REVIEW PAPER

The Natural and Cultural History of the Ku-ring-gai GeoRegion, New South Wales

R.J. Conroy[1], U.A. Bonzol[2], J.J. Illingsworth[3], J.E. Martyn[4], P.B. Mitchell[5], I.G. Percival[6] , A.M. Robinson[7], D.F. Robson[8], and J.B. Walsh[9]

[1] NPWS (Rtd.), (bobconroy44@gmail.com); [2] FOKE Inc., P.O. Box 431 Lindfield NSW 2070; [3] Pittwater Pathways, 7 Vista Ave Bayview 2104; [4] STEP Inc., P.O. Box 1536 Turramurra NSW 2074; [5] 42 Tyrell St Gladesville 2111; [6] Honorary Research Associate, Geological Survey of New South Wales, Sydney NSW; [7] Australian Geoscience Council Inc., P.O. Box 638 Strawberry Hills NSW 2012, [8] Geological Society of Australia Inc., Suite 8 Level 2 141 Peats Ferry Road Hornsby NSW 2077; [9] 36 Badcoe Road Cromer NSW 2099.

Published on 10 November 2022 at https://openjournals.library.sydney.edu.au/index.php/LIN/index

Conroy, R.J. et al. (2022) The Natural and Cultural History of the Ku-ring-gai GeoRegion, New South Wales. Proceedings of the Linnean Society of New South Wales 144, 129-226.

The proposed identification and promotion of a ‘Ku-ring-gai GeoRegion (KGR)’, an area of approximately 440 km^2, is a community project initiated by the Friends of Ku-ring-gai Environment (FOKE). The proposed GeoRegion embraces the Ku-ring-gai Chase National Park, other bushland areas, as well as the coast and estuaries located just north of the city of Sydney. This paper describes the outstanding natural history of the GeoRegion including significant examples of Permo-Triassic sedimentation with evidence of ancient climate change and Jurassic/Cenozoic volcanic activity, together with associated geomorphology, soil genesis, endemic biodiversity, and cultural values. Its preserved ancient land surface supports diverse vegetation communities and the drowned river valleys provide evidence of the continuing impacts of climate change. The strong connection between this Country, its landscape, and its First Peoples is also highlighted. This foundation of outstanding geology and geomorphology and associated values has inspired a longer-term objective of the GeoRegion being nominated as an Aspiring UNESCO Global Geopark, particularly given its accessibility and strong potential for educational and recreational outreach to a large visitor base. In the short term, it is proposed to establish demonstration geosites, many of which are connected by themed geotrails, and which are expected to provide significant benefits to conservation, education, and tourism.

Manuscript received 23 May 2022, accepted for publication 25 August 2022.

KEYWORDS: Aboriginal sites, biota, cliff stability, geoparks, geotourism, Hornsby diatreme, Ku-ring-gai GeoRegion, soils.

TABLE OF CONTENTS

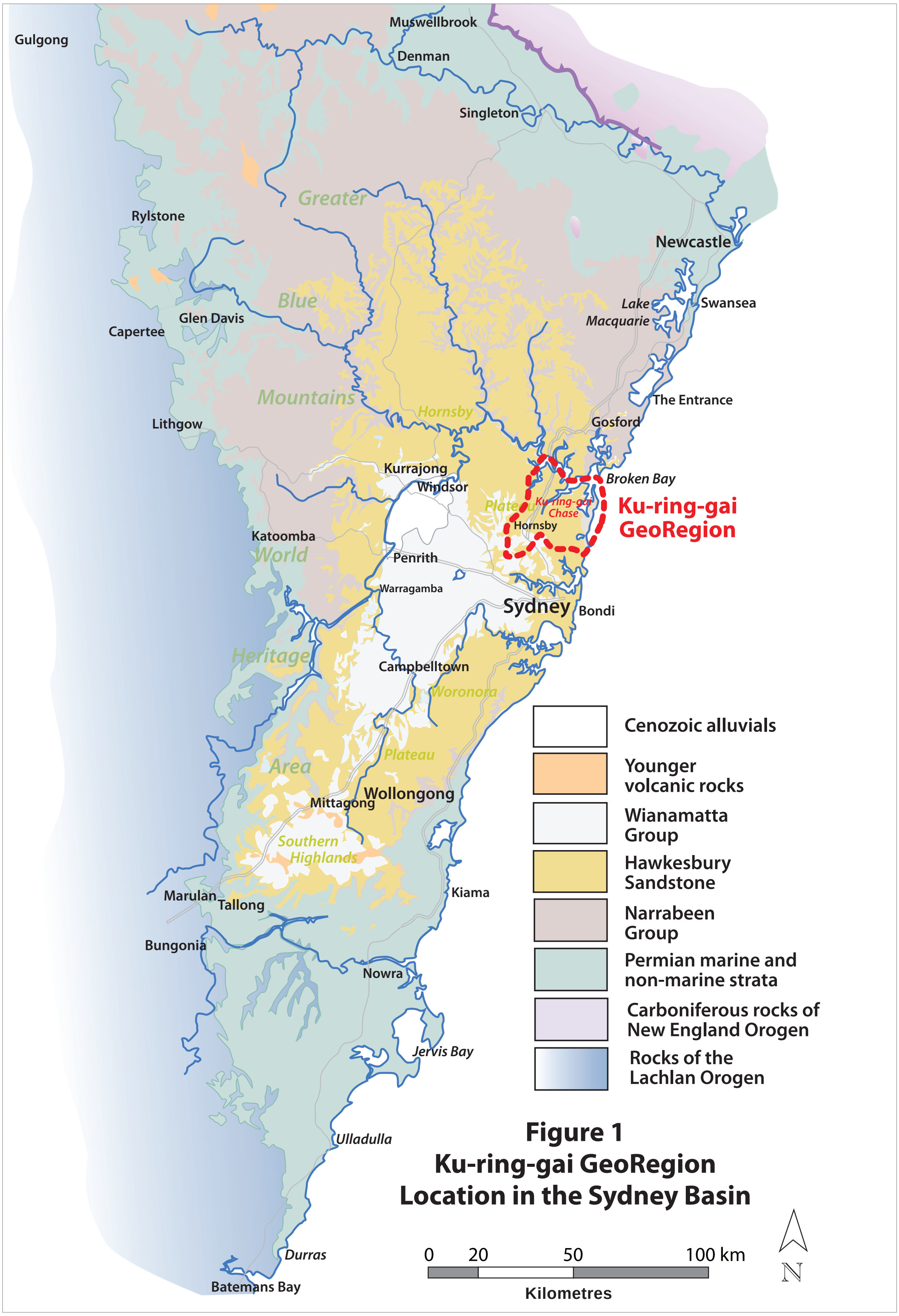

Figure 1. Map of the Ku-ring-gai GeoRegion and its location within the Sydney Basin.

INTRODUCTION (R.J. Conroy)

The Ku-ring-gai GeoRegion (KGR) embraces the upper northern suburbs and northern beaches of Sydney, essentially comprising a total area of about 44,000 ha (Figure 1). The Hornsby Plateau is a prominent feature of the KGR which rises northwards from its lowest levels around Port Jackson to elevations up to 220 to 230 metres before being deeply dissected by the drowned valley of the Hawkesbury River (Figure 2). Its rise continues northwards beyond there to terminate in a chain of escarpments overlooking the lowlands of the Hunter Valley and its 'Hunter Valley Dome Belt' of anticlines and synclines (Bembrick et al. 1973).

Figure 2. Morning Bay in Pittwater, one of many deep-water inlets in the classic drowned valley system of Broken Bay, in the northern part of the GeoRegion.

The bedrock is primarily Hawkesbury Sandstone, a lower Middle Triassic (Anisian 247-242 Ma) fluvial deposit of quartz sandstone with interbedded clayey sandstone, siltstone, shale, and minor occurrences of quartz pebble conglomerate. The sandstone has a maximum thickness of about 250 m in the northern part of the study area. It overlies other sandstones and shales in the Newport Formation (Narrabeen Group) and is conformably overlain by the Mittagong Formation (not always present), the Ashfield Shale (Wianamatta Group), and is intruded by igneous dykes and diatremes. The Hawkesbury Sandstone of the KGR contributes fundamentally to its outstanding natural and cultural heritage by shaping key features of its landscape and its diverse vegetation, and as a canvas for the artworks of its Aboriginal people.

The KGR is located within the Sydney Basin Bioregion and has a land area of some 38,000 ha comprising warm temperate rainforest, tall open forest, woodlands, shrubland and cleared and developed areas, as well as some 5,060 ha of estuaries, islands and coastal embayments, and approximately 27 km of coastline (Figure 3). A large part of the natural bushland of the KGR is conserved within eight protected areas totaling 21,073 ha (48.5% of the KGR) with the core being Ku-ring-gai Chase National Park (KCNP) and parts of other protected areas including Muogamarra Nature Reserve, Berowra Valley National Park, Lane Cove National Park, and Garigal National Park. Other large bushland reserves managed by local government are also protected within the KGR including Narrabeen Lagoon State Park (388 ha), Dee Why Lagoon Wildlife Refuge (77 ha), Ku-ring-gai Wildflower Garden (123 ha), and Sheldon Forest and Rofe Park (50 ha). The KGR also samples part of the Hawkesbury Shelf Marine Bioregion and includes three aquatic reserves at Barrenjoey Head, Narrabeen Head, and Long Reef.

The soils and vegetation communities of the KGR are heavily influenced by variation in geology, aspect, slope, and landform. The most common vegetation types occur on the Hawkesbury and Lambert soil landscapes

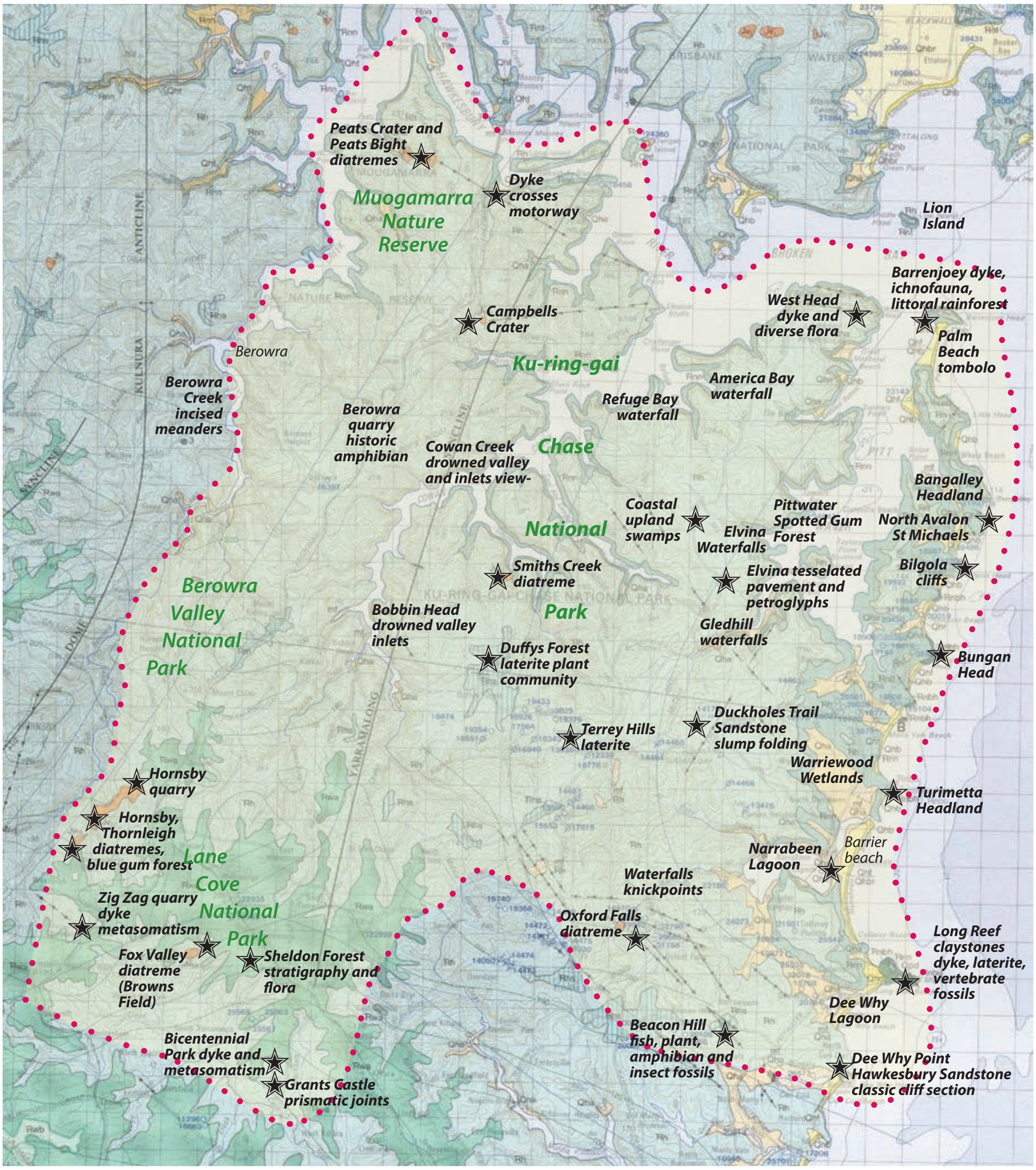

Figure 3. Designation of the KGR (dotted line) and location of some geosites.

(Chapman et al. 2009) and include Sydney Coastal Dry Sclerophyll Forest (33%), Sydney Hinterland Dry Sclerophyll Forest (18%), Sydney Coastal Heaths (8%), North Coast Wet Sclerophyll Forest (3%), and small areas of warm temperate and sub-tropical rainforest on richer soil landscapes (e.g., Hornsby, Glenorie, and Watagan soil landscapes). Mangrove, saltmarsh, and seagrass meadow communities (about 2%) are present on Quaternary sediments in the estuaries (Keith and Simpson 2010; OEH 2013). Approximately 31% of the area is cleared, primarily for residential development.

Aboriginal people have maintained, and continue to maintain, a strong association with the landscapes of the KGR. The plateaux, ridges and slopes, drowned river valleys, islands and coastal landscapes of this area contain extraordinary evidence, not only of our geological heritage, but also of Aboriginal occupation over at least the last 20,000 years, a period during which they would have been witness to generational change in climate, to inundation of the former coastal plain, the flooding of river valleys and more recently, to European colonisation and associated impacts to their Country and heritage values.

Despite these changes, evidence of their occupation and use of this landscape survives today with 1,424 recorded Aboriginal sites within the KGR. The studies reported here, and the sites identified are all located on Aboriginal Country and the authors acknowledge the role of elders and custodians of all generations in its management.

This paper describes in considerable detail the array of abiotic (landscape, geology, and soils) and biotic (flora and fauna) natural history attributes of this expansive scenic region as well as examples of Aboriginal cultural heritage which celebrate the long history of First Peoples occupation of this Region over a time frame now thought to extend back for at least the last 15,000 years and probably considerably longer.

While the biodiversity values (e.g., National Heritage listed KCNP and adjacent nature reserves) and cultural heritage values (e.g., proposed Sydney Cultural Crescent Rock Art, National Heritage Listing) of the KGR are well recognised (DAWE 2022), the conservation, understanding and promotion of sites and areas of geoheritage significance is fundamental and intrinsically linked to both. Geodiversity and geoheritage conservation underpin biodiversity and cultural heritage conservation, economic prosperity and contribute to sustainable development and are significant at many scales from the local and regional, to the national and global. The realisation and recognition of the outstanding geodiversity attributes identified below for the KGR, provides the rationale for Australian governments to consider and support the nomination of KGR as an Aspiring UNESCO Global Geopark.

INITIATING THE KGR PROJECT (U.A. Bonzol)

Friends of Ku-ring-gai Environment Inc (FOKE) is a community group dedicated to protecting and conserving the built and natural environment of the Local Government Area (LGA) of Ku-ring-gai. This KGR project was initiated in 2018 with the objective of making a positive contribution to conservation based in and around KCNP.

KCNP which lies at the centre of the KGR, is Australia's second oldest national park, having been created in 1894 through the persistent appeals of the activist and surveyor Eccleston Du Faur (Webb 2004). In 2006, KCNP was registered on the Australian National Heritage List with the following assessment.

