; Nadgee Lake and Nadgee River have no public roads in their entire catchments. They are as close to pristine as exists for NSW estuaries. During the period November 2008 to March 2009, data were collected on physical and chemical properties of the water, bathymetry, phytoplankton assemblages, pelagic chlorophyll, fish assemblages, estuarine macrophytes, sediment infauna and zooplankton in Nadgee Lake and River; and physical and chemical properties of the water and pelagic chlorophyll in Merrica River. The sampling plan was based on current conceptual understanding of the function of intermittently open estuaries in south-eastern NSW. It was intended to provide a basic representation of the ecological processes and types of organisms found in the estuaries.

There was no submerged aquatic vegetation found in any of the estuaries. Fish assemblages were relatively diverse for unvegetated intermittent estuaries, but were composed of common estuarine fish. Salinity in Nadgee Lake was about 19 psu and in the River varied between 20 and 33 psu. Concentrations of ammonia and chlorophyll in Nadgee Lake were far greater than expected for this type of estuary. Nadgee River and Merrica River were closer to expectations. These data comprise what is, to our knowledge, the first comprehensive collection of data on the aquatic ecosystems of these estuaries and represent a valuable base-line of data for pristine intermittent estuaries in NSW.

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KEYWORDS: algal bloom, chlorophyll, coastal lagoon, estuary, fish, infauna, nutrients, pristine, turbidity, water quality.

INTRODUCTION

The consistent monitoring of estuary condition in NSW is in its infancy. The first state-wide monitoring program, focussed on water column productivity (using chlorophyll as a surrogate), water clarity, fish population structure and extent of aquatic vegetation, commenced in NSW in 2008 (Roper et al. 2010). An important aspect of this type of monitoring program is having an appropriate benchmark against which to judge estuary condition. The National Water Quality Management Strategy (NWQMS; ANZECC 2000) suggests using data from reference sites to establish trigger values or reference conditions as a basis for comparison. If trigger values are exceeded, ANCECC (2000) suggests further investigation to determine if intervention is required to improve water quality. Reference sites (in the context of NWQMS) are defined as minimally impacted. There are, however, few data available from minimally impacted systems as there has been little incentive or funding available for research in unimpacted areas. Most research has focussed on impacted estuaries near large population centres (Scanes et al. 2007).

This paper provides a preliminary inventory of the aquatic environment in the estuaries of the Merrica River, Nadgee River and Nadgee Lake in far southern NSW. These estuaries are believed to be among the least disturbed estuaries in NSW (Evans 2003). The catchments of all three estuaries now lie wholly within the Nadgee Nature Reserve (Evans 2003) and thus are protected from most forms of modern human disturbance. To the knowledge of the

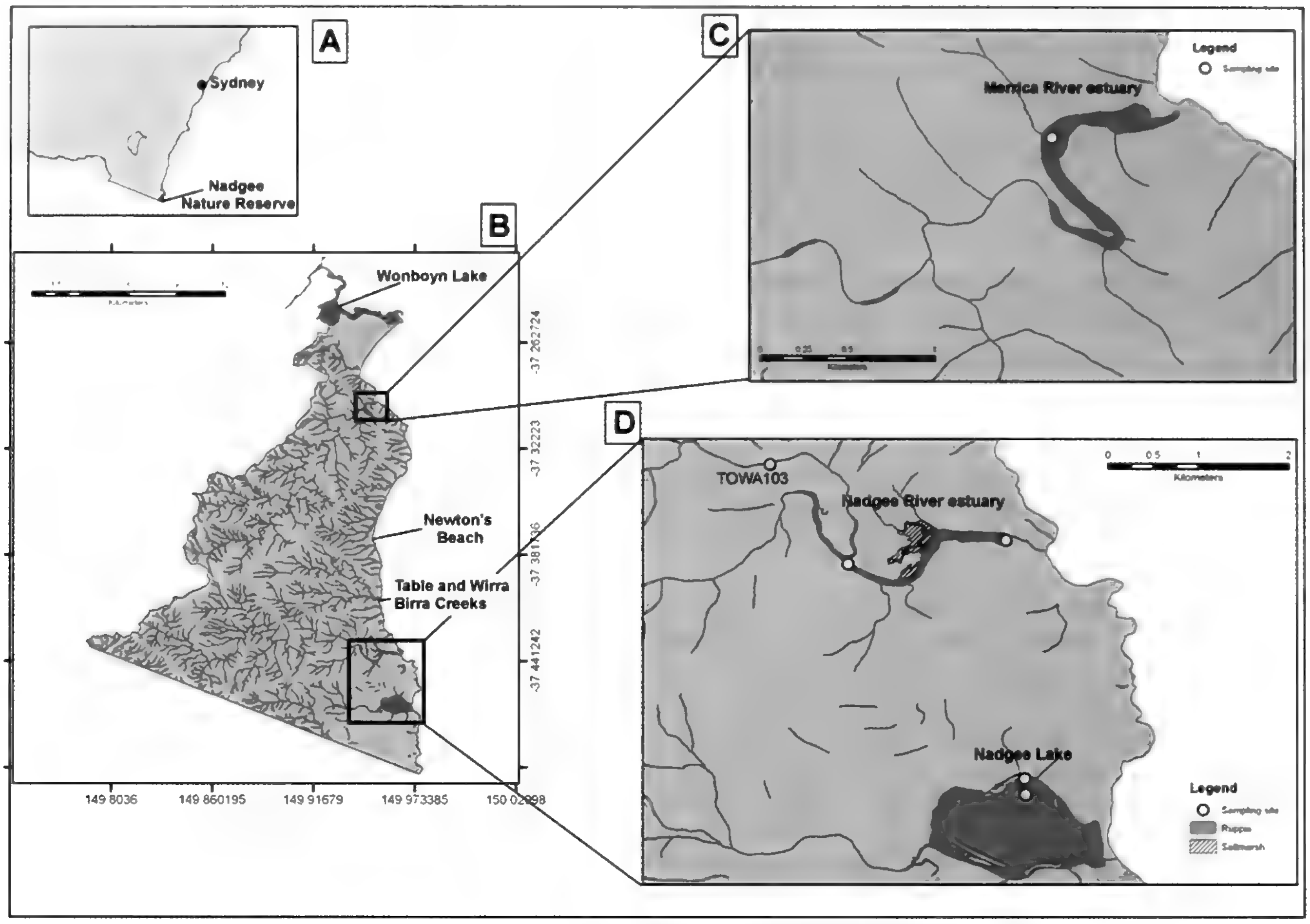

Figure 1 Location of Nadgee Nature Reserve (A, B) and sampling sites in Merrica River (lower) (C), Nadgee River freshwater (TOWA103) and upper and lower estuary, and Nadgee Lake (D). Locations of macrophytes are as shown in Williams et al. (2006) and do not reflect occurrence in 2008.

authors, there has been no previous assessment of the aquatic ecology of these systems (Evans 2003).

Nadgee Nature Reserve is located on the far south coast of NSW between Wonboyn Lake and the Victorian border (Fig. 1). The major part of the area, 11,430 ha, was initially gazetted as a faunal reserve in1957 under the Fauna Protection Act. It was dedicated as a Nature Reserve in 1967 and included the entire catchments of Merrica River, Nadgee Lake and Nadgee River. That part of Nadgee Nature Reserve south of Newtons Beach was declared the Nadgee Wilderness in 1994. The wilderness was increased in 1997 by the inclusion of the whole of the Merrica River catchment (Evans 2003), except for a narrow road corridor and infrastructure at the Merrica River.

Historical European land use in the Nadgee area commenced around the 1860's and included stock agistment and as a stock route to the south. Two graziers moved to the area in the 1890's, living near the lower Nadgee River flats and lower Table River. They used the area, mainly the heaths, for rough grazing. In 1916 a road was constructed across the Merrica River to Nadgee River flat and land was cleared to build a farm. This farm was worked until the lease was terminated shortly before creation of the reserve in 1957 (Evans 2003). Whilst there are reports of low intensity grazing and some farming around the estuaries up until the 1960s, there are no records of any settlement or disturbance in the catchment of Nadgee Lake. Current public access is restricted to pedestrian and boat access. Access is by permit and only a total of 30 persons are allowed in the combined Nadgee Wilderness and Howe Wilderness Area (Victoria). Researchers may obtain permission to drive vehicles on an established fire track as far as Nadgee River, but access to the River estuary and Lake is by foot from that point (special conditions apply).

There are estuaries on the Merrica River, Wirra Birra Creek, Table Creek, Nadgee River and at Nadgee Lake. The estuaries are deepened Pleistocene valleys which are now filled with sand, apart from the Merrica River estuary which lies in a gorge (Evans 2003). Merrica River and the two Nadgee estuaries were classified by Roy et al. (2001) as intermittently closed (Group IV) saline lagoons (Type 8). We have

Table 1 Estuary and catchment characteristics for main estuaries in Nadgee Nature Reserve. * Table Creek was not classified by Roy et al. (2001). # from Dela-Cruz and Scanes (2009). CA:SA is the ratio of catchment area to surface area of estuary. Class is the classification as defined by Roy et al. (2001).

	Class	Catchment Area (km^2)	Estuary Surface Area (km^2)	CA: SA	Total Suspended# Sediment Load ($t.yr^{-1}$)	Total Phosphorus# Load ($t.yr^{-1}$)	Total Nitrogen# Load ($t.yr^{-1}$)
MERRICA RIVER	IV 8 A	60.54	0.12	504	104.15	0.28	5.01
TABLE CREEK	IV 8 *	17.29	0.06	288	27.31	0.08	1.31
NADGEE RIVER	IV 8 D	58.80	0.27	217	240.44	0.65	11.58
NADGEE LAKE	IV 8 B	13.70	1.20	11	22.23	0.06	1.07

extended this classification to Table Creek. The Nadgee Lake estuary was described as semi-mature, Nadgee River as mature and Merrica as youthful (Table 1). Intermittent saline lagoons account for 49% of the 131 major NSW estuaries classified by Roy et al. (2001). Of those, 42% are semi-mature, 20 are mature and 31 % intermediate.

The Plan of Management (Evans 2003) provides a comprehensive collation of the available information on the Nadgee Nature Reserve. The paucity of information on the aquatic ecology of the reserve (freshwater and estuarine) is evident, there are no quantitative estuarine data referred to in the Plan of Management. Subsequently, only two sources of quantitative information on aquatic ecology could be found. A biological (AUSRIVAS macroinvertebrate) assessment of the main freshwater streams (Turak et al. 1998) concluded that "AUSRIVAS outputs from the sites sampled at Nadgee Nature reserve in 1997 and 98 … suggest that the three streams, Merrica River, Nadgee River and Table Creek have macroinvertebrate communities similar to those in reference sites sampled during the development of AUSRIVAS" (Turak 1998). Williams et al. (2006) provides maps of estuarine aquatic vegetation in Nadgee Lake and Nadgee River. These maps were produced from aerial photography with limited ground-truthing (due to the access issues) and showed saltmarsh around Nadgee River and submerged aquatic macrophytes (presumed to be *Ruppia megacarpa*) in Nadgee Lake (Figure 1). The "Development Plan" which was the basis for establishment of the Nature Reserve (NPWS 1975) refers to a "dense growth of algae and spermatophytes in lagoon bed proper" for Nadgee Lake. Presumably the spermatophyte referred to is *Ruppia megacarpa*, but that is not confirmed anywhere in the document. The Plan of Management (Evans 2003) indicated the presence of estuarine wetland and saltmarsh on the Nadgee River estuary, noting that it was dominated by rushes, sedges and swamp paperbark (*Melaleuca ericifolia*). Since the Plan of Management, there has been some desk-top work characterising all NSW estuaries, including the Nadgee estuaries. Dela-Cruz and Scanes (2009) collated catchment dimensions and modelled nutrient loads for all NSW estuaries. These data (Table 1) show that Merrica River, Table Creek and Nadgee River have relatively large catchments in comparison to the size of the estuary, meaning that they will be likely to fully displace estuary water after significant rain. Nadgee Lake, however, has a small catchment in comparison to estuary size, meaning that there will be little runoff which will, in most cases, be trapped by the estuary (Roper et al. 2010). Roper et al. (2010) used a ratio of modelled "pre-European" nutrient runoff to nutrient run-off under current landuse as a measure of catchment disturbance. All the Nadgee Nature Reserve estuaries had a ratio of 1 (i.e. no change), putting them in the pristine category.

Nadgee Lake has been used by black swans as moulting lagoon on an annual basis since at least 1972, supporting populations in excess of 300 birds which feed extensively on submerged vegetation (Evans 2003, L Evan pers. comm., P Catling pers. comm.). NPWS (1975) also refers to numerous swans on Nadgee Lake. Early reports (back to 1880, see NPWS 1975) refer to Nadgee Lake as "Saltwater Lake" so it can be assumed that it has been saline for at least 130 years.

Commencing in early November 2008, sampling was undertaken to establish a preliminary set of aquatic data for Nadgee River estuary and Nadgee Lake. This is, to our knowledge, the first comprehensive collection of data on the aquatic ecosystems of these estuaries. These data were supplemented by further collections in Nadgee Lake and River in early January, February and March 2009; and from Merrica River 6 times between December 2008 and March 2009.

Access limitations, which require most equipment and samples to be carried on foot for up to 16 kilometres constrains the type of work that can be undertaken. The sampling plan that was implemented was based on current conceptual understanding of the function of intermittently open estuaries in south-eastern NSW (Scanes et al. 2007, Dela-Cruz and Scanes 2009, Roper et al. 2010). It was intended to provide a basic representation of the ecological processes and types of organisms found in the estuaries and to complement estuarine monitoring occurring under the current NSW State Monitoring Evaluation and Report Strategy. For Nadgee Lake and River, data were initially collected on physical and chemical properties of the water, bathymetry, phytoplankton assemblages, pelagic chlorophyll, fish assemblages, estuarine macrophytes, benthic sediment chlorophyll, sediment infauna and submerged light climate. Data for Merrica River were confined to physical and chemical properties of the water and pelagic chlorophyll. These data will provide a baseline for comparison with other south eastern Australian estuaries.

METHODS

Nadgee Lake and Nadgee River will be referred to as the Lake and the River in following sections. At the time of the first sampling trip (10-12 Nov 2008), both the Lake and River estuaries were closed.

In the Lake and the River, data collection was stratified into two zones, shallow waters (< 1m deep) and deeper waters (>1 m deep). Data collection in deeper waters, and bathymetric profiles, were done from inflatable canoes which were carried to the sampling sites. In the Lake, data on water properties and biological samples were collected from two sites in each of the shallow and deep zones (Table 2). The River estuary was sub-divided into a marine-sediment dominated lower region and a riverine-sediment dominated upper region. There was no shallow zone in the upper region. The types of samples collected at each site at each time, are provided in Table 2 and are described in full below.

A - Physical and Chemical Properties of the water

Sampling during the first trip (10-12 Nov 2008) differed slightly from subsequent trips. During trip 1 the following procedures were followed. A calibrated Hydrolab® Water Quality Sonde was used to measure salinity, temperature, dissolved oxygen, pH, and turbidity at the water surface and at 0.5 m intervals to just above the bottom. At each site, a single integrated water sample was taken from the top 1m of the water column by slowly plunging a pre-rinsed bottle and allowing it to fill on the way down. The water samples were sub-sampled for the analysis of nutrients. Samples were either left unfiltered (total nutrients) or immediately filtered through a 0.45 μm filter (dissolved nutrients). Concentrations of nutrients were determined by flow-injection absorption spectrometry according to standard methods (APHA, AWWA and WPCF 1989). A sample for the determination of colour was filtered through 0.20 μm filter. Estimates of the dissolved colour or gilvin concentration were calculated as $g_{440} = 2.303 * A/0.01m^{-1}$ where A was the measured absorbance of the filtered water sample at 440 nm in a 1 cm cuvette (adapted from Heinermann et al. 1990).

Calibrated water quality data loggers (Yeokal® Model 612) were placed in 1.0 - 2.0 m of water in each estuary and data logged every 15 min. The loggers were collected approx. 4 weeks later.

Immediately after collection calibrations were checked to determine sensor drift during deployment.

During subsequent trips (see Table 2), data on physical properties of water were collected using a YSI® Model 6820V2-S multiprobe fitted with a fluorometric chlorophyll probe and a turbidity probe, as well as temperature and salinity probes. In each estuary, the probe was placed in the water over the side of a canoe and data were logged for five minutes while the canoe was allowed to drift. The reported result is a mean of the logged data and represents a zone in the estuary rather than a single point. Water samples were collected from the top 1m using an integrated sampler.

B - Depth

A simple unit which combines depth measurement (approx. accuracy 0.05 m) and GPS (approx. accuracy 1-2 m) was paddled around the water body, including transects from deep to shallow and along the thalweg (River). The unit logs depth and position continuously. In Nadgee Lake in January 2009, a bench mark was established on a fixed structure (tree) to allow calibration of relative depth of the Lake to a standard datum. In June 2010, the height of the Lake and berm above Australian Height Datum (AHD) was estimated using a hand-held surveyor's level and an estimate of sea level. This was then back-calculated to the benchmark to estimate lake level (AHD) at the time of sampling.

Table 2 Sampling sites and types of samples taken in each estuary in: A: physical and chemical properties of the water; B: depth; C: phytoplankton assemblages; D: pelagic chlorophyll; E: estuarine macrophytes; F: fish assemblages; G: sediment infauna;

Nadgee River Estuary			
Zone	Date	Time	Sample Types
Lower Shallow	12/11/08	am/noon	A, B, C, D, E, G
Lower Deep	12/11/08	am/noon	A, B, C, D, E, F, G
Upper Deep	10/11/08	pm	A, B, C, D, E, F
Upper Deep	12/01/09	am	A,D
Upper Deep	24/02/09	am	A,D
Upper Deep	13/03/09	am	A,D
Nadgee Lake			
Zone	Date	Time	Sample Types
Site 1 Shallow	11/11/08	am/noon	A, B, C, D, E, F, G
Site 1 Deep	11/11/08	am/noon	A, B, C, D, E, F, G
Site 2 Shallow	11/11/08	am/noon	E, F, G
Site 2 Deep	11/11/08	am/noon	E, F, G
Site 1,2 Shallow	12/01/09	am	A,C,D
Site 1,2 Shallow	24/02/09	am	A,C,D
Site 1,2 Shallow	13/03/09	am	A,D,
Merrica River			
Zone	Date	Time	Sample Types
Site 1 Deep	02/12/08	am/noon	A,D
Site 1 Deep	13/01/09	am/noon	A,D
Site 1 Deep	03/02/09	am/noon	A,D
Site 1 Deep	25/02/09	am/noon	A,D
Site 1 Deep	17/03/09	am/noon	A,D

C - Phytoplankton assemblages

To determine the dominant algal species present in Nadgee Lake, water samples were taken from the top 1m of the water column with a 1m integrated sampling tube. One litre of the sample was fixed with Lugol's iodine solution (5% v/v) and 500 ml was kept cool and dark to generate live cultures. When blooms were obvious in Nadgee Lake (Nov 08 , Jan, Feb 09) live material was sent to CSIRO laboratories and University of Tasmania in Hobart where it was taken into culture. Samples of the culture were inspected by light microscopy and subjected to pigment analysis to determine dominant types of algae.

D - Pelagic chlorophyll

Three replicate sub-samples (250 ml) from the integrated water samples were filtered through GF-60 filters under low vacuum pressure and the concentrations of chlorophyll retained on the filters was determined by fluoro-spectrometry after acetone extraction. In addition, a YSI ® Model 6820V2-S multiprobe fitted with a fluorometric chlorophyll probe was used to determine in-situ chlorophyll concentrations.

E - Estuarine macrophytes

Ground-truthing of the existing aquatic vegetation was done by observing the types of vegetation present. Observations were made directly or by deploying a small grapple to entangle attached vegetation from the estuary floor and bring it to the surface. Inspections of the intertidal strand line were made to identify the types of vegetation present in the estuary. Samples of salt marsh and any submerged plants found were retained for expert identification.

F - Fish assemblages

Inshore fish assemblages were sampled by 3 replicate shots with a small seine net (12 mm stretched mesh seine net with a 20 m headline, a 2 m drop and a cod-end) at each site (lower Nadgee River was not sampled by seine because the net could not be transported to the site). Each replicate net haul was done to form a U-shape that covered approximately 100 m^2. The ends were drawn together so that the sample was collected in the cod-end. By its nature, this net will only catch small or slow-moving fish. It therefore does not provide a measure of the total fish diversity at a site. To partially address this issue, fish assemblages in deeper water (< 3m) were sampled by three multi-panel monofilament gill nets at each site. Nets were set at a 45° angle from the shore and at a depth of no more than 3 m. Each gill net was left out for 30 - 45 min of fishing time. All fish captured (by both methods) were placed into a bucket to keep them alive while being identified counted and measured (fork-length), then released alive.

G - Sediment infauna

Replicate samples of sediment from depths between 0.5 m and 1.0 m were collected using a 90 mm diameter core. The sediment was passed through 1 mm and 0.5 mm sieves and the matter retained was fixed. The biota in the samples were later identified and enumerated.

H - Zooplankton

Unquantified tows with a conical plankton net (63 µm mesh) were made in August 2009 to sample the dominant zooplankton. Samples were washed from the nets into small vial, fixed with 70% v/v ethanol and examined under a Leica Wild M8 stereomicroscope at a magnification of x 25 or x 50. In a separate quantitative sampling, 10L samples of water (n=4) were collected from the Lake in June 2010 for enumeration of zooplankton. Zooplankton specimens were concentrated by filtering through a 63-µm mesh netting and fixed with 70% v/v ethanol. A 1-mL wide-mouth automatic pipette and Sedgewick-Rafter counting cell were used for subsampling and counting of zooplankton. Zooplankton specimens were examined and identified under a Leica Diaplan compound microscope at a magnification of x 100, with an image analysis system consisting of Leica DFC480 digital camera and Leica IM Version 4.0 digital imaging software (Leica Microsystems, Germany). The prime taxonomic literature used was Yamaji (1984) and Suthers et al. (2009).

Freshwater

Freshwater sampling was done at the same site sampled by Turak (1998) - Nadgee River ford; 37° 25' 48.40" 149° 56' 17.93" (TOWA103). Physical properties and nutrient concentrations (by method A above) were determined and macro-invertebrate samples were collected, sorted and analysed according to standard NSW AUSRIVAS methods (Turak and Waddell 2001).

RESULTS

Nadgee Lake

Observations

In November 2008, the lake was closed and the beach berm was wide (c.a. 40 m at narrowest point). Anecdotal information (L Evans pers. comm., P Catling pers. comm.) suggests that the lake had been closed for > 2 years in November 2008. No swans were sighted, they had been absent for at least 6 months.

Bathymetry

The lake is a simple basin, which gradually slopes to a maximum depth of 4.5 m approximately 150 m off the shore when the lake is at its highest levels. The central basin is very flat and of consistent depth. Calculations based on a relationship between salinity and lake surface height and a survey of the berm in June 2010 (DECCW, unpubl. data) indicate that in November 08, Nadgee Lake surface was at about + 0.7 m AHD (Table 3 A) and the berm was at least + 1.7 m AHD. When closed and full, the water surface area of the Lake is estimated at 120 ha, with an estimated volume of 3.86 ML.

Physical and chemical properties of the water

Surface salinity in primary samples ranged between 17.9 and 19.7 psu (Table 3 A), the variation being due to rainfall and evaporation. Salinity did not vary between surface and bottom in November 2008. Data from the submerged logger showed salinity remained constant at about 19 from 10 November until 23 November 2008, when there has heavy rainfall in the catchment (40 mm on 23, 24 November, 70 mm 29 November). After this, salinity fell to 14 psu, briefly rose again and then stabilised at 13 psu until 22 December. This plateau at 13 psu does not match other measurements and is questioned. By 12 January 2009, salinity had risen to 17.9.

Surface water temperature reached a summer

Table 3 Physical characteristics of surface waters, estimated water surface levels (Nadgee Lake) or entrance state (Nadgee River) and mean (SE) pelagic chlorophyll concentrations . Colour is inferred from the absorbance of light at 440 nm, data are adjusted to 1 cm light path. SpCond – specific conductivity at 25°C, DO dissolved oxygen; DO %sat – percentage of theoretical saturation of dissolved oxygen at ambient temperature. "NSW Trigger" is the trigger value (sensu ANZECC 2000) for chlorophyll and turbidity in lagoon estuaries calculated by Roper et al. (2010). "Median Other" are median values for 4 other NSW minimally impacted lagoons (Termeil Lake, Meroo Lake, Brou Lake, Wallagoot Lake) sampled between 2008 and 2010 (n = 60) and "80th Other" is the 80th percentile value calculated from the same data (DECCW unpublished data).

A Nadgee Lake

	Salinity (psu)	Temp (°C)	Turbidity (ntu)	pH	Lake Height (AHD)	Chlorophyll (µg.L^{-1})	Colour g m^{-1}
11/11/08	18.8	20	30 (0.02)	7.9	0.74	53 (5.1)	2.05
12/01/09	17.9				0.88	89 (6.9)	1.27
24/02/09	19.4	22.3	7.6 (0.01)		0.64	22 (0.1)	1.91
13/03/09	19.7	20.4	3.5 (0.01)		0.60	5 (0.2)	1.59
NSW Trigger			2.2 (0.01)			1.9	
Median Other						2.4	
80th Other						6.6	

B Nadgee River - estuary

	Salinity (psu)	Temp (°C)	Turbidity (ntu)	pH	Entrance	Chlorophyll (µg.L^{-1})	Colour g m^{-1}
10/11/08	21.5	21.7	6	7.6	closed	2.9 (0.01)	1.49
12/01/09	31.0		3		open	3.7 (0.17)	0.71
24/02/09	32.68	23.2	3		open	4.3 (0.37)	1.43
16/03/09	31.48	23.4	1.8		closed	4.6	1.11

C Nadgee River – freshwater (TOWA 103)

	SpCond (µS.cm^{-1})	Temp (°C)	pH	DO (% Sat)	DO (mg.L^{-1})	Turbidity (ntu)	Colour g m^{-1}
12/11/2008	79.9	20.18	7.07	56	5.11	2.1	1.61

D Merrica River

	Salinity (psu)	Temp (°C)	Turbidity (ntu)	Chlorophyll a (µg. L^{-1})	Colour g m^{-1}
02/12/2009	28.1	18.4	0.7	4.22	3.45
13/01/2009	33.70	20.13	0.74	2.46	2.79
3/02/2009	34.06	24.82	0.48	4.60	1.29
25/02/2009	30.14	18.99	1.11	3.03	2.46
17/03/2009	34.27	19.00	0.64	3.89	

maximum of 22.3 and then decreased into autumn (Table 3 A). In November 2008, water temperature showed a slight variation between surface and bottom, ranging from 20 °C on the surface to18.2 °C on the bottom.

Turbidity was high in November 2008 (30 ntu) and decreased over the time of sampling (Table 3 A) and, in November 2008, was consistent from surface and bottom.

pH was only measured in November 2008 and was slightly basic (7.9) (Table 3 A). There was no vertical stratification of pH.

Dissolved colour, gilvin, was ranged between 2.05 and 1.27, but most data were near 2.

There was a strong depth stratification of dissolved oxygen which was at 100% saturation on the water surface, but had declined to 50 to 60% at the bottom. The logger data indicated that dissolved oxygen concentrations varied between 100 and 80% on a diurnal cycle from 11 November until 14 December 2008, after which time they slowly declined to be about 40% on 22 December 2008. This latter decline probably represents degradation of the membrane in the instrument.

Concentrations of dissolved inorganic nitrogen (oxidised nitrogen, ammonia) in November 2008 were uniformly small (Table 4), but concentrations of dissolved organic nitrogen and particulate nitrogen were relatively large. This resulted in large concentrations of total nutrients. A similar pattern was evident in January 2009. In February and March 2009, however, the concentrations of ammonia had increased by two orders of magnitude, without a concomitant increase in oxidised nitrogen. Dissolved organic nitrogen almost doubled and particulate nitrogen was reduced to about one third of previous concentrations. Phosphate concentrations were small and showed a slight peak in February 2009 (Table 4). Particulate phosphorus was the largest source of phosphorus and declined over the period of sampling. Concentrations of dissolved silica varied by two orders of magnitude over the sampling period (Table 4), being high (1340-1540) in November 08 and January 09 and lower in February (15) and March 09 (140).

Biota

Phyoplankton

Pelagic chlorophyll concentrations in the Lake were a very large 53 $\mu g.L^{-1}$ in November 2008 and 89 $\mu g.L^{-1}$ in January 2009, declining to 22 $\mu g.L^{-1}$ in February 2009 and 5 $\mu g.L^{-1}$ in March 2009 (Table 3 A). These concentrations indicate the presence of a very intense algal bloom and, indeed, the water colour was almost lime green in November 2008 and January 2009.

The phytoplankton assemblage in November 2008 was dominated by an intense bloom of very small (1 -2 µm) pico-plankton tentatively identified via light microscopy and pigment profiles as a monoculture of a cyanobacterium similar to *Synechocystis* . Samples from January 2009 were found to contain a mixture of some cyanobacteria (*Synechocystis*) and some diatoms, but were dominated by a Eustigmatophyte similar to *Nannochloropsis*. This alga is typically 2-4 µm in diameter. Samples from February 2009 were dominated by typical estuarine diatoms and dinoflagellates.

Zooplankton

Qualitative net samples indicated the presence of calanoid copepodites and larval polycheate worms. Quantitative samples indicated the presence of Rotifera (*Synchaeta* sp. 4.3 L^{-1}), copepod nauplii (31.5 L^{-1}), calanoid copepodites (7 L^{-1}), polychaetes (2.3 L^{-1}) and bryozoan cyphonuate larvae (1 L^{-1}).

Estuarine Macrophytes

Anecdotal information suggests strongly that Nadgee Lake had supported abundant aquatic macrophytes. Williams et al. (2006) identified a small bed of *Ruppia megacarpa* on the north-north west shore and more extensive beds on the southern shore (Fig 1). Extensive searching of the site on the north-west shore and of the wrack on the strand line on the entire northern shore did not locate sign of *Ruppia* sp. plants. All wrack was of terrestrial origin, primarily grasses, sedges and reeds which had been recently inundated. This tends to suggest that if there was any *Ruppia* in the lake at that time it was at very low abundances and did not form perennial beds. Coring and dragging of the lake floor in the central basin indicated that the sediment was coarse sand with a thick layer of finer dark grey organic material. There was a very small amount of a charophyte growing on the sediment, but no *Ruppia* plants or wrack were collected.

Fish assemblages

The limited sampling possible means that the fish sampled are unlikely to represent a comprehensive inventory of the fish species that inhabit the Lake. A total of 13 species were caught (Table 5), including sub-adult or adult specimens of common table fish such as luderick, Australian salmon, sea mullet, bream, garfish and flounder.

Table 4 Mean (SE), n=2, nitrogen, phosphorus and silica concentrations (µg.L-1) in surface water samples. NL – Nadgee Lake; NRL, NRU - Nadgee River Lower and Upper (respectively) refers to lower and upper estuary sites (Fig. 1); MR – Merrica River. * indicates derived value. NH4-N – ammonia; NOx-N – oxidised nitrogen; DIN – dissolved inorganic nitrogen; DON – dissolved organic nitrogen; PN – particulate nitrogen; TN – total nitrogen; PO4-P – phosphate; DOP – dissolved organic phosphorus; PP – particulate phosphorus; TP – total phosphorus. "Median Other" are median values for combined data from 4 other NSW minimally impacted lagoons (Termeil Lake, Meroo Lake, Brou Lake, Wallagoot Lake) sampled using the same methods between 2008 and 2010 (n = 60) and "80th Other" is the 80th percentile value calculated from the same data (DECCW unpublished data).

Date	Location	NH4-N	NOx-N	DIN*	DON*	PN*	TN	PO4-P	DOP*	PP*	TP	Silica
Nov 08	NL	6.9 (0.2)	1.6 (0.1)	8.5	931	2236	3176 (30)	1 (0.1)	7	98	106 (2.2)	1340 (43)
Jan 09	NL	6.4 (1.1)	1.7(0.4)	8.1	1074	1921	3003 (5)	1 (0.1)	7.7	78.3	87 (0.5)	1540 (1)
Feb 09	NL	451 (0.3)	8 (0.0)	459	1861	710	3031 (2)	2.2 0.3)	14.6	44	61 (0.5)	15 (1)
Mar 09	NL	436 (0.4)	5.3 (0.2)	441	1567	421	2428 (16)	1.4 (0.3)	13	27	41 (1)	140 (2)
Nov 08	NRL	4.4 (0.2)	1.4 (0.2)	5.8	191	55	252 (13)	0.3 (0.0)	3.6	6	10 (0.5)	390 (12)
Nov 08	NRU	11.6 (0.4)	4.6 (0.5)	16.2	203	72	291 (2)	0.8 (0.2)	4.4	10	15 (0.6)	133 (0.8)
Jan 09	NRU	2 (0.8)	1.2 (0.1)	3.2	146	49	196 (15)	0.3 (0.1)	3.7	7	11 (0.6)	495 (39)
Feb 09	NRU	6.9	1.3	8.2	176	119	296	1.0	6.1	17	24.5	407
Mar 09	NRU	8.8	3.6	12.5	203	50	257	0.9	5.5	12	18.3	289
Nov 08	MR	12 (6.7)	3.5 (2.4)	15.5	186	57	260 (36)	6.3 (1.8)	2.7	8.8	18 (2.8)	302 (52)
Feb 09	MR	5.4	2.8	8.2	188	37	234	2.4	3.2	5.6	11.2	140
	Median Other	10	2.9	12.5	711	56	903	1.2	10	9	22	324
	80th Other	94	7.8	101	1377	167	1620	2	12	19	30	825

Table 5 Fish Species from Nadgee Lake and River. Data are from all shots and methods combined.