'Ku-ring-gai Chase National Park and Long Island, Lion Island, and Spectacle Island Nature Reserves contain an exceptional representation of the Sydney region biota, a region which is recognised as a nationally outstanding centre of biodiversity. The place contains a complex pattern of 24 plant communities, including heathland, woodland, open forest, swamps, and warm temperate rainforest, with a high native plant species richness of over 1000 species and an outstanding diversity of bird and other animal species. This diversity includes an outstanding representation of the species that are unique to the Sydney region, particularly those restricted to the Hawkesbury Sandstone landform. The place is an outstanding example of a centre of biodiversity.'

The Northern suburbs of Sydney have had a long tradition in conservation activism which also includes a prominent resident, Annie Wyatt who established the Australian National Trust movement in 1945, raising community concerns of widespread destruction of the built and natural heritage in Sydney (Simpson 2002). FOKE believes we have a duty to preserve our heritage areas, whether natural or cultural, for future generations. There is a need to increase protections and build conservation understanding and support among our growing population.

The KGR proposal aims to build on the existing recognised natural and cultural heritage values of the area, especially its biodiversity, natural and cultural heritage (particularly Aboriginal), and to highlight its foundation of nationally and internationally significant geology and geomorphology that has resulted in the development of these unique traits.

The boundaries of the KGR initially focused on the KCNP and Muogamarra Nature Reserve but have gradually expanded to other public land to incorporate significant geosites in nearby areas, some of which are of international significance. Through the development and promotion of geotrails which link many of the geosites, a more complete and more coherent story of the region's natural heritage will be presented. Public accessibility and connectivity between the sites were determining factors in site selection.

Following further consultation and endorsement of land managers on the establishment of the identified geosites and geotrails, the plan is to then re-invigorate and highlight the area's importance within the unifying aspects of an identified GeoRegion.

This is a complex project needing extensive consultation with local Aboriginal and other community groups, State Government agencies and three Local Government Councils (Councils) i.e., Hornsby, Ku-ring-gai, and Northern Beaches. To date a comprehensive natural and cultural heritage document has been prepared to assist in promoting the significance of the area. Presentations have made to the relevant Councils, the NSW National Parks and Wildlife Service (NPWS), and local Members of Parliament, both State and Commonwealth; these members included the then NSW Minister for the Environment and the then NSW Minister for Planning and Public Spaces. The intention is to continue to brief and seek input from incoming Ministers, local members and Councillors as might be required. FOKE has also been active in initiating briefings of other community groups across the proposed area. To date, all presentations have resulted in strong support and offers of assistance for the project.

FOKE believes that the nomination of the KGR as an Aspiring UNESCO Global Geopark would achieve an outstanding outcome to complement the Greater Blue Mountains World Heritage Area and Australia's first national park, the National Heritage-listed Royal National Park – as together these three outstanding landscapes on the rim of Australia's largest city, showcase our unique natural and cultural heritage for the world and for Sydney residents, many of whom are committed bushwalkers.

Moreover, given the substantial number of secondary schools located across Sydney's northern suburbs, the establishment of a UNESCO Global Geopark would provide a comprehensive outdoors classroom for nature conservation and biodiversity protection for young and old residents to better appreciate the international significance of the natural and cultural heritage values celebrated on their doorstep.

REGIONAL GEOLOGY AND GEOMORPHOLOGY OF THE KGR (J.E. Martyn)

Permo-Triassic stratigraphy and deposition: regional setting of the KGR

The principal outcropping strata of the KGR encapsulate the upper part of the Narrabeen Group of Early Triassic age, followed by the Middle Triassic Hawkesbury Sandstone and watershed and ridge crest outliers and tongues of the succeeding Mittagong Formation, overlain by lower Ashfield Shale of the Wianamatta Group (Figure 4), all part of what is described as the Sydney Basin (Herbert and Helby 1980).

The term Sydney Basin in its geological sense encapsulates a vast area of Permian and Triassic sedimentary and volcanic rocks, broadly triangular and with a land area of around 25,000 km2 or roughly the size of Wales, extending eastwards onto the continental shelf. It is the southernmost in a chain of foreland basins to the New England Orogen, 1,700 km long, that extends right through to the Queensland coast near Bowen. The boundary between the Sydney and adjoining Gunnedah Basins is gradational northwards, the latter asserting itself north of the Liverpool Range Cenozoic volcanic belt.

The Sydney Basin formed well to the south, in polar circle territory (Fielding et al. 2008). It began with the formation of widespread suites of shallow marine sedimentary rocks with intermittent glacial input called the Shoalhaven Group (Figure 5) in the south, locally underlain by the similar Talaterang Group in the far south.

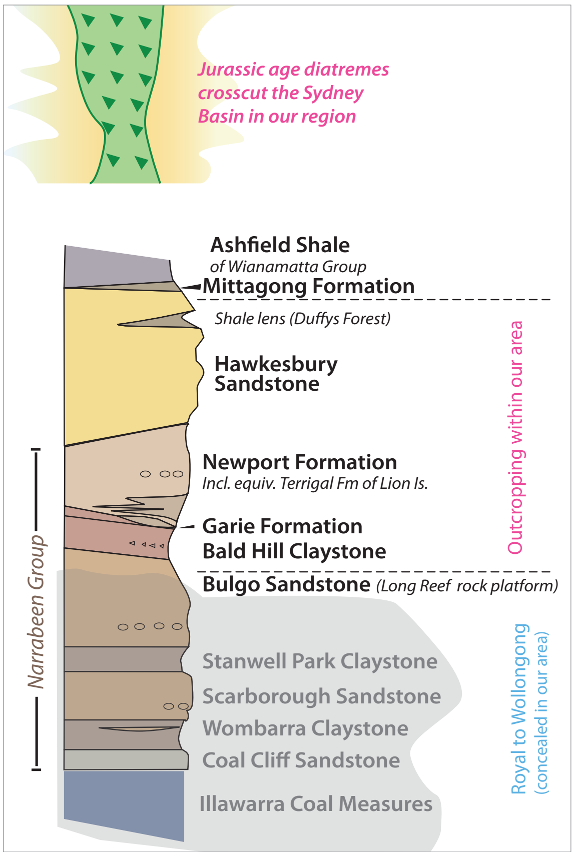

Figure 4. Stratigraphy of the Middle Triassic sedimentary sequence of the KGR.

The upper levels of the Shoalhaven Group and Lower Illawarra Coal Measures also embrace the

Figure 5. Glacial dropstone around 40 cm across in pebbly quartz lithic sandstone; Wasp Head Formation, in the lowest Permian Talaterang Group, Wasp Head (located outside of the KGR).

shoshonitic or potassium rich andesite lavas of the Gerringong Volcanics with which major early to Middle Triassic igneous intrusions, notably the Milton Monzonite and Termeil Essexite (Facer and Carr 1979) may be late co-magmatic. The Talaterang\Shoalhaven suite is paralleled in the Hunter Valley by the Dalwood Group, which is both sedimentary and volcanic, and the Maitland Group, both of shallow, cold water marine origin and separated by the terrestrial Greta Coal Measures. The terrestrial, rhyodacitic Rylstone Volcanics of early Permian age form a broken basal fringe to a thinned northern extension of the Shoalhaven Group in the far north-west, with a possible Late Carboniferous or Early Permian volcanic suite being intersected in AOG Kurrajong Heights No.1 Well in the Lower Blue Mountains (Pitt 1968).

The major coal measure suites follow; principally the 1.5 km thick Singleton Supergroup of the Hunter Valley, which includes the Newcastle, Tomago and Whittingham Coal Measures, and the broadly stratigraphic equivalent but much thinner Illawarra Coal Measures in the southern and western parts of the Basin. Apart from coal plus minor torbanite, the measures include terrestrial sedimentary rocks such as shales and sandstones and, including in the Newcastle Coal Measures, several units of conglomerate shed from a rising New England Mountain range to the north. Felsic volcaniclastic rocks also occur at intervals.

The top of the coal measures signaled the greatest life extinction event in the geological record at 252 Ma at the close of the Permian. This reset the biological clock and created a five million year 'delayed recovery' period for life forms (Metcalfe et al. 2015).

The Triassic Narrabeen Group that followed is coal seam free and dominated by sandstones rich in quartz in the west, volcanic rock fragments in the south-east and carrying yet more pebbles and sand washed from the New England Mountain front in the north. Although the Group is named after its coastal exposures within the KGR, its type section is where Sea Cliff Bridge follows the coast at Stanwell Park and Coalcliff, 25 km north of Wollongong. Here it carries three major sandstone units, the uppermost and thickest being the Bulgo Sandstone, which dips generally northwards beneath the sea to be further traceable in offshore drilling and to surface, briefly as mapped (Herbert, 1983), in the outer tip of Long Reef rock platform and arguably again at isolated Little Reef to its north. The distinctive red-brown Bald Hill Claystone, seen at Stanwell Tops and North Garie Head, also dips beneath the sea, and likewise re-emerges at Long Reef Point where it is beautifully exposed in the cliffs and rock platform, and at several seashore rock platforms northwards within the KGR. It consists of almost completely kaolinised and hematised, quartz-free, volcaniclastic sandstones and microbreccias, some thick beds of which still retain their original, largely unaltered, grey green colouration highlighting its origin. The Narrabeen Group (Figure 6) also carries fine volcanic ash, notably preserved in the thin overlying 248.33 Ma Garie Formation which carries accretionary lapilli (Deghani 1994; Metcalfe et al. 2015).

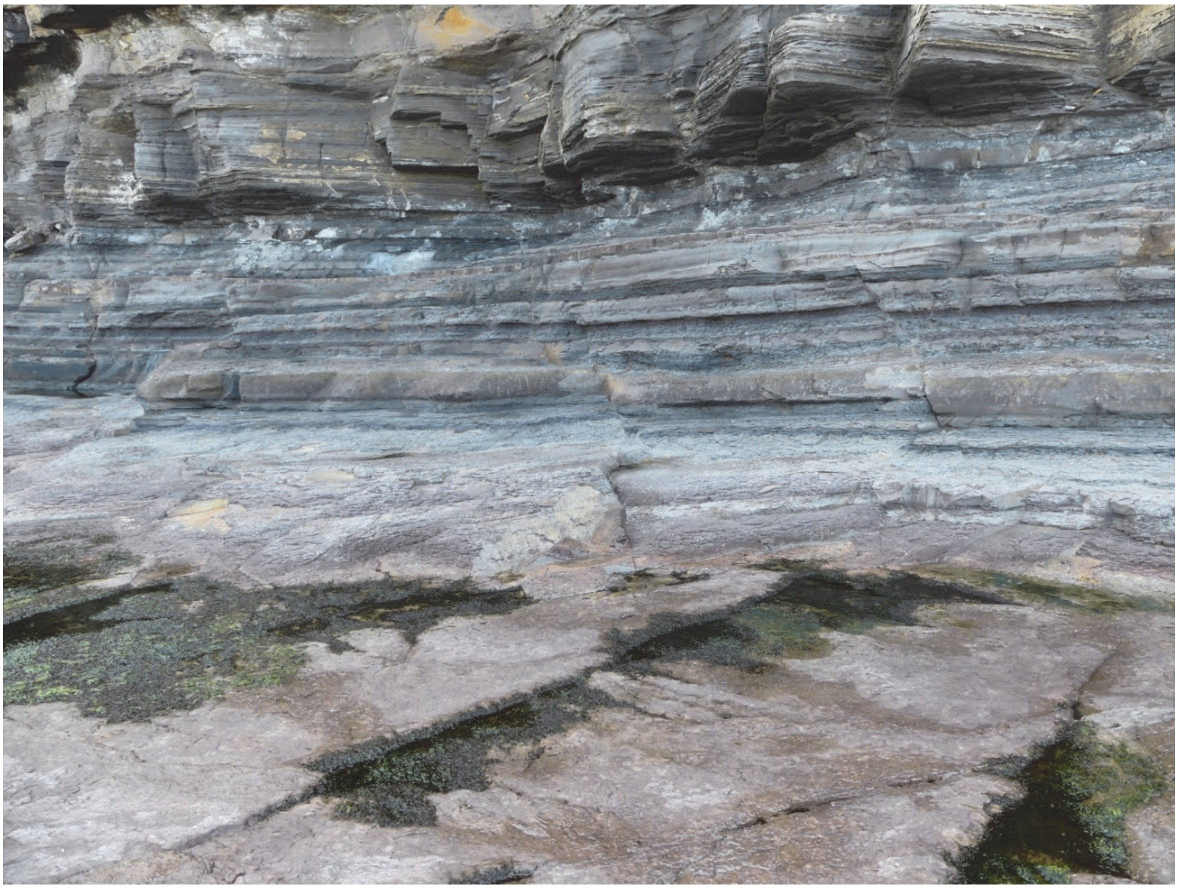

Figure 6. Upward transition from red-brown Bald Hill Claystone via thin Garie Formation to Newport Formation laminites, Narrabeen Group, Turimetta Headland.

The Bald Hill Claystone and Garie Formation are overlain by the northward thickening Newport Formation of laminites, and siltstones overlain by quartz lithic sandstones. This formation preserves numerous plant fossils, many of which reflect a shift away from Permian *Glossopteris* forests towards the seed fern *Dicroidium*, club mosses and horsetails. The exposures of Narrabeen Group strata along the coastal cliffs and shoreline of the KGR (Figure 7) are world class and include some unique windows into the biological changes and adaptations following the extinction event climatic shift (Retallack 1999).

The Newport Formation reaches more than 200 m in thickness as it crosses Broken Bay, emerging on the Central Coast as the Terrigal Formation. It becomes even more sandy in this direction too, although a significant thickness of quartz lithic sandstone is already established along the cliffs of the Northern Beaches, making up the bulk of North Avalon Head and the lower two thirds of the 102 m high Barrenjoey Headland. A thin band of polymictic conglomerate lies intermittently within these sandstones and carries chert and red jasper pebbles like those in the Munmorah Conglomerate and Newcastle Coal Measure conglomerates northwards along the Central Coast.

Forming the plateaus, cliffs and gorges of the North Shore, Hornsby, Illawarra, and lower Blue Mountains (including the KGR), the Hawkesbury Sandstone that overlies the Newport Formation is entirely of fluvial

Figure 7. The uppermost layers of the Bulgo Sandstone of the Narrabeen Group emerge from the sea at Long Reef where they form the outer tip of the point and are cut off at high tide and stormy weather.

origin, having preserved the deposits of a vast river braid plain that carried cross bedded sandbanks and meandering channels as well as oxbows and cutoff lagoons. The ultimate sources of the river were quite distant. Research has dated grains of the mineral zircon at an age that links the river's ultimate headwaters to igneous intrusions in what today are the Transantarctic Mountains (Veevers et al. 2006), as well as other sources probably now buried by ice. As part of the supercontinent of Gondwana, Antarctica was joined to Australia until final separation 45 million years ago.

The sandstones capture the conditions across the braid plain preserving migrating sandbanks and thick sand deposits, now manifest as the flat topped benches, bare rock platforms and low cliffs typical of sandstone ridges and uplands in the KGR. The formation is also well exposed at accessible sea level at Dee Why Point (Figure 8). Some of the ridgetop bare rock platforms display wonderful examples of tessellated pavements and other surficial phenomena (Figure 9) that are often misinterpreted as igneous or volcanic heating and cooling events. These features are addressed under the heading of 'Landscapes of the KGR'.

Interbedded with the thick sandstones are those that are more thinly bedded, and also siltstones, laminites, and shales laid down in the inevitable floodplain lagoons and oxbows. These deposits were preserved as lenses of shale, siltstone and laminite from centimetres up to tens of metres in thickness, the most striking example within the KGR being at Duffys Forest where a clay weathered from a 30 m thick shale was once mined for brick and ceramics manufacture. Another of the lenses, this one seven metres thick, was once exposed in a clay pit at Beacon Hill in the KGR and proved highly fossiliferous.

The Mittagong Formation forms a fairly narrow and patchy fringe bordering the Hawkesbury Sandstone at its boundary with the largely built-out Ashfield Shale along the southern borders of the KGR. Outcrop is poor to non-existent but the formation is marked by stony, iron rich soils and hosts distinct plant communities like Duffys Forest Ecological Community and Sydney Turpentine-Ironbark Forest. Excellent examples can be found in Bicentennial Park (West Pymble), the lower third of Sheldon Forest (Pymble), and ridges and spurs

Figure 8. Classic Hawkesbury Sandstone exposed in the cliff at Dee Why Point on the south-eastern edge of the KGR, readily accessible from the beach at low tide.

Figure 9. Possibly the finest example of a tessellated pavement on Hawkesbury Sandstone; Elvina Trail, KCNP.

off Bobbin Head Road (North Turramurra). Note that the Duffys Forest township area is not itself underlain by the Mittagong Formation, but rather a thick shale lens in the upper Hawkesbury Sandstone. The best example of Ashfield Shale in the KGR is undoubtedly found in Sheldon Forest with its magnificent Blue Gum High Forest community.

Fossil flora and fauna

The marine Permian of the Shoalhaven and Talaterang Groups of the South Coast (Runnegar 1980) is renowned for its abundance of cold-water shelly fossils (Figure 10), and time equivalent fossiliferous marine strata can be found in the Hunter Valley Permian though not in accessible coastal cliff outcrops as in the south. Those of the South Coast are visible and photographable (but not collectable) along several shore platforms, notably in the Wandrawandian Siltstone at Warden Head near Ulladulla and in the Broughton Formation at Black Head, Gerroa.

Figure 10. Fossil bryozoans, Westley Park Sandstone Member, Broughton Formation, Shoalhaven Group, Gerroa.

Megafossil floras have been described from much of the Sydney Basin sequence (Retallack, 1980). The onset of terrestrial freshwater environments in the Late Permian coal measures favoured the coal seam forming *Glossopteris* boreal swamp forests for a lengthy period but this was brought to a sudden close by the end-Permian extinction event at 252 Ma, widely attributed to intense end-Permian mafic volcanic activity in Siberia. A new flora gradually established itself but differed in character and the coastal shore platforms and cliffs of Sydney's Northern Beaches, within the KGR, have yielded many examples. The depositional environment was a complex mix of shallow freshwater lagoons, fluvial deltas, and estuaries with periodic intervals of emergence and weathering. Its stratigraphy revolves around the Newport Formation and Bald Hill Claystone as well as the Garie Formation. Commonest plant remains are of equisetales or horsetails such as *Phyllotheca*, grooved and jointed, carbonised fragments of which resemble broken bamboo stems. These are accompanied by a variety of other forms notably the cogwheel-like cones of a small-tree sized club moss *Cyclostrobus* and the fern-like fronds of the seed fern *Dicroidium* (Figure 11). Frequent rockfalls of shaley Newport Formation yield lots of fossils notwithstanding safety issues, and all sites lie within the KGR (Figure 12).

Figure 11. Fossil plant remains in siltstones of the Newport Formation, Narrabeen Group, Turimetta Headland. Striated stems (lower centre) are of an equisetalian or horsetail; fern-like fronds are probably of the seed fern *Dicroidium*.

Figure 12. Ichnofossils of *Barrenjoeichnus mitchelli* from a laminite horizon in the Newport Formation, Barrenjoey Headland.

The fossil remains of a large amphibian initially identified as *Paracyclotosaurus* were discovered in the lower part of the Bald Hill Claystone (previously wrongly assigned to the Bulgo Sandstone) at Long Reef in 1986 but was subsequently renamed *Bulgosuchus gargantua* (Damiani 1999) becoming the holotype of a new species. Other vertebrate discoveries at Long Reef include vertebrae of a proterosuchid archosaur, or primitive crocodilian (Kear 2009) while amphibian footprints have been found at Turimetta Headland and in the upper Hawkesbury Sandstone at Berowra (Farman and Bell 2020), both lying within the KGR. The presence of amphibians is compelling evidence for freshwater environments, compared to the present day, where of more than some 8,000 amphibian species, only one flourishes in saltwater.

Lying within the KGR is possibly the single most significant vertebrate fossil locality in the Sydney Basin, the former Beacon Hill brick and tile quarry located in a Hawkesbury Sandstone shale lens. Wade (1935) identified more than 20 different fish genera and the quarry shales also yielded fossils of amphibians, plants, and insects (Whitehouse 2016). They are probably the deposits of a large cutoff lagoon stranded on the Hawkesbury Sandstone floodplain. After infilling with hard rubbish (building materials, soil, and rock etc.), the site was sadly but inevitably developed for housing and for recreational playing fields (Beacon Hill Oval and Beacon Hill Reserve) following its closure in 1962, burying an almost unique window on a challenging period in Australia’s Gondwana history.

Igneous events

Considering its essentially and dominantly sedimentary nature, the Sydney Basin hosts a remarkably diverse range of igneous rocks, both intrusive and extrusive. The earliest events were Early Permian to very possibly latest Carboniferous in age and include the rhyodacitic Rylstone Volcanics, the basaltic to rhyolitic Gyarran Volcanics of the Dalwood Group in the Hunter Valley and probably the 384 m of undated volcanics intersected near the bottom of AOG-Exoil Kurrajong Heights No. 1 Well (Pitt 1968). The closest regional

Figure 13. Complex, banded, coarse grained alkali dolerite dyke of around 10 m width striking broadly westwards and clipping the northern shoreline of Barrenjoey Headland. The core hole is where a sample was taken for radiometric age dating featured in Embleton et al., 1985.

Figure 14. Basalt dyke, apparently undated, cutting Bald Hill Claystone on the Long Reef shore platform in a north-westward direction.

analogies are the Early Permian felsic volcanics of New England to the north. There are somewhat younger felsic pyroclastic intervals in the Late Permian Newcastle Coal Measures including the Nobbys and Awaba Tuffs, but these are of a much lesser scale.

The shoshonitic (K-rich andesite or latite) lavas (Carr 1998) that have such a profound effect on the landscape and fertility of the coastal Illawarra and Shoalhaven are Late Permian in age and were erupted from a volcanic mountain range to the south-east during the period of the Kiaman Geomagnetic Reversal. They are interlayered with shallow marine, fossiliferous volcanolithic sandstones. Volcanic activity continued to feed in clastic and airfall debris as late as the Early Triassic.

Jurassic and Cenozoic volcanic and intrusive activity in the Sydney Basin is strongly biased towards alkali basalt and differentiates such as microsyenite. Early Middle Jurassic activity is particularly relevant to our KGR which has one of the world's best exposed diatreme complexes in Hornsby-Thornleigh, and two of a mere handful of published Early Middle Jurassic radiometric dates of igneous intrusives – those of the Barrenjoey dyke (Figure 13) (171±3 and 173± 3 Ma; Embleton et al. 1985). This geosite is one of two excellent shoreline dyke exposures in the KGR, the other one, a well-known, geological locality crosses Long Reef shore platform (Figure 14).

There are several microsyenite laccoliths and one of olivine dolerite-teschenite of confirmed or probable Jurassic age intruded across the Basin, but it is the diatremes that are particularly characteristic, the KGR being host to seven of them (Crawford et al. 1980; Herbert 1983). Best available evidence links them to alkali basalt dyke activity and intrusion and the published model (Lorenz 1975) that powers them from vaporisation of Sydney Basin aquifers, thus providing a compelling mechanism, however the presence of clasts of dark grey fossiliferous marine Permian siltstone from depths of at least 1.5 km, such as found in the Thornleigh diatreme, substantially stretches the vertical dimensions. A compelling lookalike for Hornsby can be found pictured in a description of the Black Butte diatreme, Montana, in Delpit et al. (2014) in which vertical dimensions are at least two kms, subsidence along ring fractures was up to at least one km and Black Butte shows little downward tapering of its classic cylindrical form.

The clastic dyke of St Michaels Cave, in the KGR in North Avalon (Byrnes 1973; Morgan 1974), is possibly unique in the Sydney Basin, and while it carries no igneous content or obvious links, these authors have speculated on a connection to the gas-powered elements of the diatreme forming process. Some of its clasts are derived from shales of the Wianamatta Group and therefore down dropped from sources more than 200 m above.

Among other things, combustion of coal might also be considered as a possible auxilliary power source (or is the abundance of diatremes in a coal basin merely a coincidence?). A refining of the model for local diatremes should be attempted based on evidence obtained from the KGR.

Cenozoic alkali basalts in the Sydney Basin span a long time from 11 Ma going back almost to the late Cretaceous (Gibson 2007). They erupted across a broad area of the Blue Mountains World Heritage Area extending south as far as the northern Budawangs. There are none known in the KGR, the closest being a small occurrence at Maroota just to its west, however dykes of that era could easily be present but hidden from study by poor outcrop and deep weathering.

Tectonic history and setting

The timing of uplift and downwarping in the Sydney Basin is complex and varies over the broad spread of the Basin. Aspects of the Early Permian geology (280-299 Ma) are consistent with mild rifting and extension but deepening to the north into what is technically known as a foreland basin, a companion to the then rising mountain front of the New England Orogen, the eastern orogenic belt of the Tasmanides (Glen 2005). The push of this front from the north-east and east had caused basin deepening in the Hunter region by Mid Permian times at around 270-260 Ma, like a trough in front of an approaching ocean swell. These pressures also created key structures like the Hunter-Mooki thrust and the Lochinvar Anticline of the Hunter Valley. The deepened basin accumulated much thicker coal measures in the Hunter Valley area than those further south.

The New England mountains were eroded as they rose, flooding parts of the trough with gravels and sands carrying recognisable pebbles of Devonian rocks from beyond the Peel Fault. The gravels and accompanying sands spread southwards in sheets and fans during the deposition of the Newcastle Coal Measures and the overlying Narrabeen Group, although deposition in the coal measures was steered eastwards by the rise of the Lochinvar Anticline. This anticline is the prominent, south-plunging, upwarped structure that underlies the Pokolbin embayment, and it had a strong influence extending at least as far back as the Newcastle Coal Measures of Late Permian age. It also caused marked thinning of the overlying Narrabeen Group where it mantles the anticline.

Concurrently, potassium rich andesitic (shoshonitic) lavas called latites were erupted repeatedly into a region that is now the Illawarra coast south of Wollongong from centre(s) to the south-east (Campbell et al. 2001), only waning in the Late Permian Illawarra Coal Measures. Such igneous chemistry is often associated with a subsiding crustal plate. Those volcanic highlands continued to shed erosional debris through much of the Narrabeen Group and delivered late puffs of airfall ash creating the Garie Formation, perhaps drifting in on a south-easterly air stream.

The sheets of coarse sand and gravel from the north, and volcanolithic debris from the east, were gradually replaced by quartz-rich sands from the north-west then south-west, culminating in the vast sandy braid plain of a huge river. Within the Gondwana supercontinent, Australia at the time was attached to Antarctica and its upper reaches drew sand from the Transantarctic Mountains and additional unknown sources perhaps now buried by ice (Veevers et al. 2006).

The rocks of the Sydney Basin were folded and faulted in the Hunter region into domes, basins and faults of predominantly northerly alignment reflecting the contemporary west-directed compression of the New England Fold Belt. Deformation was strongest closest to the bounding Hunter-Mooki thrust system although this alignment direction is reflected in lesser folds throughout the Basin. The relatively steeply inclined Hunter-Mooki thrust pushed upwards and west to south-westwards. South and south-westwards away from the Hunter region, dips flatten across the vast tablelands of the Blue Mountains, Hornsby, and Woronora Plateaus. On a regional scale, except for the Lapstone Structural Complex, the rocks were little deformed.

The Lapstone Structural Complex bounding the Blue Mountains is the most abrupt and confronting structural landform in the Basin, being more linear and less indented than the Hunter-Mooki thrust. It is essentially an asymmetric horst complex where strata were draped into monoclines over deep rooted reverse faults (Fergusson 2006). At least two main periods of uplift were involved in combination with subsidence of the Cumberland Basin shale lowlands of Western Sydney.

Early deformation began at the soft sediment stage and in unstable settings like river braid plains, adjustments taking place under loading or due to seismic shock. Such instability created numerous slump folds and minor faults in the succession, and it can be difficult at times to pin down their relative timing where brittle and soft sediment structures intermesh at the same site. There are many examples of small-scale structures both brittle and soft sediment in the cliffs of the Northern Beaches and, also in the KCNP where small-scale soft sediment dome and basin forms can be found etched out by weathering on many sandstone platforms. Local medium and small scale 'thin-skinned' low angle faults from slightly later events and reflecting slippage and adjustment to regional extension and compression can be seen along the KGR coastline and are more common than is generally recognised.

Landscapes of the KGR

Scenery adds a substantial boost to the standing of any GeoRegion, and the KGR excels in this regard. The stunning and complex coastline and its erosional fragility will be covered in a later section, but the landscape of the central core is a major attraction, with the Hawkesbury Sandstone tableland of KCNP deeply indented by drowned inlets from post-glacial sea level rise, creating a two-tiered landscape and some striking contrasts for the visitor - from bushwalking in exposed, flower-rich heathland on the tops to boating and relaxing in quiet inlets (Figure 15).

The level but undulating surface might be interpreted as following the gently dipping bedding in the sandstone, but the base of the Hawkesbury Sandstone at Terrey Hills is more than 200 m below the land surface whereas at West Head whose land surface is only around 20-30 m lower, it is only about 100 m below, therefore we are dealing with an ancient peneplain surface. On this are the ghostly remnants of old, shallow drainage lines gently rising and branching towards low, undulating watersheds that feature many bare sandstone platforms and tors. Rainwater shed from these drains away sluggishly into swampy hollows and broader enclaves of swamp and wet heathland. Downstream those gradients steepen markedly and the water cascades over rapids

Figure 15. Coal and Candle Creek, viewed from the Centre Trail, KCNP.

and waterfalls, some reaching tens of metres in a single drop. Such knickzones and knickpoints were created by uplift leading to rejuvenation, upstream erosion, and valley deepening. The streams descend quite rapidly towards sea level but the steep, rocky valley sides of the inlets do not soften and flatten there but continue beneath the water surface framing deep inlets with strong links to the ocean.

The sandstone tableland surfaces, especially in the KCNP, carry numerous bare rock platforms and crags which usually show indurated or case-hardened surfaces that may be breached and undercut by caves and overhangs. The surfaces themselves may be covered in networks of polygonal fractures or tessellations that penetrate only tens of cms into the surface (Figure 9) but are a significant tourist attraction in the KGR. Rainwater trickling and running down low to moderate slopes has commonly etched runnels, or 'karren' by solution of silica (Figure 16). Other effects of silica solution include potholes in streams that may deepen into tunnels, particular above waterfalls, but also scattered across bare rock platforms accompanied by dimpling of the surface. Such potholes retain water for extended periods after rain, and the West Australian Nyoongar word 'gnamma' is often used for them. The hard, shell-like, case-hardened crusts of sandstone platforms are just cms in thickness as can be seen where a bench is undercut by cliffs and overhangs and softer, leached sandstones are exposed by breaching. These may commonly be honeycombed and peppered with 'tafoni.'

Figure 16. Surface solution runnels or karren created by rainwater on Hawkesbury Sandstone; McCowen Trig, Ingleside, KCNP.

Where broken and undercut by erosion, the sandstone surfaces and benches may expose the complex result of groundwater solution and migration of the original ferrous carbonate cement leading to domains of liesegang banding by iron hydroxides (Figure 17). Such domains may crosscut one another showing that this was not a one-off event but a long and complex succession of groundwater migrations.

Figure 17. Complex liesegang banding in Hawkesbury Sandstone, later domains crosscutting and obliterating earlier ones; Berowra Valley east side, Berowra.

P. Mitchell (pers. comm.) affirms that the most recent geological changes to the KGR landscape are the result of sea level change during the Pleistocene as the Earth passed through multiple ice age climate changes. According to Mitchell, this story began during the last interglacial (129-116 thousand years ago) when mean global temperature was 2°C higher and sea level was 4 to 6 m higher than present. No trace of this high stand has been identified in the KGR, but it is represented by 'raised beaches' in the Hunter River valley. Global climates became colder from about 40,000 years ago and then changed to glacial conditions in high latitudes and on mountain peaks. The coldest phase of the last glacial peaked between ~22,000 and 18,000 years ago, and the most immediate effect of this in the KGR was that sea level was depressed 120 m placing the coast some 15 km offshore. The climate in the KGR was relatively cool with an estimated average temperature drop of 5 to 9^{o}C, and a decrease in rainfall. These conditions must have affected the distribution of plants and animals, but we have little detailed information about the nature of those changes.

Mitchell points out that conditions became warmer between ~18,000 to 12,000 years ago, rainfall increased, and sclerophyll woodland and rainforests expanded. After ~6,000 years ago higher frequency climatic variability was more common probably with stronger El Niño/Southern Oscillation (ENSO) conditions in the past 3,000 to 4,000 years. In that brief period sea level rose at an average rate of about 10mm/year reaching or slightly exceeding its present level 7,800 years ago. In recent decades, these numbers have been revised and are slowly becoming more accurate, but it remains a challenge to identify specific details (Short and Woodroffe 2009).