		Lake		River	
		Total Number	Size Range (mm)	Total Number	Size Range (mm)
Acanthopagrus sp.	bream	6	104-205	33	56-168
Acentrogobius bifrenatus	bridled goby	1	42	1	68
Arripis trutta	eastern Australian salmon	4	268-325		
Afurcagobius tamarensis	Tamar River goby			2	53-56
Atherinosoma microstoma	small-mouthed hardyhead	302	41-58		
Centropogon australis	eastern fortescue	2	68-72		
Girella tricuspidata	luderick	1	318	6	295-360
Hyporhamphus regularis ardelio	eastern river garfish	13	143-186		
Leptatherina presbyteroides	silverfish	18	47-59		
Liza argentea	flat-tail mullet			13	147-295
Macquaria colonorum	estuary perch			7	325-363
Mugil cephalus	striped (sea) mullet	8	86-386	12	288-564
Myxus elongatus	sand mullet	15	150-169	43	122-280
Philypnodon grandiceps	flathead gudgeon	9	42-80		
Pomatomus saltatrix	tailor			1	215
Pseudocaranx dentex	silver (white) trevally			3	248-300
Pseudogobius olorum	blue-spot goby	4	38-44		
Pseudorhombus jenynsii	small-toothed flounder	2	194-217		
Synaptura nigra	black sole			1	170
Tetractenos glaber	smooth toadfish			5	50-110
Total Number of species: 20		No. spp. 13		No. spp. 12	

Sediment infauna

Benthic assemblages in Nadgee Lake contained groups of invertebrates typically found in estuarine habitats (Table 6). Polychaetes were numerically dominant, but diversity was evenly spread amongst the polychaetes, crustaceans and molluscan taxa. Within the polychaetes, three types of feeding modes were represented: mobile omnivores (Nereididae), burrowers (Orbiniidae) and filter feeders (Sabellidae), indicating a diverse food web in the existing assemblage, which probably depends on decaying plant material. No nematodes and relatively few oligochaetes were present, even in the fine fraction retained on 0.5 mm mesh.

Nadgee River Estuary

Observations

The river estuary was closed on 12 November 2008 and the beach berm was moderately wide (ca 15 m at narrowest point) and an estimated less than 0.5 m higher than the river surface. The river opened on 25 November 2008. Our observations are that in the period November 2008 – October 2010 the river opens 2 -3 times per year. The river was generally clear and when closed for a sufficient period (as on 08 November 2008), begins to flood up into the adjacent salt marsh and tea-tree wetlands.

Table 6 Mean (se) abundances and taxonomic richness of benthic invertebrates in Nadgee Lake. % overall abundance and summary statistics were estimated from pooled data for sites 1 and 2.

Taxonomic Group	Family	*Species*	Site 1 Mean per core n= 5	Site 2 Mean per core n= 2	% overall abundance
POLYCHAETES Class Polychaeta	Nereididae	*Simplisetia aequisetis*	4.4 (2.8)	5 (3)	17.88
	Orbiniidae	*Scoloplos normalis*	3.2 (1)	6.5 (0.5)	16.20
	Sabellidae	*Desdemona ornata*	2.6 (2.4)	0	7.26
CRUSTACEANS Order: Mysidacea	Mysidae		0.8 (0.4)	1.5 (1.5)	3.91
Order: Amphipoda	Aoridae		0.2 (0.2)	0	0.56
	Phoxocephalidae		4.2 (1.5)	9 (4.5)	21.79
	Synopiidae	*Synopia* sp.	0.8 (0.4)	0.5 (0.5)	2.79
MOLLUSCS Class Gastropoda	Hydrobiidae	*Ascorhis tasmanica*	2.4 (1.3)	7 (0.5)	14.53
Class Bivalva	Galeommatidae	*Arthritica helmsi*	0.4 (0.4)	2.5 (2)	3.91
	Tellinidae		0	0.5 (0.5)	0.56
	Veneridae		1.6 (1.6)	0	4.47
OTHER WORM PHYLA	Oligochaeta		1.6 (1.6)	0.5 (0.5)	5.03
	Platyhelminthes		0.2 (0.2)	0	0.56
OTHER PHYLA	Fish - Gobiidae		0.2 (0.2)	0	0.56

Summary statistics based on taxa	All Reps	% contribution	**Summary Statistics based on abundance**	All Reps	% contribution
Total number of taxa	14	100.00	Total number of individuals	179	100.00
Number of Polychaete taxa	3	21.43	Number of Polychaetes	74	41.34
Number of Crustacean taxa	4	28.57	Number of Crustaceans	52	29.05
Number of Mollusc taxa	4	28.57	Number of Molluscs	42	23.46
Number of Echinoderm taxa	0	0.00	Number of Echinoderms	0	0.00
Number of other worm taxa	2	14.29	Number of other worm phyla	10	5.59
Number of other taxa	1	7.14	Number of other phlya	1	0.56

Bathymetry

The estuary has relatively steep and confined banks for most of its length, meaning that maximum water depth is reached within a few metres of the bank. Banks above high tide are near-vertical for much of the length of the river. As a consequence, the surface area changes very little as the water depth increases after closure. Modal depth along the thalweg was 2.4 m, with the deepest areas 4.6 m, when closed. Low tide depths when open would be about 1 m less. The water surface area for the estuary was c.a. 18 ha, with an estimated volume of 0.43 ML, in the closed state.

Physical and chemical properties of the water

The salinity of the surface water in the upper Nadgee River estuary was strongly influenced by the entrance status. When the entrance had been closed for a while, salinity was 21 psu, but it rapidly rose to near seawater when open (Table 3 B). There was no evident stratification of the water column for salinity or DO (93 – 98% saturation) in November 2008.

Surface water temperature was slightly greater than Nadgee Lake and reached a maximum of 23.4°C in March 2009.

Turbidity was between 1.8 and 3 ntu when the river was open, but 6 ntu when closed (Table 3 B). In November 2008 there appeared to be slight increases in turbidity at the surface (6.4 ntu) and near the bottom (4.3 – 5.5 ntu) but most of the water column had low turbidity (1.7 – 1.9 ntu).

pH was only measured once, in November 2008. It was 7.6 and did not vary with water depth (Table 3 B). Gilvin colour ranged between 0.71 and 1.43 making it the least coloured of the estuaries (Table 3 B)

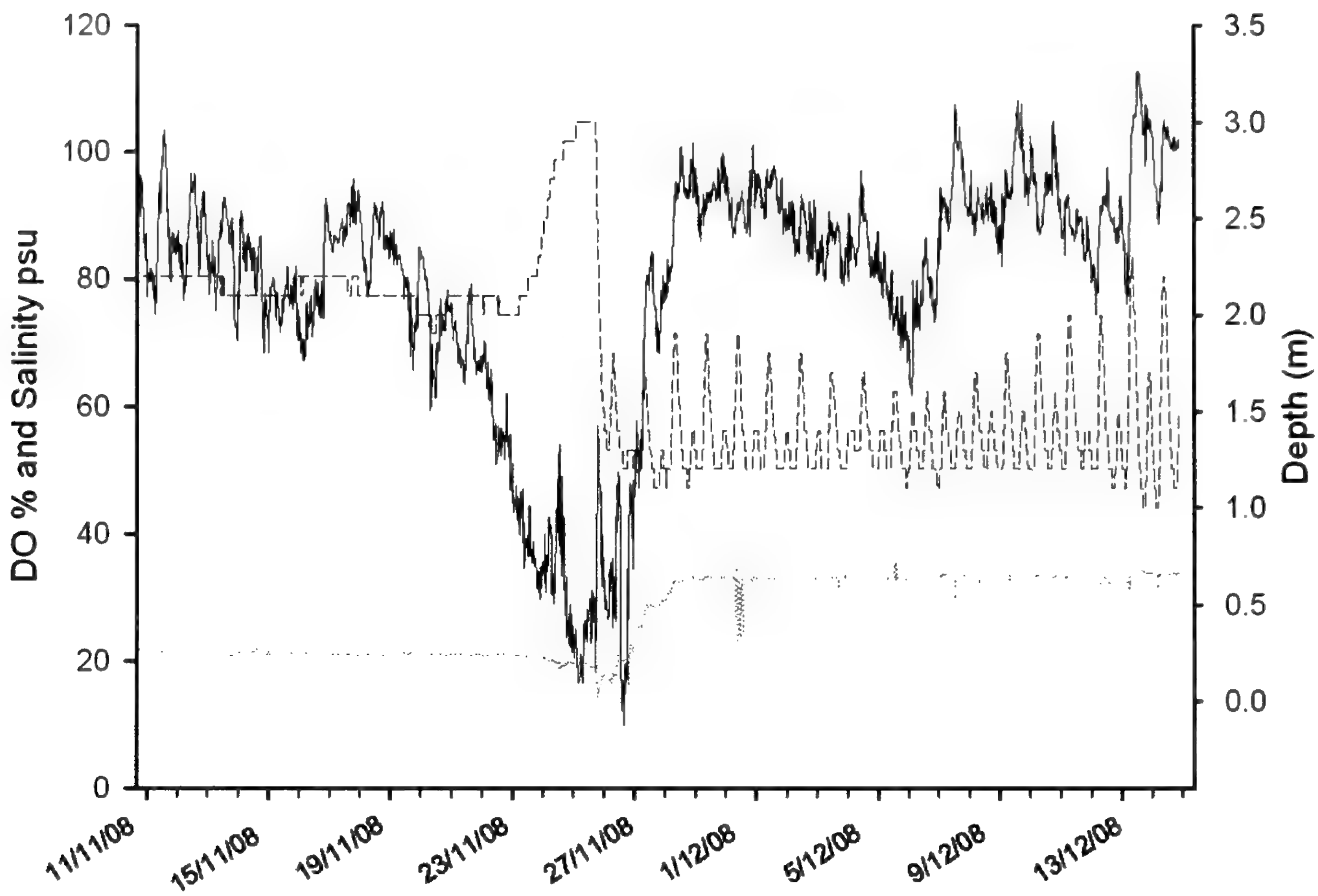

Figure 2 Salinity, depth and dissolved oxygen Nadgee River 11 November 2008 to 14 December 2008. Salinity (psu) – dotted line; depth (m) – dashed line and dissolved oxygen (% sat) solid line. Dates are at commencement of each day (00:00 hrs).

A water quality logger was deployed at a depth of 2.2 m in the River from 10 November until 14 December 2008 (Figure 2). Over the first 12 days salinity showed a slow decline from 21.8 to 20.7, depth was almost constant and dissolved oxygen saturation showed diurnal variation between 75% and 95%. Heavy rainfall in the catchment on about 23 November 2008 resulted in a rapid 1m increase in depth over 48 hours, followed by a 1.7 m drop. During this period, dissolved oxygen saturation dropped to 9%, but salinity at the probe only dropped by 4 psu – indicating stratification in the river. The salinity increased to 33 psu in three days and dissolved oxygen saturation returned to diurnal oscillations around 90% in the same time frame. Water depth began to show semi-diurnal tidal oscillations, with a neap range of 0.5m and a spring range of 1.2 m. It is clear from these data that the entrance opened late on 25 November following the rain on 23 and 24 November 2008 and near oceanic salinities established within 60 hours and remained for the duration of data collection.

Concentrations of dissolved inorganic nutrients (oxidised nitrogen, ammonia, phosphate) were small in November 2008 (Table 4). They were slightly greater in the upper parts of the estuary than the lower. Following opening, upper estuary concentrations in January 2009 were similar to lower estuary concentrations in November 2008, but by February and March 2009 the upper estuary concentrations had increased again to be similar to November 2008 (Table 4). These concentrations were similar to those initially measured at the Lake, but were two orders of magnitude smaller than the eventual ammonia concentrations at the lake. Concentrations of organic, particulate and total nutrient in the river were all about half those of the Lake (Table 4).

<u>Biota</u>

Phytoplankton

Mean pelagic chlorophyll concentrations in the River were 2.9, 2.6 $\mu g.L^{-1}$ (upper and lower, respectively) in Nov 08, 3.7 $\mu g.L^{-1}$ in January 09, 4.3 $\mu g.L^{-1}$ in February 09 and 4.6 $\mu g.L^{-1}$ in March 09 (Table 3 B).

Zooplankton

Net samples indicated the presence of calanoid copepodites, siphonophores, chaetognaths and microscopic jellyfish medusae.

Estuarine macrophytes

No submerged macrophytes (seagrass) were found in Nadgee River estuary, despite searches of the areas indicated as seagrass beds in Williams et al. (2006) and searches of wrack on the strandline. There were, however, considerable areas of saltmarsh on the shores of the estuary. The main species were *Melaleuca ericifolia*, *Juncus kraussii*, *Sarcocornia quinqueflora*, *Phragmites australis*, *Samolus repens*, *Leptinella longipes* and *Apium prostratum*. The limited observation possible confirmed the general locations of saltmarsh as shown in Williams et al. (2006) with the exception that the marsh area on the southern bank near the entrance is probably larger than indicated.

Fish assemblages

The limited sampling possible means that the fish sampled are unlikely to represent a comprehensive inventory of the fish species that inhabit the Lake. All data from each estuary have been combined into a single presentation. A total of 12 species were caught (Table 5), including sub-adult or adult specimens of common table fish such as bream, luderick, mullet (3 species), estuary perch, tailor and trevally.

Though only juvenile and sub-adult bream were caught in the nets, many large bream were observed at times along the banks.

Sediment infauna

Benthic assemblages in Nadgee River were only sampled in the marine bar near the river entrance. These samples contained groups typical of estuarine habitats, and were numerically and taxonomically dominated by crustacean amphipods (Table 7). The crustaceans were relatively diverse, with abundance distributed over five families, probably indicating diverse habitats and food pathways.

Nadgee River Freshwater Reaches

Waters at the Nadgee River ford were clear and slightly acidic, had low conductivity and moderate oxygenation (Table 3 C). The freshwaters were slightly more coloured than the estuary with a gilvin colour of 1.61, which represents only a low level of colouration.

The macro-invertebrate sampling showed a high diversity of families were present (Table 8). There were 22 taxa identified, compared with 19 in spring 1998. 5 taxa collected in 1998 were not found in 2008 and 8 taxa from 2008 were not found in 1998. The AUSRIVAS O/E score for 2008 was 0.91, putting it in Band A and indicating that the assemblage was close to reference.

Merrica River

Physical and chemical properties of the water

Surface salinity ranged between 28.1 and 34.3 psu (Table 3 D). The increase in salinity between 2 December 2008 and 13 January 2009 was a result of the river mouth opening. Turbidity was uniformly low (about 1 ntu). Merrica was the most coloured of the estuaries, ranging between 3.45 and 1.3, with three samples greater than 2.5.

Concentrations of dissolved inorganic nutrients were generally small (DIN 15.5 – 8.2 $\mu g.L^{-1}$, PO_4 6.3 – 2.4 $\mu g.L^{-1}$; Table 4), and were greater in November 2008 (when the estuary mouth was closed) than in February 2009 after the mouth had opened.

Biota

Chlorophyll concentrations ranged from 4.24 $\mu g.L^{-1}$ (when closed) to 2.54 $\mu g.L^{-1}$ when open.

DISCUSSION

The estuaries in the Nadgee Wilderness are subject to almost nil human intervention, around their shores, on their waters and in their catchments. Accordingly they represent conditions that are as near to natural as can be found in NSW. The physical, biological and chemical characteristics of the three estuaries studied were, however, quite different.

Nadgee River opened during the period of the data reported here and has opened a number of times since (DECCW unpublished data). The current opening frequency is 2-3 times per year. This is less than the frequency of "about 5 times per year" reported for the 1960s (NPWS 1975). Nadgee Lake, however, has not opened since November 2008 (DECCW unpublished data), despite several large storms. One storm in June 2010 led to overtopping of the berm by storm waves, but little significant outflow. NPWS (1975) report Nadgee Lake opened twice in 1969 and at those times Lake depths were about "4 feet" (1.2m). These relative opening frequencies agree with the inferences drawn from the ratios of catchment:area to lake surface area (Table 1) mentioned in the introduction. The estuary depths found here are similar (or perhaps a bit deeper) to those reported for 1969 (NPWS 1975), when the

Table 7 Mean (se) abundances and taxonomic richness of benthic invertebrates from Nadgee River. % overall abundance and summary statistics were estimated from pooled data for sites 1 and 2.

Taxonomic Group	Class	*Species*	Site 1 Mean per core n=2	Site 2 Mean per core n=3	% overall abundance
POLYCHAETES **Class Polychaeta**	Nereididae	*Australonereis ehlersi*	0.5 (0.5)	0	0.54
	Spionidae	*Dipolydora* sp.	0	0.7 (0.2)	1.08
CRUSTACEANS **Order: Mysidacea**	Mysidae		1 (1)	4.0 (1.6)	7.53
Order: Amphipoda	Aoridae		18.5 (17.5)	2.3 (0.7)	23.66
	Phoxocephalidae		6.5 (6.5)	11.7 (2.5)	25.81
	Platyischnopidae		1 (1)	7.7 (2.4)	13.44
	Synopiidae	*Synopia* sp.	3.5 (3.5)	4.3 (1.8)	10.75
	Urothoidae	*Urothoe* sp.	4.5 (1.5)	0.3 (0.2)	5.38
Order: Isopoda	Anthuridae	*Mesanthura* sp.	1 (0)	0.3 (0.2)	1.61
	Cirolanidae		0	0.3 (0.2)	0.54
Order: Cumacea	Diastylidae/ Gynodiastylidae		0.5 (0.5)	0.3 (0.2)	1.08
SubClass Copepoda	Copepoda		2.0 (1)	0.00	2.15
MOLLUSCS **Class Bivalva**	Galeommatidae		0.00	1.7 (0.5)	2.69
	Psammobiidae	*Soletellina alba*	0.50 (0.5)	0.7 (0.3)	1.61
	Veneridae		0.00	1.3 (0.7)	2.15

Summary statistics based on taxa	**Number**	**% contribution**	**Summary Statistics based on abundance**	**Number**	**% contribution**
Total number of taxa	15	100.00	Total number of individuals	186	100.00
Number of Polychaete taxa	2	13.33	Number of Polychaetes	3	1.61
Number of Crustacean taxa	10	66.67	Number of Crustaceans	171	91.94
Number of Mollusc taxa	3	20.00	Number of Molluscs	12	6.45
Number of Echinoderm taxa	0	0.00	Number of Echinoderms	0	0.00
Number of other worm taxa	0	0.00	Number of other worm phyla	0	0.00
Number of other taxa	0	0.00	Number of other phlya	0	0.00

Table 8 Abundances of macroinvertebrate taxa from Nadgee River (edge habitat) on 24 March 1998 and two collections on 12 November 2008.

Family	24 March 1998	12 November 2008	12 November 2008
Aeshnidae	1	0	0
Araneae	0	0	3
Atriplectididae	4	0	0
Atyidae	18	49	20
Calamoceratidae	7	1	1
Ceratopogonidae	0	2	2
Chironominae	99	4	7
Corixidae	1	0	1
Dytiscidae	3	0	3
Gerridae	7	0	0
Gomphidae	0	1	2
Gordiidae	1	2	1
Gripopterygidae	2	0	0
Gyrinidae	6	0	1
Hydracarina	13	9	9
Hydrophilidae	0	0	1
Leptoceridae	99	31	13
Leptophlebiidae	14	41	10
Megapodagrionidae	1	1	1
Odontoceridae	13	0	1
Oligochaeta	0	0	1
Philorheithridae	0	1	1
Scirtidae	2	4	1
Sisyridae	0	0	1
Sphaeriidae	0	0	4
Tanypodinae	8	1	5
Veliidae	2	0	0
Total Families	19	13	22

lake was "about 10 feet [3.3 m] when full" and the river was " 12 feet [4m] deep in holes". This indicates that there has not been any significant infilling in the last 40 years.

The presence of an intense algal bloom in the lake was not expected, nor was the extremely large concentrations of ammonia that followed the bloom. The extremely large chlorophyll concentrations and development of a monospecific bloom of cyanobacterial pico-plankton is without precedent (to the knowledge of the authors) in NSW. It appears that the cyanobacterium involved is a previously unknown species but the resources to confirm this were not available. The progression of the bloom from cyanobacteria to a eustigmatophyte and then diatoms was also of interest because this type of succession has not been previously reported in NSW estuaries

Scanes et al. (2007) showed that small levels of catchment disturbance do not always imply small concentrations of dissolved inorganic nutrients in estuarine receiving waters. In fact, they could find no relationship at all between magnitude of catchment disturbance and ambient nutrient concentrations. Those findings are confirmed in the data from Nadgee Wilderness, where ammonia concentrations ranged between 6 and 450 $\mu g.L^{-1}$ over a time span of 6 weeks, with no external inputs to the system. Data from other physically similar NSW estuaries (DECCW unpublished data) show that ammonia concentrations in some undisturbed estuaries can regularly reach 100 $\mu g.L^{-1}$. The default National Water Quality Management Strategy trigger value for ammonia is 15 $\mu g.L^{-1}$. The National Water Quality Management Strategy does, however, recommend that local "Trigger Values" for water quality variables be calculated by taking the 80^{th} percentile value of data from reference estuaries. For ammonia in small south-coast lagoons (other than Nadgee estuaries), the 80^{th} percentile value was 94 $\mu g.L^{-1}$, while the median value was 10 $\mu g.L^{-1}$ (Table 4). This indicates that while much of the time ammonia concentrations are small (about 10 $\mu g.L^{-1}$), at least 20% of the time they can be above 100 $\mu g.L^{-1}$, far greater than the default value. Ammonia concentrations in Nadgee Lake following the collapse of the algal bloom were, however, in excess of 400 $\mu g.L^{-1}$, which is much greater than seen anywhere else. We assume that these concentrations are a direct result of mineralisation of dead algal cells releasing ammonia to the water column. Ammonia concentrations in Nadgee River and Merrica River estuaries were much lower, only once exceeding 10 $\mu g.L^{-1}$. Batley and Simpson (2009) provided guidelines for toxicity of ammonia in estuarine systems. They recommend a toxicity trigger value of 160 $\mu g.L^{-1}$ for systems with high conservation values (this will protect an estimated 99% of species) and note that concentrations of 460 $\mu g.L^{-1}$ represent a low risk of acute or chronic toxic effects, protecting 95% of species. The (natural) ammonia concentrations in Nadgee are therefore at only low risk of causing toxic effects but are more than twice the high conservation criterion.

Concentrations of phosphorus in all estuaries were small, generally around the median value for south coast lagoons. The exception was particulate phosphorus in Nadgee Lake which was very high during the bloom – this is a consequence of the phosphorus in suspended algal cells.

All estuaries were coloured, but to varying extents. Colour was most intense in Merrica (mean 2.5), with a maxium of 3.45 when closed. This indicates colouration of waters from dissolved organic matter – strongly colour waters (e.g. Myall Lakes) have a gilvin colour of about 6.5, whilst clear estuarine water (e.g. Wallis Lakes) in NSW is about 1.2. Very clear waters (e.g. alpine lakes), have gilvin colour of 0.6 (Heinermann et al. 1990). Nadgee Lake was the next most coloured (mean 1.7) and Nadgee River the least coloured (mean 1.2). Nadgee River colour decreased markedly between the first and second samples, coinciding with the entrance opening.

The number of fish species caught in the Lake and River were about the same (13 and 12 respectively), but of the total species pool of 20, only 5 were common to both estuaries – bream, bridled goby, luderick and striped and sand mullet. Nine of the species caught in Nadgee Lake and 8 of those in Nadgee River were listed as abundant in seagrass by Jones and West (2005), who used a very similar seine in 6 south coast estuaries. All the others were noted as abundant in southern estuaries by Hutchins and Swainston (1986). It would be expected that the absence of seagrass or other submerged macrophytes would reduce the numbers of species likely to occur in the estuary (Bell and Westoby 1986, Scanes et al. 2010). Estuaries that remain closed for long periods also may have fewer species and reduced density of fish than those open more often (Loneragan and Potter 1990), though Jones and West (2005) found only weak support for this hypothesis. Given the relatively small fishing effort, both estuaries had reasonably diverse assemblages with means of 4.4 spp. per seine haul in the Lake and 3.3 spp. per seine haul in the River. This compares to approx. 6 spp. per seine haul in seagrass beds in the study of Jones and West (2005). Scanes et al (2010) sampled open estuaries with the same combined seine/mesh net techniques. They found a mean of 7 spp. per sample in samples over bare substrata, compared to a mean of 6 spp. per sample in both the Lake and River in this study. The fish assemblages of the Lake and Estuary can therefore be considered to be almost as diverse as those found in bare areas of open estuaries. About 60% of the species caught in the Nadgee estuaries are common in seagrass, but none of the species can be considered to be strongly attached to seagrass. Common strongly-associated seagrass species such as striped trumpeter, sygnathids and monocanthids were not found in either the Lake or Estuary. These data do not support the hypothesis that estuaries closed for long periods (e.g. Nadgee Lake) have depauperate fish assemblages. It should be noted, however, that the sampling effort in this study was relatively small, so it can be assumed that even more species would be found in the Nadgee estuaries with greater sampling effort.

The sediment invertebrate data indicated that, overall in the Lake, the number of animals per sample was low relative to other coastal estuarine habitats, however the assemblage was not considered depauperate. No nematodes and relatively few oligochaetes were present indicating that habitat disturbance or prevalent eutrophic conditions are not a regular occurrence in the Lake. In the River the crustaceans were the dominant fauna. They were relatively diverse, with abundance distributed over five families, probably indicating diverse habitats and food pathways. These samples were taken from the landward edge of the estuary bar-barrier and may be regularly disturbed when the barrier is broken open.

Although limited observations were made, the community structure of the zooplankton was relatively simple and reflected the typical estuarine conditions of Nadgee Lake and River. The dominance of the crustacean copepods in both Nadgee Lake and River are similar to that in other coastal estuarine habitats (Suthers et al. 2009).

Neither of the Nadgee estuaries had submerged macrophytes (seagrass or charophytes). This is not uncommon in intermittent estuaries, where the presence of seagrass or other macrophytes seems to be determined by factors other than human disturbance (West 1983). Some of the factors that are implicated are long-term recruitment success, salinity (which influences composition more than presence), opening frequency and stability of shallow substratum (Scanes and Coade in press, West 1983). NPWS (1975) noted that in the 1960s Nadgee Lake had dense beds of macrophytes but that in Nadgee River and Merrica River "macro-vegetation … is rare".

The Nadgee Wilderness estuaries are intact examples of estuaries that have had minimal to nil European intervention and therefore represent a very rare and important asset for future study. The few data that are now available suggest that there is, for some variables, considerable variation between the two estuaries. This is most likely due to the differences in ratios of catchment size to estuary volume, and hence propensity to open. The Nadgee Lake data indicate that some (or all) of our preconceptions about the chemical and algal dynamics of infrequently opened coastal lagoons may need to be re-examined. Fish appear to be diverse and abundant and assemblages do differ between the two estuaries.

Despite consistent reports and recordings of annual moulting aggregations of swans on Nadgee Lake from the previous 3 decades, swans (and any source of macrophyte or algal food) were absent from the Lake (and have remained absent until at least March 2011 – DECCW unpublished data). Perhaps this, along with the micro-algal blooms and anomalous ammonia concentrations, indicates that the ecology of Nadgee Lake has changed fundamentally and is moving into a new state. Perhaps this is how all NSW coastal lagoons functioned prior to large-scale land clearing released tonnes of sediment into them? These questions will only be answered by continued research into the ecology, aquatic chemistry and biogeochemistry of these pristine systems.

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Microkarst, Palaeosols, and Calcrete along Subaerial Disconformities in the Ordovician Daylesford Limestone, Bowan Park, Central Western New South Wales

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Accumulation of the Ordovician Daylesford Limestone at Bowan Park, west of Orange, NSW, has been repetitively interrupted by subaerial disconformities. There are distinct diagenetic and pedogenetic suites of products within diverse fossiliferous carbonate lithologies associated with the disconformities as expressed in grains and minerals, fabrics and structures, and lithologies. These include: lithoclasts, calcrete-coated and peripherally-altered lithoclasts, remanié fossils, diagenetic (internal) sediments, terrigenous mud and silica; fossil molds, enlarged fossil molds, cavities, mottles, fissures and irregular surfaces, patches of cryptocrystalline and microcrystalline calcite, bleached zones; and various lithologies such as vugular limestone, mottled limestone, massive light grey limestone, lithoclast grainstone, calcrete-ooid grainstone, calcrete-ooid packstone and wackestone, pellet packstone and wackestone, (terrigenous) mudstone, and palaeosols. Lithoclasts (of vugular limestone with diagenetic sediment) above disconformities, and the restriction of vugular limestone with variable diagenetic sediment-filled cavities beneath disconformities, indicate leaching and internal sedimentation was early and associated with subaerial exposure. The most important factor affecting profile variation is the type of host rock, i.e. grainstone *versus* muddy limestone. Palaeosols are mostly developed on muddy limestone, and leaching is most common within the altered muddy limestone, whereas for grainstones, palaeosols are generally absent, and cryptocrystalline (and microcrystalline) calcite (calcrete) patches are probably the most important diagenetic product. Beneath the disconformities, ten types of subaerially developed profiles are recognised: erosionally truncated vugular limestone with coralline encrustation on the disconformity, erosionally truncated vugular limestone without palaeosol cover, erosionally truncated vugular limestone with thin palaeosol cover, muddy limestone with thin palaeosol cover with calcrete ooids and remanié fossils, muddy limestone with thick palaeosol cover with calcrete ooids and remanié fossils, muddy limestone with marine-reworked lithoclastic and calcrete ooid grainstone and remanié fossils, solution-altered grainstone with overlying lithoclastic and calcrete ooid grainstone, thick calcrete developed on grainstone, wackestone/lime-mudstone (marl) with overlying sheet of (terrigenous) mudstone, and silicified limestone. Of the range of products and profiles, the vugular limestones stand as the most important indicators of subaerial exposure.

The information in this study provides insights into the types of subaerial diagenesis and pedogenesis operating during the Ordovician, and also into landscape setting, palaeo-hydrology and depth of the vadose zone, climate, and groundwater/rainwater alkalinity.

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KEYWORDS: calcrete, Daylesford Limestone, diagenesis, limestone, microkarst, Ordovician, pedogenesis, subaerial palaeosols.

INTRODUCTION

Detecting subaerial disconformities is important in stratigraphic and environmental studies of marine carbonate rocks in order to recognise discontinuities in the sequence, and to be able to identify and relate those specific diagenetic alteration effects which may be attendant to subaerial exposure. Diagenetic phenomena associated with subaerial exposure of marine and palustral carbonates have been documented from Pleistocene to Holocene sequences (Friedman

1964; Roehl 1967; Matthews 1967, 1968; Purdy 1968), soils (Gile et al. 1966; Reeves 1970; Read 1974; Brown and Woods 1974) and pre-Quaternary sequences (Dunham 1969a, 1969b; Francis 1986; Driese and Foreman 1991; Melchor et al. 2002). These phenomena include solution, calcretisation, pedogenesis (forming palaeosols), illuviation, brecciation, and ichnofaunal effects, amongst others. Subaerial diagenetically altered horizons often form a natural capping lithology to regressive carbonate cycles, and in this context, their recognition signals the emergence of a shoaling sequence into the subaerial environment (Read 1973; Goldhammer and Elmore 1984).

Palaeosols are especially important products of subaerially exposed marine carbonate sequences, because they represent the direct surface effects of subaerial diagenesis and pedogenesis, as distinct from more shallowly buried features such as solution (including microkarst) and illuviation, the latter nonetheless still signalling subaerial exposure and subaerial diagenesis. Subaerial disconformities, and palaeosols in particular, have been used as markers to map facies changes in sedimentary sequences and in metamorphic terranes between isochronous 'bounding surfaces' (Semeniuk 1973a; Barrientos and Selverstone 1987). Recognition of palaeosols and their associated ichnofauna, and evidence of plant life also have been central to the reconstruction of geochemistry, hydrochemistry and atmosphere composition of the Precambrian and early Palaeozoic, and when terrestrial environments were first being inhabited [see contrasting interpretations of Precambrian palaeosols by Palmer et al. (1989a, 1989b) and Holland and Feakes (1989), and of Ordovician strata by Retallack and Feakes 1987; Retallack 2001a; and Davies et al. 2010].

The diagenetic and pedogenic effects of subaerial unconformities, with particular emphasis on palaeosols, have been recognised as far back as the Precambrian, and described from a variety of parent rocks, ranging from igneous, metamorphic, sandstones, and carbonate rocks (Wright 1986; Duffin et al. 1989; Retallack and Mindszenty 1994; Retallack 2001b, 2009; Melchor et al. 2002; Jutras et al. 2009). The focus on the more ancient palaeosols from Precambrian to Devonian times has been to determine geochemical changes effected in the weathering materials, provide insight into earlier atmosphere and hydrochemistry in a vegetation-free landscape, to develop criteria to separate pedogenic effects from diagenesis, or to trace the beginnings of plant and animal advance onto the land from the sea (Retallack 1985; Reinhardt and Sigleo 1988). For instance, Jutras et al. (2009) document geochemical features of Ordovician palaeosols to reconstruct climate, content of atmospheric CO_2, groundwater hydrochemistry, and to interpret terrain conditions at the dawn of land plant radiation.

However, while there has been some study of Ordovician palaeosols in carbonate rocks, the focus has been on Ordovician pedogenesis of terrigenous sediments and igneous rocks (Feakes et al. 1989; Driese and Foreman 1991, 1992; Jutras et al. 2009). Few papers have described the effects of subaerial exposure specifically on Ordovician carbonate rocks.

This paper is important, therefore, in that it describes the products of Ordovician subaerial diagenesis and pedogenesis along the subaerial disconformities on varied limestones in the Ordovician Daylesford Limestone (Semeniuk 1973b) at Bowan Park, west of Orange in central western New South Wales, providing details of grains, structures, lithology, and stratigraphy to a level not previously documented regionally or globally. It presents a model of subaerial diagenesis and pedogenesis for Ordovician carbonate rocks and provides indicators for recognising subaerial disconformities in the Ordovician and generally in the geological record.

Semeniuk (1971) described the effects of leaching on these limestones, effectively focusing on the near-surface subterranean effects of subaerial exposure. This paper provides a fuller account of the effects of diagenesis and pedogenesis, with an emphasis on microkarst, internal sedimentation, palaeosols, calcrete, and reworked palaeosols, and on the variable subaerial diagenetic response by the three main parent marine sediments of the sequence, viz., lime mudstone, shelly lime wackestone, and grainstone.

Karst refers to landscape and subterranean structures produced by dissolution of soluble rocks (mainly limestone) that results in large landscape features, dolines, caves, subterranean drainage, and even small-scale features such as pitting, flutes, karren, solution cavities, fossil molds, and bedding plane partings, amongst others (Jennings, 1971, 1985; Sweeting 1972; Bates and Jackson 1987; Ford 1988). The term 'karst' generally has no scale connotations. There have been no large-scale features such as caves, speleothems, dolines, depressions, or cave-fill breccias recorded along the Ordovician subaerial disconformities of the limestones of this study, however, there is a plethora of smaller-scale structural features of dissolution. In this paper, the term 'microkarst' is used to emphasise that there are definitively small-scale products of karst in Ordovician limestone as a result of subaerial exposure and dissolution. Jakucs (1977) uses the term 'microforms' for some features of this scale.

Some explanation of terms is provided here. Diagenesis refers to the alteration of sediments after deposition - it includes solution, cementation, and grain alteration, amongst other effects. In this paper there is focus on sediment alteration that is shallow just below the former subaerial surface. Pedogenesis refers to the alteration of sediments to develop soils – thus, it is a suite of alteration processes that operate from the surface downwards, and its final product is the surface soil. However, as processes, diagenesis and pedogenesis can spatially overlap. The term 'diagenetic sediment' is used herein to refer to the mainly fine-grained sediment that infiltrated the Ordovician sediment or limestone during diagenesis, and partly to fully filled pore space and cavities. It includes the crystal silt of Dunham (1969a), pellets, calcrete-coated and peripherally altered grains, lithoclasts, internally generated "micro-breccias", terrigenous mud, and quartz silt, or can be comprised of mixtures of these materials. Its origin can be internal to the sediment or rock, or illuvial (illuvium being the material transported down a soil profile usually from the surface by the action of rainwater). Generally, diagenetic sediment is fine-grained (i.e., silt to very fine sand-sized), but locally some lithoclasts within cavities are up to medium sand-size. A ped is a unit of soil structure, such as an aggregate, crumb, prism, block, or granule, formed by natural processes and, as such, soils with ped structure commonly have interconnected inter-ped spaces.

The limestone classification of Dunham (1962) is used in this paper. Based on depositional fabric, Dunham (1962) recognised six types of limestone, four of which are relevant here: 1. lime grainstone (equivalent to calcareous sand and gravel deposits); 2. lime packstone (equivalent to calcareous muddy sand and gravel deposits); 3. lime wackestone (equivalent to calcareous sandy and gravelly lime mud deposits); and 4. lime mudstone (equivalent to calcareous mud deposits). Since the majority of sediments in this study are limestones, the terms of Dunham (1962) are generally shortened to grainstone, packstone, wackestone and mudstone to refer to the four depositional categories, and the adjectival descriptor 'skeletal', or 'lithoclastic' is used to refer to the calcareous sand or gravel grains that comprise the grainstone, packstone, or wackestone. The general term 'muddy limestone' refers to all limestones that formerly were composed totally or partly of calcareous mud (and hence refers to lime packstones, lime wackestones and lime mudstones). Distinguished from the muddy limestones is a small proportion of terrigenous mudstone in the Daylesford Limestone, that can be sedimentary or pedogenic in origin.

Fine-grained calcite has been described in this paper in terms of grainsize as cryptocrystalline (crystals < 1 μm), and microcrystalline (crystals 1 μm to 10 μm) (Folk 1959; Bissell and Chillingar 1967; Bathurst 1975). In the patches of fine-grained calcite (formerly either sedimentary lime mudstone or calcrete patches), the fine-grained mosaics are inter-gradational because of recrystallisation. Cryptocrystalline calcite can be recrystallised to microcrystalline calcite. Interstitial pores, or interstices, in formerly calcareous sand, can be filled with cryptocrystalline and/or microcrystalline calcite, and the grains of the sand can be recrystallised to cryptocrystalline and/or microcrystalline calcite. Consequently, there is not a sharp distinction made in this paper between cryptocrystalline and microcrystalline.

The study is based on field sites, stratigraphy along five transects, and on 470 samples, the latter examined mainly in thin section and as polished slabs. Staining methods of Friedman (1959) and X-Ray Diffraction (XRD) were used to distinguish calcite from dolomite, and quantitative XRD was used to determine the content of pyrite and Fe-oxides. Scanning Electron Microscopy (SEM) was used to investigate fine-grained crystal textures, and Electron Dissipative Spectroscopy (EDS) was used to determine element distribution and mineral phases, especially of Fe and Mn minerals at the micron-scale. Numbers prefixed USGD and SUP refer to specimens formerly catalogued in the petrology and palaeontology sections, respectively, of the Department of Geology and Geophysics, University of Sydney and now housed at the Geological Survey of New South Wales at Londonderry, NSW.

PROCESSES AND PRODUCTS ALONG SUBAERIAL DISCONFORMITIES – A BRIEF REVIEW AS BACKGROUND TO INTERPRETING ORDOVICIAN SUBAERIAL EXPOSURE

The processes and products operating along and developed on subaerial disconformities on marine carbonate sediments of Holocene, Pleistocene, and pre-Quaternary carbonate rocks in various climatic settings are well documented (Fairbridge and Teichert 1953; Friedman 1964; Gile et al. 1966; Roehl 1967; Matthews 1967, 1968; Purdy 1968; Dunham 1969a, 1969b; Kendall 1969; Land 1970; Reeves 1970; Semeniuk 1971; Chafetz 1972; Purser 1973; Brown and Woods 1974; Logan 1974; Read 1974; Braithwaite 1975; Read and Grover 1977; Videtich and Mathews 1980; Esteban and Klappa 1983; Esteban and Pray 1983; Goldhammer and Elmore 1984; Harris et al. 1985; Francis 1986; Wright 1986; Brewer and Sleeman 1988; Ford 1988; Tucker and Wright 1990; Wright and Tucker 1991; and Melchor et al. 2002). There are also many processes and products resulting from subaerial exposure, weathering, and pedogenesis of other rock types from a range of geological ages that nevertheless are universal and applicable also to carbonate rocks, e.g., root-structuring, humification, illuviation, geochemical alteration (Retallack 1985, 2001b, 2009; Wright 1986; Reinhardt and Sigleo 1988; Feakes et al. 1989; Holland and Feakes 1989; Palmer et al. 1989a, 1989b; Driese and Foreman 1991; Retallack and Mindszeny 1994; Jutras et al. 2009). Similarly, texts such as Buol et al. (1973), FitzPatrick (1983), Wilding et al (1983), Brewer and Sleeman (1988), and Leeper and Uren (1993), refer to the general principles of alteration and pedogenesis involved in subaerial environments, and provide principles and processes in pedogenesis that are applicable to interpreting subaerial diagenetic and pedogenetic effects in carbonate rocks.

However, depending on climate (in particular rainfall), and the parent material and its geochemical lability, subaerial exposure will generate various products. The literature on palaeosols and weathering, and effects of subaerial exposure from modern and/ or ancient sequences should be carefully applied to interpret those rocks and sediments of different petrology, different climate environment, or different landscape and hydrological setting. At best, the descriptions of subaerially altered materials and ancient palaeosols serve to show firstly, that there was subaerial exposure in a given geological age, secondly, that there are some consistently developed products that can signal environmental setting (e.g., plant roots), thirdly, the potential geochemical and hydrochemical processes and products that can derive from subaerial exposure, and fourthly, the nature of the environment in which the alteration took place in terms of its climate, landscape, hydrology, and biology. As such, granites, basalts, sandstones, shales, and carbonate rocks and carbonate sediments may respond differently, and some of the criteria developed to identify subaerial exposure and weathering in one suite of materials cannot always be applied to another. For this paper, a summary of the literature cited above will focus on the effects of subaerial exposure and pedogenesis on carbonate rocks and carbonate sediments, and those aspects of subaerial alteration and pedogenesis derived from other materials that *can* be applied to carbonate rocks.

For carbonate sediments and rocks, it is also important to separate pedogenesis and subaerial diagenetic effects on unlithified marine carbonate sediments from those that are weakly cemented or fully indurated to limestone. At one extreme, there would be a suite of metastable grains of varying carbonate composition, and material that is permeable to groundwater and vadose water, and hence subject to particular pathways of pedogenesis and diagenesis. At the other extreme, there would be indurated and relatively impermeable materials that would be subject more to karst processes.

Diagenetic effects on unlithified to weakly cemented marine carbonate sediments beneath and at subaerial disconformities at local to regional scale are characterised by (Dunham 1969a; Land 1970; Bathurst 1975; Esteban and Klappa 1983; Wright and Tucker 1991):

1. root features;
2. ped development;
3. humification at the surface;
4. illuviation of fine-grained sediment (mainly crystal silt of Dunham 1969a);
5. illuviation of exotic sediment (such as aeolian dust);
6. geochemical alteration and adjustments from the surface downwards;
7. development of a K-horizon or some form of hardpan in the shallow subsurface;
8. specific types of geochemical effects at the water table (e.g., Fe precipitation);
9. pitting and whole-scale solution of selected grains (e.g., aragonite shells);
10. disaggregation of polymineralic and/or multi-textured skeletons to form internal sediment;
11. fossil molds and solution cavities (if the sediment is weakly coherent or cemented);
12. small- to large-scale depressions, cracks, fissures, and irregular surfaces;
13. erosional surfaces at the disconformity with truncation of structural and petrographic features at the disconformity;
14. regional erosional pinch-out of beds;
15. iron-staining of disconformity surfaces; and
16. silicification, including silicification of fossils.

Indurated marine carbonate sediments (limestones) beneath and at subaerial disconformities at local to regional scale are characterised by:

1. microkarst and macrokarst features;
2. fossil molds and irregular solution cavities, commonly with internal sediment (mainly crystal silt of Dunham 1969a);
3. small- to large-scale depressions, cracks, fissures, and irregular surfaces filled with marine sediment or soil;
4. fracture and veining;
5. illuviation of fine-grained sediment (mainly crystal silt of Dunham 1969a);
6. illuviation of exotic sediment (such as aeolian dust);
7. geochemical alteration and adjustments from the surface downwards;
8. erosional surfaces at the disconformity with truncation of structural, fossil, and petrographic features at the disconformity;
9. regional erosional pinch-out of beds;
10. iron-oxide staining of disconformity surfaces; and
11. silicification, including silicification of fossils.

There is a wider range of effects in uncemented marine sediments because they tend to be geochemically more diverse than limestones (Bathurst 1975), and hydrologically more porous and permeable.

Evidence of a disconformity in overlying units includes:

1. palaeosols;
2. surface residues of leaching (e.g., clay mineral or quartz silt residue);
3. lithoclasts and grains coated by cryptocrystalline calcite (calcrete-ooids of Read 1974) which represent reworked palaeosols;
4. marine sediments containing abundant grains coated, and peripherally replaced by cryptocrystalline calcite and representing reworked soils;
5. abundant gravel- and sand-sized lithoclasts in the marine limestone immediately above the disconformity;
6. remanié fossils (reworked fossils) in the marine limestone immediately above the disconformity;
7. abrupt lithology changes that are unrelated to underlying facies; and
8. organic encrustations (such as corals and stromatoporoids) and borings either on erosionally-planed, sparry calcite-cemented grainstone or on brittle muddy limestones.

Major disconformities with their associated diagenetic alteration can be recognised regionally. Minor disconformities may be of local significance, and associated with less intense alteration. That is, some disconformities were not major events and the subaerial alteration associated with them was not consistently developed regionally.

GEOLOGIC SETTING OF THE DAYLESFORD LIMESTONE

The Ordovician Daylesford Limestone (Semeniuk 1973b) is the basal formation of the Bowan Park Group, which crops out in central western New South Wales (Fig. 1). The Daylesford Limestone disconformably overlies the Cargo Volcanics and is disconformably overlain by Quondong Limestone. At its type section, the formation is 250 m thick and contains six members which in ascending order are: 1. Ranch Member; 2. Bourimbla Limestone Member; 3. Manooka Limestone Member; 4. Gerybong Limestone Member; 5. Glenrae Limestone Member; and 6. Davys Plains Limestone Member. The Oakley Limestone Member is laterally equivalent to Manooka and Gerybong Limestone Members to the east and occurs between Bourimbla and Glenrae Limestone Members. Table 1 summarises lithologies and stratigraphic relationships of the members.

The focus of this paper is on the Ranch Member, Bourimbla Limestone Member, Manooka Limestone Member, Gerybong Limestone Member, Glenrae Limestone Member, and the Oakley Limestone Member, where disconformities are well marked and separate distinct sedimentation phases. At the top of the Glenrae Limestone Member is a major disconformity above which occurs the Davys Plains Limestone Member (which contains skeletal lithoclast grainstone, pisolitic lithoclast grainstone, dark grey skeletal packstone and wackestone, pellet packstone). The Davys Plains Limestone Member contains numerous disconformities and records a phase of the history of the Daylesford Limestone wherein there was much subaerial exposure and reworking. This topmost unit of the Daylesford Limestone is overlain disconformably by the Quondong Limestone (Semeniuk 1973b).

The Daylesford Limestone consists mainly of four broad limestone types which are: 1. grainstone; 2. skeletal wackestone and packstone; 3. burrowed wackestone and packstone; and 4. burrowed lime mudstone. The limestones strike approximately east-west for 9 km permitting analysis of facies changes in

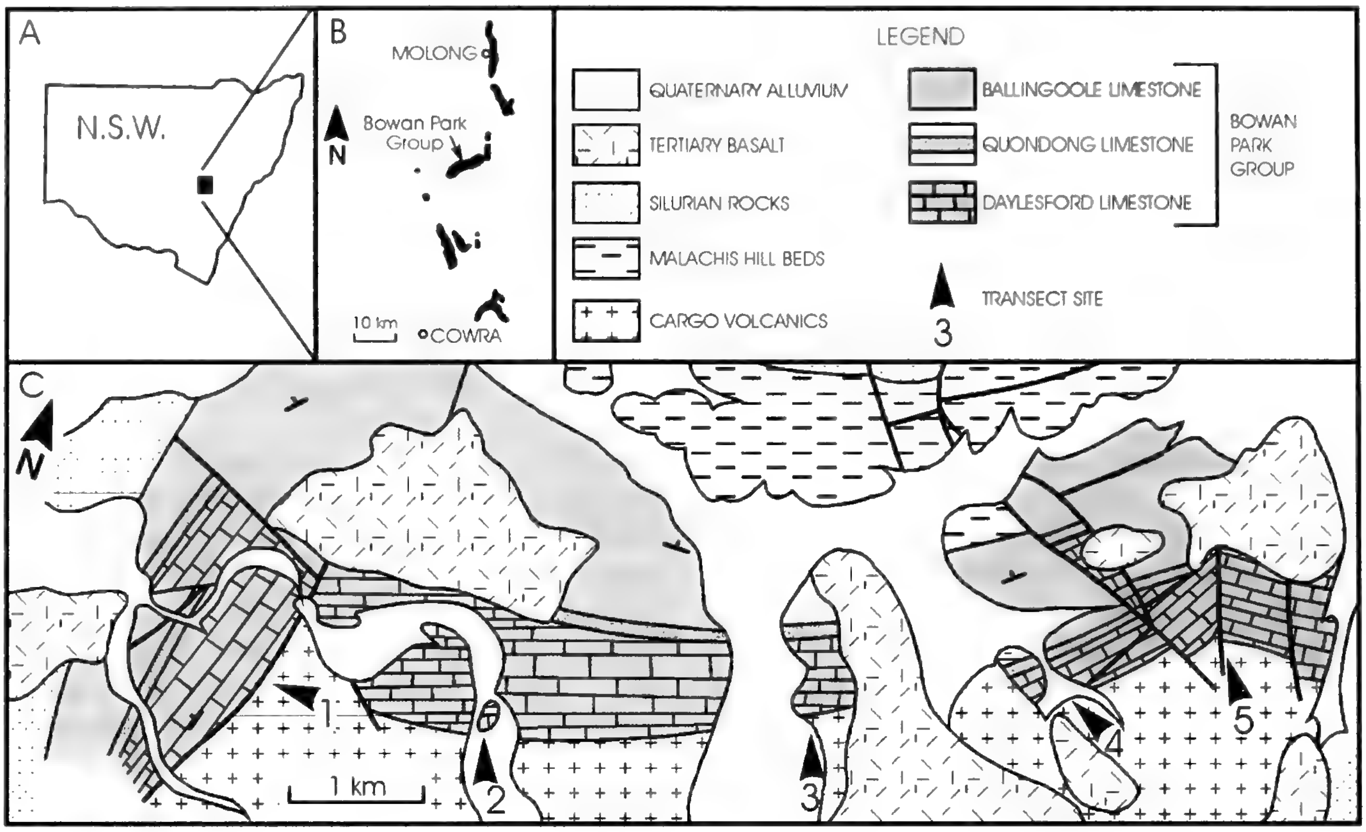


Figure 1. Simplified geological map of the Bowan Park area showing distribution of the Daylesford Limestone (after Semeniuk 1973a, 1973b), and location of the stratigraphic transects.

<table>
<tr><td>Western localities</td><td>Eastern localities</td></tr>
<tr><td colspan="2">Davys Plains Limestone Member (95 m thick): interbedded massive skeletal lithoclast grainstone, pisolitic lithoclast grainstone, dark grey skeletal packstone and wackestone, pellet packstone; disconformably overlain by Quondong Limestone and disconformably overlies:</td></tr>
<tr><td colspan="2">Glenrae Limestone Member (25 m thick): in western localities consists of intercalated and burrow-mottled grainstone, skeletal wackestone and lime mudstone in lower part and massive light grey mottled limestone in upper part; in eastern localities consists of massive light grey mottled limestone; overlies and grades into:</td></tr>
<tr><td>Gerybong Limestone Member (64 m thick): intercalated, thinly bedded dark grey lime mudstone and skeletal wackestone; conformably overlies:</td><td rowspan="2">Oakley Limestone Member (90 m thick): massive skeletal grainstone and skeletal lithoclast grainstone.</td></tr>
<tr><td>Manooka Limestone Member (16 m thick): skeletal lithoclast grainstone, skeletal grainstone, dark grey skeletal packstone, wackestone, lime mudstone; disconformably overlies:</td></tr>
<tr><td colspan="2">Bourimbla Limestone Member (24 m maximum thickness): thinly to massively bedded grey skeletal wackestone and packstone, dark grey skeletal wackestone, lime mudstone; disconformably overlies:</td></tr>
<tr><td colspan="2">Ranch Member (34 m thick): mainly thinly bedded marl, terrigenous mudstone and, towards base, lithic sandstone and mudstone; disconformably overlies Cargo Volcanics</td></tr>
</table>

Table 1: Stratigraphy and lithologies of the Daylesford Limestone

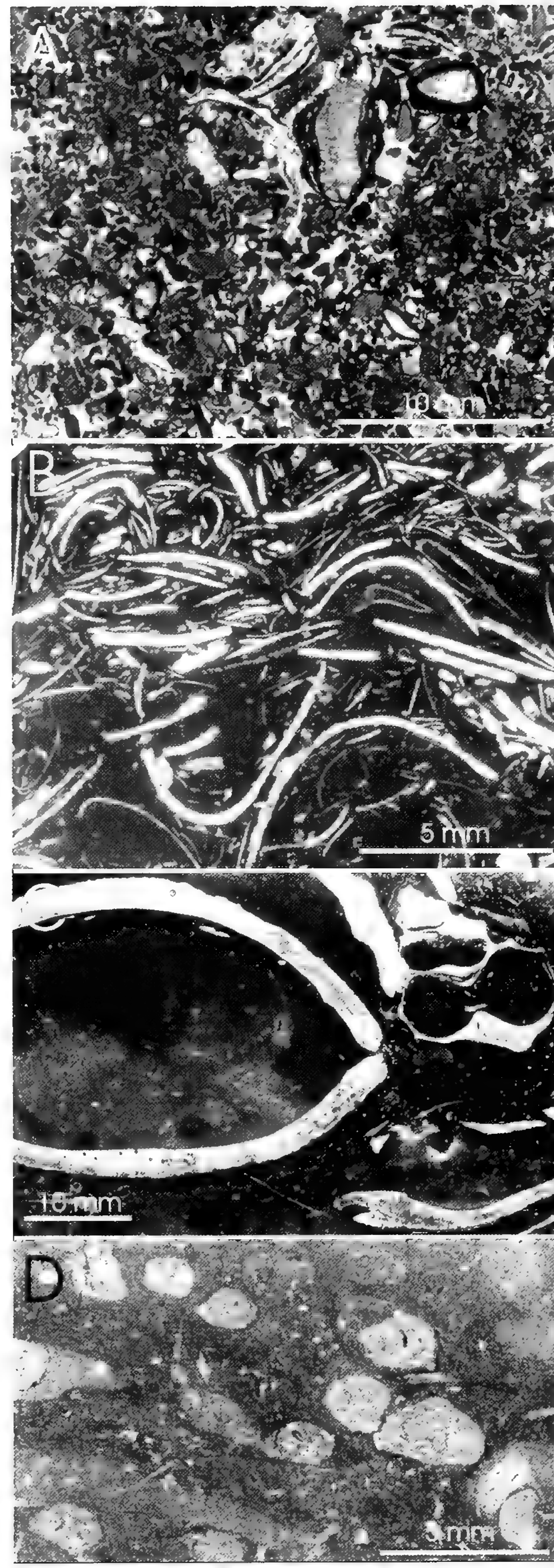


Figure 2 RIGHT. Thin sections of parent limestones in the Daylesford Limestone. A. Skeletal grainstone, from the Manooka Limestone Member, composed dominantly of crinoid ossicles, and subordinate mollusc and coral fragments (USGD 46711). B. Skeletal packstone, from the Ranch Member, composed dominantly of molluscs (USGD 46673). C. Skeletal wackestone, from the Bourimbla Limestone Member, composed of gastropods and the brachiopod Eodinobolus (USGD 46651). D. Burrowed lime mudstone, from the Ranch Member (USGD 47034).

a direction perpendicular to the original Ordovician shoreline (Semeniuk 1973a). Grainstone and skeletal wackestone and packstone dominate eastern sections of the Formation; they are laterally equivalent to, and interfinger with, muddy limestone that dominates western sections (Semeniuk 1973a). Lithoclasts occur in the grainstones but are absent from muddy sections to the west, except in thin horizons above disconformities.

In more lithologic detail, host limestones beneath subaerial disconformities include lithoclast and skeletal grainstones and muddy limestones (Semeniuk 1973a). Grainstones are medium to coarse sand-sized sediments, composed of skeletons (mostly calcareous algae, echinoderms, and molluscs) and lithoclasts with layers of gravel-sized fossils, lithoclasts, and *Girvanella* nodules; grainstones are cemented by sparry calcite. Muddy limestones include skeletal wackestones and packstones, and lime mudstones. Skeletal wackestone and packstones tend to be dark grey and contain sand- and gravel-sized whole and fragmented fossils in a lime mud matrix; some sediments contain abundant pellets. Once accumulated, under the low energy conditions of their depositional environment, they remained anoxic. Large fossils include brachiopods, molluscs, stromatoporoids, corals and calcareous algae; these are oriented and in layers, or randomly oriented and disrupted by burrows. The matrix is lime mud containing abundant, poorly sorted, angular, fine to coarse sand-sized skeletal fragments, particularly if the sediments are burrowed. Skeletal fragments in the lime mud matrix include thin-shelled brachiopods, sponge spicules, dasycladacean algae, ostracods, trilobites, bryozoans, and small gastropods. Lime mudstones tend to be dark grey, commonly burrowed, and composed of cryptocrystalline calcite, patches of microcrystalline calcite, and < 10% silt- to sand-sized skeletal fragments similar to those in the matrix of skeletal wackestones and packstones. Intraskeletal voids of fossils in muddy limestones are filled with sparry calcite. As with the packstones and wackestones, once accumulated, under the low energy conditions of their depositional environment, they remained anoxic.

A range of the primary lithologies of the Daylesford Limestone are illustrated in Figure 2 to provide a baseline of limestone types that are host to the Ordovician subaerial diagenesis. These range from grainstone to lime mudstone, and show relatively intact fabrics of grains, cements, lime mud fabrics, and well preserved fossil material.

Numerous subaerial disconformities occur within many limestone members and separate major sedimentological phases in the Daylesford Limestone. The disconformities converge eastwards and cause wedging-out of units indicating that, during deposition, the Daylesford Limestone was flanking an axis to the east known as the Molong Volcanic Belt. For a history of the nomenclature of this axis see Packham (1969), Gilligan and Scheibner (1978), Packham et al. (2003), Gray and Foster (2004), Glen et al. (2007), and Percival and Glen (2007). The significant features of this axis are that deposition of the Daylesford Limestone took place on its western flank, and consequently in eastern parts of the Daylesford Limestone during times of subaerial exposure, with any relative change in sea level in the Ordovician, there was enough relief for limestones to be subaerially eroded and reworked as lithoclasts into the depositional basin to the west (Semeniuk 1973a). In this palaeogeographic setting, grainstone, grey skeletal wackestone and packstone accumulated in nearshore environments nearest to the axis of the Molong Volcanic Belt as suggested by their stratigraphic position and abundant lithoclasts, and by their association with desiccated sediments. Dark grey lime mudstone formed in offshore, low-energy environments further to the west, as suggested by their stratigraphic location, abundance of lime mud and lack of shallow-water indicators. Dark grey wackestone and packstone formed in intermediate environments. Burrowing organisms locally produced burrow-mottled limestone or mixed, interbedded grainstone and muddy limestone.

Prior to describing and assigning early diagenetic/pedogenetic effects to subaerial disconformities in the Ordovician limestones, it is necessary to describe the products of later diagenesis and low grade regional metamorphism (cf. Ryall 1965; Smith 1968) to separate their effects from subaerial effects. This is important because the subaerial diagenesis/pedogenesis in the Daylesford Limestone is Ordovician in age and sets a standard of such alteration in marine carbonate sediments that is not well described globally, and thus needs to be clearly viewed through and separated from later overprints.

Given the limited mineralogy of the Ordovician limestones (i.e., calcite, and silica) and their labile nature, alteration deriving from later diagenetic and low grade regional metamorphic processes may overlap in time and in products. Late diagenesis and low grade regional metamorphism resulted in recrystallisation of microcrystalline and cryptocrystalline calcite to coarser crystal fabrics, recrystallisation of sparry calcite to coarse textures and blocky calcite, twinning of calcite, intergranular suturing of calcite crystal mosaics, development of triple junction interfaces in calcite crystal mosaics, dolomitisation, fluorite replacement of calcite, gypsum precipitation and its later calcitisation, stylolite development, brittle fracturing and cavity filling (i.e., calcite veining), and some silicification. This later diagenesis and low grade metamorphism in fact overprints the products of diagenesis and pedogenesis associated with subaerial esposure.

DIAGENETIC EFFECTS ASSOCIATED WITH SUBAERIAL DISCONFORMITY SURFACES IN THE DAYLESFORD LIMESTONE

Limestone are described in increasing scale from grains, fabrics and structures, building up to lithologies, and then stratigraphic profiles. The products of Ordovician subaerial exposure are described in increasing scale because the recognition of subaerial surfaces is very important in ancient sequences dating as far back as the Ordovician. Given that descriptions of Ordovician subaerial diagenesis and pedogenesis are rare globally, all components of the alteration associated with subaerial exposure in the Daylesford Limestone need to be individually addressed and described: from grains that are developed under, at, or above disconformities, to the fully developed palaeosols or microkarst features where the entire suite of grains and minerals, fabrics and structures, and lithologies are preserved in context. In this scalar framework, the signal that there has been subaerial exposure of marine sediments can be reconstructed at one extreme, in the best preserved situations, from fully developed profiles to an intermediate situation where there is only a portion of the profile (if eroded during the Ordovician, or later faulted or metamorphosed), to the other extreme, in the least preserved situation, where the only evidence of subaerial exposure are grains derived from subaerial profiles that have been reworked into the next cycle of marine sediments.

Grains and minerals, fabrics and structures, and lithologies associated with disconformities include: 1. (for grains and minerals) lithoclasts, calcrete-coated and peripherally-altered lithoclasts, remanié fossils, internal sediments, terrigenous mud, and silica; 2. (for fabrics and structures) fossil molds, enlarged fossil molds, cavities, mottles, fissures and irregular surfaces, patches of cryptocrystalline and microcrystalline calcite, and bleaching; and 3. (for lithologies) vugular limestone, mottled limestone, massive light grey limestone, lithoclast grainstone, calcrete-ooid grainstone, calcrete-ooid packstone and wackestone, pellet packstone and wackestone, (terrigenous) mudstone, and palaeosols.

GRAINS AND MINERALS

Lithoclasts

Lithoclasts are sand- and gravel-sized carbonate rock fragments eroded from older lithified carbonate rocks beneath disconformities (Folk 1959). In the Daylesford Limestone, lithoclasts include fragments of lime mudstone, skeletal, pelletal, and lithoclast wackestone, packstone, and grainstone (Fig. 3A), calcrete-cemented grainstone, laminar calcrete (Fig. 3B), veined laminar calcrete, and reworked fossil casts of 'steinkerns' (Fig. 3C). Lithoclasts are recognised by drusy and blocky calcite internal cements, solution textures, calcite veins, limonite pigments, silica-replacement textures, and recrystallisation textures within the grain; grain boundaries truncate these internal diagenetic fabrics.

Calcrete-ooids

Many sand-sized lithoclasts in the Daylesford Limestone are superficially coated by concentrically laminated envelopes of cryptocrystalline calcite (Figs 3D and 3E). The envelopes are commonly asymmetrically concentrically laminated. There are internal micro-unconformities within the lamination of the ooids, and these are commonly pigmented by limonite. They are comparable to Quaternary calcrete-ooids formed by soil processes (see Fig. 3F; and Read 1974), both in terms of morphology and limonite pigmentation. They are also termed 'vadoids' by Peryt (1983), to refer to coated grains formed in the vadose zone. The calcrete-ooid envelopes (simple, cryptocrystalline, free-grain cutan or calcitan of Brewer 1964) have sharp contacts with the grain and are commonly asymmetrical. They are readily distinguished from marine ooids: the former composed of asymmetric concentric envelopes of fine-grained equant calcite, with internal Fe-oxide rinds marking micro-unconformities; the latter having a strong symmetric concentric structure of tangentially aligned carbonate crystals or (for recrystallised ooids) strong radial array of carbonate crystals (Bathurst 1972).

The coats are mostly developed on lithoclasts and some remanié fossils. In contrast, fossils and fossil fragments that are autochthonous within a bed are uncoated, or algal-micrite coated and bored. The absence of both tubules and penetrating contacts distinguishes these surficial calcrete envelopes from algal-micrite envelopes produced by algal borings (Bathurst 1966; Logan 1974).