Effects of this coastal flooding were that all the coastal valleys were converted to tidal estuaries. The soils that formerly covered the coastal plain eroded before the advancing sea and sand was swept to the present coast forming today's beaches. At Dee Why, Narrabeen, Mona Vale, and Palm Beach, the volume of sand deposited in the coastal barriers (beaches and dunes) was sufficient to block the streams and form lagoons. Palm Beach is a special case, where the 'Pittwater River' originally flowed to the sea in a bedrock valley 75 m beneath the Palm Beach barrier. When the rising sea reached an elevation of about -30 m the river overtopped the sandstone ridge that joined West Head and Barrenjoey and then flowed north directly to the Hawkesbury River. This allowed the Palm Beach barrier to close and form today's landscape. Mitchell also points out that another consequence of these changes is that sediments and water depths in Broken Bay, Pittwater, and Sydney Harbour are very variable.

FLORA OF THE KGR (J.E. Martyn and J.B. Walsh)

The vegetation formations (Keith 2004; Thomas 1985) of the KGR include rainforest, wet sclerophyll forest, dry sclerophyll forest, heathland, forested wetland, saline wetland, and small areas of grassland on the coastal headlands. These formations support diverse plant communities and plant species with many identified as threatened under both state and federal legislation.

Vegetation classes (Keith 2004) within these formations include Sydney coastal dry sclerophyll forests and Sydney coastal heaths which come in many forms that frequently intergrade and complement a canopy of red bloodwood (*Corymbia gummifera*), scribbly gum (*Eucalyptus haemastoma*) and silvertop ash (*Eucalyptus sieberi*) on ridgetops and smooth-barked apple (*Angophora costata*), Sydney peppermint (*Eucalyptus piperita*), and grey gum *(Eucalyptus punctata*) on slopes. Where soils are shallow and fire frequency high, eucalypts endemic to the KGR including yellow top mallee ash (*Eucalyptus luehmanniana*), and the vulnerable Camfield's stringybark (*Eucalyptus camfieldii*), plus *Angophora crassifolia* are present. Understorey composition varies greatly. Sydney coastal heaths are characterised by a relatively open or eucalypt-free canopy with an abundance of flowering mid-storey and groundcover plants. They are highly fire prone, quick to regenerate and gradually change in structure and species composition in relation to age since burnt and fire frequency.

Rocks and trees – the links between the KGR's geology and flora

Geology is a major influence and control on vegetation in the KGR. There are many other influences, especially terrain and microclimate, including distance or protection from the exposed, windy coast, but then geology's influence on terrain also has a critical downstream effect on microclimates. The flora of the KGR is rich and highly variable beyond any attempt at a full description in this paper, but below are some highlights (Martyn 2018).

Narrabeen Group and Hawkesbury Sandstone of the coast

The northward thickening quartz lithic sandstones of the Newport Formation dominate the cliffs of the KGR's ocean coast, intermittently capped by Hawkesbury Sandstone. The impure nature of the Newport Formation sandstones and their interleaved laminites support a richer and more varied flora than that of the quartz rich Hawkesbury Sandstone, although only a small percentage of its original natural cover survives. Plant communities include critically endangered littoral rainforest and coastal vine thickets of Eastern Australia, notably on Barrenjoey Headland (Figure 18), and the endangered communities known as the *Themeda* grassland on seacliffs and coastal headlands at Turimetta, Narrabeen (Figure 19), and Pittwater, as well as the Pittwater and Wagstaffe spotted gum forest around the shores, lower slopes, and islands of Pittwater (Figure 20).

Hawkesbury Sandstone and its thin skeletal soils and rocky hillsides carry coastal heathland on Barrenjoey and Bangalley Headlands. The latter shows a classic case of microclimate effects where a dense, low woodland of broad-leaved white mahogany (*Eucalyptus umbra)* near the southern limits of its natural range takes over from heathland on the protected, shoreward side.

Hawkesbury Sandstone of KCNP

The sandstone tableland of the KCNP is undulating and intricately indented, with vertical relief reaching more than 150 m around its margins. Fire history has impacted and modified a patchwork mosaic of woodland, shrubland, and heathland (Figure 21) and the circumstantial history of fire at a particular location is responsible for how that impact is expressed. In other respects, gentle hollows in an ancient drainage profile host upland swamp of the endangered coastal upland swamp in the Sydney Basin Bioregion ecological community (Figure 22). These and surrounding heaths and wet heaths are florally rich giving some spectacular wildflower displays. Descending the stepped profile of the hillsides, lush, moist, fern-rich communities at cliff bases can be encountered, and perhaps even a colony of the endangered *Haloragodendron lucasii.* Lower slopes and ravines host warm temperate rainforest pockets with coachwood (*Ceratopetalum apetalum*), crabapple (*Schizomeria ovata*), lilly pilly (*Acmena smithii*), and black wattle (*Callicoma serratifolia*), while rocky creek lines (Figure 23) are home to water gums (*Tristaniopsis laurina*) intruding their roots under boulders and into wet crevices.

Hawkesbury Sandstone shale lenses, Mittagong Formation, and Ashfield Shale

The sometimes-substantial shale lenses in the upper Hawkesbury Sandstone and the overlying transition via Mittagong Formation to Ashfield Shale, often overprinted by lateritisation and draped in detrital laterite, carry their own floral suites. The critically endangered Caley's grevillea (*Grevillea caleyi*) (Figure 24) is endemic to the lateritised transitional strata in the Terrey Hills-Duffys Forest area, an environment that also hosts waratahs (*Telopea speciosissima*) (Figure 25) - the bright red bush beacons, florally prized but unfortunately often plundered. The transition to Ashfield Shale brings in two critically endangered plant communities, the Sydney Turpentine-Ironbark Forest (Figure 26) and Blue Gum High Forest, the latter sadly depleted, although hosted by Ashfield Shale and well protected in Sheldon Forest in the Turramurra/Pymble area.

Flora of diatremes

Of the seven diatremes within the KGR, two, Oxford Falls and Peats Crater, are largely cleared of natural vegetation, however the others have no consistent patterns in their vegetation. Surviving forest in the Hornsby-Thornleigh diatreme complex belongs to a variety of the Blue Gum High Forest community (Figure 27) that has a higher proportion of mostly rainforest understory species but is rumoured to have once supported an undocumented number of red cedars (*Toona ciliata*).

Surviving natural fringes of Fox Valley diatreme (Browns Field) are thickly forested with warm temperate rainforest while trial and local community plantings have expanded the species range into subtropical territory (Figure 81). The Peats Bight diatreme is partly under the influence of a tidal inlet while the adjoining Peats Crater, which once contained some Sydney blue gums (*Eucalyptus saligna*) was largely cleared for farming and grazing until about 1974. It also contains remnants of an Osage orange (*Maclura pomifera*) hedgerow. A relatively large population of Eastern Grey Kangaroos (*Macropus giganteus*), reported to have been introduced at some unknown date, have continued to inhibit regeneration of the original vegetation in the Crater. The Smiths Creek Crater hosts cabbage tree palms and rough-barked apple (*Angophora floribunda*) in the overstorey, while the Campbells Crater near Cowan, which sits at a higher elevation, hosts rejuvenating red cedar, rough-barked apple, crabapple, and blue-leaved stringybark (*Eucalyptus agglomerata*). Smiths Crater and Campbells Crater also each contain rainforest understorey species typically dominated by mesic shrubs and ferns such as scentless rosewood (*Synoum glandulosum*) and rough tree fern (*Cyathea australis*).

Dykes are normally too narrow to register in the vegetation, but West Head is an exception where the dyke linked to West Head swells and branches reaching several tens of metres in width, supporting complex mixed forest with grey ironbark (*Eucalyptus paniculata*), turpentine (*Syncarpia glomulifera*) and large-fruited red mahogany (*Eucalyptus scias*) in the overstorey and a mesic or littoral rainforest understorey dominated by cabbage tree palms (*Livistona australis*) and burrawang (*Macrozamia communis*), two plants known to be harvested as 'bush-tucker' by Aboriginal people (Figure 28).

Figure 18. Endangered littoral rainforest on Narrabeen Group laminites and quartz lithic sandstones; sheltered west side of Barrenjoey Headland.

Figure 19. Endangered *Themeda* grassland on the cliff top, north of Narrabeen.

Figure 20. Endangered Pittwater and Wagstaffe Spotted Gum Forest, Lovett Bay, Pittwater.

Figure 21. Heath with scattered woodland trees and prolific flowering of Sydney boronia (*Boronia ledifolia*).

Figure 22. Endangered coastal upland swamp dominated by red saw sedge (*Gahnia sieberiana*), Salvation Creek, KCNP.

Figure 23. Valley rainforest dominated by coachwood and water gum, Cockle Creek tributary, Bobbin Head area.

Figure 24. Critically endangered Caley's grevillea (*Grevillea caleyi*) on lateritised shale in the Terrey Hills area.

Figure 25. Endangered Duffys Forest ecological community growing on mixed laterite and a Hawkesbury Sandstone shale lens.

Figure 26. Blackbutt dominant forest growing on Mittagong Formation with native indigo (*Indigofera australis*) in full flower, Sheldon Forest, Turramurra.

Figure 27. Critically endangered Blue Gum High Forest, Thornleigh diatreme.

Figure 28. Lush forest and rainforest over thickened dolerite dyke, West Head, KCNP.

Figure 29. View of the eastern face of Hornsby quarry in 1978 (then actively being worked).

THE HORNSBY DIATREME (I.G. Percival)

Introduction

Nearly 100 volcanic necks (the eroded remains of various types of intrusive and associated extrusive igneous features) have been mapped in the Sydney Basin (Crawford et al. 1980). Many of these are deeply weathered and form topographic hollows. The Hornsby Diatreme is unique among these shallow intrusive bodies in that quarrying operations have exposed a spectacular cross section through the upper part of a volcanic neck which is relatively unweathered and hence retains characteristic phenomena that developed immediately post eruption. Diatremes are quite rare geological features, and the Hornsby Diatreme is certainly the best example known in NSW, if not in all of Australia.

The presence of a volcanic neck in Old Mans Valley, west of Hornsby Railway Station, was first recognised in the early 20th Century, at the time quarrying operations commenced. Initial studies were undertaken by Morrison (1904), Benson (1911) and Andrews (1924). Interpretation of the structure as a diatreme came much later (Wilshire 1961) as the structures in the east face of the quarry were exposed. Through its inclusion in field guides by Nashar (1967), Adamson and Taylor (1976), Percival (1985), and Branagan and Packham (2000), and its illustration in a coffee-table book on volcanoes by Sutherland (1995), the diatreme has been recognised as being important both for geological research and public education, and as an outstanding item of geological heritage.

Location and quarrying activities

The now-disused Hornsby Quarry is located within Old Mans Valley, 1 km west of Hornsby Railway Station, with access from Quarry Road (Figure 3). At the time of writing the quarry void, which was partly infilled using spoil excavated from the NorthConnex road tunnel (2016-2019), is being landscaped and developed by Hornsby Council into an extensive public recreation area (Hornsby Park). Quarrying operations commenced in 1905 to exploit a deposit of volcanic breccia including large clasts of basalt. It was operated by Hornsby Shire Council during the 1920s, producing ‘blue metal’ or crushed rock aggregate for road building purposes. Subsequently the quarry was acquired and operated by Farley and Lewers, later combined with Readymix (now CSR Construction Materials), from 1959 to 2003. During its operation, the quarry was excavated to a maximum depth of approximately 120 m adjacent to the southern face but has now been infilled to about half that depth. The east face of the quarry exposes a cross section through the diatreme, exhibiting stratified volcanic breccia in a convex-down, basin-like configuration (Figure 29). The diatreme, which extends well beyond the quarry footprint, is approximately 1.5 km long trending north-east / south-west and approximately 500 m wide in a north-west / south-east direction. The total length is nearly doubled (2.7 km) if the Thornleigh diatreme adjoining to the southwest, which is demonstrably part of the same system, is included.

Geological significance

Hornsby Quarry is the largest diatreme known in the Sydney Basin and provides the last remaining artificial section through a diatreme in this State. Diatremes are the remains of maar volcanoes, produced by explosive eruptions that cut deeply into the country rock. A maar is the crater cut into the ground and surrounded by an ejecta ring, while the diatreme structure continues downward and encloses diatreme and root zone deposits (White and Ross 2011). Maars typically form because of the explosive interaction between molten volcanic material and groundwater. No surface trace of any maar associated with the Hornsby Diatreme has survived as the explosive surface of the vent was much higher than the present landscape.

The Hornsby Diatreme is composed of volcanic breccia containing large fragments of basalt and smaller fragments of a range of igneous rocks including granite, gabbro, and rare peridotite. Also associated are fragments of shale, sandstone, conglomerate, and coal, which represent Sydney Basin strata intersected by the diatreme conduit as it intruded, combined with cover deposits that fell into the crater resulting from the explosive eruption. A further significant volcanic phenomenon recognised in the diatreme at Hornsby Quarry is the presence of accretionary lapilli (Byrnes 1982), which refers to pebble sized (4-32 mm) spherical particles found in blocks of rock in various parts of the quarry. These are interpreted to have formed in an ash cloud when hot ash particles cool to form nuclei around which layers of ash and mud coalesce as they descend. Such evidence of explosive eruptions (Hamilton 1970) is an important feature representative of a maar (or steam) volcano. An example from the Hornsby Diatreme is illustrated in Figure 30 and is comparable with accretionary lapilli collected from the Missouri Breaks diatreme in Montana (Delpit et al. 2014, fig. 13).

The occurrence of coal fragments in the Hornsby Diatreme, and presence of Permian marine fossils in clasts within the nearby Thornleigh Diatreme indicates that steam-driven brecciation of these strata took place at a depth of approximately 1,300-1,500 m (the thickness of the Triassic sediments overlying Permian strata in the central Sydney Basin). That may imply the presence of deep aquifers to supply water that was explosively converted to steam when it encountered magma (e.g., Delpit et al. 2014). However, the Triassic sediments would not have been fully compacted at the time of the diatreme intrusion and silica overgrowths probably did not occlude porosity to the extent seen today; hence there may have been considerable interstitial water present in pores of the sandstones. Explosive vaporisation of this connate water in contact with magma potentially contributed to the brecciation at depth. J. Martyn (pers. comm.) also suggests that coalified material and gas in the underlying Permian section may have ignited when intruded by the rising magma, generating fractures.

The Hornsby Diatreme therefore provides a rare window into the petrology of the rocks forming the Earth's crust through which the molten material passed on its way to the surface. This is due to the inclusion of xenoliths in the diatreme material which provide evidence about the physical and chemical conditions of the lower crust below the Sydney area (Wilshire and Binns 1961; Joplin 1968; Griffin and O'Reilly 1986). An example is shown in Figure 31.

Figure 30. Lapilli in a fallen block on the 40 m bench of Hornsby quarry.

Figure 31. Small dark xenolith, in front of boot, embedded in larger rock fragment on access track at Hornsby quarry.

Dish beds

The most noteworthy features seen in the eastern face of the quarry are dish beds, as shown in Figures 29 and 32. Dish beds, or 'centroclinal (saucer-shaped) bedding' of White and Ross (2011), have been attributed to subsidence of the diatreme fill during the eruption. Barron and Barron (2001) have suggested a new interpretation of the saucer bedding as being a result of original deposition, rather than slumping or subsidence as previously thought, and contributed to recognition of a previously undescribed lithology known as muddy breccia. Although White and Ross (2011), in their global review of maars and related volcanic features, depict dish beds and bedding in diatremes, none are comparable with the exposure in Hornsby Quarry.

In recent years there has been considerable geological interest in diatremes because of their potential to host valuable ore deposits such as diamonds in kimberlite pipes. As a result, new structural information has been collected overseas (Kurszlaukis and Fulop 2013) and it will be instructive to see how Sydney diatremes fit these models.

Diatremes are both more complex and more common than have previously been described. The general model of them being emplaced by a single eruption now seems to be unlikely and detailed mapping of their stratified fills suggests that multiple eruptions are the norm, and that the eruption centre usually moves deeper in the feeder pipe over time.

The first stages of formation are simply the injection of magma upwards through country rock. When this hot magma comes in contact with saturated rock or sediments a phreatic explosion occurs establishing a shallow crater which may become a maar if flooded. Subsequent explosions widen the upper throat of the diatreme, and the explosion centre moves deeper. As debris is ejected at the surface and as the available water supply is reduced the highest parts of the pipe widen, and the dish beds are formed. At depth, the conical pipe becomes narrower, brecciation is reduced, and more solid magma, which typically contains xenoliths (foreign rocks) derived from the lower crust or even the Earth's mantle fills the pipe (conduit). Such xenoliths have been described from several Sydney diatremes, including Hornsby, and have been used to infer the composition of the deep crust at a depth of perhaps 20-30 km.