Some of the calcrete-coated grains are gravel-sized and would be termed calcrete pisolites. However, they are not common as a grain type. Moreover, the calcrete coating on the gravel-sized grains are thin, not like the thickly and multiply coated pisolites of the Guadalupe Mountains (Kendall 1969) and Shark Bay (Read 1974). Figure 3G shows a *Girvanella* nodule to contrast the internal laminar structure of these algal concretions with calcrete ooids.

Peripherally-altered lithoclasts

Lithoclasts may also be peripherally altered with a cryptocrystalline calcite rind that is gradational into the unaltered core of the grain (Fig. 3H). The alteration is most evident in clasts comprised of grainstone or packstone. Alteration is most complete in outer portions of rinds and inner portions commonly retain relict limestone textures (Fig. 3H). Alteration zones range from thin veneers (0.1 mm) to thick rinds (10 mm) that are up to half the grain radius. Some rinds are limonite-stained. The association of cryptocrystalline calcite rinds with lithoclasts, calcrete-coated lithoclasts, and limonite-pigmented grains indicates that they are the weathered margins of grains. Similar cryptocrystalline rinds around carbonate grains occur in modern calcareous soils (Read 1974), where microsolution and precipitation of calcium carbonate occurs on outer portions of grains. The rinds are distinguished from algal micrite envelopes (Bathurst 1975) by their gradational contact with the parent grain, pigmentation, and lack of (tubular) penetrative contact with the unaltered core.

Remanié fossils

Remanié fossils are skeletons as free fossil grains reworked from previously deposited sediments or rocks (Fig. 4). To some extent, remanié fossils grade into lithoclasts and calcrete-ooids in that they commonly have some adhering matrix, or may be coated by calcrete envelopes. Hollow skeletons such as gastropods and *Tetradium* tubules exemplify this as they have marine mud as internal sediment and, as such, when reworked, this sediment forms the majority of the reworked mass. Grains that are thinly coated by calcrete, and those that have a minority of externally adhering matrix are assigned to remanié fossils, while those with thick envelopes of calcrete, or where the fossil is a minor component of the rock-fragment grain are assigned to calcrete-ooids and

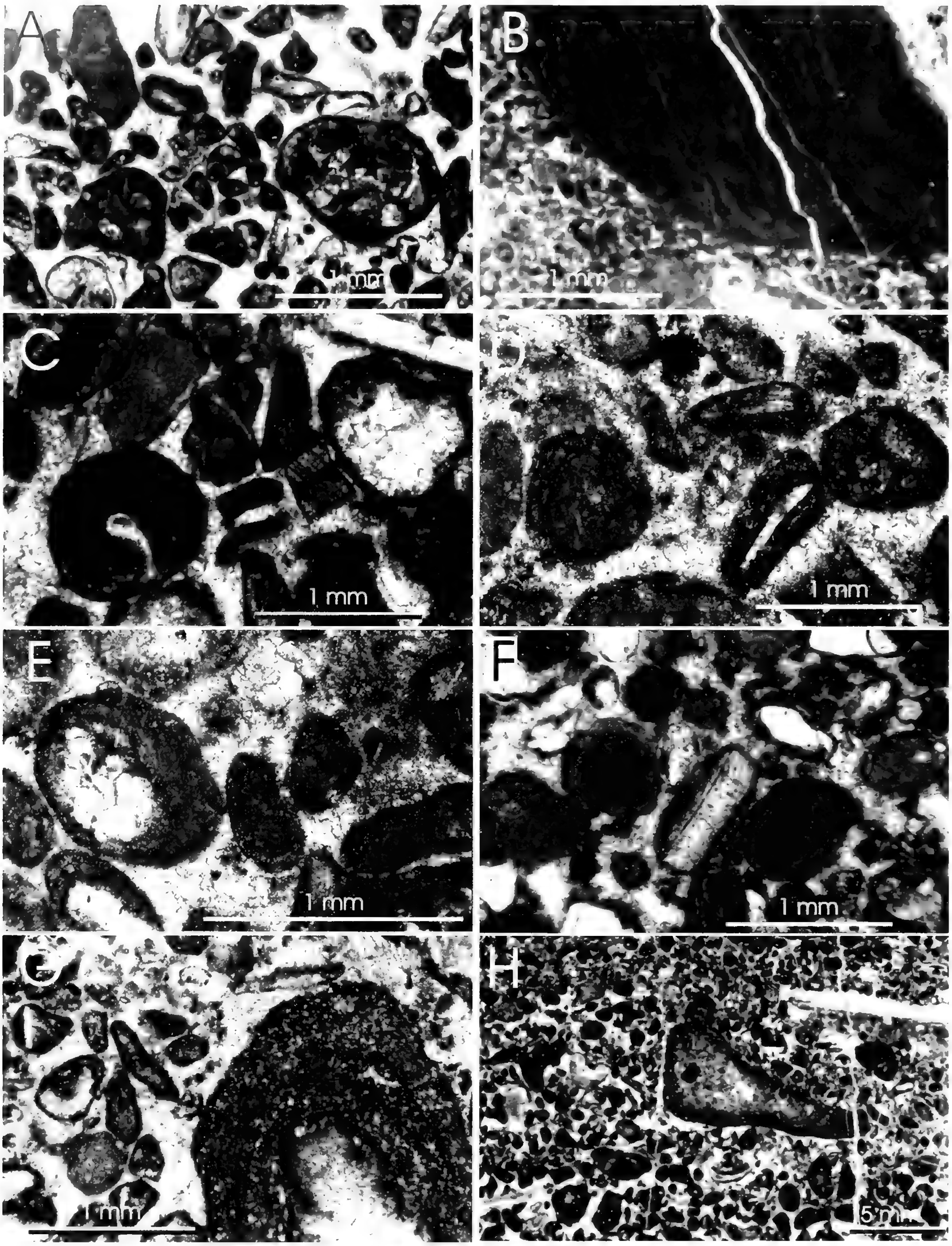

A
1 mm
B
1 mm
C
1 mm
1 mm
E
1 mm
F
1 mm
1 mm
H
5 m

Figure 3 LEFT. Thin sections of grains that are products of subaerial exposure. A. Lithoclasts in a grainstone (Davys Plains Limestone Member; USGD 47040). B. Rounded lithoclast of laminar calcrete, showing laminae parallel cracking (now veins; probably crystallaria of Wright and Tucker 1991), reworked into the overlying Quondong Limestone from the disconformity at the top of the Glenrae Limestone Member (USGD 42144). C. Steinkern (internal gastropod cast) and lithoclasts from the Manooka Limestone Member (USGD 46711). D. Calcrete ooids in a grainstone (Davys Plains Limestone Member) showing concentric lamination; laminae are highlighted by limonite staining (USGD 41815). E. Close-up of calcrete ooids showing details of ooid laminae (Davys Plains Limestone Member; USGD 41815). F. Calcrete ooids from the Quaternary of Shark Bay for comparison with (C) and (D). G. Girvanella nodule showing lamination, tubules, and spongy internal fabric from the Davys Plains Limestone Member to contrast with the calcrete ooids (USGD 47041). H. Peripherally altered lithoclast in the Davys Plains Limestone Member (USGD 47036).

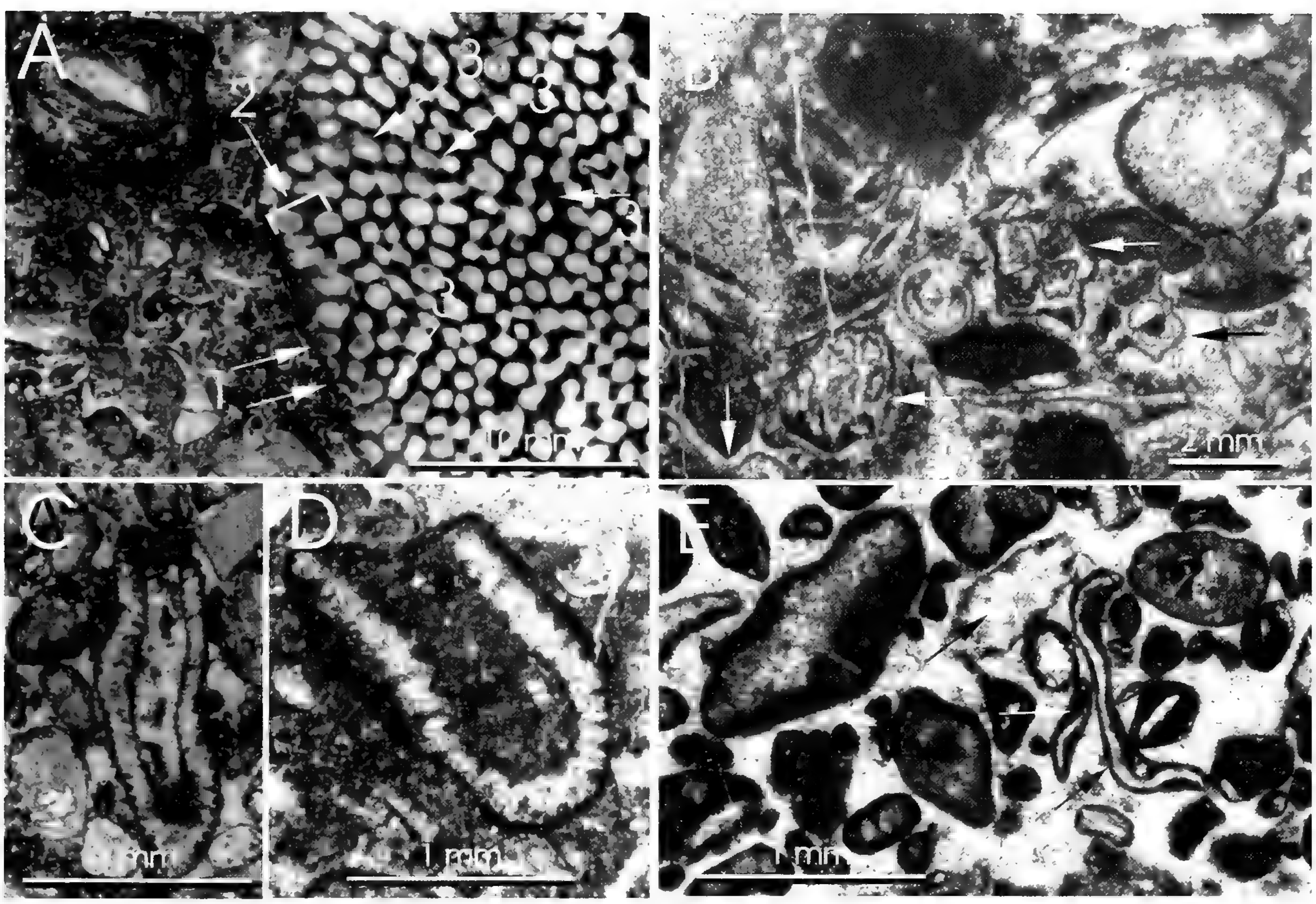


Figure 4. Thin sections of remanié fossils. A. Reworked gravel-sized clast of Tetradium in grainstone. This remanié fossil shows mud between the tubules. The exterior of the clast is limonite stained (arrow 1). The interior of the clast is dark grey lime mudstone, while the exterior rind is bleached lighter grey (arrow 2). The Tetradium is leached, and while most of the skeletal molds have been filled with sparry calcite that is truncated by the clast boundary, some of the skeletal molds are partially filled with diagenetic sediment (arrow 3). B. Broken Tetradium tubules as remanié fossils (arrowed) in a lithoclastic grainstone; some of these remanié fossils exhibit lime mud in the skeletal cavity, as it typical of the Tetradium lithosome. C. Vermiporella fragment in a grainstone for contrast with the remanié fossil to be shown in (D); USGD 46703. D. Vermiporella reworked from a skeletal packstone, occurring as a remanié fossil; the interior of the fossil is lime mud (USGD 46704). E. Remanié fossils of ostracods, coral fragments, brachiopods, and molluscs (three are arrowed); most of the fossils are lightly to more thickly coated by calcrete envelopes (USGD 41814).

lithoclasts, respectively. In the Daylesford Limestone remanié fossils occur in soils or are mixed with marine sediments above disconformities. Remanié fossils are readily detected where they occur either as exotic, silicified fossils in palaeosols and sediments which overlie skeletal limestones containing similar fossils autochthonously, or in lithoclastic grainstones as fossils that are exotic to the skeletal assemblage of the host sediment. The latter remanié fossils either occur elsewhere autochthonously in muddy rocks (e.g., *Tetradium* colonies now embedded in grainstone), or are part of a similar skeletal assemblage to those in lithoclasts. Skeletons, such as the *Tetradium* mentioned above, if exotic in lithoclastic grainstones commonly have mud-filled, inter- and intra-skeletal voids or diagenetic textures (internal cements, leached cavities with internal sediment) that are truncated by the grain boundary (Figs 4A and 4B).

Reworked algal (*Girvanella*) nodules also can be remanié fossils. Remanié algal nodules, in contrast to the spongy internal texture and sparry calcite-filled tubules, that *Girvanella* nodules exhibit in their autochthonous settings, are partly to completely impregnated with cryptocrystalline (and microcrystalline) calcite, though *Girvanella* tubules are still recognisable. Some remanié nodules also have patches of cemented limestone attached to their margin. These types of remanié *Girvanella* nodules appear to have been calcrete-impregnated and/or calcrete-altered when the *Girvanella*–bearing limestone was subaerially exposed.

Diagenetic sediment, including illuvium

Diagenetic sediment is used as a term here to refer to that sediment that has infiltrated into the sediment or rock profile during diagenesis (Fig. 5). Some of this sediment had been generated within the sediment and/or rock profile (e.g., crystal silt of Dunham [1969a], pellets, lithoclasts). Exotic sediment, such as aeolian dust, and other forms of fine-grained sediment generated on the subaerial surface and washed into the sediment/rock profile is termed illuvium (this includes pellets, calcrete-coated and peripherally altered grains, lithoclasts, terrigenous mud, and quartz silt that formerly were on the disconformity surface). Diagenetic sediment partly to completely fills intergranular voids, fossil molds, irregular solution cavities and fractures (Fig. 5). Crystal silt (Dunham 1969a) is the most common internal sediment. It is a well-sorted accumulation of silt-sized calcite crystals (0.01 mm to 0.03 mm in size) and is commonly light grey in tone. Some crystal silt, mixed with terrigenous clay and quartz silt (i.e., crystal silt mixed with exotic fine-grained illuvium), forms brown internal sediment. Pellets and sand-sized grains are less common as a constituent of internal sediment and illuvium, and are mixed with crystal silt. Pellets are angular to round aggregates (0.05 mm to 0.2 mm in size) of cryptocrystalline calcite. Lithoclasts are sand-sized grains of cryptocrystalline calcite. Locally, collapse of solution cavities produces a micro-breccia.

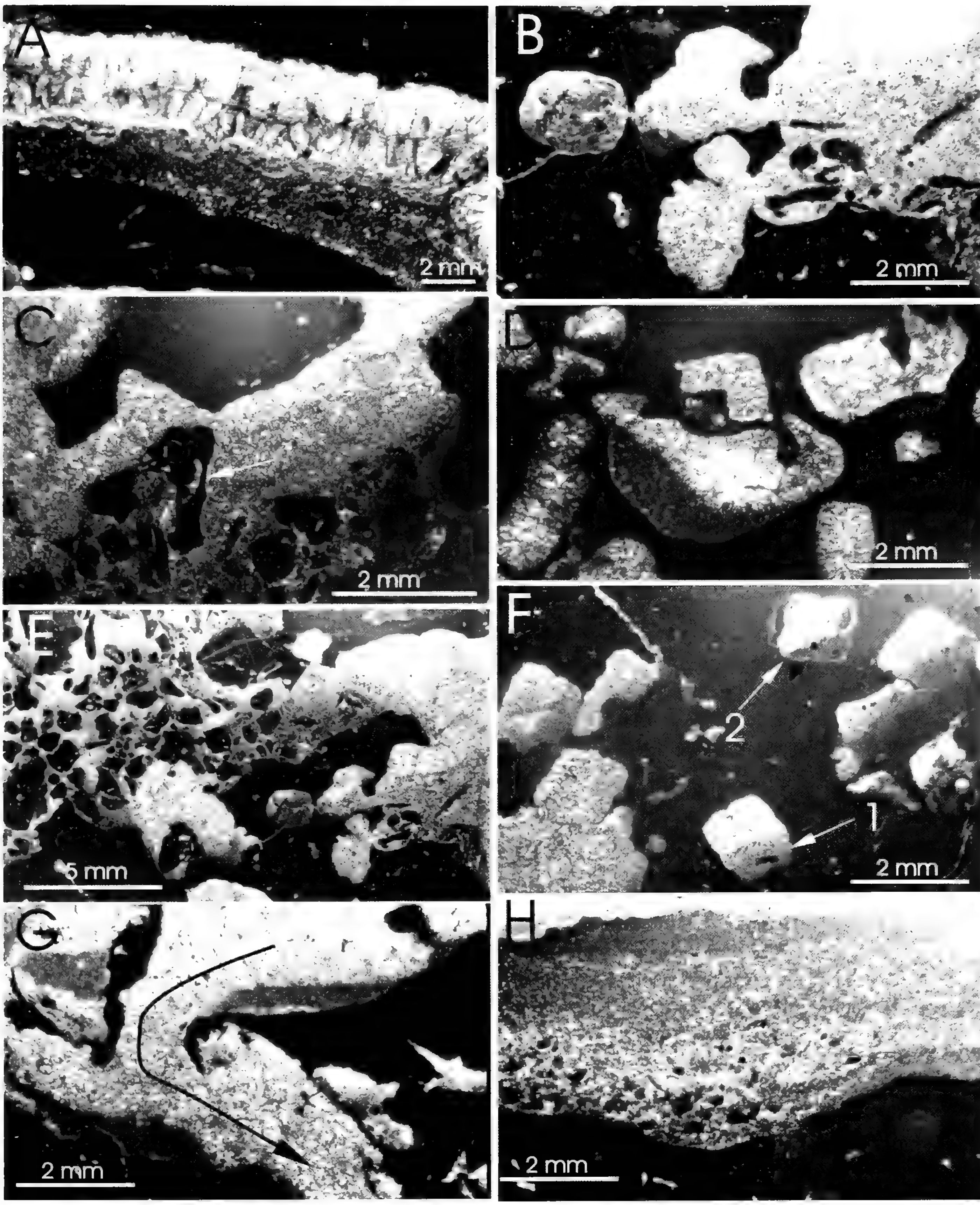
Terrigenous mud

Locally, either as a bed, or mixed with the internal sediment as described above, there is terrigenous mud composed of terrigenous clay, fine-grained mica, and quartz silt.

Silica

Fossils and sparry calcite are replaced by silica beneath some disconformities. Replacement silica is a mixture of chalcedony and equant quartz (average size 0.03 mm). Original fibrous nature of skeletons

Figure 5 RIGHT. Thin sections of diagenetic sediment. A. Crystal silt and pellets partially filling an Eodinobolus mold (USGD 46641). B. Diagenetic sediment of crystal silt, pellets and lithoclasts partially filling Tetradium molds (USGD 46643). C. Layered and graded deposit of diagenetic sediment, with coarse lithoclasts, finer lithoclasts, and crystal silt; lithoclasts produced by wall collapse; Tetradium fragment in one of the lithoclasts is arrowed (USGD 46643). D. Diagenetic sediment filling cavities derived by dissolution of Tetradium; the large central cavity is an enlarged Tetradium mold with crystal silt resting directly on the cavity floor. E. Micro-breccia of lithoclasts formed by collapse of walls and roof of solution-enlarged Tetradium molds; the square cross-sectional shape of Tetradium is still evident in many of the molds (USGD 46641). F. Contrast in sediment-fill in Tetradium cavities; arrow 1 shows diagenetic sediment of crystal silt and pellets in a mold, with diagenetic sediment resting directly on the floor of the mold arrow 2 shows lime mud on the inside wall of the Tetradium tubules and the colour and texture of the mud is the same as the sedimentary matrix surrounding the corallites. G. Diagenetic sediment deposited on the floors of inter-connected enlarged (Tetradium mold) vughs; the diagenetic sediment, as crystal silt, has cascaded gravitationally along the vugh network (one pathway is shown by the arrow); USGD 46658). H. Granulometrically graded, and laminated diagenetic sediment in a solution cavity, with lithoclasts and pellets towards the base, and crystal silt in the upper part (USGD 47037).


A
2 mm
B
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C
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D
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F
2
1
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G
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H
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is obliterated and replaced with radiating bundles of silica fibres or equant silica grains, or both. Where silica replaces sparry calcite, it may pseudomorph the carbonate crystal habit. (The origin of diagenetic silica and metamorphic silica is discussed later).

FABRICS AND STRUCTURES

The fabrics and structures associated with subaerial disconformities include fossil molds, enlarged fossil molds, cavities, mottles, fissures and irregular surfaces, cryptocrystalline (and microcrystalline) calcite patches and bleaching.

Fossil molds, enlarged fossil molds, cavities and mottles

Fossil molds, enlarged fossil molds, cavities and mottles are intergradational (Fig. 6). Selective leaching of fossils, particularly in wackestones and packstones, forms fossil molds. At this stage of solution, the fossil shapes are clearly evident, viz., the shapes of *Tetradium* (a tubular skeleton), *Eodinobolus* (a brachiopod), or *Alleynodictyon* (a cylindrical stromatoporoid). At the next stage, where fossil molds are enlarged by solution, part of the cavity is still discernable as to fossil origin (and species origin). Some of these enlarged fossil molds are further enlarged by solution, and form interconnecting and irregular cavities in the host sediment. Thus, there is an intergradational and interconnecting range of structures from molds, enlarged fossil molds, and irregular cavities.

Subsequent filling of cavities with a mosaic of calcite and/or diagenetic sediment of crystal silt, pellets, calcrete-coated and peripherally altered grains, or lithoclasts has formed: 1. fossil casts in limestone in which leached fossil molds have been filled with sparry calcite and internal sediment (crystal silt, some pellets, and lesser amounts of lithoclasts); 2. interconnecting spar-filled vughs; 3. mottled limestone with cavities and fractures filled, partly or completely, with internal sediment; and 4. '*Stromatactis*' structures composed of enlarged fossil molds with irregular roofs, flat floors of crystal silt and remaining fill of sparry calcite. Where partially filled by internal sediment, the internal sediment is geopetal. Where fully filled by internal sediment, the fossil molds become casts of internal sediment. Where interconnecting and irregular cavities are filled with internal sediment, the former shelly or fossiliferous limestone becomes mottled limestone. Often there is intergradation between fossil, solution-enlarged fossil shapes, and mottled limestone that shows the relationship in the fabric and structure types.

Intergranular voids of grainstones also are filled with a sparry calcite mosaic and internal sediment; and the internal sediment which commonly overlies fringing sparry calcite is continuous around solution cavities and grains in such limestones.

Fissures and irregular surfaces

Locally, lime mudstones and shelly wackestones have fissures and/or irregular upper surfaces along a disconformity. The details of a fissure developed on a *Tetradium*-bearing limestone are shown and described in Figure 7. Fissures are sharp-edged, V-shaped cracks, 10-30 cm deep, descending into the limestone. Irregular surfaces are undulating to sharp-edged disconformity surfaces 20-30 cm across and 5-10 cm deep. The fissures and irregular upper surfaces are not soft sediment features because they transgress fossils, and hence are developed in brittle limestone. They are not late stage tectonic features because they are filled with internal sediment, or soils, or sedimentary deposits of the overlying material.

Cryptocrystalline (and microcrystalline) calcite patches

Grainstones beneath some major disconformities are altered in patches to cryptocrystalline (and microcrystalline) calcite. The patches are closely scattered and vary in size from a millimetre to several centimetres. The patches of cryptocrystalline (and microcrystalline) calcite grade into relicts of grainstone fabric which, in turn, grade into unaltered grainstone. Cavities and fissures wholly filled with internal sediment are associated with the cryptocrystalline patches. Grainstones also may be cemented in patches by cryptocrystalline calcite instead of sparry calcite. The cryptocrystalline calcite may be in patches in an otherwise sparry calcite-cemented grainstone or may be the sole cement present. Locally, the cryptocrystalline cement is faintly laminated (see Fig. 10B).

Bleaching (bleached zones)

The lime mudstones and shelly lime wackestones are normally black to dark grey to medium grey, but proximal to some disconformities, involving tens of centimetres, roughly parallel to and underlying the disconformity surface, limestone is bleached to a lighter grey, or to a cream tone, or to brown. XRD of black to dark-grey limestones shows pyrite as the colouring mineral. In bleached limestones, Fe-oxides may be the colouring mineral, or there is no colouring mineral. In the Glenrae Limestone Member, the formerly dark to medium grey limestones have been

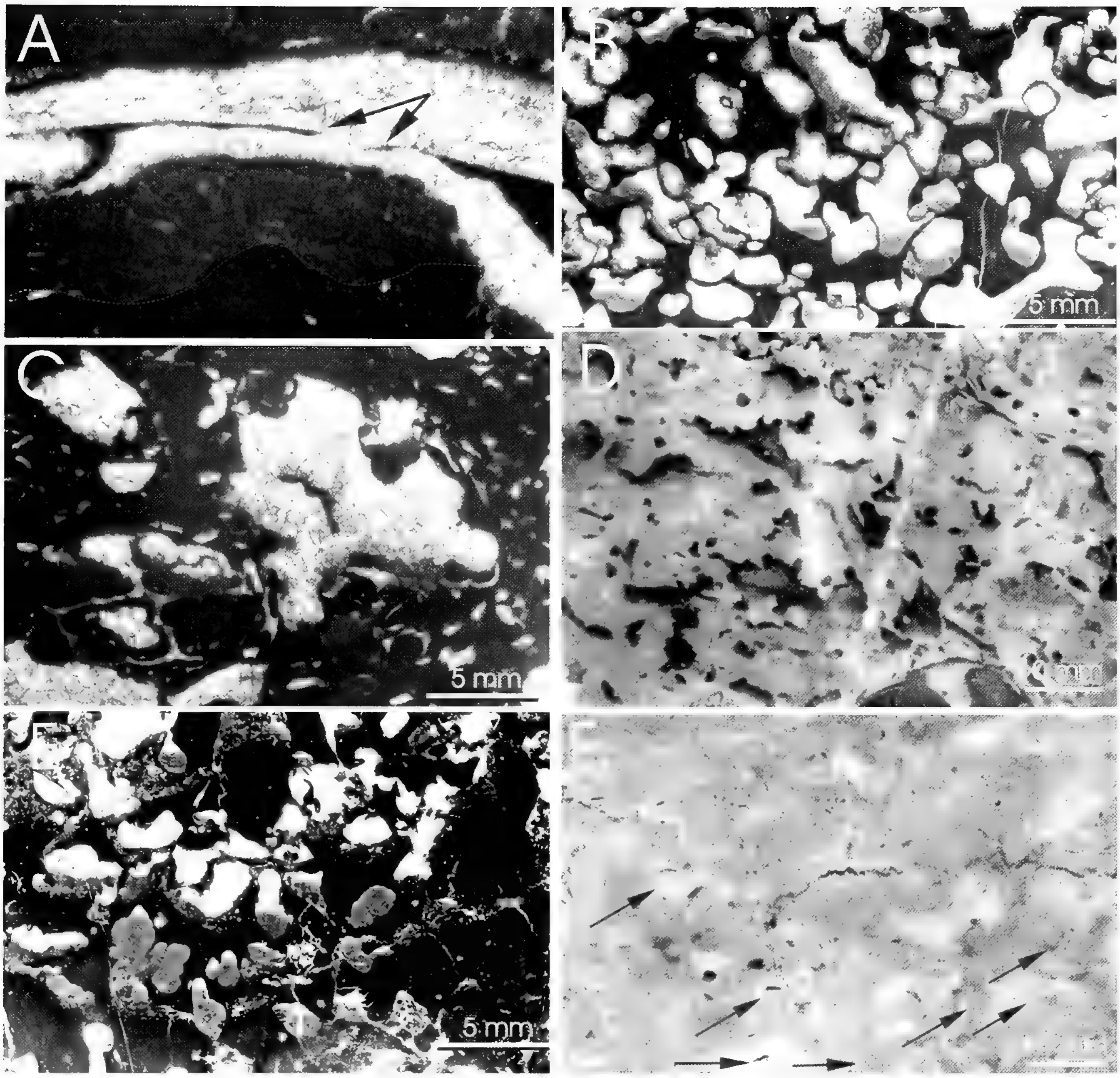


Figure 6. Thin sections and polished slabs of a variety of limestones produced by subaerial diagenesis. A. Enlarged fossil mold (Eodinobolus) leading to vuggy limestone; the floor of the enlarged cavity is shown in white dashed line; diagenetic sediment is in the lower part of the cavity; the micrite envelope around the Eodinobolus, and the fragmenting micrite envelope are arrowed. B. Inter-connected vughs of solution-enlarged Tetradium molds, here partially filled with diagenetic sediment, leading to development of vugular limestone (SUP 29176). C. Solution-enlarged Tetradium molds. D. Solution enlarged Tetradium molds partly filled with crystal silt leading to development of "Stromatactis" structures (note that the limestone is bleached to light grey); USGD 466143. E. Solution enlarged Tetradium molds with molds in the upper part of the view filled dominantly by sparry calcite and the lower part filled dominantly by crystal silt, the latter leading to the development of mottled limestone. F. Polished slab of mottled limestone wherein fossil molds are filled with crystal silt (some are arrowed where the upper part of the cavity has some sparry calcite lining the roof; note that the limestone is bleached to light grey.

bleached and, additionally, have been impregnated by light-toned calcrete as a cementing agent that renders them light grey. In the dark grey limestones of the Bourimbla, Manooka, and Gerybong Limestone Members, Fe content is 2-4%. In the light grey limestones of the Glenrae Limestone Member, Fe content is 0%-0.06%. Elemental maps (derived by SEM-EDS) of Fe concentration in the dark grey

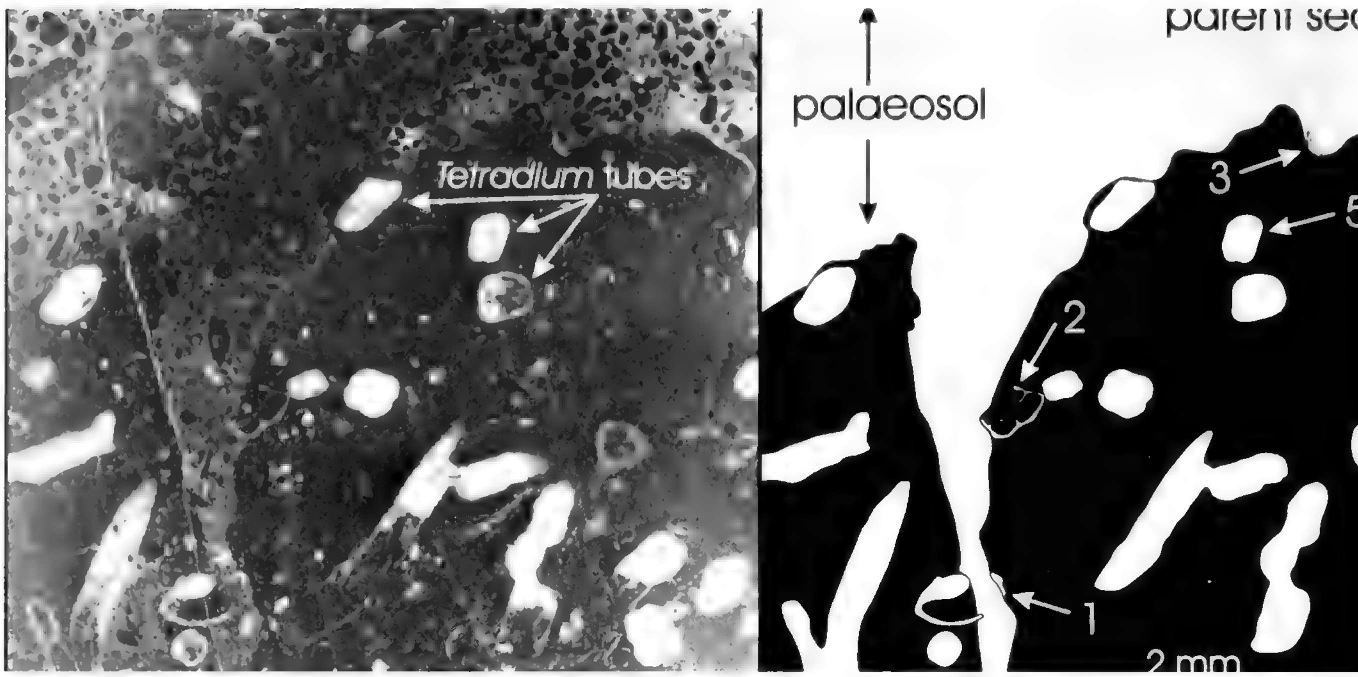


Figure 7. Thin section of a palaeosol infiltrating a downward narrowing fissure in Tetradium-bearing skeletal wackestone (USGD 46662). The paleosol is lithoclastic grainstone. The fissure truncates fossils in the underlying limestone. Some key features are arrowed: (1) outlier of a gastropod that has been truncated by the fissure; (2) Tetradium tubule truncated by the wall of the fissure; (3) inner wall of Tetradium tubule forming surface of the contact between palaeosol and underlying limestone – the interior of the Tetradium has been removed by erosion and/or solution; (4) shell of ostracod forming resistant surface to the contact between palaeosol and underlying limestone; (5) Tetradium as spar-filled mold (casts) or sediment filled corallites.

limestone compared to the light grey limestone, confirms that bleaching involved removal of Fe. The weathering surface on outcrops of the dark grey limestones provides a modern analogue for such bleaching in the Ordovician – the dark grey limestones at the modern weathering surface have a fine micro-laminated crust, 10-25 μm thick, of light grey calcium carbonate, where the Fe-bearing dark grey limestone has been altered (oxidised) and leached free of Fe. The bleaching of the modern weathered limestone surfaces is only an analogue in terms of Fe removal and change in tone from dark grey to light grey, because the crust on the weathered limestone is micro-laminated similar to a patina (cf. Clifford 2008), and not massive and mottled as the bleached limestones of Ordovician age.

LITHOLOGIES

The lithologies associated with subaerial disconformities are vugular limestone, mottled limestone, massive light grey limestone, lithoclast grainstone, calcrete-ooid grainstone, calcrete-ooid packstone and wackestone, palaeosols, and (terrigenous) mudstone.

Vugular limestone

Vugular limestone is usually a muddy limestone, such as skeletal wackestone, skeletal packstone, or lime mudstone, in which there are fossil-shaped to irregular vughs filled with sparry calcite or with internal sediment and sparry calcite (Fig. 8). The vughs are scattered to closely arrayed in the limestone, depending on the extent that the original limestone was fossiliferous. In geometry, the vughs also are clearly related to fossil content, where they are dissolved *Tetradium*, *Eodinobolus*, and *Alleynodictyon*, and in this context they are strictly fossil molds, but with solutional enlargement, the vughs grade in shape to irregular cavities. Small-scale conduits (filled with sparry calcite, or with internal sediment and sparry calcite) connect many of the vughs. The vugular limestone forms zones 10-100 cm thick under subaerial disconformities, and in this stratigraphic setting, the extent of infill by internal sediment decreases downwards from the subaerial disconformity surface. With increasing irregularity of the upper vugh shape, and with increasing vugh-fills of internal sediment partly filling the cavity to create a flat base to the vugh, vugular limestone becomes '*Stromatactis*' limestone (Fig. 6D; Semeniuk 1971). Note that this origin of '*Stromatacti*s', that in the Daylesford Limestone is clearly derived by leaching

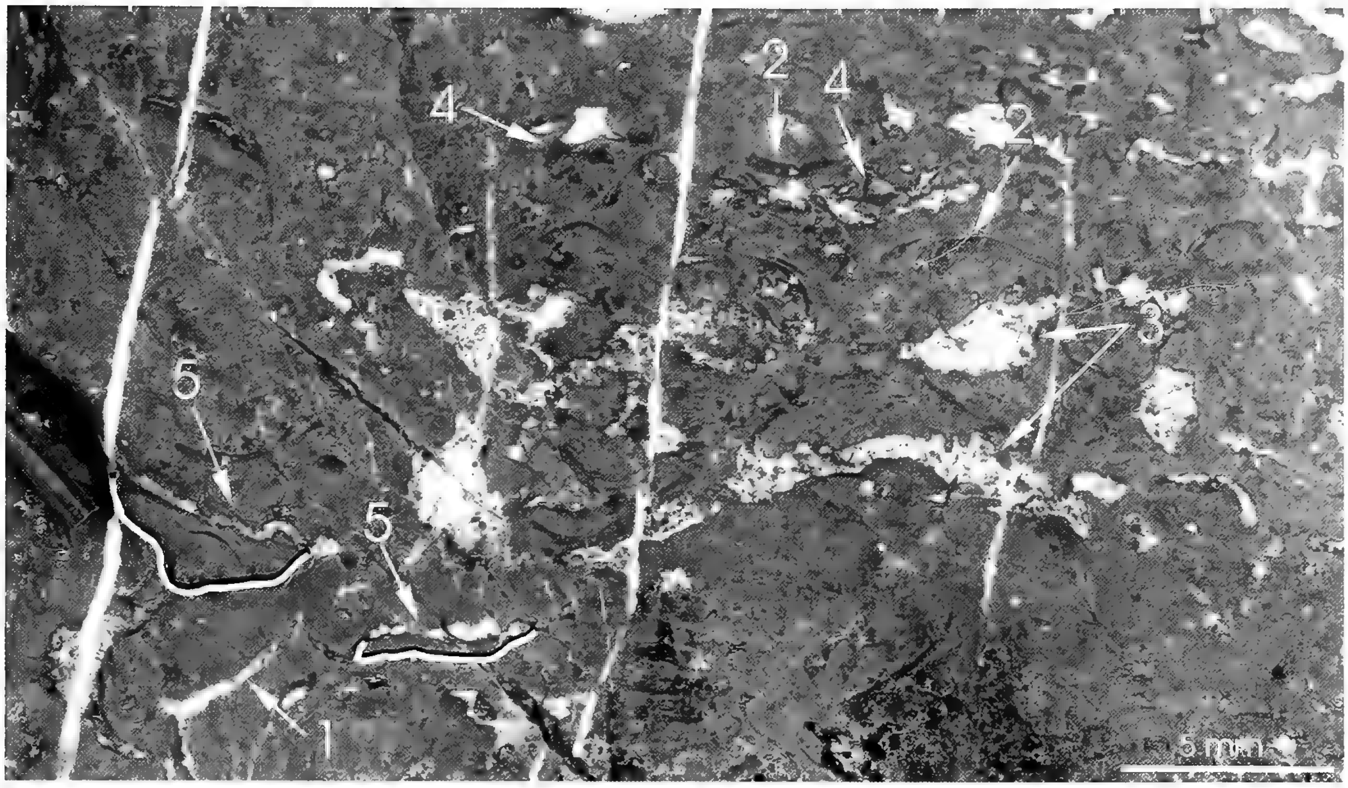


Figure 8. Outcrop of vugular limestone developed within Eodinobolus limestone. The arrows show sparry calcite filled fossil mold (1), diagenetic sediment-filled fossil mold (2), irregular sparry-calcite-filled vughs (3), vughs that are partially filled with diagenetic sediment with upper part filled with sparry calcite (4), and vughs that are nearly wholly filled with diagenetic sediment (5), the bases of which are outlined. Note that the limestone is bleached to light grey. Aligned calcite-filled tectonic fractures clearly are later features that postdate the vugular structures.

of *Tetradium* tubules, differs from the origin of '*Stromatactis*' proposed by Lees (1961) for the Waulsortian Mounds and its origins as proposed by Bathurst (1982) and Krause et al. (2004). With increasing irregularity of vugh shape, and with increasing vugh fills of internal sediment, vugular limestone grades into mottled limestone. The different fabrics, structures and lithologies produced by various pathways of solution and internal sedimentation are summarised in Figure 9. The contact with underlying sediment is sharp, and varies from highly irregular at the small-scale to planar.

Mottled limestone

Mottled limestone is developed in muddy limestones, such as skeletal wackestone, skeletal packstone, or lime mudstone (Fig. 6F). It is the end product of a process where vugular limestones with irregular and interconnecting cavities have been infiltrated by internal sediment. Within the mottled limestone, internal-sediment-filled irregular vughs dominate, but locally there are internal-sediment-filled enlarged fossil molds and some internal-sediment-filled fossil casts. As a rock type, mottled limestone is subordinate to vugular limestone. As with the vugular limestone, the mottles in this limestone, founded on cavities now filled with internal sediment, are scattered to closely arrayed, depending on the extent that the original limestone was fossiliferous. Small-scale conduits (filled with internal sediment) connect many of the mottles. The mottled limestone forms patches and local zones < 50 cm thick under subaerial disconformities. The contact with underlying sediment is sharp, and varies from highly irregular at the small scale to planar.

Massive light grey limestone

Massive light grey limestone is a complex of lithologies. As a broad overview, essentially there is patchy cementation by, and alteration of grainstone to cryptocrystalline calcite. The patches grade into relicts of the original texture, and they vary in size from a fraction of a millimetre to several centimetres, and are closely spaced to scattered in distribution. Where the patches are scattered, the altered limestone is mottled, consisting of grainstone areas which are interspersed with, and grade into, cryptocrystalline areas; where the patches are closely spaced, the limestone is fine-grained and dense with minor grainstone areas. Fossil molds, irregular solution cavities and fractures filled

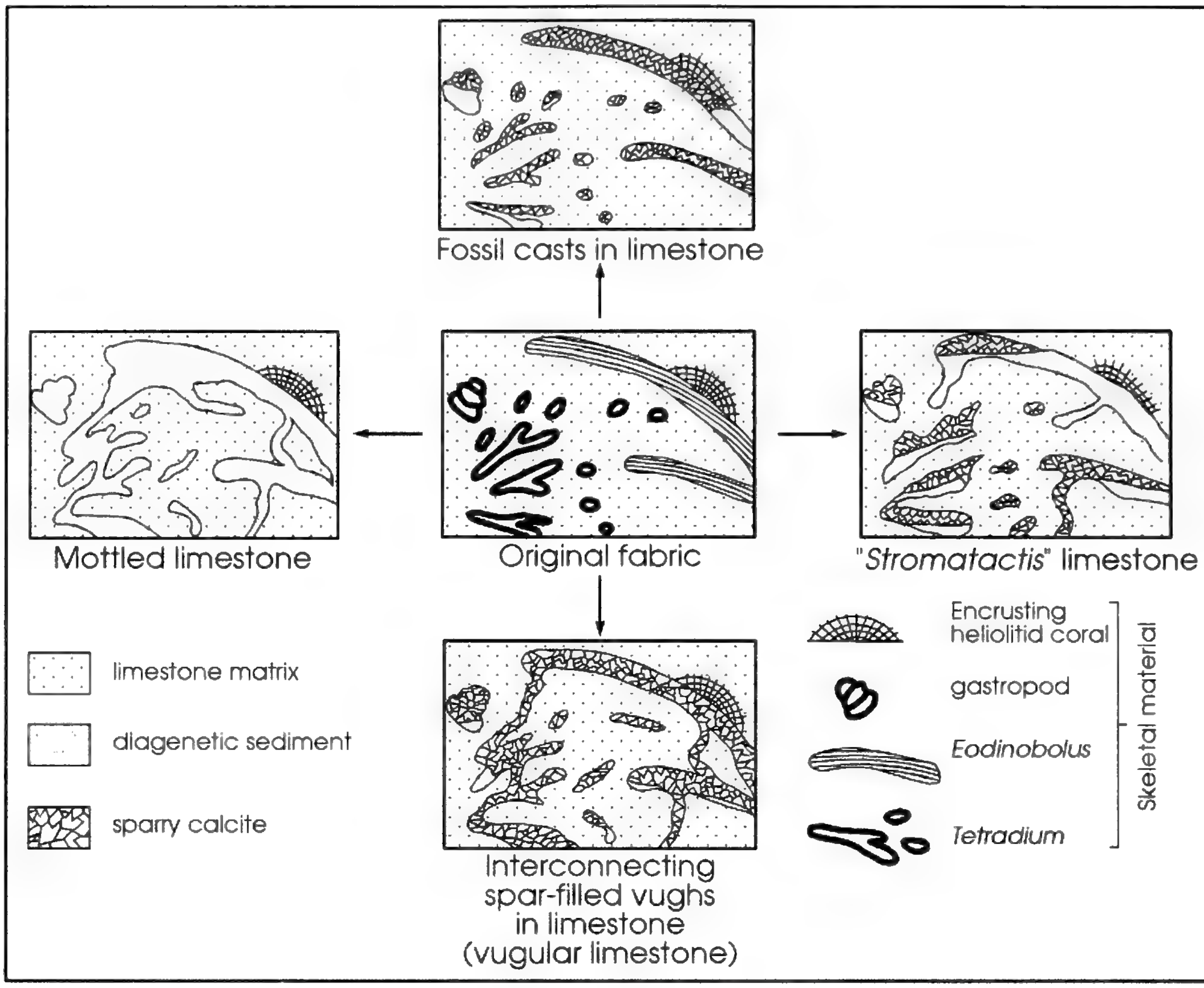


Figure 9. Pathways to develop lithologies and structures by solution, cavity enlargement, and diagenetic sediment infiltration: fossil molds in limestone, vugular limestone, "Stromatactis" limestone, and mottled limestone.

with crystal silt and pellets are associated with the cryptocrystalline calcite.

In detail, there are four lithotypes in the suite of mottled light grey limestone, and they grade in series from grainstone to mottled light grey limestone. At one extreme of the gradational series, the first lithology is a rock type that while it can be broadly described as a grainstone, is cemented interstitially by sparry calcite and by fine-grained (microcrystalline) calcite. Skeletal and lithoclastic grains in this grainstone are still evident. This limestone grades into the second type of grainstone that has increasing content of fine-grained (microcrystalline) calcite as interstitial cement, and the grains comprising the grainstone are more commonly altered to fine-grained (microcrystalline) calcite. As such, in this second type of grainstone, the distinction between fine-grained (microcrystalline) grains and fine-grained (microcrystalline) interstitial cement calcite is becoming blurred. The grainstone is being transformed to diagenetic 'muddy' limestone. The third limestone lithology is a massive fine-grained (microcrystalline) limestone wherein there are only vestiges of grains that once comprised the grainstone fabric, and the lithology is dominated by the fine-grained 'matrix', that is, it has become a diagenetic 'muddy' limestone. This lithology also has cracks and fissures ~ 1-2 mm in width, filled with fine-grained calcite and internal sediment, and grades into breccioid structure. This rock therefore has, with the patches of fine-grained calcite and the sediment-filled cracks and fissures, a light grey mottled appearance. The next stage of lithology development is a massive fine-grained light grey limestone with abundant cracks and fissures (filled with fine-grained calcite and with internal sediment) that impart a breccioid structure to the limestone. This final lithology in the gradational series also has a light grey mottled and locally brecciated appearance.

Lithoclast grainstone

Lithoclast grainstone is composed of medium to coarse-grained sand-sized lithoclasts, lithoclasts with altered periphery, and lesser remanié fossils, calcrete ooids, and fossils, as well as some gravel-sized lithoclasts and remanié fossils. The lithoclast grainstones are structureless to laminated, with gravel-sized components aligned to lamination, or defining the lamination. The grainstones are cemented by sparry calcite.

Calcrete-ooid grainstone

Calcrete-ooid grainstone is brown and composed of medium to coarse-grained sand-sized calcrete ooids and lesser remanié fossils, and also some gravel-sized lithoclasts and remanié fossils. The calcrete ooid grainstones are structureless. The grainstones are cemented by sparry calcite. Interstitial to the grains there is some minor internal sediment.

Calcrete-ooid packstone and wackestone

Calcrete-ooid packstone and wackestone are brown to grey and composed of medium sand-sized calcrete ooids and lesser remanié fossils, and also some gravel-sized lithoclasts and remanié fossils set in a matrix of lime mudstone with scattered sand-sized fossil skeleton fragments. The calcrete ooid packstone and wackestone are structureless to burrowed. Calcrete-ooid packstone and wackestone grade into palaeosols.

Palaeosols

Palaeosols are structureless to mottled, brown to grey, grain-supported and composed of medium to coarse, sand- and gravel-sized, round to irregular, lithoclasts, calcrete-coated lithoclasts (mainly calcrete ooids, and minor pisolites with thin calcrete envelopes), peripherally altered lithoclasts, calcrete-coated remanié fossils, and silicified remanié fossils (Figs 7 and 10). Crystal silt occurs in patches and either completely fills, geopetally rests on grains, or floors intergranular voids (Fig. 10). Locally, laminar calcrete is developed in patches (Fig. 10B). Palaeosols in the Daylesford Limestone have been cemented by cryptocrystalline calcite and, in patches, by sparry calcite. Lithologically, the sediments resemble modern and Pleistocene soils developed on carbonate sediments (Read 1974).

Figure 10 RIGHT. Thin section of palaeosols developed on Tetradium-bearing limestone. A. Palaeosols on Tetradium-bearing skeletal wackestone (SUP 29172). The arrows show fragments of Tetradium with mud within the tubules, and crystal silt that has infiltrated the intergranular void network resting geopetally on tops of grains. The upper right side of the photograph is an open framework of grains (lithoclasts and remanié fossils of Tetradium) and voids with infiltrated crystal silt, separated by the dashed line from the upper left side of the photograph which is an framework of grains (lithoclasts and remanié fossils of Tetradium) and voids packed with infiltrated crystal silt. B. Complex palaeosol fabric composed of (1) remanié fossils of Tetradium partly filled with marine sediment and partly filled with diagenetic sediment, (2) vughs filled with diagenetic sediment, and (3) patches of laminar calcrete encrusting the remanié fossil.

The palaeosols form thin horizons (generally up to 10 cm thick). The contact with underlying parent sediment is highly irregular and locally gradational; the soil commonly infiltrates along cracks and fissures (Fig. 7) which penetrate underlying limestone up to 30 cm, or forms a layer on an irregular disconformity surface. Contacts with overlying marine limestone commonly are mixed by burrows.

Palaeosols are developed mainly on muddy limestones in the Daylesford Limestone. Palaeosols are more difficult to recognise in grainstone sequences because of their lithologic similarity to lithoclastic grainstones in the Formation, and because they are more likely to have been reworked under high energy conditions into the marine grainstones overlying the disconformity (and hence cease being palaeosols). Generally, palaeosols are distinguished from lithoclast grainstone, and calcrete-ooid grainstone in that the former are in situ on the disconformity, whereas the latter have been transported and show transportation structures, and current depositional structures (e.g., aligned platy fossils).

(Terrigenous) mudstone

Mudstone comprising terrigenous clay and quartz silt is a brown, structureless fine –grained rock. Generally, it is fossil-free (but see later). This mudstone is interpreted as a palaeosol developed by solution of a marl, or a lime wackestone/mudstone that had a small component of clay mineral, mica, and quartz silt.

Silicified limestone

The lithologies of vugular limestone, and fossiliferous limestone such as skeletal wackestone and skeletal packstone with solution cavities and sparry calcite filled fossil casts, can be silicified. The silica, as noted above, replaces both fossils and sparry calcite. The horizons of silicification coincide with leaching beneath some subaerial disconformities, as evident in the Bourimbla Limestone Member, between Bourimbla and Manooka Limestone Members, within the Manooka Limestone Member, and between Daylesford and Quondong Limestones. Sparry calcite fringing solution cavities in these horizons is silicified whereas later generations are not. Silicified fossils occur as clasts in lithoclast grainstones overlying some disconformities.

STRATIGRAPHIC PROFILES ASSOCIATED WITH DISCONFORMITIES

Subaerial disconformities are located in a number of stratigraphic levels in the Daylesford Limestone (Figure 11). They are underlain by and associated with a diagenetic stratigraphic sequence and sedimentary stratigraphic sequence consisting of, in descending order:

4. the new cycle of sediments overlying the disconformity;
3. grainstone composed of lithoclasts, remanié fossils and calcrete-coated grains, or a palaeosol, both several centimetres thick;
2. altered host rock (tens of centimetres to tens of metres thick); and
1. unaltered host rock.

The most important factor to vary the profile is the type of host rock (Fig. 12), i.e. grainstone versus muddy limestone. Profiles developed on the two end-member host sediments differ in detail. For instance, palaeosols are mostly developed on muddy limestone, and leaching is the most common phenomenon in the altered muddy limestone, whereas for grainstones, palaeosols are generally absent, and cryptocrystalline (and microcrystalline) calcite (calcrete) patches are the most important features.

There is a gradient of diagenetic effects and lithology from the disconformity downwards (Fig. 13). Thus irregular cavities, enlarged fossil molds and internal sediments are most common in the upper parts of a diagenetically subaerially altered profile, with diagenesis decreasing downwards from the disconformity, and lower parts of the diagenetically altered profile mainly containing spar-filled fossil molds, enlarged fossil molds, and only minor internal sediment.

Ten types of diagenetically altered profiles are recognised under subaerial disconformities in the Daylesford Limestone:

1. erosionally truncated vugular limestone with coralline encrustation on the disconformity;
2. erosionally truncated vugular limestone without palaeosol cover;
3. erosionally truncated vugular limestone with thin palaeosol cover;
4. muddy limestone with thin palaeosol cover with calcrete ooids and remanié fossils;
5. muddy limestone with thick palaeosol cover with calcrete ooids and remanié fossils;
6. muddy limestone with lithoclastic and calcrete ooid grainstone and remanié fossils;
7. solution-altered grainstone with overlying lithoclastic and calcrete ooid grainstone;
8. thick calcrete developed on grainstone (= Glenrae Limestone Member);

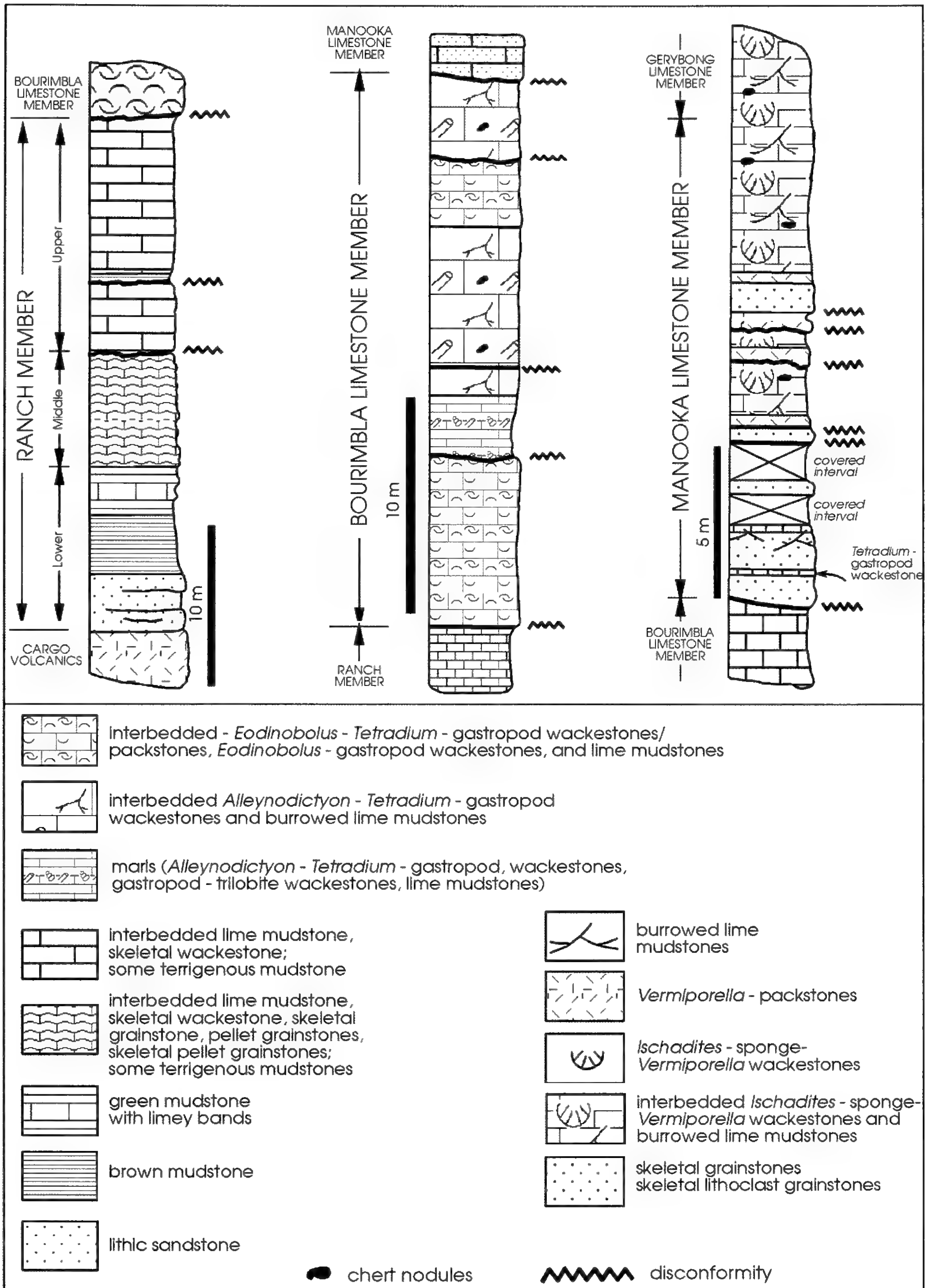


Figure 11. Stratigraphic columns of the Ranch Member, and Bourimbla and Manooka Limestone Members showing sequences of lithologies and occurrence of disconformities.

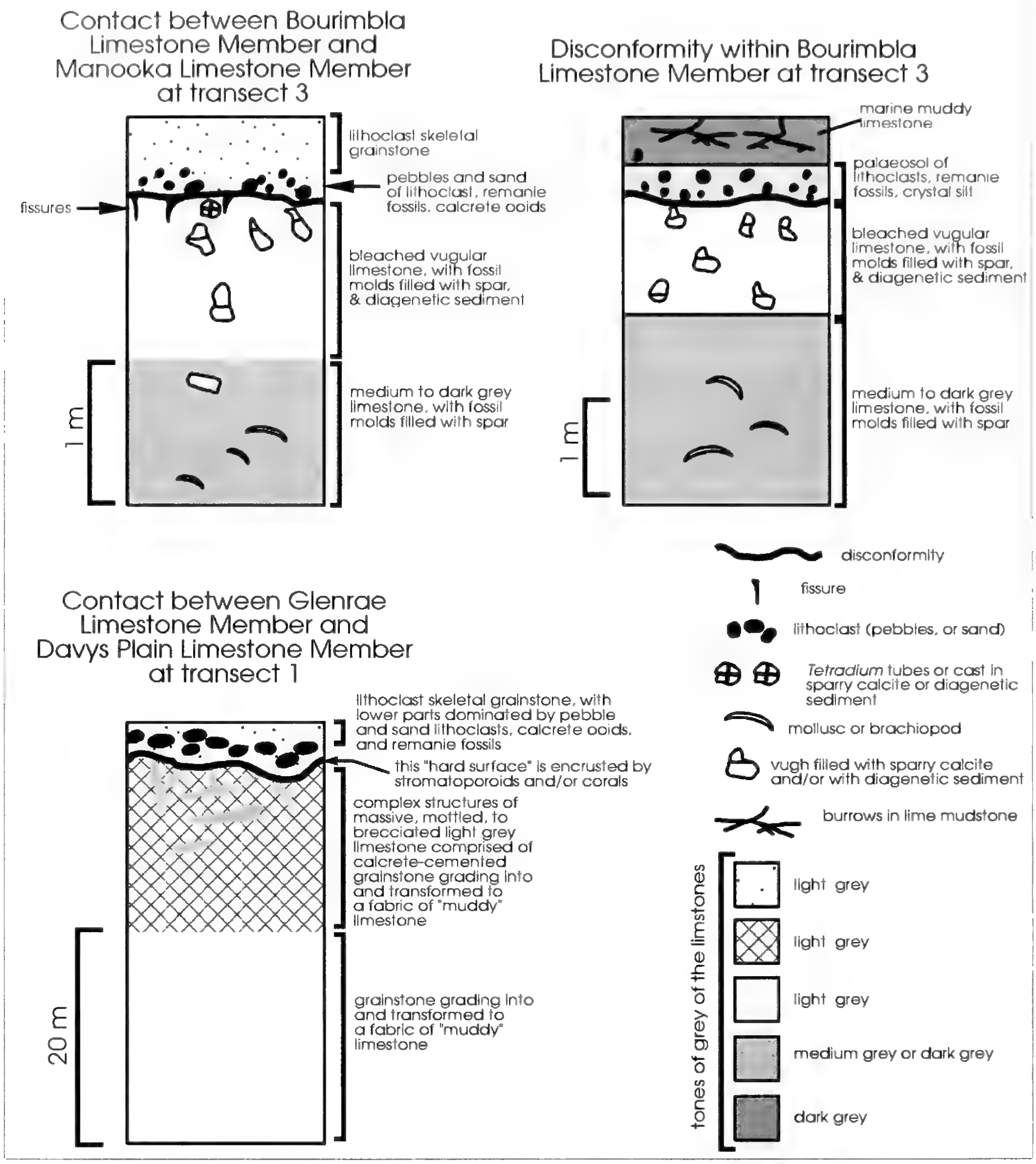


Figure 12. Some representative stratigraphic profiles across disconformities in the Daylesford Limestone.

Figure 13 RIGHT. A. Stratigraphic profiles west to east across the Bowan Park area of the Bourimbla Limestone Member showing correlation of disconformities and the occurrence of paleosols and vugular and mottled limestones associated with subaerial exposure. B. Details of subaerial diagenesis showing stratigraphic distribution of sparry calcite, diagenetic sediment, pellets and lithoclasts, mottled limestone and "Stromatactis" limestone beneath disconformities (modified from Semeniuk 1971). Stratigraphic location of outcrops, slabs and thin sections illustrated in earlier Figures are shown on the profile.

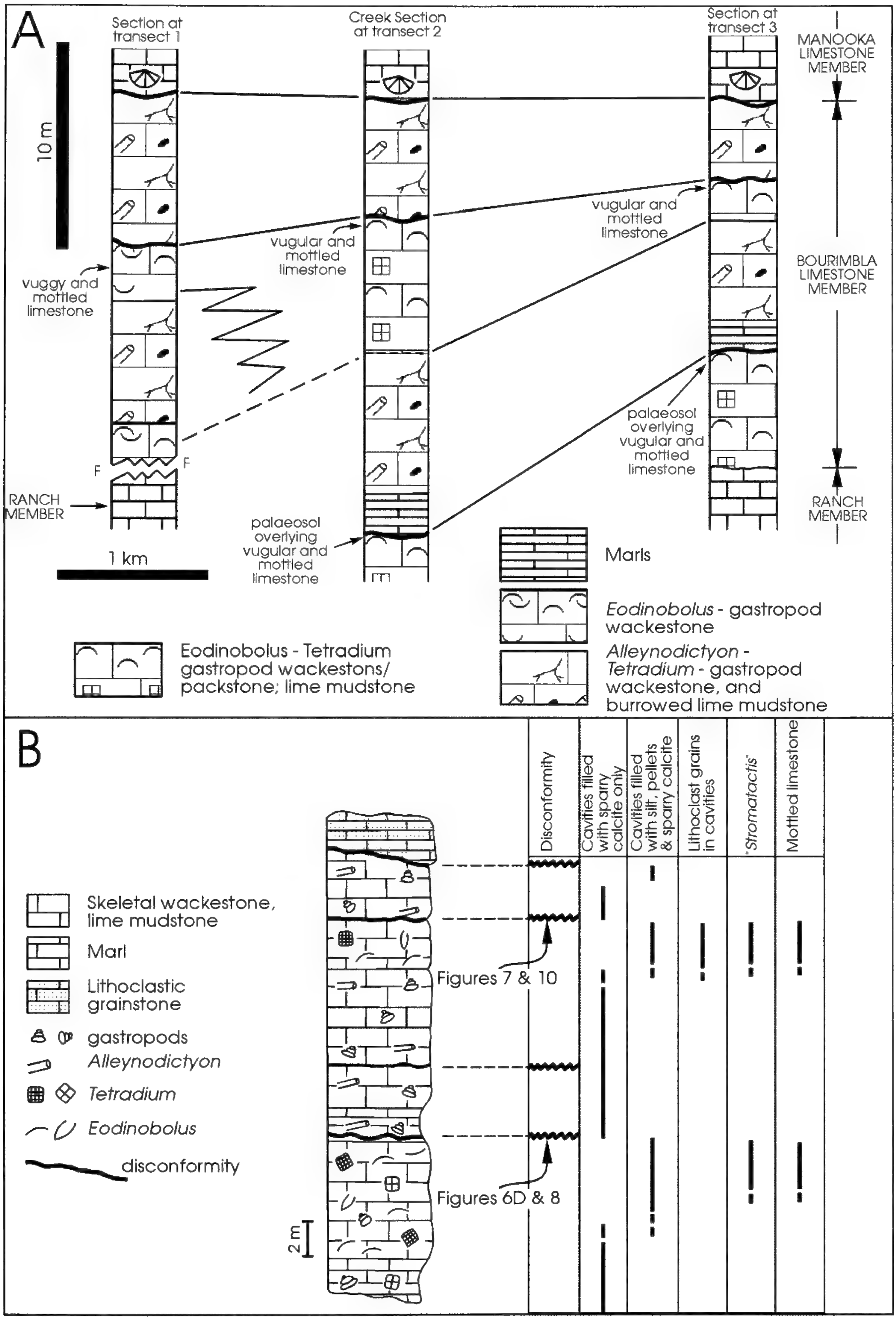

A
Section at transect 1
Creek Section at transect 2
Section at transect 3
10 m
MANOOKA LIMESTONE MEMBER
BOURIMBLA LIMESTONE MEMBER
RANCH MEMBER
vuggy and mottled limestone
vugular and mottled limestone
vugular and mottled limestone
palaeosol overlying vugular and mottled limestone
palaeosol overlying vugular and mottled limestone
F
F
RANCH MEMBER
1 km
Marls
Eodinobolus - gastropod wackestone
Eodinobolus - Tetradium gastropod wackestons/ packstone; lime mudstone
Alleynodictyon - Tetradium - gastropod wackestone, and burrowed lime mudstone
B
Disconformity
Cavities filled with sparry calcite only
Cavities filled with silt, pellets & sparry calcite
Lithoclast grains in cavities
'Stromatactis'
Mottled limestone
Skeletal wackestone, lime mudstone
Marl
Lithoclastic grainstone
gastropods
Alleynodictyon
Tetradium
Eodinobolus
disconformity
Figures 7 & 10
Figures 6D & 8
2 m

Figure 14 RIGHT. Stratigraphic profiles showing the weathering (calcretised) transition from sandy facies of the Oakley Limestone Member to the east to the muddy facies of the Gerybong Limestone Member to the west. The Glenrae Limestone Member is mottled with grainstone at the top of the Oakley Limestone Member. Photographs show the nature of the bleached light grey limestone that comprises the Glenrae Limestone Member. A. Polished slab showing light grey (bleached) limestone; evident here are the mottles throughout the limestone, and its brecciated nature along the lower margin of the polished slab. B. Thin section of grainstone of the upper Oakley Limestone Member impregnated interstitially with fine grained calcite (calcrete). C. Thin section of former grainstone of the Glenrae Limestone Member (USGD 41806) impregnated interstitially with fine grained calcite (calcrete) and skeletal molds filled with crystal silt (arrowed). D. Thin section of former grainstone of the Glenrae Limestone Member (USGD 41806) impregnated interstitially with fine grained calcite (calcrete) [medium grey lithology] and sharp-edged fissures (marked by arrows) filled with diagenetic sediment of (mainly) crystal silt and pellets [light grey lithology]; the sharp edges to the fissures, and multiplicity of fissures will create a brecciated appearance (see A above).