Sometimes the explosive centre can also move laterally, and this is the probable explanation of twinned diatremes such as those at Hornsby/Thornleigh and Peats Crater/Peats Bight.

Exposed unweathered diatreme structures and rock

Hornsby Quarry is now the only easily accessible locality in the Sydney Basin where it is possible for scientists and students to examine and access internal features and investigate the unweathered rock forming this feature. When the diatreme formed, the crater and its filling was at ground level, perhaps slightly elevated, but erosion since the Jurassic has eroded a significant – though difficult to quantify – thickness of sediment to expose the unweathered upper part of the diatreme infill. Taken together with the naturally exposed Bondi Diatreme on the coast at Bondi, the cross section exposed on the eastern face of Hornsby Quarry comprise a pair of exposures showing both the lower and upper parts of diatremes as per the models of Lorenz (1973) and Delpit et al. (2014), (see also Crawford et al. 1980; Rickwood 1985). Exposures of the diatreme margin recently uncovered in access road cuttings on the north flank of the quarry reveal the highly faulted nature of this margin with steepening of dips to about 70º due to ring fault drag (J. Martyn, pers. comm.).

Age of the diatreme

Studies of pollen, coal and wood fragments incorporated in the volcanic breccia at Hornsby Quarry (Joplin 1968; Taylor 1976; Morgan 1976, 1977, 1978; Helby and Morgan 1979) revealed that it, and most likely the other 95 known and sixty inferred diatremes in the Sydney Basin, are of Early to Middle Jurassic age (201-163 Ma). This suggests that at that time the land was characterised by swampy environments with high groundwater tables and was peppered with exploding maars.

Geoheritage documentation, threats, and status

Uniquely exposed in the quarry wall at the eastern end of the site, the cross-section through the dish beds of a Jurassic age diatreme is of state, national and arguably of global significance. No other sites are known in NSW or Australia where dish beds in a diatreme are exposed, making the Hornsby Quarry unique on a national level. Furthermore, an international image and literature search also found no sites with an exposure of dish bedding comparable with that in the eastern face of the quarry, which is therefore likely to be a geoheritage feature of international significance, given how well it illustrates cross-sectional models (e.g., Delpit et al. 2014).

The geoheritage significance of the Hornsby Diatreme at the Hornsby Quarry site was first documented in the initial report into the Geological Heritage of NSW (Percival 1979) coordinated by the Geological Society of Australia (GSA) for the Heritage Commission of NSW. This information on the Hornsby Diatreme was subsequently published in a book by Percival (1985) and around this time the site was listed on the Register of the National Estate. When the Register of the National Estate was closed to further listings in 2007, and existing listings were required to be renominated for inclusion in the Australian National Heritage List, unfortunately this was overlooked, and national listing of the Hornsby Diatreme lapsed. The diatreme cross section was listed on the Register of The National Trust in September 2016. It is not currently listed in the NSW State Heritage Inventory.

In response to the plan of the Roads and Maritime Services to partly fill the quarry void with spoil from the NorthConnex project, a submission was made in 2016 by the Geological Heritage Subcommittee of the NSW Division of the GSA to the NSW Department of Planning and Environment. Though this submission appears to have been substantially ignored, with spoil from the NorthConnex tunnel being emptied into the quarry void directly over the eastern face of the quarry where the cross-section through the diatreme is exposed, a second opportunity for geological input eventuated in late 2019 when Hornsby Council sought public input into plans for the future development of the quarry void. The GSA argued that Council must incorporate the diatreme cross-section as a focal point of the new park. The GSA submission also urged Council to maintain access to the quarry face for the purposes of close scientific examination by researchers and students under supervision. Following submissions put to the Sydney North Planning Panel at a public hearing in May 2020, planning approval for the proposed redevelopment of the former Hornsby Quarry was deferred pending satisfactory resolution of several issues broadly including access to and visibility of the diatreme exposed in the eastern face of the quarry. These matters were addressed during a subsequent site visit facilitated by Hornsby Council, leading to planning consent being granted with redevelopment of the site now well underway.

Status of the diatreme exposure

The eastern face of the quarry that exposes a near-complete cross section through the dish beds of the diatreme has now been cleaned of all the excess spoil, which was delivered by a mobile conveyer system that discharged directly over this face. Only small pockets of pebble- and cobble-size white Hawkesbury Sandstone remained in crevices on the face, contrasting with the dark grey volcanoclastic breccia forming the diatreme layers. The compacted spoil material infilling the quarry void has been redistributed to create, at RL48, a lower level adjacent to the eastern face that will be the site of a lake as a central feature of the redevelopment. The effect on the diatreme cross section was to initially expose a further 5 m at the base of the section where more of the dish beds would appear to be flattening out in the centre of the visible structure. However, the depth of water in the lake may reduce this additional exposure. Comparison of photographs taken in 1978 (Figure 29) and 2020 (Figure 32) shows that the final level proposed for the quarry floor in the redevelopment will be like the exposure visible more than four decades ago.

Two bench levels retained from the original quarrying operations are still evident extending across the eastern face. The lower one is about 5-10 m above the current infill level, while the higher bench is at RL88 and can easily be accessed and walked along. This bench has a constant width of several metres, with a 35 m drop-off into the quarry (directly above the proposed water feature). Preliminary plans to construct an accessible

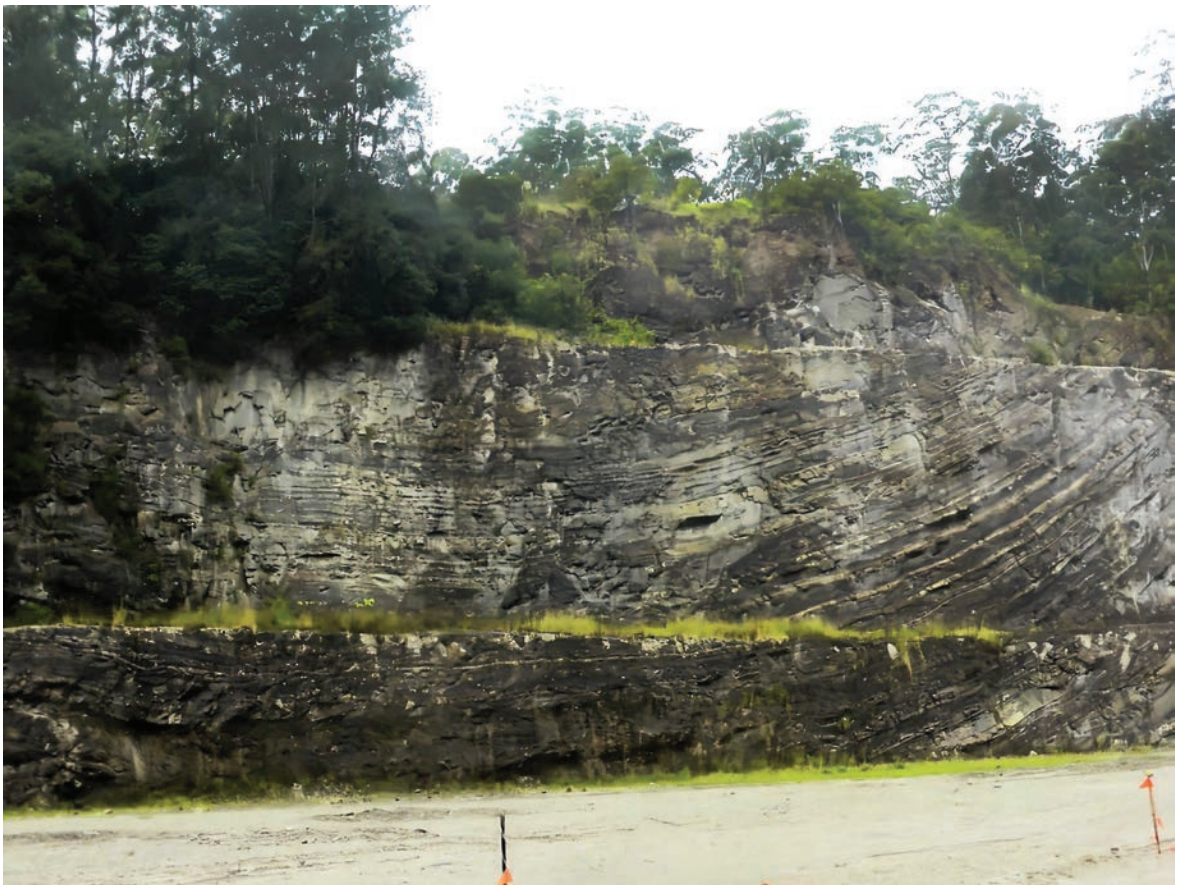

Figure 32. View of the eastern face of the now partly infilled and inactive Hornsby Quarry, taken during the site visit facilitated by Hornsby Shire Council on 10th June 2020, for comparison with Figure 29. The higher bench at RL88, extending from the dark green vegetation on the left and marked by small flags along the cliff edge, is the site of the proposed boardwalk. The compacted spoil in the foreground of the image will be excavated by a further 5 m. Note that the quality of this image was affected by the showery and overcast conditions on the day of the field inspection.

Figure 33. View of the dipping dish beds of the diatreme and the varied lithological components (including angular clasts, and fine-grained volcaniclastic material forming the matrix, also known as muddy breccia) of the diatreme. Geological hammer for scale and indication of verticality. Image taken on bench at RL88, 10th June 2020.

raised boardwalk along this bench, flanked on one side by a safety fence adjacent to the cliff edge, and on the other by a chain-link (or similar) fence that would permit largely unrestricted visibility of the bedding comprising the diatreme (Figure 33) but would prevent visitors from touching or closely examining the rock face. This barrier was necessary to prevent vandalism of the beds, and as a safety measure to guard against rocks from the face being dislodged.

While the east face prominently displays the dish beds, surge deposits, rock lenses, breccia layers, and accretionary lapilli (amongst other geological attributes), it should be noted that some of the other quarry faces potentially reveal volcanogenic phenomena that complement or add to those mentioned previously. In particular, the adjoining face extending to the south is significant in showing the contact between the diatreme and the sedimentary rocks (here the Hawkesbury Sandstone) of the Sydney Basin through which it intruded. Previous geological investigations of the entire site have revealed the presence of slumped bedding, sandstone dykes, surge-and pebble-rich layers, and a wide variety of ejecta associated with the violent intrusion, including basalt bombs with chilled margins, lithic fragments of charcoal in breccia layers, accretionary lapilli, and xenoliths. As many of these unusual geological features were recorded when the quarry was operational, it is unknown what remains of them, or whether new structures and volcanogenic phenomena will be revealed as covering vegetation and unstable spoil heaps are removed during redevelopment of the site.

Conclusion

The Hornsby Diatreme is a unique feature of geoheritage significance at state, national and arguably international levels. It captures a moment in geological time perhaps as much as 200 Ma and is at least as old as 163 Ma. The deposits so spectacularly displayed in the dish beds include rock samples brought up from deep in the Earth's crust. The cross section through the diatreme will form the focus of the redevelopment of the former quarry site into Hornsby Park.

Geotourism is an increasingly popular area of nature-based tourism, where geologists and the educated public travel to accessible sites to examine or view unique or spectacular geological phenomena. The Hornsby Diatreme is both. Increasing development in the Sydney region has left very few localities with geological heritage significance available to visitors (apart from those exposed along the coastline) - and certainly none as spectacular as the Hornsby Diatreme. Another advantage is that it is readily accessible by public transport. Given the known age of the volcanic event that produced this unique geological feature, conceivably rebranding the site as 'Sydney's own Jurassic Park' would present many opportunities to Council to promote the Hornsby area to local and international tourists.

STABILITY OF THE COASTAL CLIFFS OF THE KGR AND CLIMATE CHANGE IMPLICATIONS (J.J. Illingsworth and P.B. Mitchell)

Introduction

The coast of NSW is frequently affected by severe coastal storms which erode beaches and foredunes and can cause significant property damage. Such events occur about every decade and since the 1940s they have caused community concern that has prompted the NSW Government to address the issue through legislation such as the Coastal Protection Act 1979, the Coastal Management Act 2016, and by providing grant funding to local governments for protective works.

Storms and coastal erosion have been commented on since the earliest days of European settlement, but it was not until the mid-20th Century that they received much attention from the media. When lives were lost, and property destroyed, newspapers recorded the event but in the absence of those effects even very severe storms were largely unreported.

Until the mid-20th Century there were few cliff-top buildings and therefore little risk of property damage. The cliff-top margin is often reserve land and public parks or bush reserves. However, some sub-divisions within the Northern Beaches Council area placed Lot boundaries at the cliff margin or even at high water mark. This means that some cliffs are in private ownership and that several buildings and assets such as private swimming pools or public roads are constructed to within a few metres of the cliff edge. Some public swimming pools on shore platforms have had their safety conditions improved by cutting cliff faces back and installing wire mesh and rock bolts. The long-term success of these efforts is unknown.

As urban development spread along the coast, media coverage of major storms dealt more effectively with beach erosion, but it is still exceptional to find a comprehensive account of cliff failure. Part of the problem being that rockfall events are rarely witnessed and they often occur along parts of the coast that are difficult to view or access.

The access problem is reduced with the availability of unmanned aerial vehicles (drones) and high-definition video cameras. In 2020/2021 one of us (JL) flew a drone along the entire ocean coast from Dee Why Lagoon to Barrenjoey. This video material is available in the public domain (Pittwaterpathways 2022), and this paper is a first attempt to provide a comprehensive account of coastal cliff stability in that sector.

Local geological environment

This part of the coast all lies within the Triassic sedimentary sequence from the Bald Hill Claystone exposed at Long Reef up to the Hawkesbury Sandstone at the top of Barrenjoey. The lithologies vary from fine grained mud-rocks (Bald Hill Claystone) which fret readily on wetting and drying, through argillaceous and quartz lithic sandstones and laminites (Narrabeen Group), to very competent, well cemented quartz sandstones (Hawkesbury Sandstone) that normally fail along fault, joint and bedding planes as large, roughly cubic blocks.

The sequence is almost flat lying but with a gentle slope to the north. Tectonic jointing along the coast is recorded as being different from joint patterns in the same rocks a few kms inland and Norman (1986) described two important near vertical joint sets along the Northern Beaches coast with the dominant master joints having a NE (50^o true) trend which are crosscut by NW (120^o) joints. Norman noted that this pattern varies from headland to headland partly in relation to the lithology, and that a slight change in trend direction (~15^o) occurs between Narrabeen Group rocks and Hawkesbury Sandstone. Norman's total sample number for coastal observations is relatively low (n=173) but the patterns support a strong correlation between cliff orientation, joint directions, and the likely occurrence of rockfalls.

Coastal Geomorphology

The cliffs range in height from a few metres of rock face emerging from beaches to about 80m of free face on Bangalley Head. Most cliffs stand at an angle of between 70 and 80^{o} and are topped by a stepped and vegetated slope that extends back to the higher points along the coast. Nearly all cliffs have a sub-horizontal shore platform at their base. Platforms eroded in the Bald Hill Claystone are the widest, and in places where Narrabeen Group sandstones are at the base of the cliff, the platform can be quite narrow or locally absent. In these areas evidence for recent rockfalls is limited to 'fresh' scars on the cliff face as debris falls directly into deep water or is quickly removed. Where the shore platforms are wider, the base of the cliff may be partly buried by a wedge of vegetated scree which provides some protection from undercutting by waves.

Kotze (2007) identified toppling and sliding failures from the cliffs and emphasised the importance of undercutting which led to rockfalls. Two other modes of failure are apparent when cliffs in the Bald Hill Claystone are included. These are dry weather fretting and wet weather rilling which are constant and create small debris cones at the cliff base that are rapidly removed by waves during high tides and storms. The second failure type is limited to the extremely weathered faces of Bald Hill Claystone at Long Reef where planar slumps occur.

Rock weathering and the dilation of vertical joints behind the cliff face allowing the entry of water, iron oxides, and debris from the surface are also important steps in preparing cliffs for failure. Failure can occur at any time with little warning but is probably more common after periods of heavy rain and during violent coastal storms.

Previous literature

Other than occasional limited descriptions of rockfalls in the media, and rare photographs of particular events, there is little scientific literature relating to cliff failures on the Sydney coast. Roy (1983) assessed the few recorded rockfalls from sandstone cliffs south of Sydney and using limited data concluded that the mean long-term rate of cliff recession was probably less than 5mm/year and perhaps as low as 1mm/year. He noted that three Hawkesbury Sandstone rockfalls had been documented between 1935 and 1972, and that such events were episodic as time was required to undercut the cliff face. He supplemented his estimates with casual observation of rock weathering such as the period elapsed before the replacement of fishermen's rope anchor points, the loss of definition of carved and dated graffiti, and the apparent rate of weathering of sandstone sea walls. None of these approaches are very reliable but the estimates were consistent.