9. wackestone/lime-mudstone (marl) with overlying sheet of (terrigenous) mudstone;
10. silicified limestone.

The stratigraphy of some of these profiles is shown in Figures 12 and 13. The profile varies in thickness from 30 cm (beneath minor disconformities) to a maximum of 45 m beneath the major disconformities at the base of the Davys Plains Limestone member. The distribution of lithologies in the massive light grey limestone suite is shown in Figure 14. There is also lithologic variation of diagenetic products developed along an unconformity and, axiomatically, in profile. Fossil content, type of primary skeletons, granulometry, and Ordovician local topography, for example, can affect the extent or intensity of diagenesis and the pathway it may have taken.

The critical features of the profiles are the palaeosols, the irregular surfaces with infiltrated palaeosols, the vugular limestones under the disconformities, the mottled limestones also under the disconformities, the restriction of internal sediment under disconformities, and the grain types associated with subaerial disconformities, namely, the lithoclasts, calcrete ooids and remanié fossils.

At many stratigraphic levels in the Daylesford Limestone, the subaerially altered limestones have been reworked or stripped with the disconformity surfaces cut into altered limestone: internal sediment and infiltrated soils occur in solution cavities and fissures in altered limestone beneath some disconformities and/or soil particles have been reworked into marine sediments overlying disconformities. Reworked palaeosols are evident where lithoclastic skeletal grainstone rests with sharp contact on altered limestone. In addition to containing normal marine fossils, these grainstones contain gravel-sized lithoclasts, calcrete-coated lithoclasts, peripherally-altered lithoclasts and remanié fossils. *Girvanella*, coral or stromatoporoid encrustations occur on some gravel-sized lithoclasts indicating that reworking occurred under high-energy conditions during a marine phase following the subaerial exposure. The lithoclastic grainstones above such disconformities are distinguished from palaeosols by their sedimentary structures and marine fauna. Palaeosols, in contrast, contain only minor unaltered marine fossils, are poorly bedded, and commonly gradationally overlie and infiltrate the parent sediment.

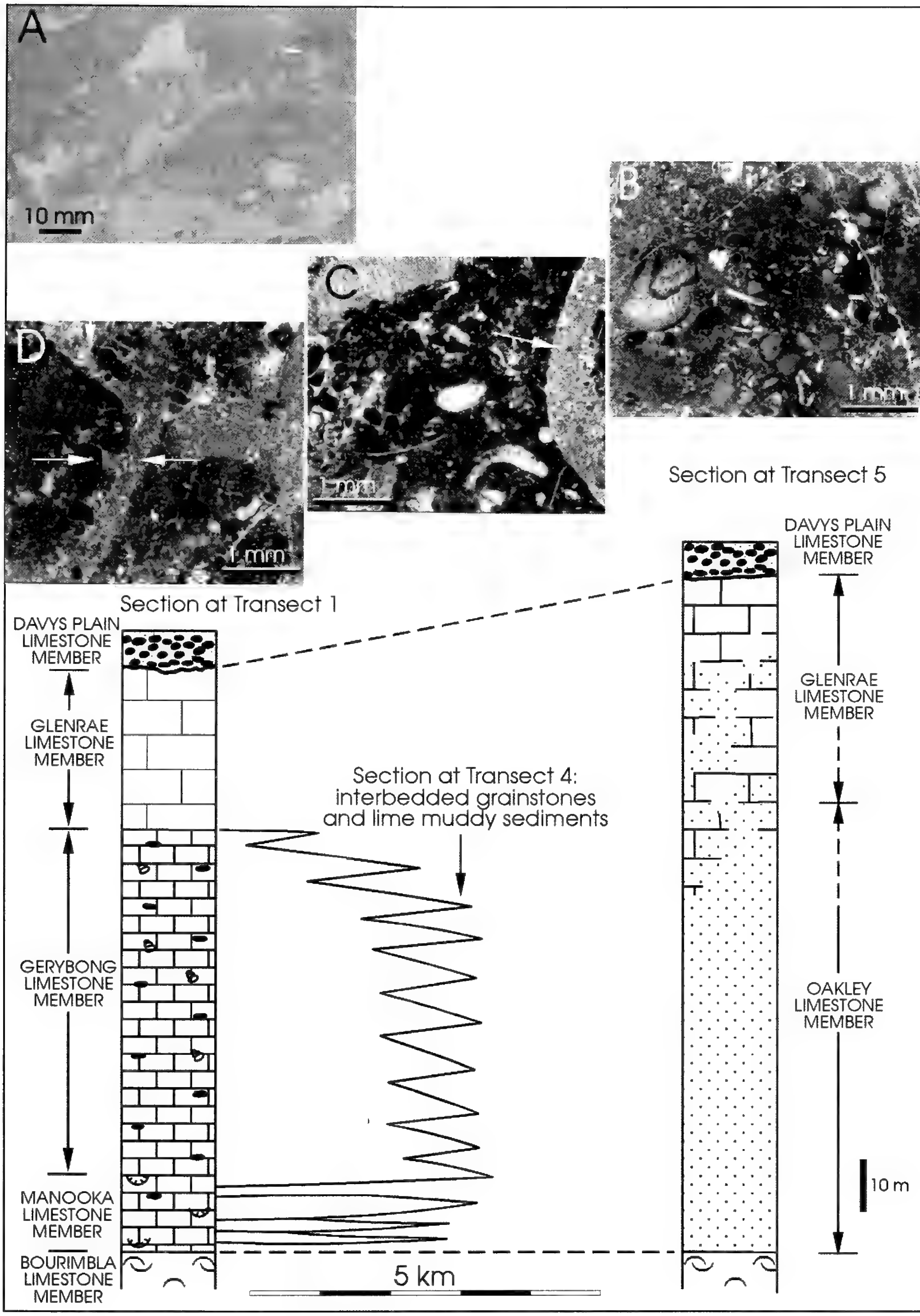
Thus, weathering, erosion, and subsequent marine reworking of a profile down into the altered limestone zone resulted in lithoclastic grainstones that contain soil particles and gravel-sized clasts of altered limestone, including cemented limestone, leached limestone, remanié fossils, and silicified fossils.

Biogenically reworked palaeosols also occur where (marine) muddy sediments overlie a disconformity. The zone of reworking is thin and consist of burrow-mottled, lithoclastic skeletal wackestone or packstone, which may grade down into undisturbed palaeosols and grade up into marine limestone lacking exotic grains. In this case, burrowing organisms mixed soil and muddy marine sediment.

In terms of silicified limestones, there is an abundance of silicified fossils and silicified sparry calcite mosaics in altered muddy limestone beneath disconformities in the Daylesford Limestone. In these leached horizons, silica replaced fossils that resisted solution and early sparry calcite that fringed molds, thereby preserving the fossil outlines.

DISCUSSION AND CONCLUSIONS

This Discussion is structured into an interpretative section on the grains, fabrics and structure, and lithologies developed by subaerial exposure of the


A
10 mm
B
1 mm
C
1 mm
D
1 mm
Section at Transect 5
DAVYS PLAIN LIMESTONE MEMBER
GLENRAE LIMESTONE MEMBER
OAKLEY LIMESTONE MEMBER
10 m
Section at Transect 1
DAVYS PLAIN LIMESTONE MEMBER
GLENRAE LIMESTONE MEMBER
GERYBONG LIMESTONE MEMBER
MANOOKA LIMESTONE MEMBER
BOURIMBLA LIMESTONE MEMBER
Section at Transect 4: interbedded grainstones and lime muddy sediments
5 km

Ordovician limestones, including the occurrence of calcrete, the occurrence of calcrete without plants, the significance of bleaching, the significance of the Glenrae Limestone Member, the occurrence of silica, and the environmental implications of diagenesis and pedogenesis in relation to landscape setting, palaeohydrology and depth of the vadose zone, climate, and hydrochemistry that can be inferred from the subaerial diagenesis and pedogenesis of these limestones.

In the first instance, the altered limestones beneath disconformities in the Daylesford Limestone are classic expressions of subaerially altered profiles. Within the sequence there are numerous indicators of the early nature of this subaerial diagenesis. Alteration of carbonate sediments and limestone in modern subaerial environments (Friedman 1964; Matthews 1968; Purdy 1968; Esteban and Klappa 1983) and inferred ancient subaerial environments (Schlanger 1963; Dunham 1969a), indicate that there are four main processes operating in modern environments: 1. solution; 2. cementation by sparry, cryptocrystalline and microcrystalline calcite; 3. internal (diagenetic) sedimentation and illuviation; and 4. recrystallisation of limestone to cryptocrystalline (and microcrystalline) calcite to form calcrete. For the Daylesford Limestone, the occurrence of vugular limestones and mottled limestones immediately beneath disconformities indicates the close association between dissolution and disconformity surfaces, and subaerial exposure (Semeniuk 1971). Lack of appreciable structural and fabric alteration lower in the stratigraphic profile (the unaltered host rock), is similar to phreatic or deep levels of the vadose zones in modern weathering profiles where micro-solution and replacement (of metastable aragonite and high-Mg calcite), and cementation by sparry calcite, are the main diagenetic processes, but the structure, fabric, and texture of the sediment remain unaltered (Friedman 1964; Land 1967; Matthews 1967). In terms of calcite precipitation and cementation, calcite mosaics in the Daylesford Limestone in solution cavities of all lithologies and in intergranular voids of grainstones are analogues of those precipitated in fresh-water diagenetic environments (Friedman 1964; Land 1967; Matthews 1967).

In the context of the amount of dissolution of calcium carbonate effected on the limestones during Ordovician subaerial exposure, rock types such as marls would generate insoluble residues and form terrigenous mudstones as palaeosols. In a situation where a marine transgression immediately followed, these originally terrigenous muddy substrates may be colonised by marine biota, or by burrowing organisms, that resulted in mixing of the mudstones into the overlying sediments.

Calcrete ooids, lithoclasts, peripherally-altered grains and remanié fossils are common in modern and Pleistocene calcareous soils (Brown and Woods 1974; Read 1974). The modern soils form in situ by alteration of unconsolidated sediments, or by disintegration and alteration of partly lithified to lithified rock. Palaeosols developed on muddy limestones of the Daylesford Limestone were probably originated by surficial break-up of the sediment into sand- and gravel-sized mudstone clasts and component fossils, controlled by peds and cracking, as suggested by fissures in the underlying limestone and the locally gradational contact of soil with parent sediment. These surface grains were subsequently peripherally altered and calcrete-coated, i.e., they formed the nuclei for the calcrete-ooids. The break-up of fossiliferous and pellet-bearing lime mudstone, and the release of fine-grained mudstone clumps (or clots), pellets and shells provided some of the source material that would infiltrate the solution cavities developing in the muddy limestone. In contrast, palaeosols developed on grainstones formed on an already sandy parent, and peripheral alteration and calcrete-coating of grains, cementation, and diagenetic (internal) sedimentation would have been the main surface alteration processes.

In sediments above the disconformity, sand- and pebble-sized lithoclasts of skeletal limestone with sparry calcite-filled and diagenetic sediment-filled fossil molds truncated along the grain boundary, and clasts of vugular limestone indicate that the disconformity-related solution features were eroded and reworked into the next cycle of sedimentation. Lithoclasts of sparry calcite-cemented grainstone also indicate early cementation. Sparry calcite lining solution cavities and cementing grainstones indicate penecontemporaneous subaerial solution and cementation.

Internal (diagenetic) sedimentation and illuviation are important processes in modern subaerial environments, with fine-grained material being transported gravitationally though the vadose zone. These processes and sedimentary products signal subaerial conditions both in the generation of specific vadose-environment grain types, and in the vadose conditions of delivery. Internal sediments (diagenetic sediments) and illuvium can develop specific rock types under subaerial disconformities. As fine-grained material, they fill pore spaces, solution cavities, and other types of opening such as fissures and ped boundaries. Taken to completion, diagenetic sedimentation and illuviation can finally plug all porosity in the upper parts of the host material. In the case of the Daylesford Limestone, diagenetic sedimentation and illuviation resulted in partially filled vughs (some of which are termed '*Stromatactis*' limestone), partially filled inter-granular pores of grainstones, and fully plugged cavities that comprise the mottled limestones. In a study of the Townsend Mound in New Mexico, for example, Dunham (1969a) related diagenetic sediment in cavities and inter-granular pores to remobilised crystal silt in the vadose zone, gravitationally descending but screened by the small pore spaces and fine-scale fractures in a subaerially exposed limestone, thus accounting for the well sorted nature of much of this type of internal sediment. However, there are other types of internal sediment and illuvium that were: 1. produced internally in the rock by the disintegration of polymineralic and/or multi-textured skeletal grains, 2. produced as insoluble residue at the surface of the rock and washed in as illuvium, and 3. delivered as aeolian carbonate dust to the rock surface and washed in as illuvium. Pellets within the suite of diagenetic sediment in the Daylesford Limestone may be fine-grained calcreted grains washed into the profile by vadose waters, or algal or calcrete micrite envelopes that have fragmented, after the primary calcareous interior of a calcareous skeleton, to which they were envelopes, has dissolved. Lithoclasts that occur within the internal sediment suite, if derived from the surface, clearly have been fine enough grains to infiltrate the pores, solution cavities, fractures and fissures of the subaerially exposed limestone, but some sand-sized 'lithoclasts' have been formed by collapse of a limestone matrix into its enlargening solution cavity (essential an in situ 'auto-microbreccia'). All five types of diagenetic (internal) sediment and illuvium indicate gravitational delivery and hence vadose conditions.

Calcrete is an important part of the subaerial diagenesis of the Daylesford Limestone. While occurring as calcrete-ooids, mottled calcrete, and as massive calcrete, its most prevalent form is expressed as recrystallisation of limestone to cryptocrystalline (and microcrystalline) calcite. Cementation of grainstone by cryptocrystalline calcite (calcrete), and recrystallisation of grains to cryptocrystalline calcite (calcrete) is best developed beneath major subaerial disconformities and is commonly associated with solution and internal sediments.

Fine-grained calcite, where it is a replacement of (former) grainstones, and the cementation of grainstones by fine-grained calcite are analogues of Quaternary calcretes (Gile et al. 1966; Read 1974; Semeniuk and Meagher 1981). In modern environments, solution and then rapid precipitation of carbonate by vadose waters produce patches of cryptocrystalline calcite which either replaces grains or occurs as cement. These patches progressively enlarge, locally forming massive, fine-grained limestone, but more generally forming mottled limestone (Read 1974; Semeniuk and Meagher 1981). In the Daylesford Limestone, thick, porous grainstones allow widespread and deep percolation by vadose waters and, consequently, the calcrete alteration in grainstones is pervasive in upper parts of the profile, and developed to some depth. In contrast, low porosity in muddy limestones allow vadose waters access only through cavities such as fossil molds, enlarged fossil molds, and other interconnecting vughs.

In this context, one of the major disconformities, where sedimentation style changed from that dominated by low-energy muddy lime sediments (the Bourimbla, Manooka, and Gerybong limestone members) to one dominated by high-energy sandy and gravelly calcareous sediments, is the contact between suite of limestones of the Gerybong/Glenrae Limestone Member and the Davys Plains Limestone Member. This major subaerial disconformity and change in sedimentation style is marked by the development of massive calcrete. At this stratigraphic interval, western parts of the Daylesford Limestone, where muddy lime sediments dominated, the calcrete is relatively thin, though it does exhibit features of mottling, fine-grained calcite cementation, and bleaching. Eastern parts of the Daylesford Limestone, where sandy lime sediments dominated, the stratigraphic pile was thick, and porous lime sand subject to deep percolation by vadose waters, the calcrete is relatively thick, and calcrete development has gone to completion, with development of mottled calcrete, massive calcrete, and fissured and fractured limestone (brecciated) with calcrete and diagenetic sediment (mainly crystal silt) filling the fissures and fractures.

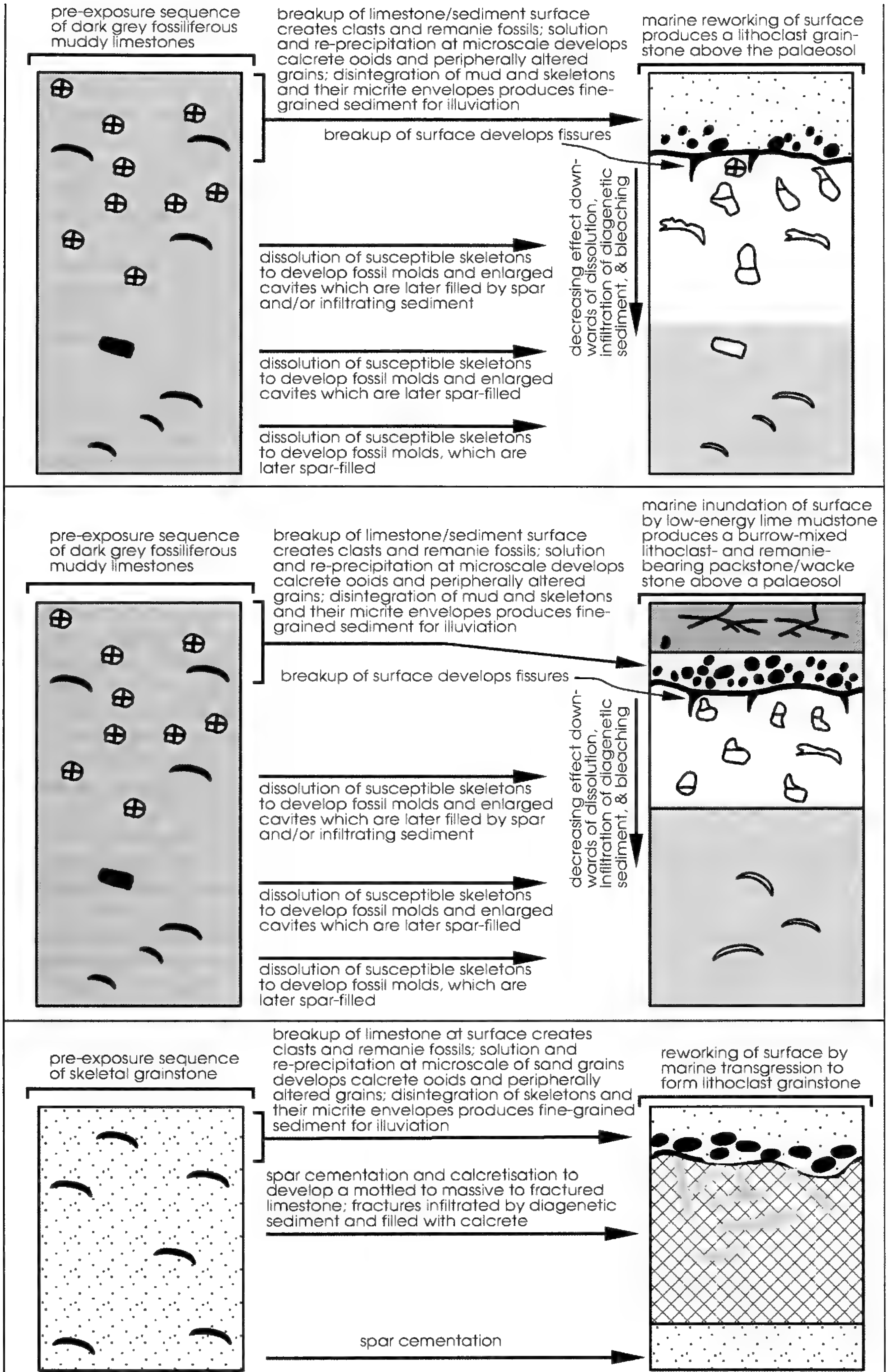
There is a notable lack of abundant calcrete pisolites (in palaeosols and reworked palaeosols) and absence of in situ laminar calcrete (at tops of grainstone sections altered to cryptocrystalline calcite). Both pisolitic and laminar calcrete are common in fully developed Quaternary calcrete profiles (Gile et al. 1966; Read 1974). Pisolites develop where calcrete envelopes nucleate on gravel grains or where calcrete accretion is thick. Laminar calcrete developed in Quaternary soil profiles is only a few centimetres thick (Gile et al. 1966; Read 1974). Erosion and stripping of Daylesford Limestone soils down to altered grainstones may have stripped laminar calcrete. There are clasts of laminar calcrete in the lithoclastic grainstones above disconformities, indicating that it had been present in the profile. However, it may not have been well developed. Gile et al. (1966) consider laminar calcrete to form only after lower horizons of a profile are plugged by cryptocrystalline calcite, with the laminar calcrete forming above the plugged zone where vadose water movement is impeded. Calcretisation of grainstones in the Daylesford Limestone may not have proceeded to the extent that lower parts of the profile were fully impregnated. The factor of time, or duration of exposure, may be reasons for this. On the other hand, continual erosional stripping of the area along the Molong Volcanic Belt, precluding mature calcrete development, may be another reason in that laminar calcrete is not common as an in situ layer. With continual erosional stripping, surface soils, and the immediately underlying laminar calcrete would be the first materials to be eroded. Figure 10B shows that laminar calcrete was present in the subaerially altered profiles. The lithoclast of veined laminar calcrete illustrated in Figure 3B also shows that laminar calcrete was present but it has been stripped and reworked.

There are various types of calcrete as described by Knox (1977), Klappa (1978), Semeniuk and Meagher (1981), and Wright and Tucker (1991). They can be summarised as belonging to two end-members of a spectrum of types: alpha calcretes - those generated dominantly by abiotic processes; beta calcrete - those with a biogenic or biologically mediated structure/fabric. Calcretes described by Gile et al. (1966) and some by Knox (1977) illustrate those that largely reflect abiotic processes. Microscale solution and re-precipitation in arid climates, where rainfall is seasonal and is followed by rapid evaporation, often results in abiotically formed microcrystalline or cryptocrystalline calcite mosaics (that are calcrete). Knox (1977), Klappa (1978), and Semeniuk and Meagher (1981) describe calcretes that have structure/fabric indicating biological mediation, with an abundance of permineralised, or calcrete coated filaments of fungi or of algae, and root hairs. Some of the calcretes described by Knox (1977) reflect combined abiotic and biotic processes. In many of the ancient and Quaternary calcrete, there is evidence of biomediation of calcrete development by the occurrence of fungi hyphae, algal threads, and plant root hairs (Knox 1977; Klappa 1978; Semeniuk and Meagher 1981; Wright and Tucker 1991). In this context, the calcretes in the Daylesford Limestone are alpha-types, lacking evidence of biomediation, and indicate that land plants were not instrumental in calcrete development. Rather, calcrete development was a product of solution and precipitation of metastable skeleton grains at microscale. Similarly, and corroboratively, there is an absence of plant root structures in the palaeosols, again indicating that land plants were not instrumental in palaeosol development.

Bleaching is an important product of subaerial diagenesis in these Ordovician limestones, and is a significant indicator of Ordovician subaerial exposure. Primary muddy limestones in the sequence are commonly dark grey to medium grey, as described above, with the dark colouration due to Fe-sulphides. Under disconformities, the limestones are bleached to light grey, very light grey, or even a cream tone. This, essentially, exhibits the oxidation and mobilisation of Fe-sulphides. This type of bleaching is common in modern subaerially exposed materials where the colouring agents such as Fe minerals, are mobilised away from the surface. For instance, the grey calcilutites of the Holocene coastal sequences of the Canning Coast in Western Australia are bleached to cream tones by exposure and oxidation of the Fe sulphides (Semeniuk 2008). The modern weathering surfaces of the Fe-bearing dark grey Ordovician limestones at Bowan Park have a thin crust or patina of Fe-free light grey carbonate, as described earlier. They provide modern analogues of how dark grey Fe-bearing limestone can be bleached under subaerial conditions to be bleached to a cream tone.

A summary in general form of the main processes operating during Ordovician subaerial exposure of the marine limestones, to produce three end-member stratigraphic profiles, is provided in Figure 15. Under subaerial conditions impermeable mudstones best produce palaeosols and fissures, irregular surfaces, and microkarst. Grainstones are indurated by sparry calcite but, because of their permeability, also best produce calcrete profiles wherein the fine-grained calcite (as calcrete) functions as an additional cementing agent. Once cemented, these indurated grainstones are subject to further calcretisation, but also to fracturing and development of fissures within which calcrete can precipitate and diagenetic sediment can

Figure 15 RIGHT. Processes operating during Ordovician subaerial diagenesis and pedogenesis to generate the various grain types, fabrics, structures, lithologies, and stratigraphic sequences diagnostic of subaerial exposure of lime grainstones and muddy limestones.


pre-exposure sequence of dark grey fossiliferous muddy limestones
breakup of limestone/sediment surface creates clasts and remanie fossils; solution and re-precipitation at microscale develops calcrete ooids and peripherally altered grains; disintegration of mud and skeletons and their micrite envelopes produces fine-grained sediment for illuviation
marine reworking of surface produces a lithoclast grainstone above the palaeosol
breakup of surface develops fissures
decreasing effect downwards of dissolution, infiltration of diagenetic sediment, & bleaching
dissolution of susceptible skeletons to develop fossil molds and enlarged cavites which are later filled by spar and/or infiltrating sediment
dissolution of susceptible skeletons to develop fossil molds and enlarged cavites which are later spar-filled
dissolution of susceptible skeletons to develop fossil molds, which are later spar-filled
pre-exposure sequence of dark grey fossiliferous muddy limestones
breakup of limestone/sediment surface creates clasts and remanie fossils; solution and re-precipitation at microscale develops calcrete ooids and peripherally altered grains; disintegration of mud and skeletons and their micrite envelopes produces fine-grained sediment for illuviation
marine inundation of surface by low-energy lime mudstone produces a burrow-mixed lithoclast- and remanie-bearing packstone/wacke stone above a palaeosol
breakup of surface develops fissures
decreasing effect downwards of dissolution, infiltration of diagenetic sediment, & bleaching
dissolution of susceptible skeletons to develop fossil molds and enlarged cavites which are later filled by spar and/or infiltrating sediment
dissolution of susceptible skeletons to develop fossil molds and enlarged cavites which are later spar-filled
dissolution of susceptible skeletons to develop fossil molds, which are later spar-filled
pre-exposure sequence of skeletal grainstone
breakup of limestone at surface creates clasts and remanie fossils; solution and re-precipitation at microscale of sand grains develops calcrete ooids and peripherally altered grains; disintegration of skeletons and their micrite envelopes produces fine-grained sediment for illuviation
reworking of surface by marine transgression to form lithoclast grainstone
spar cementation and calcretisation to develop a mottled to massive to fractured limestone; fractures infiltrated by diagenetic sediment and filled with calcrete
spar cementation

infiltrate. Subaerial exposure and dissolution of marls produces "terrigenous" mudstones as palaeosols, with terrigenous clay and quartz silt as insoluble residue. At smaller scales, there are several key processes operating: (1) muddy limestones disintegrate at the surface into components of clasts (probably controlled by ped structure), fossils, broken fossils, and into mud particles; (2) subaerially exposed sites develop calcrete ooids (the result of solution of metastable skeletons and clasts of disintegrated sediment, and its reprecipitation as thin envelopes of stable fine-grained calcite); and (3) pellets in palaeosols and in diagenetic sediment are disaggregated micrite envelopes following skeletal dissolution, and crystal silt may be mechanically derived by internally screened crystal fragments (following Dunham 1969a) but also may be relatively less soluble calcite particles derived from polymineralic and/or multi-textured shells differentially disaggregated under subaerial conditions. The suite of diagenetic and pedogenic products described in this paper, as illustrated in Figure 15, from grain-scale to fabrics/structures to lithology, provide a contrast to the products developed along discontinuity surfaces that been interpreted as submarine hardgrounds (cf., Jaanusson 1961; Kennedy and Garrison 1975; Furisch 1979; Brett and Brookfield 1984) and serve as a set of criteria to distinguish between the two types of stratigraphic discontinuities.

The features of microkarst, i.e., the fossil molds, sparry-calcite-filled casts, and sparry calcite and/or diagenetic sediment filled enlarged solution cavities, indicate that the carbonate sediments during subaerial exposure were indurated, and perhaps were even brittle. Their induration is an important factor because, from the range of products developed during subaerial diagenesis, it is vugular indurated limestone that would stand the most chance of preservation following any erosion by the next marine transgression. Even if erosionally planed and reduced to rocky shore pavement, it is a rock type that will remain in situ. And if the subaerial diagenesis and microkarst features were developed to some metres in depth below the disconformity surface, then erosion would have to remove substantial thickness of indurated limestone to eliminate all evidence of the subaerial exposure. Thus, microkarst expressed as vugular limestone, with its associated sparry calcite fill, and diagenetic sediment fill, stands as one of the more permanent indicators of subaerial exposure, and is the most important indictor of such exposure in these Ordovician limestones. Calcareous sand, while it readily transforms to a palaeosol and will provide abundant nuclei for development of calcrete-ooids, can be without difficulty transported and remobilised. Thus, while lithoclasts (including lithoclasts of limestone with microkarst features), calcrete-ooids, remanié fossils, and reworked subaerially exposed calcareous sands signal that there has been subaerial exposure and pedogenesis, they may have been transported from the source of their development, leaving the stratigrapher to interpret the underlying stratigraphic contact as a subaerial disconformity. As such, they often are more indirect indicators of subaerial exposure. The occurrence of palaeosols is direct evidence of subaerial exposure and pedogenesis, but the preservation of paleosols relies on little or no reworking of this material during the next marine transgression.

The alteration of limestone, and the depth to which diagenetic sediment and illuviation penetrate the limestone profile provide insight into the depth of the vadose zone during the subaerial exposure of the marine limestones. Figure 13 shows penetration of internal sediment for the disconformities in the Bourimbla Limestone Member to generally vary from 1 m to 3 m to 6 m. This would be the main interval of efficient vadose water penetration. At lower levels in the phreatic zone, groundwater alternatively undersaturated and saturated with carbonate, eventually dissolved the geochemically susceptible fossils to form fossil molds filled with sparry calcite.

For the Glenrae Limestone Member, with its thick development of calcrete in eastern sections, the depth of calcretisation would imply a vadose zone of some 50 m. The western section has a calcrete profile more or less 20 m, suggesting a vadose zone of some 20 m depth. The deep vadose zone for the eastern part of the Glenrae Limestone Member is not surprising, as this part of the limestone adjoins the axis of the Molong Volcanic Belt, a positive area to the east that was the determinant of subaerial exposure during deposition of the Daylesford Limestone. A relative higher topographic relief during periods of subaerial exposure, progressively higher to the east towards the axis of the Molong Volcanic Belt, would produce a deep vadose zone in eastern sections of the Daylesford Limestone which would be altered if the parent sediments were porous grainstones. Upper parts of the weathering profile of the eastern sections thus would be continually stripped. Repetitive exposure of limestones along an axis of topographic relief, i.e., along the axis of the Molong Volcanic Belt, would also explain the regressions and the abundance of disconformities throughout the sequence of the Daylesford Limestone, as well as the depth of alteration achieved in some profiles, and the reworking of older limestones as lithoclasts.

Diagenesis and paragenesis of silica in the Daylesford Limestone is a complex issue. Silica is clearly labile in the geological record, and can be dissolved and precipitated depending on the chemistry of pore waters (Walker 1962). Some remobilisation of chalcedonic silica is interpreted to be related to weathering during the Ordovician, as distinct bands of silicification occur beneath some disconformities, as noted earlier. This is not unusual, as silica has been noted in weathering profiles and calcrete profiles by Watts (1980) and Hay and Wiggins (1980), with any available metastable silica dissolved at surface and precipitated at depth. In calcareous soils, silica is re-precipitated at the base of the calcrete profile (Reeves 1970). Clifford (2008), for example, describes the microscale solution and reprecipitation of silica as a laminated patina in a very modern carbonate soil environment where the metastable silica is anthropogenic glass < 100 years old (and geochemically equivalent to metastable biogenic silica), and texturally shows the rapid and labile nature of the silica-and-carbonate interactions. The geochemistry of the solution of silica and its precipitation may be related to the alternation of groundwater pH at the pellicular water microscale from alkaline (and silica dissolving and carbonate precipitating) to acid (and silica precipitating and carbonate dissolving) as discussed by Walker (1962). In the Daylesford Limestone, silicification of limestones is most prevalent in muddy rocks with abundant calcitised triaxon sponge spicules, thus signalling a local source of silica (i.e., metastable opaline silica of sponge spicules) in the soil profile (cf. Watts 1980, and Hay and Wiggins 1980). In the Daylesford Limestone, silicified fossils occur as (rotated) clasts in lithoclast grainstones overlying some disconformities further indicating that silicification was an early diagenetic event associated with pedogenetic processes.

However, being labile, not all silica precipitation is related to disconformities. Elsewhere in the Daylesford Limestone, silica occurs as dark chert nodules (replacement of dark grey, muddy limestone), chalcedonic and quartzose fossil replacements in horizons not associated with disconformities, minor veins and minor euhedra (concentrated in stylolites). These occurrences are silica remobilised during late diagenesis or low-temperature metamorphism.

Dissolution of limestone in the vadose and phreatic zone suggests that the Ordovician environment had moderate rainfall, i.e., it was not arid, wherein the evaporation would have markedly exceeded precipitation. Carbonate sediments and rocks exposed subaerially in arid regions tend to develop specific types of calcrete (pisolites, laminar calcrete), red soils, and lesser leaching because of the deficit of freshwater. These features are absent from the rocks of the Daylesford Limestone.

There has been discussion in the literature that, with atmospheric carbon estimated to have been ~500 times more abundant in Hadean time than at present, and its concentration gradually decreasing since then due to storage in sedimentary rocks, rain pH has been gradually increasing through geologic time, such that groundwaters are less acidic today than they were in the distant past (Jutras et al. 2009). Based on studies of pre-Silurian palaeosols developed on primary rocks, however, Jutras et al. (2009) suggest that groundwater pH was, on average, highest shortly before the Late Ordovician to Silurian proliferation of root-forming land plants, i.e., there was a greater tendency for alkalinity during this time period than during previous and subsequent geologic periods. The results from the Daylesford Limestone provide some insight into this argument: the solution of limestones in subaerial environments during the Ordovician suggests that both rainwater and percolating groundwater (as vadose water and phreatic water) were sufficiently acidic to drive dissolution of limestone as a major and prominent process in the surface and near-surface environments. While vadose processes may involve alternating alkalinity and acidity at pellicular water scale, alkaline rainwater and groundwater would not drive such marked dissolution. Weathering of primary rocks to form palaeosols in the Middle Ordovician, based on mineral transformations as described by Jutras et al. (2009), may have been in an alkaline groundwater environment, but this should not be taken to imply that globally groundwater also was alkaline.

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Reassessment of Lower Palaeozoic geology west of the Catombal Range, Wellington region, central New South Wales

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Percival, I.G. and Quinn, C.D. 2011. Reassessment of Lower Palaeozoic geology west of the Catombal Range, Wellington region, central New South Wales. *Proceedings of the Linnean Society of New South Wales* **132**, 221-235.

New palaeontological discoveries and revised mapping of Lower Palaeozoic sedimentary rocks located west of the Catombal Range, between Wellington and Yeoval in central New South Wales, underpins a new model for the Ordovician and Silurian geological history of this region. West of the abandoned Gunners Dam gold mine, large blocks of deep-water siltstones, spiculite, and laminated chert contain Late Ordovician graptolites, including *Dicellograptus* and *Climacograptus* (associated with the dendroid *Dendrograptus*). Along strike to the north near Arthurville, west of Wellington, lensoidal outcrops of sandstone, conglomerate and limestone (previously assigned to the Oakdale Formation) contain a new brachiopod genus and species, described here as *Narrawaella wellingtonense*, that is associated with conodonts and lingulate brachiopods of Late Ordovician (Katian) age. We interpret all these Upper Ordovician rocks as allochthonous, having been redeposited into Silurian sediments of the Cowra Trough. Similar occurrences of allochthonous Upper Ordovician limestones at Eurimbla and Cumnock to the south, and comparable deposits previously recognised in the Hill End Trough further to the east, suggest this model is widely applicable to areas peripheral to the Macquarie Arc in central New South Wales.

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KEYWORDS: allochthonous blocks, brachiopods, graptolites, Silurian, stratigraphy, Upper Ordovician

INTRODUCTION

Ordovician rocks in the eastern Lachlan Orogen of south-eastern Australia include continent-derived, quartz-rich turbidite sequences (VandenBerg and Stewart 1992; Glen et al. 2009) and volcanic-volcaniclastic sequences with associated shelfal limestones and slope to basinal sediments (Fig. 1A). The latter are collectively attributed to the Macquarie Arc, an intra-oceanic arc system (Glen et al. 1998; Crawford et al. 2007). These Ordovician strata are now largely separated by Silurian and Devonian trough deposits (Glen 2005). The arc sequences are fragmented, with the westerly Junee-Narromine Volcanic Belt separated from the central Molong Volcanic Belt by the Silurian-Devonian Cowra Trough.

Due to their structural dismemberment, relationships between the belts of the former island arc are not well-preserved, particularly in areas of isolated exposures. The most recent geological map of the Wellington region (Morgan et al. 1999a) depicts two belts of Ordovician strata, bounded on their eastern sides by major north-south faults (Cudal Fault and Manildra Fault) extending between Ponto in the north and Cumnock in the south. These rocks were mapped as Oakdale Formation (in the Arthurville area to the north, and between Smokey Camp and Bournewood localities further south), Sourges Shale in the vicinity of Cumnock, northwest of Molong, and the regionally extensive Kabadah Formation (Fig. 1B). Outcrops in these belts include large blocks and lenses of deep water chert and spiculitic siltstone in the vicinity of the abandoned Gunners Dam mine, and shallow water limestone, conglomerate and sandstone on Narrawa property, west of Arthurville. Additional fossil discoveries confirm the Late Ordovician age of these rocks which recent field mapping suggests have

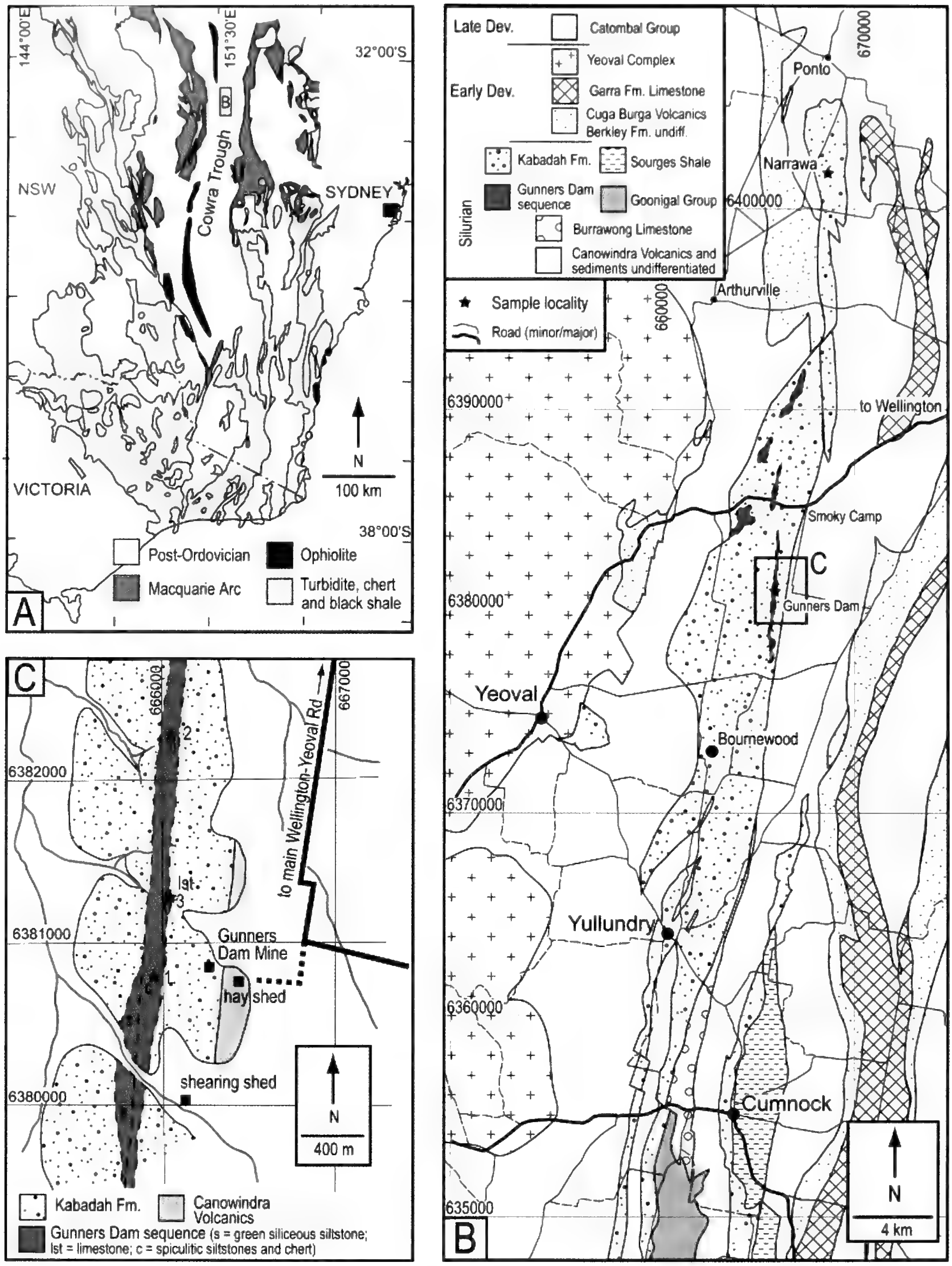

Figure 1. A. Locality map showing distribution of Ordovician rocks in eastern New South Wales and northeastern Victoria. B. Revised geological map of the area west of the Catombal Range near Wellington in central New South Wales. C. Detailed geological map of the area immediately west and north of the abandoned Gunners Dam mine, showing distribution of allochthonous blocks of Upper Ordovician rocks that are the subject of this paper.

all been redeposited into younger sediments, leading to a reassessment of structural and stratigraphic relationships in the region.

STRATIGRAPHIC RELATIONSHIPS ON NARRAWA

A prominent belt of Upper Devonian rocks forming the Catombal Range, extending west and southwest of Wellington, separates two areas in the central west of NSW that have previously been mapped as Oakdale Formation. Southeast of Wellington near Dripstone, in its type area in the Oakdale Anticline, the Oakdale Formation consists of volcaniclastic sandstone, siltstone and occasional allochthonous limestone lenses and clasts that range in age from late Darriwilian (Da3: Zhen and Percival 2004) to Eastonian (Morgan et al. 1999c).

Rocks assigned to the Oakdale Formation on Narrawa property, adjacent to the Arthurville Road west of Wellington (Fig. 1B), occur in paddocks centred on GR 669255 6402762 (GDA), 1.5 km northeast of Narrawa homestead. These outcrops include metre-scale blocks of moderate to coarse-grained, thinly to moderately thick-bedded quartz sandstones rich in brachiopods, overlain by discontinuous exposures of maroon siltstones and fine-grained sandstones, in which trilobite remains are abundant. Contacts between the various blocks and lenses are covered by soil, so that stratigraphic continuity and thickness cannot be established. Where dips can be measured, all beds are east-dipping at about 10–20 degrees. In stratigraphically higher beds, clasts of limestone become progressively more common, forming allochthonous limestone breccia that includes blocks containing halysitid corals (presumably of shallow water origin), intermixed with clasts derived from a deeper water depositional setting (indicated by their microbrachiopod fauna). Age of these limestones is late Eastonian to early Bolindian (i.e. mid to late Katian of international usage), based on conodonts and microbrachiopods (Percival et al. 1999).

Biostratigraphy

Percival et al. (1999) published a preliminary faunal list from exposures then referred to Oakdale Formation on Narrawa and discussed the age implications. Updated determinations are as follows:

<u>allochthonous limestone blocks (NSWGS conodont sample C1491)</u>

Conodonta

Belodina confluens

Drepanoistodus sp.

Panderodus gracilis

Periodon grandis

Protopanderodus sp. cf. *P. liripipus*

Yaoxianognathus? sp.

Brachiopoda

Atansoria sp. nov.

Nushbiella sp. nov.

Paterula malongulliensis Percival, 1978

Cnidaria

Halysitid coral cf. *Halysites praecedens* Webby and Semeniuk, 1969

<u>underlying sandstone blocks at GR 669255 6402762 (GDA)</u>

Brachiopoda

Narrawaella wellingtonense gen. et sp. nov.

Trilobita

indet. encrinurid

indet. dikelocephalinid

Although several of the identifications given in Percival et al. (1999) have been revised, the age of the limestone clasts at Narrawa is still regarded as most likely late Eastonian (Ea3-4), or late Katian, based on the occurrence of conodonts and brachiopods identical at species level with those in the Malongulli Formation in the Cliefden Caves area (Trotter and Webby 1995; Percival et al. in review), and in the Downderry Limestone Member of the Ballingoole Limestone and overlying basal beds of the Malachis Hill Formation at Bowan Park (Zhen et al. 1999). All these units contain elements of the same lingulate brachiopod assemblage (particularly the new species of *Atansoria* and *Nushbiella*, described by Percival et al. in review) as recognised in allochthonous limestone blocks at Narrawa. However, the new brachiopod *Narrawaella wellingtonense* and associated trilobites found in the underlying sandstones and siltstones are unknown in Ordovician rocks of eastern Australia; their assumed late Eastonian age is based on proximity to the stratigraphically overlying limestone blocks.

STRATIGRAPHIC RELATIONSHIPS AROUND GUNNERS DAM MINE

The abandoned Gunners Dam gold mine (situated approximately 25 km southwest of Wellington: Fig. 1B, C) was previously interpreted by Warren (in Morgan 1997) and Morgan et al. (1999c) to be situated within the Oakdale Formation. These authors described andesitic breccia and volcaniclastic cobble conglomerate in the vicinity of the mine, relating these

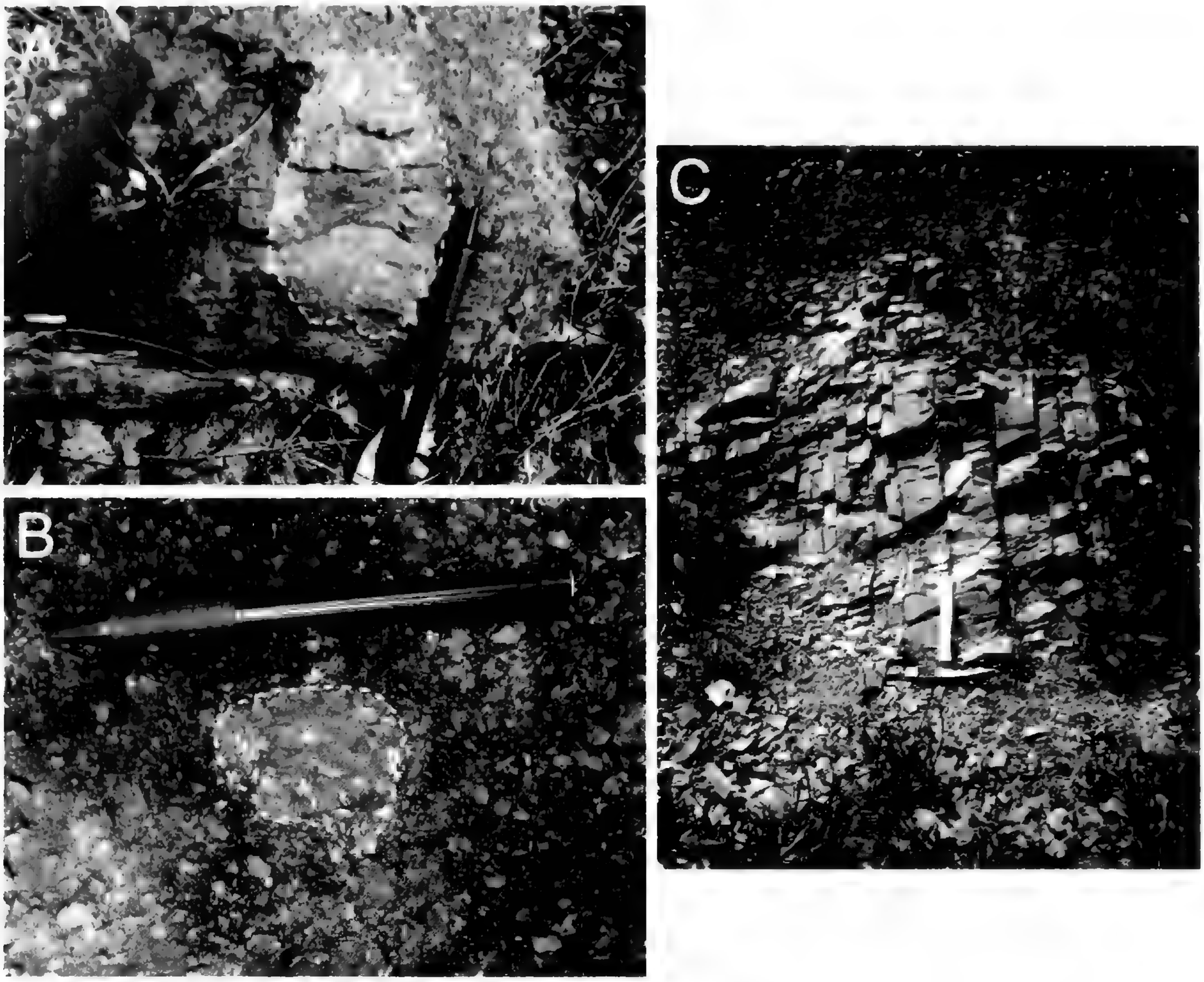

Figure 2. Field photographs of representative lithologies. A. clasts of plagioclase-phyric andesitic volcanic rock within a locally monomictic conglomerate. This outcrop, about 20 m east of the allochthonous limestone block described herein (sample locality 3 in Figure 1C), was originally attributed to the Oakdale Formation but is here regarded as part of the Lower Silurian Kabadah Formation. These clasts are superficially similar to the Devonian Cuga Burga Volcanics. B. Detailed view of clast in A. C. bedded siliceous siltstones forming a clast within the Gunners Dam sequence; outcrop is approximately 50 m west of the limestone block (locality 3).

rocks to a nearby volcanic centre. Gold mineralisation at Gunners Dam has been briefly discussed by Warren (in Morgan 1997) as occurring in quartz reefs emplaced along fault zones. Relatively undeformed sedimentary rocks forming the ridge to the west of the mine workings, in which Late Ordovician graptolites and other fauna (documented herein) occur, were originally assigned to the Kabadah Formation, most recently by Morgan et al. (1999a, b), who thereby inferred an extended Late Ordovician to Early Silurian age for that unit. Percival and Glen (2007, p.152-153) briefly compared the lithology and fossil content of the Kabadah Formation with the exposures in the vicinity of Gunners Dam and on the adjoining property Pine Not, concluding that a separate stratigraphic name was warranted for the Upper Ordovician deep-water strata that they informally termed the Gunners Dam beds. However, as is now apparent from the latest detailed mapping of the area presented herein, these exposures are discontinuous and likely represent large-scale (up to km-long) allochthonous olistoliths rather than either an in-situ formation, or tectonically-emplaced slivers.

In the immediate vicinity of the Gunners Dam mine, rocks consistently dip moderately to steeply to the west (mean ca. 65 degrees). The sequence is here reinterpreted to pass from crystal-rich dacites and sedimentary rocks of the Lower Silurian Canowindra Volcanics to the east, upwards through volcanic debris flows, conglomerate with chert and volcanic fragments, and mafic to intermediate autobreccia (Fig. 2A-B). These rocks are apparently overlain along the ridge to the west by deep-water spiculitic and graptolitic siltstones (Fig. 2C) associated with laminated cherts (laminations ca. 5-10 mm) yielding Late Ordovician fossils, discussed further below.

Still further west above this succession, along a north-south trend, lie mafic sandstones, grits and conglomerates (with chert, andesite and granite clasts) of the Lower Silurian Kabadah Formation. Small (ca. 1-2 cm) granite and volcanic clasts were observed in the vicinity of GR 665600 6381150 (GDA) on Pine Not property south of the main Wellington – Yeoval road (known as Renshaw-McGirr Way).

Although siltstone matrix separating blocks of chert within the mapped horizon could not be confirmed during this fieldwork, the Ordovician chert horizon was found to be discontinuous along strike – particularly in the vicinity of GR 665710 6376860 (GDA) where it gave way to green siliceous siltstones exposed in a quarry. These siltstones were also observed in the creek at GR 665750 6380250 (GDA) and perhaps correlate with the Lower Silurian Sourges Shale to the south near Cumnock.

Biostratigraphy

Rocks surrounding the abandoned mine workings are strongly cleaved and lack fossils, so their age is uncertain. Poorly preserved graptolites from overlying siltstones exposed in the ridge 200-300 m to the west of the mine site had been determined by A.H.M. VandenBerg (cited in Morgan et al. 1999b) to indicate a Late Ordovician age, though none could be identified to genus level. Associated cherty beds contained conodonts (also indeterminate) regarded by I. Stewart (cited in Morgan et al. 1999b) as no older than Darriwilian in age. Further intensive searching of these beds by R.A. Glen and I.G. Percival on field trips in 2002 and 2006 revealed additional graptolite fragments including an indeterminate orthograptid, although again this material was inconclusive in providing a definitive age.

Recent collecting at this locality (Fig. 1C, locality 1), and in siltstones apparently at a higher stratigraphic level in exposures to the north (locality 2) has yielded a graptolite fauna that includes several species confirming a Late Ordovician (late Katian: Eastonian 3 to Bolindian 2) age. The fauna includes the following:

<u>Locality 1 GR 665950 6380820 (GDA)</u>: siltstones and interbedded cherts
Graptolithina (Fig. 3, 4, 5B-D, I)
- *Dendrograptus* sp.
- *Dictyonema*? sp.
- *Dicellograptus* sp.
- climacograptid indet.

Conodonta (Fig. 5E, F, H, J)
- *Belodina* sp.
- *Paroistodus venustus*?
- *Phragmodus*? sp.

Scolecodonta indet. (Fig. 5G)
Porifera (Fig. 5A)
- Sponge spicules

<u>Locality 2 GR 666080 6382250 (GDA)</u>: siltstone (apparently higher in section)
Graptolithina (Fig. 4)
- *Climacograptus* spp.

A solitary limestone block (ca. 15 m diameter), itself consisting of redeposited limestone clasts rich in echinoderm fragments, lies immediately east of the chert package within a creek at GR 666005 6381265 (GDA) (Fig. 1C). Although contacts with nearby outcrops (Fig. 2) were not exposed due to thick soil cover, and matrix siltstones again were not observed, based on regional dips this limestone block appears to lie directly above conglomerates (Fig. 2A-B) and underlies the cherts and graptolitic siltstones previously discussed (Fig. 2C). Acid-insoluble residue from the limestone block (locality 3) yielded the following microfauna:

<u>Locality 3 GR 666005 6381265 (GDA)</u>: allochthonous limestone

Conodonts	*Periodon* sp. (possibly *P. grandis*)
	Panderodus sp.
	Pseudooneotodus? sp.
	Yaoxianognathus? sp.
Brachiopods	*Paterula* sp
	indet. orbiculoidid
Bivalves	indet. fragments
Bryozoan	fragment
Indeterminate conical tubes	

Despite the paucity of conodont elements recovered from this sample, the assemblage is certainly of Late Ordovician, most likely Eastonian, age, and is therefore approximately contemporaneous with the ages obtained from other clasts investigated in this study. These fossiliferous Ordovician rocks are adjacent to debris-flows and conglomerates within siltstone matrix and probably represent large olistoliths several tens to hundreds of metres long, rather than having been emplaced as extremely thin thrust-imbricated slices. None of the fossils in these rocks are distorted, and no increases in strain were observed towards any contacts.

AGE OF THE KABADAH FORMATION AND AFFINITIES WITH CANOWINDRA VOLCANICS

The Kabadah Formation, as defined by Maggs (1963) from the vicinity of Cumnock, consists of

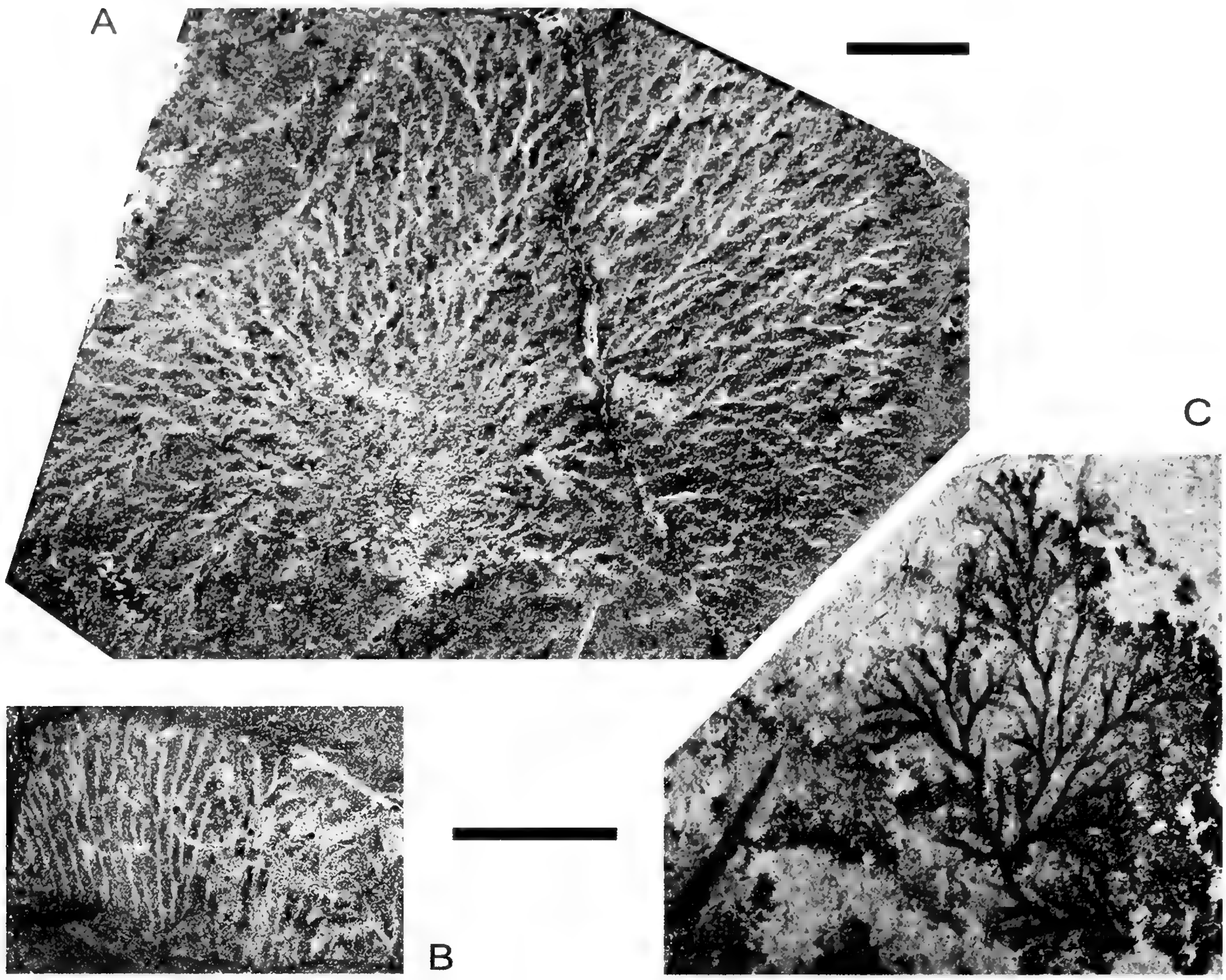

Figure 3. A. *Dendrograptus* sp., a near complete rhabdosome preserved in slight positive relief, MMF 45087. Scale bar represents 10 mm (magnification x1.5). B. *Dictyonema*? sp., fragment exhibiting parallel stipes and rare dissepiments (note that right-hand side of specimen is damaged with scratch-marks), MMF 45088. C. *Dendrograptus* sp. showing irregular widely-spaced dichotomous branching of stipes, MMF 45089; note specimen of *Climacograptus* sp. in lower left of photograph. Scale bar represents 10 mm (magnification of specimens B and C is x2). All specimens from ridge crest west of Gunners Dam mine at locality 1 (see Fig. 1 and text for details).

a series of matrix-supported, limestone-clast and angular polymictic conglomerates or debris flows within a cleaved and deformed siltstone-coarse shale matrix. Sherwin (1973) identified graptolites within the basal shale that indicated an age no older than early Llandoverian, prompting Bradley (*in* Pickett 1982) to include the Kabadah Formation in the Silurian Cudal Group.

Raymond and Pogson (1998), followed by Morgan et al. (1999b), mapped the spatial distribution of the Kabadah Formation by its high K-radiometric response that they attributed to arc-related detritus, and so included the formation in the Cabonne Group that otherwise consists of Late Ordovician volcaniclastic and volcanic rocks associated with the Macquarie intra-oceanic arc. The presence of Early Silurian fossils in the Kabadah Formation was used to support the extension of the age of the Cabonne Group across the Ordovician-Silurian boundary. However, as pointed out by Percival and Glen (2007), such a high-K radiometric response is not unique to Macquarie Arc-related rocks in the Lachlan Orogen, and merely reflects the presence of arc detritus subsequently redeposited into the Kabadah Formation. High K-radiometric responses are also typical of Early Devonian debris flow horizons elsewhere in the Lachlan Orogen and on closer inspection contrasts with a slightly higher U and Th response of the arc rocks.