Estimates of this nature even over a period of 37 years can be immediately changed by the random occurrence of a single large event such as occurred in Sydney Harbour at North Head on 10 or 11th August 2016, when a 70 m length of Hawkesbury Sandstone collapsed into the sea. Located 300m northwest of the Fairfax Lookout the cliff at this point is between 18 and 22 m high, and the total rockfall volume estimated from Google Earth imagery is between 25,000 and 28,000 m^3 (see Water Research Laboratory 2016 for an oblique aerial view).

The structure of the sandstone and the stratigraphy of the cliff face appear to be important factors in the location of this failure. The base of the cliff is in Narrabeen Group sandstones which presumably weathered more rapidly than the Hawkesbury Sandstone and undercut the cliff. The fall aligns with the Watsons Bay Fault Zone (Och et al. 2009) which includes persistent vertical joints orientated NNE (30^{o} true) with mean spacing of 1 to 2 m, crosscut by a secondary vertical set-oriented NNW (145^{o} true) with mean spacing of 2 to 4 m.

In the less competent and more varied lithologies of the Narrabeen Group rocks to the north of Sydney Harbour cliff failures might be expected to occur more often. The only study that attempted to quantify failures from these cliffs was by Kotze (2007) who looked at the frequency of rockfalls from the coastal cliffs within the LGA of the former Pittwater Council. He worked from Council records which were probably incomplete and was unable to access 25% of the cliffs in his study area. Kotze found that over a 15-year study period, 15 rockfall events with volumes greater than one cubic metre were known, the largest fall was 400 m^3 at South Avalon, and a total of 950 m^3 of rock was involved which equated to a rounded figure of 10 m^3 of rockfall per km of cliff per year.

Methodology

The drone was flown at a height approximately equal to the middle of the cliffs and at a variable distance from them. The video data was edited to provide continuous cover and examined to derive descriptions of the nature of the coast and to identify what appeared to be 'recent' cliff failures.

The definition of 'recent' was not well constrained and was based on the absence of dark rock weathering on the scar compared with the adjacent cliff and the angularity and absence of vegetation on the rockfall debris. In a few cases, falls of a known age could be compared with others. By using stratigraphic evidence of rockfall debris resting on concrete structures of known age and attempting to match individual falls with air photographs, we believe that all ‘recent’ falls have occurred since 1975; therefore the elapsed time in our data set is about 45 years. A second problem was how to estimate the volume of the fall. Where possible this was measured on the scar rather than the debris and the scale most often used was human figures on the shore platform. It was assumed that the height of people visible in the image was 1.8 m and this could be matched against the rockfall dimensions.

Inevitably the results presented here reflect our judgement about time and scale and the data should only be seen as estimates. The real value of the video will become apparent on the next occasion that the flight path is repeated, and new images can be compared with the present set.

Results

Between the mouth of Dee Why Lagoon and Barrenjoey there are 11 sections of cliff, five zeta curve beaches on barrier systems, and eight pocket beaches. Only the five larger beaches contain a considerable volume of sand, whereas the other eight are much smaller and are simply a thin wedge of sand on buried shore platforms that abut inactive cliffs on the landward side.

The total length of coast flown was 26.8 km. Of this, 12.9 km or 48% was cliff that is accessible to present day waves, 3.8km or 14% was inactive and vegetated cliff at the rear of the smaller beaches. The total length of beach and dune was 13.9 km or 52% of the study section. Table 1 summarises the statistics of all the cliffs and the individual sections are described below.

Location	Cliff length m	Number of recent falls	Estimated total volume m^3	Mean volume (m^3) per km (rounded)	Joint directions (degrees true)	Comment
Long Reef Point	1,210	9	280	200	39, 122, 182	Jointing is weakly developed, slumps of weathered rock and fretting common.
Narrabeen Head	260	4	710	2,700	33, 98,122	Fault zone at north end of platform.
Turimetta Head	1,090	15	4,900	4,500	36, 129	Very active fall environment, approximate alignment with the Woolloomooloo Fault zone.
Mona Vale South	310	2	280	900	22, 138	Weathered rock, close spaced, iron filled vertical joints
Mona Vale Head	860	9	2260	2600	25, 80, 143	Several curved faults with 3m throw, exposed claystones subject to fretting.
Bungan Head	910	5	530	600	35, 82, 163	
Bilgola South	360	5	940	2,600	48, 100	Closely spaced joints, fragile cliff, engineering works at the rock pool.
Bilgola Head	1,210	9	6,720	5,500	47, 97, 151	Possible fault zone.
Avalon Head, Bangalley Head, Careel Head	3190	17	15,750	5,000	50, 130, 164	Possible fault zone. Curved joints common on Careel Head
Little Head	1,460	13	2310	1600	58, 157	Curved joints common
Barrenjoey Head	1,990	13	2,010	1,000	34, 115 Dyke 100	Sliding blocks from Hawkesbury Sandstone on the crest are common.

Table 1. Basic statistics of all the cliffs and cliff failures in the survey area.

Long Reef

Long Reef Point is different from other headlands through to Barrenjoey because it is formed on the Bald Hill Claystone and possibly Garie Formation. Geological mapping needs revision as rock unit boundaries have not been clearly identified and several recent papers have erroneously included Bulgo Sandstone in the cliffs and the shore platform. Cliffs range from 5 to ~30 m high and stand at about 60^0. Norman (1986) noted that joints at Long Reef were both more variable and less extensive than those recorded elsewhere but the same two dominant sets (NNE and NW) seen along the coast were present. Several small faults with limited vertical displacement and some movement parallel to the bedding are also present.

The weathered nature of the claystone and its tendency to fret during dry conditions and to develop rills during rain means that few of the cliff failures are identifiable as discrete events and debris accumulates until it is removed from the beaches or shore platform by higher waves. This means that failures identified today will be quite difficult to monitor over time as the rate of change is rapid. The total volume of failed rock visible at the time of the survey was estimated at 280 m^3 and the largest single failure was the remains of a planar slump in white plastic clays 120 m east of the Fishermen's huts on the north side of the headland. This slump was first observed after storms in 2016 (Figure 34) and is reactivated every time the toe is eroded by high waves. Earlier slumps close to this location have been observed but not recorded over the past 30 years. The cliff face angle in this area is only about 40^o and the long-term rate of recession is probably rapid.

Figure 34. Planar slump in weathered Bald Hill Claystone on Long Reef Point. Photo taken shortly after the initial collapse in 2016.

Narrabeen Head

Jointing is reasonably developed in Newport Formation sandstones and near the northern end of the platform joints are more persistent and closer spaced. This fracture zone is closely aligned with the master joint set on Turimetta Head (129^o) and appear to be a south-westerly extension of the Fault Zone identified there. The remainder of the cliff and platform lie just east of the Fault Zone and cliff failures are smaller.

Turimetta Head

The SE facing aspect and the point of Turimetta Head are judged to be the most unstable length of the surveyed coast. Thirteen rockfalls have occurred over 510 m of cliff line within the last 45 years (Figures 35 and 36). The shore platform is formed on Bald Hill Claystone, which is overlain by about 5m of Garie

Figure 35. Rotated slab fall on Turimetta Head, initiated by a storm in 2015 and still failing in 2022.

Figure 36. Large volume rockfall on Turimetta Head with extensive cracking in the face. Bald Hill Claystone and Garie Formation are 8 m thick at the base of the cliff.

Formation with the remainder of the cliff being in the lower Newport Formation. The cliff face angle ranges from about 70° to near vertical and several faults are visible with minor vertical displacement and larger strike slip movement. The sandstone is competent but the other units less so, and their erosion slowly undercuts the sandstone face, open joints near the cliff edge are heavily stained by iron oxides and some accumulate surface debris washed into the open crack.

Two major near vertical joint sets (36° and 129°) with average spacing of about 500 mm and the bedding planes allow large blocks to break away from the cliff and to topple forward or sideways and slowly break down further. This zone of close spaced joints is 50 to 80 m wide and extends right along the SE aspect of the headland. When projected to the south the fracture zone just intersects the northern end of Narrabeen Head and aligns with the Woolloomooloo Fault zone mapped by Och et al. (2009). The fault zone cannot be traced between Sydney Harbour and Turimetta Head as the area is fully urbanised and there are few deep excavations where it could be visible.

Unstable cliffs on Turimetta Head challenged engineers when the Warriewood sewer outfall was constructed between 1975 and 1989 (A. Gordon 2021, pers. comm.). Since then, several rockfalls have come to rest on top of the concrete pavement placed over the sewer line. At the time of the drone survey the headland was visibly unstable with extensive open cracks and new falls could occur at any time.

On the north face of the headland beyond the margin of the fault zone, rockfall frequency declines and volumes are smaller, but joint spacing becomes closer at Warriewood Beach where joint planes are filled with 5 to 10 cm thick layers of iron oxides.

Mona Vale South

This cliff is formed in weathered Newport Formation and is intersected by prominent vertical joints trending 22° and 138° filled with iron oxides (Figure 37). There is no vertical displacement on these planes, but the width of the oxide filled zone increases toward the top of the cliff indicating that some lateral expansion of the rock body is occurring as the cliff face unloads (Hencher and Knipe 2007).

Figure 37. Extensive iron oxide cementation along vertical joints in lower Newport Formation on Mona Vale South Headland.

Mona Vale North

The base of this cliff is partly covered by vegetated scree, but this only provides a low level of protection from wave undercutting. At the headland jointing is strong and there are at least three prominent faults with curved fault planes that have displaced the Bald Hill Claystone by as much as 3 m (Figure 38). The faults extend the full height of the cliff and create failure planes for large rockfalls. The largest single block of sandstone on the platform had a volume of 300 m^3 but is now broken into two fractured blocks.

Figure 38. Curved fault plane with displacement of the Bald Hill Claystone by 3 m on Mona Vale Headland.

Bungan Head

This is one location in the Northern Beaches where property lines extend to high water mark therefore the cliffs are private land. One consequence of this subdivision is that some buildings and service facilities such as roads and power lines are close (<10 m) to the cliff edge. Jointing in the Newport Formation is strong and there may be a small number of dykes obscured in vegetated crevices. The base of the cliff is like Mona Vale and moderately protected by vegetated scree which sits on a boulder beach that presently absorbs most wave energy. This coastal section is presently quasi-stable but that could change rapidly with sea level rise.

Bilgola South

Bald Hill Claystone is present on the shore platform. Joint patterns are not clear but closely spaced in weak sandstones and shales therefore scree is abundant at the cliff base. The cliff at the rockpool has undergone several engineering programs to improve public safety since 1968 including slope grooming and wire meshing in the 1990s.

Bilgola Head

This headland has extensive boulder protection at the cliff base. In the more competent sandstones on the shore platform curved joints are common and often do not proceed right through the block which is defined by rectangular joints.

Avalon North

This headland also has a long history of rockfalls including a major one on 11 August 2017. This headland is 63 m high and all of it is in Narrabeen Group sandstones and shales. At the time of first European occupation a feature on the headland was known as 'The Hole in the Wall,' or St Michael's Arch. A watercolour painting ('St Michael's Arch, Avalon') by R.H. Raworth of this sea arch was completed in about 1860, but in 1867 the arch collapsed leaving an 8 m high rock stack standing on the shore platform that was variously known as 'The Stone Lady,' 'Lot's Wife', and 'The Foreign Legionnaire'. Over time the stack was slowly under-cut and surrounding boulders vanished. It was still present, but much reduced in 1944 and the last known photograph was taken in 1962 (see; Pittwater Online News 2017 for a longer account and a reproduction of the painting).

There was another fall from the headland in 1980, after which it acquired a new name – 'Indian Head'. Then at dusk on 11 August 2017, a major collapse occurred which was described by eyewitnesses. Early reports claimed that the fall was preceded by two minor offshore earthquakes; one on 17 July with magnitude of 3.2, and the other of magnitude 1.8 some hours before the fall. Recalculation of the data for the second event showed that this tremor occurred at the time of the fall and was caused by it.

The 2017 fall illustrates the difficulty of calculating the volume of rock involved. Media reports just use adjectives like 'massive' and 'huge' but with the drone image (Figure 39), it is possible to attempt quantification. Using the dimension of the scar provides a more accurate figure than trying to assess all the fallen blocks because the surface on which they rest is not visible, some debris may have entered deep water, and the bulking factor from solid rock to debris pile must be at least 30-50%. In this case it is known that the headland is 63 m high. The fresh scar is about 50 x 40 m in dimensions and its thickness is probably between 3 and 4 m. Accepting these figures then this fall involved 6,000 to 8,000 m^3 of solid rock which equates to 15 to 20,000 tonnes calculated using a specific gravity of 2.5.

Three strong joint sets are evident on Avalon Headland with the major set trending at 121^o and individual fractures can be traced for 90 to 100 m. Given the rockfall history at Avalon and the large volumes of debris visible at Bilgola and Avalon Heads it is possible that these are on a fault zone that may align with the Luna Park Fault Zone of Och et al. (2009).

Figure 39. Rockfall of August 2017 from Avalon Head, image taken in 2021 after the largest blocks had broken. The cliff face is 63 m high.

Bangally Head and Careel Head

This section of coast is capped by Hawkesbury Sandstone above the full thickness of the upper and lower Newport Formation sandstones. Joints in the Hawkesbury Sandstone define large blocks (circa 40 to 60 m^3) that detach from their bedding planes and can creep/slide across vegetated benches and sometimes perch on the cliff edge above weak shales (Figure 40). As the shales fret away these blocks are undercut, and fall. There was a fatality in this area in 2004 when a visitor was crushed by a sliding block.

Figure 40. Large blocks of Hawkesbury Sandstone perched in the cliff top and resting on unstable shale. The three precariously stacked blocks on the left have a total volume of about 70 m^3 and weigh about 175 tonnes.

Figure 41. Joint patterns in the Lower Newport Sandstone on the shore platform of Careel Head. Two strong straight sets close to right angles and less persistent discontinuous curved planes within the main blocks.

This cliff height reaches 100 m height in places and much of it is inaccessible. Several faults and a dyke swarm are present in a vertical face near The Ovens Sea Caves. The caves appear to be eroded on a close spaced joint swarm, but igneous dykes may also be present. The shore platform is quite narrow or even absent. Massive blocks on the shore platform in the lower Newport Formation have distinctive curved joints (Figure 41).

Little Head

On the north-eastern end of Little Head seven or more exceptionally large sandstone blocks lie on the shore platform. They average about 200 m^3 each and have fallen and partly rolled from the low cliff, but all are well covered by a black film of blue-green algae, and they are judged to be older than the nominal 45 years 'recent' age bracket (Figure 42). They have not been included in Table 1, and their arrangement is quite different from all other falls in the study area, and they may have a different geomorphic explanation.

Figure 42. Part of the line of anomalous fallen blocks resting on the shore platform near Little Head. These have detached from the cliff face and appear not to have moved for a long time and need further geomorphic enquiry. The total volume of these blocks is about 1,400 m^3.

Barrenjoey Head

The highest point on Barrenjoey is 102 m ASL near the lighthouse (Figure 43) and the headland has the form of a typical sandstone hillslope with repeating stepped and vegetated benches above a cliff face that extends to a scree slope on a narrow shore platform. Hawkesbury Sandstone forms the upper benches and is strongly jointed to form large blocks that slowly separate from one another, and which can eventually creep down slope as individual boulders. The largest of these can be 150 m^3 and some can eventually slip over the cliff edge and fall to the shore platform. From the video imagery it is difficult to determine exactly where the Hawkesbury Sandstone contacts the upper Newport Sandstone, but Cowan (1993) places this boundary at 45 m elevation on the northern face of the headland.

Joint trends in the cliff and on the shore platform are difficult to measure from the available imagery and the only identifiable fracture zones with close spaced joints are adjacent to the igneous dyke exposed on the northern shoreline that has a trend of 100°.

Figure 43. North face of Barrenjoey headland showing the stepped cliff face in Narrabeen Group sandstones and Hawkesbury Sandstone. The pale green grass land on the scree slope is composed of *Themeda*. Lion Island is visible in the far right.

Discussion

How big is the problem?

In the 12.85 km of cliff line examined 101 'recent' failures were recorded with a total estimated debris volume of some 36,990 m^3. When these figures are converted to volume per km of cliff line the range is from 200 m^3/km to 5,500 m^3/km, with a mean of 2,500 m^3/km, but it must be acknowledged that a single large event such as the rockfall from Avalon Head in 2017 can skew these numbers.

Compared with the data presented by Kotze (2007) the figures reported here are higher. Kotze recorded 15 falls in 15 years along 6.8 km of coast involving 950 m^3 of material or 10m^3/km/yr (rounded). This paper records 101 falls over a nominal 45 years along 12.85 km of coast involving some 36,990 m^3 or 60 m^3/km/yr. In other words, the falls tallied here have occurred at a slightly higher rate than Kotze calculated, and they involved six times the volume of his estimates. The weakness in this line of argument is that the period identified as 'recent' is poorly constrained. However, this is where the greatest value of the drone video lies. If the exercise is repeated in say, five or 10 years-time then event timing and the statistics will be considerably improved.

Table 1 shows that the most unstable cliff sectors are Bilgola, Avalon to Careel, and Turimetta Head. But this ranking does not actually identify the visibly most active sector which is the relatively short length of 510 m from Turimetta Beach to Turimetta Head where an estimated 4,680 m^3 of 'recent' debris was measured and where the timing of the rockfalls is better known because the section has been frequently visited (by PM), and the timing of some falls can be bracketed by sequential air photos and engineering structures of known age.

The largest recent falls all occurred on or close to the point of each headland where waves can approach directly from several directions, and the oldest and largely vegetated bodies of debris occur close to the beaches particularly on the north-easterly facing aspects. Geologic structure as expressed in rock jointing and faulting is a factor in the location of active fall zones, and rock weathering influences the nature of the cliff failures especially where shales and claystone are highly to completely weathered to clays or where rock fretting occurs during wetting and drying cycles.

Part of Narrabeen and Turimetta Heads are located on a fault zone 50 to 80 m wide where joints are close spaced and persistent. Mona Vale Head has more faults with vertical displacement of up to 3m than other places, although this may also be true in the less accessible section from Avalon to Careel Heads where faults and dykes are visible in the video. The Turimetta Head Fault Zone appears to be an extension of the Woolloomooloo Fault Zone although confirming this is difficult because of the absence of exposure north of Sydney Harbour. The trend direction of the fault zones identified by Och et al. (2009) is consistent with this interpretation and if this suggestion has merit, then it might be expected that the Luna Park Fault Zone may link with the larger faults observed on Mona Vale Head and perhaps the active cliff failure zones at Bilgola and Avalon Heads.

Sea level rise

Projected sea level rise caused by climate change is frequently revised and the only certainty about it is that it is occurring. In NSW, Councils have been generally planning for a one metre increase by the year 2100, and although the figures change with each new report, this is considered a reasonable number to accept (AdaptNSW 2022).

To date most of the discussion and an increasing amount of activity has concerned the effects of sea level rise on the beaches. The construction of a sea wall, estimated to cost $25 million, along part of Collaroy-Narrabeen Beach is perhaps the largest project of its kind in NSW (Northern Beaches Council 2022). Far less consideration has been given to the cliffs.

With sea level up one metre (or more) and a possible increase in storm frequency, particularly those driven by east coast lows, waves will more frequently reach the base of the cliffs and they will carry more energy as there will be less attenuation across the shore platforms. The immediate effects of this change will be that the debris cones and vegetated scree slopes at the base of the cliffs will be eroded, and the toe of the cliff will be subject to direct wave impact and increased wetting and drying. Where the cliff toe is in Bald Hill Claystone or Garie Formation undercutting will proceed rapidly and an increase in cliff failure will occur.

On those areas of the coast where property lines extend to high water mark and assets have been constructed close to the cliff top, some property will be endangered. Elsewhere the existing coastal reserves will provide a buffer.

On the shore platforms the risk to human lives will increase because the duration of platform exposure at low tide and thus time for safe passage will be reduced, waves breaking on the platform will be deeper and more energetic, and rockfalls impacting the platform will be both bigger and more frequent.

On the pocket beaches which are backed by vegetated cliffs such as Turimetta, Warriewood, and Bilgola, it is likely that erosion will remove all the sand and reactivate the buried shore platforms. These beaches are presently used by bathers and surfers and often have an associated surf club building on them. Such recreational activities will no longer be attractive. It is estimated that the proportion of cliffs to beaches could shift from the present 48% cliff and 52% beach, to 62% cliff and 38% beach.

Extreme weather of 2022

In 2022 the east coast of New South Wales and southern Queensland was subject to extreme rainfall and several intense storms between February and April. Beaches were severely eroded and several small rockfalls caused concern. The authors have not had the opportunity to repeat the video recording described here but have noted significant differences in cliff failures during this period.

No large rockfalls were noted but exceptionally heavy rain caused multiple slump failures from vegetated cliff faces and scree slopes. Adjacent to Newport Beach along 150m of coast where there was one active slump in 2021, there were seven at the end of May 2022.

The largest observed slump failure on a vegetated cliff occurred on the north face of Long Reef Headland after 315mm of rain fell on the 8th and 9th of March 2022 (Pittwaterpathways May 2022).

The collapse involved 160m length of cliff which was well vegetated by native plants including mature trees. The plants were rooted in a plastic clay derived from weathering of the lower Newport Formation shales and sandstones and the cliff failure occurred when the regolith became saturated and could no longer stand. The cliff initially failed as a series of slumps which left two or three vertical headwalls up to 3m high, and as the rain continued secondary failures occurred as debris flows when rocks and mud cascaded directly down the bare slope onto the narrow beach and shore platform. In time, waves will remove the loose material at the toe of the slope and debris will continue to slip until the vegetation recovers. The consequences of this complex cliff failure are:

- A good cover of native vegetation and the habitat that it provided was destroyed and will take some years to recover.
- The cliff receded by about 1m in a single event over perhaps two days.
- The cliff face is now inherently unstable and further small failures are likely.
- The walkway at the top of the cliff is more precarious than it used to be.

Should we do something about it? With higher sea level more frequent wave attack at the base of the cliff will exacerbate failures, but the only practical thing that could be done would be to hasten vegetation recovery by planting advanced tube stock of native species when it is safe to access the slope.

The big lesson is obvious; even a good vegetation cover will not prevent failures of this nature during conditions like those experienced in early 2022.

Conclusions and recommendations

When considering the predicted effects of sea level rise on the NSW coast, beach and dune recession have been of primary concern because of the loss of urban amenity and the economic cost of management. Less attention has been given to the present and future stability of the coastal cliffs even though many large rockfall events have been observed.

With the availability of small drones (unmanned aerial vehicles UAVs) fitted with high-definition video cameras, the ability to observe and record changes in otherwise almost inaccessible locations has changed and continuous video cover of the coast from Dee Why Lagoon to Barrenjoey in 2020/2021 has been successfully completed.

This material is in the public domain and available to any researcher seeking an improved and safer view of the coast. In time, it is hoped that it will assist in improving delineation of the geology, and if the video data collection is repeated it could be used to better quantify the rockfall hazard.

Despite the obvious shortcomings in data collection and analyses this study has shown that the frequency and volume of rockfalls from the Northern Beaches cliffs is substantially greater than has previously been recognised. From now on the geotechnical hazard of cliff failure should not be considered as a ‘rare’ event in risk analyses, but as an ‘unlikely’ event and rising to a ‘possible’ event as time passes and sea level does increase.

The first need is to improve the data. Both this paper and that of Kotze (2007) should be seen as no more than exploratory works as both give an indication of the scale and location of the issues but neither are well constrained with respect to event timing and quantification of volumes. This paper does describe an effective methodology for improving data collection at reasonable cost. Several important points can be made.

- A video equipped drone should be used to record all major falls as soon as possible after they occur.
- The drone flight path should be repeated at say five or 10-year intervals as when future images are compared with the present record, managers will have the first-time constrained data set that should provide much more reliable figures on event frequency and volume.
- Council and/or the State Government should engage an experienced structural geologist to fully assess the role of structure (joints, faults, and bedding) in cliff stability within the study area.
- Council should review the numbers and location of assets at risk on the clifftops and ensure that Section 10.7 planning certificates are properly annotated with respect to present and future cliff stability. A priority for this review should be those properties where Lot margins extend to high water mark.

SOIL MATERIALS IN THE HAWKESBURY SANDSTONE LANDSCAPES OF THE KGR (P.B. Mitchell)

Introduction

The purposes of this paper are to outline previous work on the soils found in the Hawkesbury Sandstone landscapes typified by KCNP. It will demonstrate how this relatively simple landscape became a test bed for new ideas in pedology developed at Macquarie University and present a different approach to understanding soil formation and distribution. It expands on the soil landscape framework of Chapman and Murphy (1989) by using a stratigraphic approach to soil material distribution and presents an integrative concept diagram that has been successfully applied elsewhere.

Soil parent material

The accepted origin of the sandstone is that quartz sands were laid down in a major braided river system that flowed from the southwest. The average composition of the sandstone is 68% quartz sand (mean grain size ~0.3 mm), 20% clay matrix, 10% quartz and siderite cement, with the remainder being grains of feldspar, mica, graphite, other lithics, and traces of fine grained, heavy minerals such as rutile, tourmaline, zircon, ilmenite, and magnetite (Standard 1969).

Conaghan and Jones (1975) and Conaghan (1980) described three lithological facies.

1. Massive sandstones which are internally homogenous, lenticular in cross section channel deposits that were deposited by floods and that often contain a thin basal layer of quartz pebble conglomerate or shale ‘rip-up’ clasts.
2. Sheet sandstones of cross-bedded sets ranging in thickness from a few centimetres up to five metres, which represent quiet water deposition of migrating sand waves.
3. Laterally discontinuous mudstone (shale lenses) interbedded with siltstone or fine sandstone deposited in abandoned channels. Corkery (1980) described the occurrence and characteristics of the thicker shales noting that the unweathered shale contained quartz, kaolinite, siderite, and often has macroscopic mica flakes on bedding planes. Grey, unweathered shale contains 8-12% Fe_2O_3 whereas white, weathered shale is clay with <2% Fe_2O_3.

With such a simple geology of nearly horizontal mature sedimentary rocks, weathering involves little more than disaggregation of their constituent minerals to produce quartz sand, kaolinite, iron oxides, sandstone rubble, and durable quartz pebbles. The rearrangement of these weathering products in different topographic positions and their interaction with the biosphere might only be expected to create a limited range of soils.

Geomorphological influences

The highest points in the KGR are small peaks reaching 220-230 m ASL and the lowest points are tidal waters in the Hawkesbury River estuary. The higher ground has local relief of about 40 m along numerous ridges generally only 200-300 m wide but up to 1 km wide on the Lambert Peninsula. Ridges have ground slopes of between 3^o and 8^o, and often terminate in a sandstone free face (cliff). Below the ridges steeper slopes descend in steps of regolith covered benches alternating with rock outcrop and cliffs. Overall slope angles are around 15^o to 20^o, but individual benches are more often only 5^o to 8^o with the flatter examples being wider.

The KGR has a quasi-rectangular drainage network of 3rd to 4th order streams (Strahler 1957) with mean catchment areas of 4 or 5 km^2. Individual stream segments and cliff lines tend to follow the direction of major vertical joints in the sandstone. Streams descend to the Hawkesbury River with steep gradients through a series of knick-points above which hanging swamps with slope angles of <2^o may occur. Little alluvium accumulates in or adjacent to the streams, fluvial terraces are rare, and the only larger alluvial deposits are found where tributary streams enter hanging swamps or small basins, and in the tidal waters of the Hawkesbury River tributaries.

Vegetation

All soil derived from the Hawkesbury Sandstone contains very low levels of phosphorus as noted by Jensen (1912) and investigated as a factor controlling the distribution of plant communities by Beadle and Burges (1949) and Beadle (1953, 1954). Native plants growing on Hawkesbury Sandstone are adapted to this limit and have mechanisms to maximise phosphorus uptake such as mycorrhizal fungi, proteiod roots, and the ability to scavenge phosphorus from aging tissue. Where phosphorus levels are raised by urban drainage, native species are disadvantaged in relation to exotics and fail to thrive (Leishman 1990; Thompson and Leishman

2004). Some plants are also known to be able to concentrate other nutrients such as calcium but there is little literature on this subject (Humphreys et al. 2004).

Despite the apparent simplicity of the geology and topography, and the limited nutrient status of the soil, the sandstone landscape has a remarkable diversity of vegetation ranging from heath to closed forest with elements of rainforest. Within KCNP and Muogamarra Nature Reserve there are 12 to 15 mapped plant associations on Hawkesbury Sandstone plus nine on sandy alluvium supporting more than 600 plant species (Benson and Howell 1994). Explanation of this high plant diversity on a seemingly simple substrate lies in the complex relationships between presence and absence of rock outcrop, slope angle and aspect, fire frequency and intensity, biospheric nutrient cycling, and accumulation or removal of surface materials including litter.

Previous soil studies

The earliest European experience of soil on Hawkesbury Sandstone was Governor Arthur Phillip’s attempt to establish crops at Farm Cove (present day Royal Botanic Gardens) in February 1788. Two of the reasons for crop failure were the poor water-holding capacity and low nutrient status of the sandy soil which led Governor Phillip to seek better land elsewhere.

There are few early descriptions of soil in the KGR, and no attempts were made to map soil distribution until Jensen (1912). The earliest workers such as de Strzelecki (1845), Guthrie (1898), Jensen (1912), and Prescott (1931) all had chemistry backgrounds and were most concerned with the nutrient status of the soils they identified as the questions they sought to answer were agricultural.

Jensen (1912) mapped the soils of NSW and emphasized the importance of the geological substrate on which they were found. His soil map identified the soils of the Sydney region as poor, and those on the Hawkesbury Sandstone as poor, light sandy soils, with low water capacity which required humus and fertilizers to become productive. This was a practical approach to management problems, but his work provided no insight into questions of soil genesis or the subtleties of soil distribution.

Prescott (1931, 1944) attempted to map Australian soils at an atlas scale and applied a genesis model from Russian and American work. His 1933 map depicted the entire east coast from western Victoria to the eastern side of Cape York, as podsolised soils which he differentiated from the podsols found in sub-alpine to alpine environments. (Note: The letters ‘s’ or ‘z’ are interchangeable in the spelling of podsol/podzol and related words). In 1944 Prescott expanded the number of soil groups, modified the boundaries, and dropped the name podsolised soils in favour of podsols. This was the beginning of nomenclatural confusion that has plagued Australian studies ever since.

Although there are numerous site-based soil studies in the KGR, there are only three soil maps. The first of these was by Little and Storrier (1954) covering the Ku-ring-gai Municipality. Their map was based on geology and topography and delineated four Soil Associations in which 18 Soil Series were noted and 29 soil types identified. To assist users, they provided simple bifurcating keys to the Soil Series.

Their Awatea - Roland Association was based on the Hawkesbury Sandstone and this contained shallow skeletal profiles with sand or loamy sand surface horizons over clayey sand subsoils, comprising the Tyron Series with slightly developed profiles that sometimes included coffee rock or mottling in the subsoil, and the Awatea, Roland, Cockle, and Curugal Series where the profiles had moderate to strong texture contrast between the A and B horizons which were yellow, yellow brown, or red clay.

Awatea, Roland, Cockle, and Curragal profiles fit the description of podsolic profiles as understood at that time, or texture contrast profiles as later defined by Northcote (1960, 1979). The Tyron soils may be podsols, but their description is insufficiently detailed to be certain.

Walker (1960) surveyed the soils of the County of Cumberland including the area previously covered by Little and Storrier (1954). Those authors assisted Walker in the field, but he did not cite their work and did not use their established names.

As with all soil surveys Walker faced the problem of how to depict the distribution of soil profiles (vertical slices) on a map. He applied the standard answer and identified characteristic soil profiles (13 Great Soil Groups), placed these in Series based on their parent material, and then assembled the Series into larger Associations. Whilst this provided an understanding of soil distribution, the map itself (Associations) is generalised and little different from a geological map. To address the disconnect between profile and plan, Walker included a small table which matched the distribution of named profiles in the series with their slope position.