Barron et al. (2007), after Barron and Warren (1998), reported ultramafic, arc-related and other

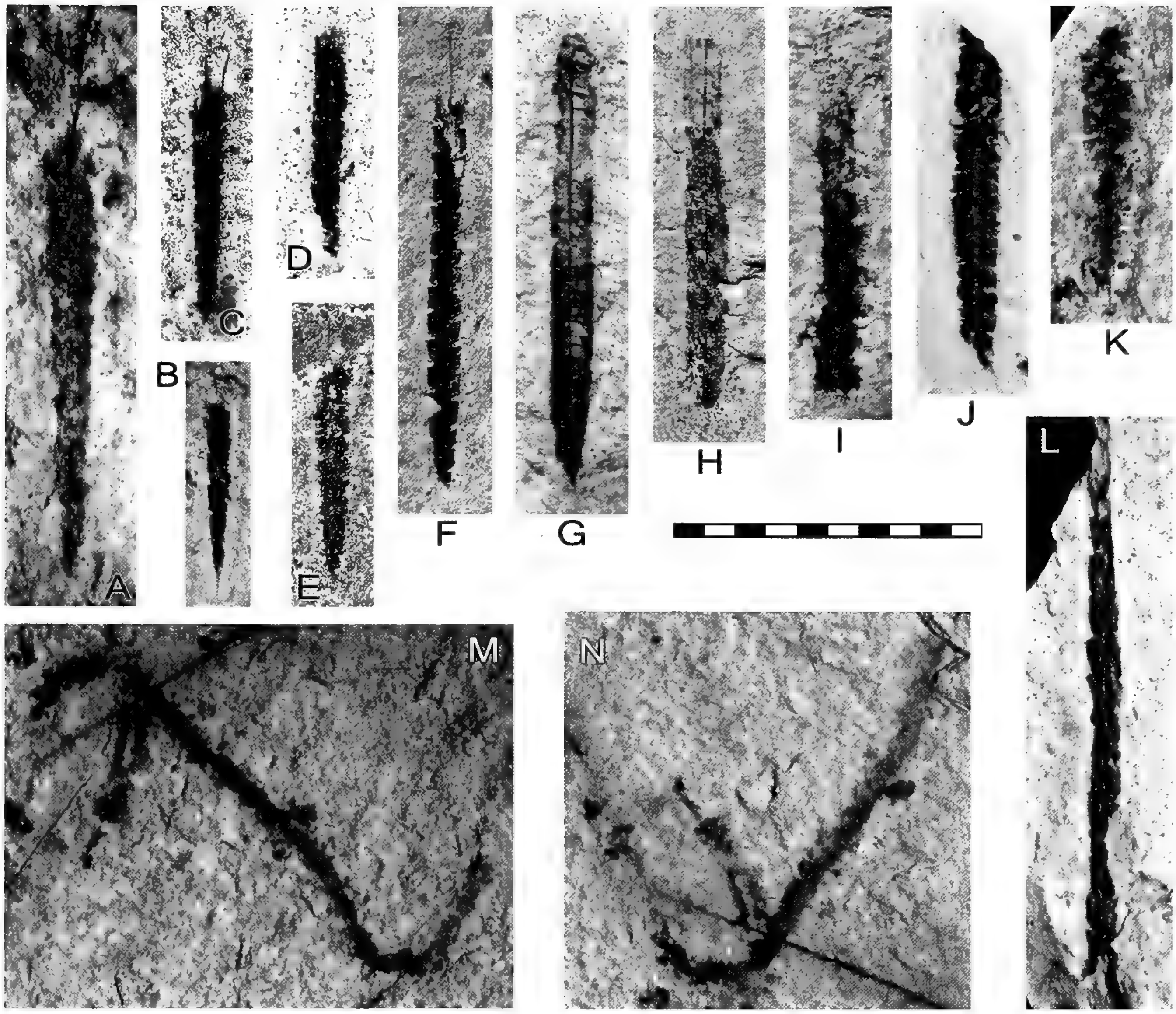

Figure 4. Graptolites from west (locality 1, specimens A, M and N) and northwest (locality 2, specimens B – L) of abandoned Gunners Dam mine (see text for details). A: climacograptid indet., MMF 45090; note that the nema-like artefact at the top of the specimen is a crack in the rock surface. B: *Climacograptus* sp., MMF 45091; note that the right-hand side of the proximal part of this specimen is broken obliquely to the stipe, giving an impression of a more sharply tapering outline than is in fact the case. C: *Climacograptus* sp., with a near-vertical rock fracture intersecting upper right side of specimen. MMF 45092. D: *Climacograptus* sp., MMF 45093. E: *Climacograptus* sp., MMF 45094. F: *Climacograptus* sp., MMF 45095. G: *Climacograptus* sp., MMF 45096. H: climacograptid indet., MMF 45097. I: indeterminate climacograptid lacking proximal half, MMF 45098. J: *Climacograptus* sp. in oblique scalariform view, MMF 45099. K. *Climacograptus* sp., MMF 45100. L. fragment of stipe of an indeterminate dicellograptid, MMF 45101. M: *Dicellograptus* cf. *D. minor,* MMF 45102a, in lower right of image; N: interpreted as a single stipe of an indeterminate dicellograptid, representing the counterpart (MMF 45102b) of the upper left side of M, that overlaps the specimen of *Dicellograptus* cf. *D. minor*. Scale bar represents 1 cm, with 1 mm increments; all specimens enlarged x4.

detritus within sandstones and conglomerates of the Kabadah Formation, including detrital chromite, pyroxene, volcanic quartz, garnet, lithic clasts of S-type cordierite + garnet-bearing dacitic volcanics, granite clasts (most likely related to the Cowra Granodiorite) and deformed sediments. Barron et al. (2007) argued that the Kabadah Formation was entirely restricted to the Early Silurian, and attributed the existence of the cordierite + garnet-bearing dacite clasts to an early unexposed phase of the Canowindra Volcanics.

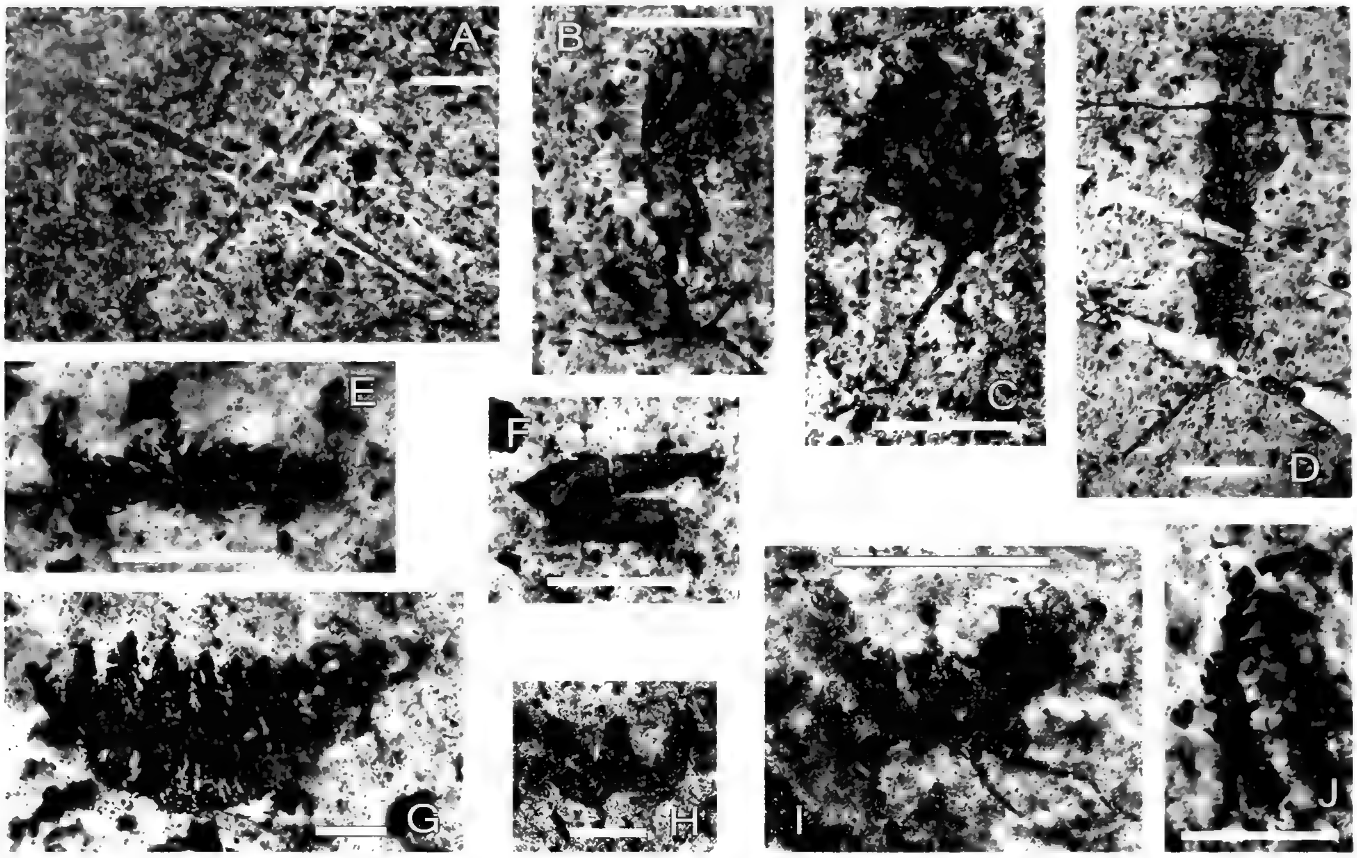

Figure 5. Fossils in thick-sections of chert from locality 1, west of abandoned Gunners Dam mine (see Fig. 1C and text for details). Scale bars represent 1 mm. A: sponge spicule, MMMC 4400. B – D, I: proximal ends of graptolites. B. indeterminate climacograptid with two basal spines, MMMC 4401. C: indeterminate orthograptid?, MMMC 4402. D: indeterminate climacograptid with two basal spines, overlain by two sponge spicules, MMMC 4403. I: indeterminate dicellograptid, MMMC 4404. E – F, H, J: conodonts. E: *Phragmodus*? sp., MMMC 4405. F: *Paroistodus venustus*?, MMMC 4406. H: indeterminate element, MMMC 4407. J: *Belodina* sp., MMMC 4408. G: indeterminate scolecodont MMMC 4409.

The Canowindra Volcanics elsewhere overlies the Gospel Oak Shale (Ryall 1966) which contains a graptolite fauna spanning the middle late Llandovery to earliest Wenlock interval, and is overlain disconformably by the Avoca Valley Shale (Bradley, in Pickett 1982) and Ghost Hill Formation (Ryall 1966), both of which contain the graptolite *Pristiograptus dubius* indicative of a broad Wenlock to Ludlow age (Krynen and Pogson 1998). The calculated weighted mean U-Pb zircon ages for the Canowindra Volcanics (432 ± 7Ma and 431.7 ± 3.1 Ma) are latest Llandovery (after Pogson 2009) or late Llandovery (mid Telychian, *M. turriculatus* to *M. crispus* graptolite zones, according to the Silurian timescale proposed by Sadler et al. 2009). The presence in the Kabadah Formation of lithic clasts with probable Canowindra Volcanics affinities confirms that the age of the Kabadah Formation most likely ranges from the Llandovery into the Wenlock, with the possibility that the upper part extends into the Late Silurian. Much more fieldwork and sampling is needed to accurately constrain the extent of both formations.

DISCUSSION

The lithological, depositional and biostratigraphic attributes of the rock successions in the Narrawa and Gunners Dam–Pine Not areas combine to support a re-evaluation of Upper Ordovician stratigraphy in the belt west of the Catombal Range. All these isolated outcrops of Ordovician fossiliferous rocks most likely (given their juxtaposition over such a small area) represent allochthonous blocks (here informally termed the Gunners Dam sequence – see Fig. 1C) redeposited into Silurian sediments of the Cowra Trough succession.

Sandstone and carbonate rocks at Narrawa are reinterpreted as an outer shelf facies equivalent of the deeper water Gunners Dam sequence. These lithologies are all late Eastonian to early Bolindian in age. Faunas within the limestone clasts at Narrawa are very similar to those of deep-water limestones found in the Malongulli Formation that overlies the Cliefden Caves Limestone Subgroup in the southern Molong Volcanic Belt of the Macquarie Arc. However, the tectonic setting of these areas is very different. The Gunners Dam – Narrawa area lies west of the Catombal Range, which is a belt of Upper Devonian rocks along the margin of the Cowra Trough, separating that area from the northern part of the Molong Volcanic Belt (east of the Catombal Range). Whereas allochthonous clasts in the Malongulli Formation were deposited penecontemporaneously into that formation, the allochthonous rocks of Late Ordovician age west of the Catombal Range were redeposited into Silurian rocks of the Cowra Trough. A comparable situation has been described from the Eurimbla area some 10 km to the south of the Gunners Dam area, where clasts of Late Ordovician limestone were redeposited in sediments forming the Late Silurian Barnby Hills Shale (Zhen et al. 2003).

Similarly, the status of several km-long limestone lenses of Late Ordovician age previously mapped as an unnamed member within the Sourges Shale in the vicinity of Cumnock (Percival et al. 1999: fig. 5) requires revision – the southernmost one is of early Eastonian (Ea1) age and of very shallow water aspect, whereas those to the north on a markedly different trend are significantly younger (Ea3) and contain a deeper water fauna. Recognition of these limestones as allochthonous blocks enclosed within sediments of known Llandovery age confirms that the Sourges Shale reverts to a Silurian formation within the Cudal Group, as foreshadowed by Morgan (1999).

Recognition of widespread allochthoneity of rocks formerly mapped as Ordovician in the region between Ponto in the north and Cumnock in the south, bounded to the east by the Catombal Range and to the west by the Yeoval Granite, removes the need to infer the Cudal and Manildra faults that previously were mapped between belts of Ordovician and Silurian strata. In-situ Ordovician strata appear to be lacking in this region.

CONCLUSIONS

This study highlights the need to re-assess the distribution of rocks referred to the Ordovician Oakdale Formation and other conglomerate-olistostromal units attributed to the Macquarie Arc. According to our new interpretation, no autochthonous strata of Ordovician age are recognised in the belt extending from Cumnock to Ponto, west of the Catombal Range. Rocks previously mapped as Oakdale Formation surrounding the abandoned Gunners Dam gold mine are now regarded as a conglomeratic phase of the Kabadah Formation, restricted in age to the Early Silurian. Evidence for the presence of Late Ordovician deep water sediments exposed on the ridge west of Gunners Dam mine (earlier assigned to the Silurian Kabadah Formation, and more recently recognised by Percival and Glen (2007) as a distinctly older unit, the Gunners Dam beds) has been significantly enhanced and confirmed with documentation of a graptolite fauna in siltstones and spiculites, together with conodonts and graptolites in associated cherts. However, these rocks are demonstrably not in place, and (together with a limestone clast of Late Ordovician age) were redeposited into the Silurian sediments. Sandstones and limestones – both abundantly fossiliferous with Late Ordovician faunas – from Narrawa in the Arthurville area along strike to the north, are similarly interpreted as allochthonous blocks emplaced in strata of probable Silurian age. Discrete limestone lenses of Late Ordovician age, previously mapped as an unnamed member within the Sourges Shale at Cumnock, are also here reinterpreted as large allochthonous blocks redeposited in Early Silurian time. Redeposition of Late Ordovician shelfal limestone into trough sediments continued locally (Eurimbla area) into the Late Silurian, while in the Hill End Trough to the east of Wellington, Talent and Mawson (1999) documented an extended history of such events. The presence of allochthonous Ordovician clasts and blocks redeposited into Silurian strata is now widely recognised in central western NSW, and is a significant aspect of the geological history of the Lachlan Orogen.

SYSTEMATIC PALAEONTOLOGY
[I.G. Percival]

Type material (designated MMF), comprising specimens described and illustrated or listed herein, is curated in the palaeontological collections of the Geological Survey of New South Wales held at Londonderry in western Sydney. For brevity, authorship of taxonomic hierarchy above genus level is not cited in the References; these bibliographic sources are listed for brachiopods in the revised (2nd edition) Treatise of Invertebrate Paleontology, Part H: Brachiopoda Volume 3 (Williams et al. 2000), and for graptoloids in the revised (2nd edition) Treatise of Invertebrate Paleontology, Part V (Bulman 1970).

Phylum Brachiopoda Duméril, 1806
Subphylum Rhynchonelliformea Williams, Carlson, Brunton, Holmer and Popov, 1996
Class Strophomenata Williams, Carlson, Brunton, Holmer and Popov, 1996
Order Billingsellida Schuchert, 1893
Superfamily Polytoechioidea Öpik, 1934
Family Tritoechiidae Ulrich and Cooper, 1936

***Narrawaella* gen. nov.**
Type species (by monotypy): *Narrawaella wellingtonense* gen. et sp. nov.

Etymology

In reference to the property Narrawa on which is the type locality lies (gender of name is feminine);

Diagnosis

Planoconvex to ventribiconvex tritoechiid with dorsal sulcus, simple ridge-like cardinal process and complete chilidium; dental plates recessive and merging with delthyrial cavity walls.

Remarks

Narrawaella is assigned to the Tritoechiidae (as revised by Popov et al. 2001) on the basis of possessing a convex deltidial cover, complete chilidium, and a pronounced saccate mantle canal system in the ventral valve, and absence of an anteriorly-elevated ventral muscle platform. Of presumed late Katian age, it is perhaps the youngest representative of this group of billingsellide brachiopods. The preservation of *Narrawaella* is imperfect, as moulds and casts in the medium-coarse grained sandstone matrix do not satisfactorily reproduce fine-scale morphological details. Thus it cannot be confirmed from available material whether a small foramen is present at the apex of the deltidial cover, nor is the precise pattern of mantle canals in the dorsal valve known. Nonetheless, sufficient information is available to readily distinguish *Narrawaella* from other tritoechiids, and to confirm the new genus as an important representative of this group (in fact the first known) from the Ordovician of eastern Australia.

In its plexus of morphological characters, *Narrawaella* has some features reminiscent of the much older (Middle Cambrian to Tremadocian) *Billingsella*, including general shell shape and profile, possession of a tongue-like callus extending anteriorly to support the diductors in the ventral valve, and a similar pattern of ventral valve mantle canals. These general similarities support the argument advanced by Popov et al. (2001) for reassigning the redefined Tritoechiidae from the suborder Clitambonitidina to the suborder Billingsellidina. Although *Narrawaella* is presently known only from an allochthonous deposit (and therefore its age is open to interpretation), lingulate brachiopods and trilobites in closely associated strata provide adequate justification of a Late Ordovician age. Hence it is unlikely that *Narrawaella* is very closely related to *Billingsella*, from which it differs most noticeably in lacking divergent dental plates supporting the teeth. *Narrawaella* also has a shorter ventral interarea, and different ribbing (unequally parvicostellate rather than multicostellate) compared to *Billingsella*.

Narrawaella is readily distinguished from other genera included by Popov et al. (2001) in their redefined Tritoechiidae. In having a planoconvex to ventribiconvex profile with a dorsal sulcus, it differs from *Acanthotoechia* (concavoconvex), *Admixtella* (planoconvex, with dorsal fold and ventral sulcus), *Asymphylotoechia* (biconvex, with dorsal fold and ventral sulcus), *Eremotoechia* (dorsibiconvex), *Platytoechia* (convexiplanar to convexoconcave), and *Protambonites* (dorsibiconvex to resupinate). The simple ridge-like cardinal process of *Narrawaella* is quite unlike the trilobed cardinal process of *Eremotoechia* and *Peritritoechia*, or the swollen cardinal process of many species of *Tritoechia*. *Narrawaella* displays a complete chilidium, rather than the chilidial plates of *Eremotoechia*, *Pomatotrema* and most species of *Tritoechia*. *Korinevskia* Popov et al., 2001 shares several attributes with *Narrawaella*, including a simple cardinal process, complete chilidium, and a fine ridge bisecting the posterior part of the ventral muscle field; *Korinevskia* is, however, convexiplanar, has more prominent dental plates resembling those of *Billingsella*, and the *vascula media* in the ventral valve are subparallel rather than divergent as in *Narrawaella*. Of tritoechiids not mentioned previously, *Martellia* is similar to *Narrawaella* in profile, cardinal process, chilidium, and possessing a strong median septum in the dorsal valve, but differs in having a pronounced median ridge in the ventral valve extending forward of the muscle field (not present in *Narrawaella*).

***Narrawaella wellingtonense* gen. et sp. nov.**
Fig. 6A-T

Diagnosis

As for genus.

Etymology

In reference to the nearby town of Wellington, administrative centre for the district.

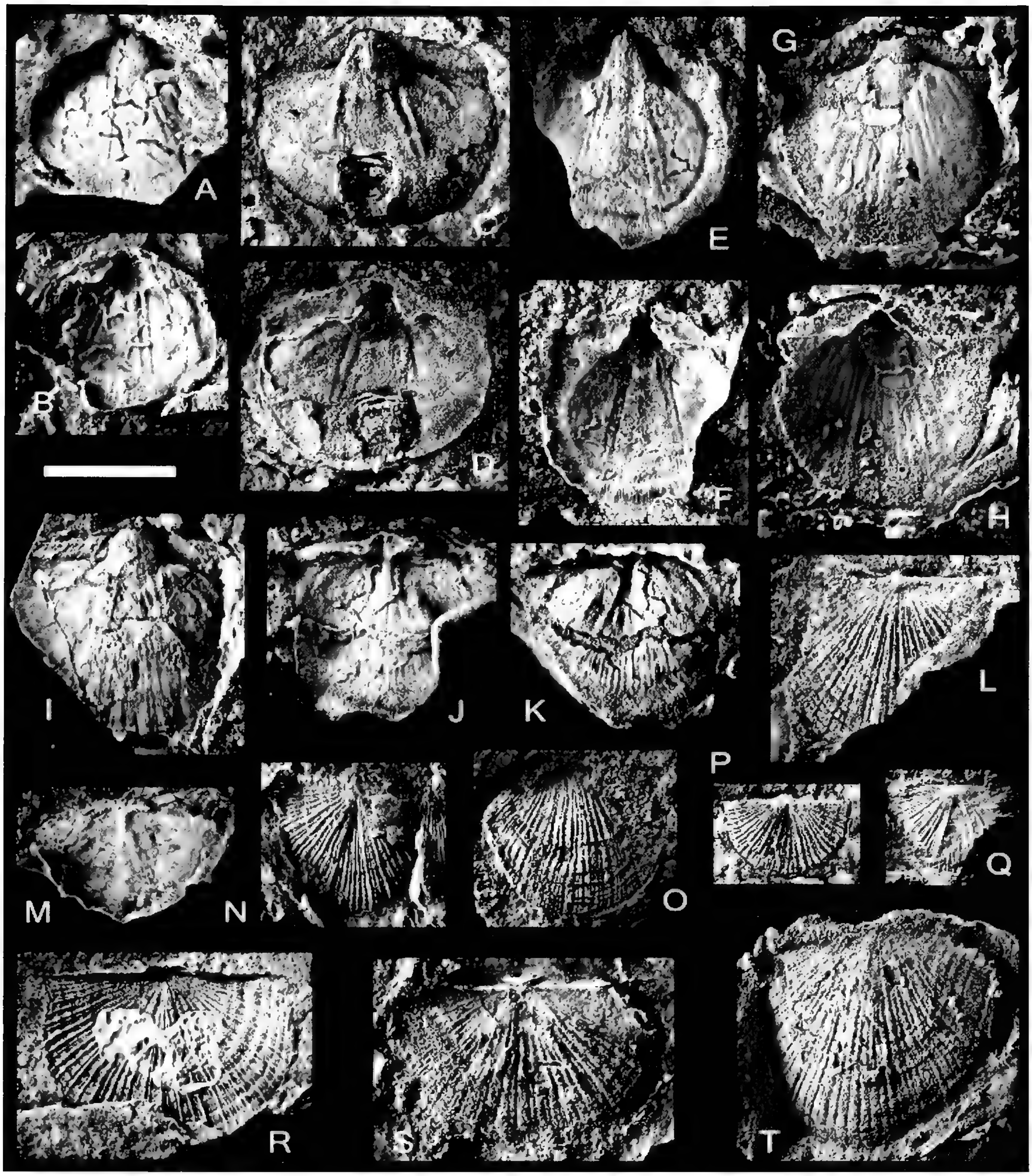

Figure 6. ***Narrawaella wellingtonense*** **gen. et sp. nov; A – B: internal mould and latex cast of ventral valve interior, MMF 45056. C – D: internal mould and latex cast of ventral valve interior, holotype MMF 45053. E – F: internal mould and latex cast of ventral valve interior, MMF 45054. G – H: internal mould and latex cast of ventral valve interior, MMF 45055. I: internal mould of ventral valve interior, MMF 45057. J – K: latex cast and internal mould of dorsal valve interior, MMF 45063. L: latex cast of exterior of dorsal valve, MMF 45065; M: latex cast of interior of dorsal valve, MMF 45064. N: latex cast of exterior of dorsal valve, MMF 45066. O: latex cast of exterior of ventral valve, MMF 45059. P: latex cast of exterior of juvenile dorsal valve, MMF 45067. Q: exterior of juvenile dorsal valve, MMF 45068. R: external mould of exterior of dorsal valve with some adherent shell material, MMF 45069. S: latex cast of exterior of dorsal valve, MMF 45070. T: latex cast of exterior of ventral valve, MMF 45060. Scale bar below B represents 10 mm (magnification x2). All specimens from allochthonous sandstone blocks on Narrawa property, northwest of Wellington.**

Material

Six internal moulds and four external moulds of ventral valves; two internal moulds and eight external moulds of dorsal valves; all shells disarticulated. Holotype is ventral valve MMF 45053; paratypes include ventral valves MMF 45054 – MMF 45062, and dorsal valves MMF 45063 – 45070 (MMF 45058, 45061 and 45062a-b are unfigured).

Type locality

Type (and currently, the only known) locality is low outcrop in paddock, approximately 1.5 km north-north-east of Narrawa homestead, off the Ponto – Arthurville Road about 16 km west of Wellington; GR 669255 6402762 (GDA).

Description

Shell planoconvex to slightly ventribiconvex, with maximum thickness near posterior extremity; outline transversely subquadrate to subquadrate with maximum width generally at, or occasionally immediately anterior to, long straight hingeline; lateral and anterior margins broadly curved; ventral valve with broad median fold of low to moderate convexity and slightly flattened lateral flanks; dorsal valve bearing shallow median sulcus that expands anteriorly. Shell small to moderate in size, ranging in length from 12 to nearly 17 mm, and in width from 15 to about 21 mm (estimated) in largest specimens; length to width ratio 0.85-0.98 (ventral valves), dorsal valves considerably more variable from 0.53 (juveniles) to 0.89 (fully grown). Ventral valve interarea apsacline, of short to moderate length, triangular on each side of a wide delthyrium partly covered posteriorly by a convex cover e.g. Fig. 6D, H (whether deltidium or pseudodeltidium cannot be determined in the available material); dorsal valve interarea catacline to anacline with prominent chilidium (Fig. 6S). Ornament unequally parvicostellate, with 1-2 minor ribs separating rounded major ribs, with very fine concentric filae observed on one specimen (mostly obscured by preservation in medium-coarse grained sandstone), and infrequent concentric growth discontinuities developed anteriorly on larger specimens. Shell material thin; apparently impunctate, but available material is insufficient for more detailed study.

Ventral interior: large, narrowly triangular teeth supported by short convex plates forming walls of delthyrial cavity and extending to valve floor, posteriorly enclosing a moderately deeply excavated muscle field that is supported anteriorly on a very low sessile spondylium extending to approximately one-fifth valve length (Fig. 6G, H); diductor scars entirely enclose narrow median pair of adductor scars that are confined to delthyrial cavity and may be separated by delicate median ridge (Fig. 6A, C), although this is replaced in other specimens by a fine linear cleft (Fig. 6E, G). Mantle canals of saccate type with prominent divergent *vascula media* that extend to four-fifths valve length before branching into fine network of canals (*vascula terminalia*) that occupy the peripheral zone of valve, reaching nearly to the lateral extremities (Fig. 6F); *vascula genitalia* indistinct.

Dorsal interior (Fig. 6J): chilidium is entire, convex, and covers posterior of single thin ridge-like cardinal process supported on a prominent notothyrial platform that merges laterally with short, widely divergent socket ridges; notothyrial platform is slightly undercut anteriorly on either side of a stout low median septum extending to about one-third valve length where it seems to bifurcate in one specimen (Fig. 6M). Muscle scars and mantle canals indistinct, the latter possibly digitate on one specimen (Fig. 6K).

Dimensions (note: for incomplete specimens, full dimensions have been estimated where possible by doubling the measurement of the more complete half)

Holotype MMF 45053 ventral valve: length 15.0 mm, width 17.7 mm; paratypes MMF 45054 ventral valve: length 16.7 mm, estimated width 17 mm; MMF 45055 ventral valve: length 16.0 mm, estimated width 17 mm; MMF 45056 ventral valve: length 13.1 mm, estimated width 15 mm; MMF 45057 ventral valve: length 16.5 mm, estimated width 19.5 mm; MMF 45059 ventral valve: length 11.5+ mm, estimated width 14 mm; MMF 45060 ventral valve: length 16.4+ mm, estimated width 21 mm; MMF 45063 dorsal valve: length 13.1 mm, estimated width 16+ mm; MMF 45064 dorsal valve: length 9.4+ mm, width 15.4+ mm; MMF 45065 dorsal valve: length 15.3+ mm, width 10.5+ mm; MMF 45066 dorsal valve: length 9.8 mm, estimated width 11 mm; MMF 45067 juvenile dorsal valve: length 6.1 mm, width 11.3 mm; MMF 45068 juvenile dorsal valve: length 6.8 mm, estimated width 9 mm; MMF 45069 dorsal valve: length 11.8 mm, width 17.1 mm; MMF 45070 dorsal valve: length 12.5 mm, estimated width 19 mm.

Discussion

Popov et al. (2001) observed that there is considerable variation present within the current concept of *Tritoechia*. These authors described a new species, *T. crassa* from the early Darriwilian Uzunbulak Formation of south Kazakhstan (see also Nikitina et al. 2006) that has a simple cardinal process, complete chilidium, dorsal sulcus, unequally parvicostellate ornament, and a similar ventral muscle field to that of *Narrawaella*. A highly ventribiconvex profile distinguishes *T. crassa* from *N. wellingtonense*, but it is feasible that it and the Kazakhstan species are quite closely related.

Distribution

Late Eastonian (Ea3-4), equivalent to late Katian; presently monotypic and known only from allochthonous sandstone redeposited into Silurian sediments, west of Wellington in central NSW.

Phylum Hemichordata Bateson, 1885, emend. Fowler, 1892
Class Graptolithina Bronn, 1846
Order Dendroidea Nicholson, 1872
Family Dendrograptidae Roemer in Frech, 1897
***Dendrograptus* J. Hall, 1858**

***Dendrograptus* sp.**
Fig. 3A, C

Material

Two specimens, MMF 45087 and MMF 45089, from an allochthonous block in the Gunners Dam sequence at Locality 1, GR 665950 6380820 (GDA), west of abandoned Gunners Dam mine, southwest of Wellington, NSW.

Description

Rhabdosome laterally flattened in both cases; the larger specimen (MMF 45087, Fig. 3A) retains some relief above the bedding plane and is approximately 7.4 cm across and 4.7 cm high. Stipes radiate from a diffuse node, branching at a constant rate of 5-6 stipes per cm to form a moderately clustered network exhibiting continuous expanding dichotomisation. There is very little variation in stipe thickness (approximately 1.0 mm), except at their slightly thinner terminations. No autothecae or bithecae visible, nor are any dissepiments seen.

The second specimen (MMF 45089, Fig. 3C) is better preserved but considerably smaller, only 2.0 cm across by 2.8 cm high. Branching is relatively open and apparently more ordered than in the other specimen, with new stipes arising on average every 2 mm (about the same as in MMF 45087), but they are comparatively thinner (0.5-0.6 mm). Autothecae not confirmed; dissepiments lacking.

Remarks

Only one species is believed to be present, the differences in stipe thickness being attributable to preservational vagaries (the larger specimen occurring in spiculitic siltstone, the smaller one being preserved in finer grained siltstone).

Species of *Dendrograptus* have previously been described in NSW from Upper Ordovician black shales (Bendoc Group) at Tomingley north of Peak Hill (Sherrard 1956), from the Lower Silurian (Llandovery) Glendalough Formation of the Waugoola Group in the Four Mile Creek area west of Cadia (Rickards et al. 2003), and from the late Ludlow upper Black Bog Shale at Yass (Rickards and Wright 1999). An additional undetermined species of Wenlock to Ludlow age was illustrated by Rickards et al. (1995) from the Panuara Formation of the Quarry Creek area west of Mount Canobolas. The branching pattern of none of these previously documented species closely resembles that of the Gunners Dam specimens, but the latter are not sufficiently well preserved to establish as new species.

An additional dendroid specimen (MMF 45088, Fig. 3B) from the same locality is tentatively attributed to *Dictyonema*, on the basis of having parallel stipes (12-13 per cm) connected by sparse dissepiments. Although too poorly preserved to describe, it is documented here by illustration.

NOTES ON ASSOCIATED DICRANOGRAPTID AND DIPLOGRAPTID GRAPTOLITES

Graptolites have now been found at two localities in the Gunners Dam sequence. None is sufficiently well-preserved to be described and confidently assigned to a species. Nonetheless their occurrence is crucial for confirming the Late Ordovician age of the allochthonous siltstones in this belt to the west of the Gunners Dam mine, so they will be briefly discussed here.

The most significant is a specimen of *Dicellograptus* (Fig. 4N), which shows broad similarities to several species that typically range from mid to late Eastonian into the early and mid Bolindian (VandenBerg and Cooper 1992). In the absence of details of thecae it is pointless to speculate about its identity. Associated graptoloids found at locality 1 include *Dendrograptus* sp. (described above), and an indeterminate climacograptid (Fig. 3C, and another example Fig. 4A). Sections cut of chert from this locality revealed proximal ends of four graptolites, two of which (Fig. 5B, D) display a pair of basal spines, similar to those exhibited by *Diplacanthograptus spiniferus* (mid to late Eastonian) or *Appendispinograptus supernus* (of Bolindian age). The available material, although too poor to confirm an identification, lends support to the general Late Ordovician age of the fauna.

Graptolites from locality 2 in the Gunners Dam sequence (Fig. 4B – L) are more prolific but less diverse. The majority appear to be referable to *Climacograptus*, perhaps here represented by more than one species. Better preserved examples (e.g. Fig. 4F) are 15 mm in length (including nema), have 12 thecae per cm, with stipes a relatively constant 1 mm in thickness. Other specimens show a gentle taper throughout the length of the stipe (Fig. 4C). No definite age connotations can be ascribed to this fauna, but it is again entirely consistent with a Late Ordovician age.

ACKNOWLEDGEMENTS

Original mapping in the area of this investigation was undertaken by Alice Warren and Larry Barron as part of the Geological Survey of NSW's regional mapping program on the Dubbo 1:250 000 sheet. We acknowledge assistance in the initial fieldwork by Dick Glen (Geological Survey of NSW) who provided the impetus for revision of the stratigraphy in the Gunners Dam region. Landholders in the area (Paul Vernon of Gunners Dam, Bruce Bishop of Pine Not, and the Morley family of Narrawa) are thanked for permitting access to their properties. David Barnes (Industry & Investment NSW) expertly prepared the photographic illustrations. Reviews by Tony Wright (Wollongong), Dick Glen and an anonymous referee were very helpful in improving the manuscript for publication. Both authors publish with permission of the Acting Director, Geological Survey of New South Wales, I&I NSW.

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