Walker used the laterite as the basis of his Woronora Association and only dealt with the modern soil derived from them. He placed all the soil profiles found on the Hawkesbury Sandstone within his Hawkesbury Association. Within this he recognised Hawkesbury, Warriewood, Birrilee, Hammondville, Cowan, and Commodore Soil Series. He described the catenary distribution of soil in this association as Hammondville fine sandy loam (a texture contrast profile with a yellowish clay B horizon); Birrilee sand and Cowan sand (both sandy skeletal profiles with no texture variation with depth) on the hill crests; Hawkesbury sand (sandy skeletal profiles with slight variation in texture and colour in the subsoil) and rock outcrops on the mid-slopes; Commodore sand (uniform textured sand with distinctive dark brown or coffee-coloured mottling or pan formation in the B horizon); and Hawkesbury sand at the base of the slopes. As with the earlier survey Walker's soil types included skeletal profiles, podsolics and podsols (Commodore Series) with the latter two being accepted as mature profiles of considerable age (circa 30,000 years according to Walker 1962).

Soil landscape mapping - Soil Conservation Service of NSW

In 1988 the Soil Conservation Service of NSW celebrated its Golden Jubilee (Breckwoldt 1988), at a time when the number of staff peaked, and extension services and soil research were extremely strong. In the previous 15 years many new graduates had been employed and established staff had upgraded their qualifications from Agricultural College Diplomas. Macquarie University was at the forefront of this training because of their open course structure and expertise in external teaching. All the Soil Conservation Service graduates had taken courses in pedology presented by T.R. Paton where Paton (1978) and precursors to it provided the core content. Paton's text was a radical departure from conventional pedology, but the ideas incorporated in it were well accepted by a large cohort of practiced soil conservationists and his teaching contributed to change in the values and practices of the Service. Regional mapping of land systems across the Western Division of the State was almost complete and a new program to cover the Eastern Division at 1:100,000 scale was initiated. For a brief history of this work see Edye et al. (undated) and Murphy et al. (2022). The first of these maps covering the Sydney region was presented by Chapman and Murphy (1989), both of whom were Macquarie University graduates.

Some criticisms can be made of this publication.

- Exactly what was meant using geomorphic process terms such as residual, colluvial, erosional, and fluvial in the categorisation of landscapes was not defined, although this was partly remedied in OEH (2017).
- The presence of identical soil materials in different landscapes was not discussed and there are issues with correlation between maps because funding was limited (G. Chapman pers. comm.).
- Some of the boundaries and polygons are questionable. For example, there is only one small area of Faulconbridge Soil Landscape plotted in the KGR which is quite distant from its type area in the Blue Mountains.
- The distribution and treatment of laterite was subsumed in the idea of 'friable sandstone.' This was a surprising shift given the volume of literature on the subject (Woolnough 1927; Hallsworth and Costin 1953; Faniran 1971 and Hunt et al. 1977), some of which claimed that the laterite was formed on Hawkesbury Sandstone.
- The widespread occurrence of ironstone and other surface gravel sheets and stone layers on many sites, especially the crests and ridges, was almost ignored.

These criticisms aside, this map and text is by far the most detailed of any previous work and provides useful information about soil and land use and potential soil limitations or natural hazards. Chapman and Murphy's mapping differed from previous work in that the coverage was more detailed, the base maps and air photos used were more informative, and the focus shifted from soil profiles assembled in series and associations to 'soil landscapes' set in a geomorphic context as described below.

Residual landscapes

Level to undulating elevated summit surfaces, with deep soils formed by in situ weathering of parent materials (OEH 2017). This included the Faulconbridge Soil Landscape which contained three dominant soil materials identified as fb1, fb2, and fb3, and the Somersby Soil Landscape which partly matched the distribution of laterite and contains seven dominant soil materials (so1, so2, etc). Various vertical combinations of the soil materials created 19 different Great Soil Group profiles (sensu Stace et al. 1968) such as siliceous sands/lithosols, leached sands, earthy sands, red earths, yellow earths, grey earths, and gleyed podsolics.

Colluvial landscapes

Moderately inclined to precipitous hillslopes with cliffs and cliff-foot slopes, where soil parent material consists mostly of colluvial debris (OEH 2017). The Hawkesbury Soil Landscape, with three dominant soil materials and two associated materials, is placed here and is the most extensive soil landscape in the region. Great Soil Group profiles are siliceous sands, earthy sands, yellow earths, red podsolics, and yellow podsolics.

Erosional landscapes

Steep to undulating hillslopes that may include benches and rock outcrop where the erosive action of running water is important (OEH 2017). Soils are shallow and their mode of origin is variable and complex. In many instances, subsoils have formed in situ while topsoils have formed from materials washed from further upslope. The Lambert Soil Landscape with six dominant soil materials and three associated materials, and the Gymea Soil Landscape with four dominant soil materials and two associated materials were placed here. Both are like the Hawkesbury Soil Landscape but with subtle differences in topography and vegetation. Soil profiles are siliceous sands/lithosols, leached sands, earthy sands, yellow earths, grey earths, gleyed podsolics, and yellow podsolics.

Fluvial landscapes

Also described as an alluvial landscape (OEH 2017) this includes floodplains, benches, and terrace deposits along streams where soil parent material is deep alluvium. The Deep Creek Soil Landscape consists of five dominant soil materials and one associated material found in the lower reaches of larger streams. The Oxford Falls Soil Landscape contains five dominant soil materials and six associated materials some of which are identical to those in the Deep Creek Soil Landscape. It is found in higher valleys, in small basins, and marginal to large swamps. Soil profiles are siliceous sands, leached sands, earthy sands, yellow earths, grey earths, podsols, and humus podsols.

Each soil landscape description includes a schematic slope diagram that depicts the distribution of the different soil materials topographically and in relation to one another. These reveal that some of the soil materials are always paired but others can overlie several different substrates. This allows the diagrams to be read stratigraphically. For example, in the Hawkesbury Soil Landscape the loose sand to sandy loam topsoil (ha1) can be found on rock where it makes a lithosol or siliceous sand. The same material can overlie a yellowish brown, sandy clay loam subsoil (ha2) making an earthy sand or a yellow earth. Soil material (ha3) is a pedal light clay and is only found as a subsoil derived from shale lenses in the sandstone. When it is overlain by ha1 and ha2, it makes a yellow podsolic profile.

Hawkesbury soil landscape summary

In the Sydney area 26 soil landscapes were identified. Of these, seven were on the Hawkesbury Sandstone (excluded shale/sandstone transition landscapes on the Mittagong Formation), a total of 33 dominant soil materials are described which in various vertical combinations made 29 Principal Profile Forms (Northcote 1979) or 11 named Great Soil Groups. Table 2 summarises the relationships between the listed profiles and includes matching terminology from Isbell (2021) and the World Reference Base (2015) both of which are usually required for use in scientific publications.

Great Soil Groups (Stace et al. 1968)	Principal Profile Forms (Northcote 1979)	Australian Soil Classification (Isbell 2021)	World Reference Base (WRB 2015)
Siliceous Sands Leached Sands Lithosols	Uc1.21, Uc1.22, Uc1.4, Uc2.21, Uc2.23	Rudosols	Fluvisols Leptosols
Earthy Sands	Uc4.21, Uc 5.11, Uc 5.22, Uc5.23,	Tenosols	Arenosols
Red Earths Yellow Earths Grey Earths	Gn1.21, Gn2.14, Gn 2.21, Gn2.24, Gn2.41, Gn2.81, Gn2.84, Gn2.94,	Arenosols Kandosols	Arenosols Ferralsols
Podsols	Uc2.2, Uc2.32, Uc2.36	Podosols	Podzols Arenosols
Red Podsolics Yellow Podsolics Gleyed Podsolics	Dr5.11, Dr5.21, Dy4.1, Dy5.11, Dy5.21, Dy5.41, Dg3.82, Dg4.21, Dg4.51	Kurosols	Acrisols Lixisols Luvisols

Table 2. Correlation between the Australian Great Soil Groups, and Northcote PPFs, recognised by Chapman and Murphy (1989) with their approximate equivalents in the Australian Soil Classification (Isbell 2021) and the World Reference Base (2015).

Important soil profiles in the KGR

Three Great Soil Group profiles: podsols, podsolics, and laterites, have been repeatedly identified as characteristic of the Hawkesbury Sandstone landscapes (Prescott 1931, 1944; Hallsworth and Costin 1953; Hallsworth et al. 1953; Little and Storrier 1954; Walker 1962; Stephens 1962; Stace et al. 1968; Corbett 1969; Charman and Murphy 1991; McKenzie et al. 2004) and all have been subject to controversy about their relationship to one another, and their modes of formation.

Podsols and podsolics

In the simplest terms podsols (Figure 44) are uniformly textured sandy or loamy sand profiles with a strongly bleached A_2 horizon and bright coloured B horizons which contain an accumulation of iron oxides and/or organic materials, often forming cemented pans (sometimes called 'coffee rock'). Podsolics (Figure 45) are texture contrast profiles, commonly loamy sand A horizons over pedal clay B horizons and although the colour of the horizons is like the podsols almost no other properties are comparable.

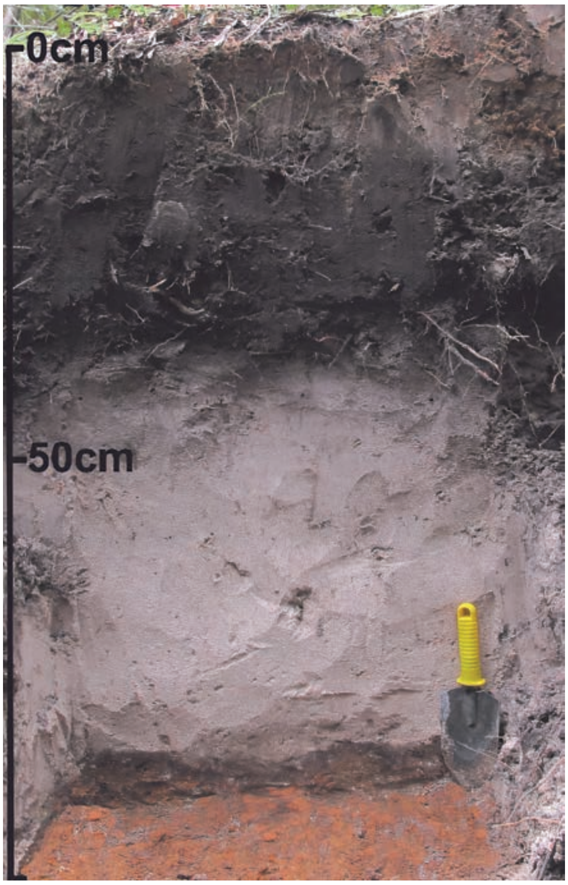

Figure 44. A simple podsol profile with organic and iron pans beneath a deep bleached A2 horizon formed in a sand body in the Oxford Falls Soil Landscape.

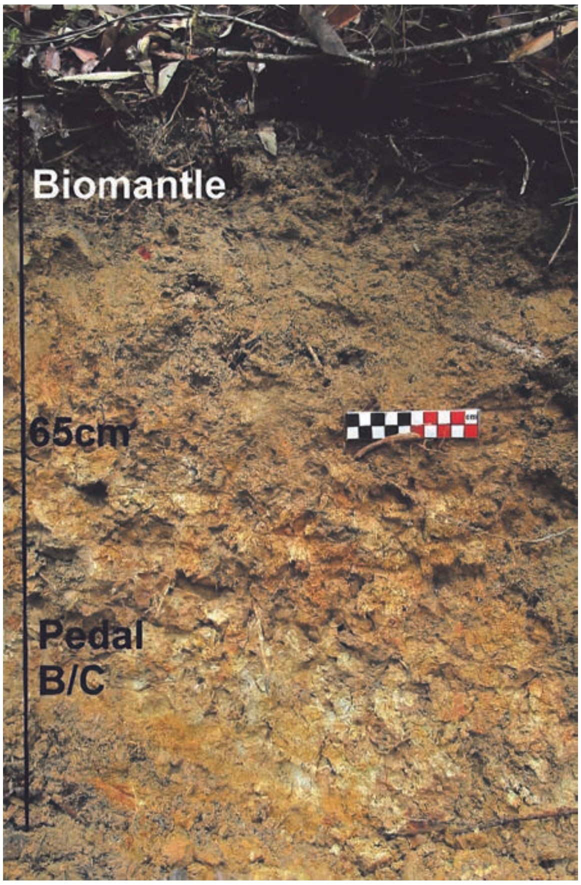

Figure 45. Yellow podsolic profile in which the surface horizons are an identifiable stratum (biomantle) created by bioturbation and erosion from upslope and which are moving over pedal clay weathered in situ from clayey sandstone.

There have been numerous attempts to improve the classification and nomenclature of podsols and podsolics. Hallsworth et al. (1953) tried to rationalise the classification but instead of recognising two different groups – uniform textured profiles with pans, and texture contrast profiles with clay subsoils – they erected five Great Soil Groups and 20 subgroups all with names assembled from partial Greek or Latin terms such as 'sidero-(nomo-) podzol' for the uniform profile, and 'yellow amphi-podzol' for a typical yellow podsolic. Stephens (1962) kept podsols and podsolics together even though he recognised that all the podsolics (i.e., Prescott's 'simple podsols') had considerable texture contrast between the A and B horizons and in every case, he explained the texture contrast by eluviation of clay down the profile from the A horizon into the B horizon. Stace et al. (1968) expanded Stephen's classification and 14 of their 43 soil groups included texture contrast as an essential character of description, and another six groups included described examples that had a texture contrast, even though they were defined as having uniform or gradational profiles. The podsols and podsolics remained together and these authors extended the supposed mechanisms of formation of the podsolics to six speculative processes.

1. Clay destruction in the A horizon
2. Clay illuviation
3. Differential weathering
4. Lateral clay transfer
5. Layering of the parent material
6. Addition to the A_1 horizon of coarse material from upslope (one example).

A clear morphological separation of podsols and podsolics was finally achieved in the Factual Key developed by Northcote (1960 with revisions to 1979) which placed podsol profiles in the Uniform Primary Profile Forms, and the podsolics in the Duplex Primary Profile Forms. This categorisation followed earlier suggestions of Leeper (1943, 1954).

The current Australian soil classification scheme (Isbell 2021) replaced podsol with another coined term, podosols, modified from the USDA (2014) term spodosol. Isbell separated the podsolics and placed them in his scheme as chromosols, and kurosols. None of these terms appear to have any connection with the USDA (2014) equivalents of alfisol, ultisol, and some aridisols. Soil profile names remain a nomenclatural minefield for the uninitiated; for an extended discussion of this tangled history see Isbell (1992).

Laterite

A similar confused history concerning the nature and genesis of laterite (Figure 46) and lateritic ironstones (Figure 47) can be seen with respect to the indurated iron oxide materials found close to the plateau top on the Hawkesbury Sandstone.

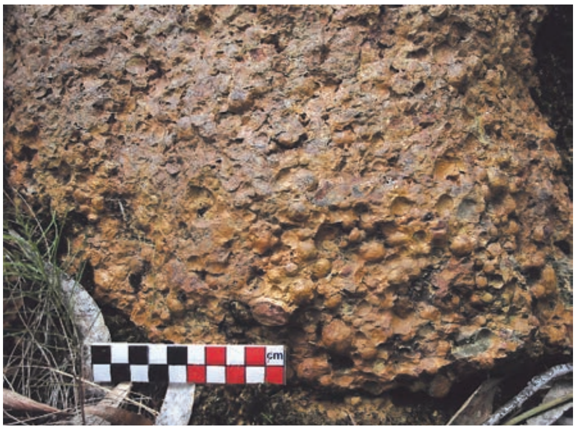

Figure 46. Pisolitic laterite from Terrey Hills. Scale is 10 cm long.

Figure 47. Alleged 'lateritic ironstone.' A surface lag gravel of iron rich sandstone, some with yellow-brown goethite coating. Lambert Peninsula. Scale is 10 cm long.

The early workers were influenced by the cyclic landscape evolution model of Davis (1899) which led Woolnough (1927) to speculate that laterite in Western Australia was an iron rich material that had formed under a seasonal tropical environment and accumulated on a peneplain. As those conditions no longer existed, he hypothesised that the laterite must be a fossil soil and it could be used as a time stratigraphic marker conveying information about past environmental conditions. Subsequent workers in geology, geomorphology and pedology accepted this 'duricrust hypothesis' almost without question even though Woolnough himself was uncertain of its application in the Sydney district.

In Sydney, Burges and Beadle (1952) attempted to use grain size analysis of the sand fraction in the laterites to demonstrate that they were derived from shales of the Wianamatta Group. This study is unconvincing because of the limited number of samples tested, their wide distribution, and the aggressive acid digestion process that was needed to free the sand from the ironstone matrix.

Hallsworth and Costin (1953) also recognised that the term laterite was not consistently used and tried to separate laterites from ‘ortsteins’. They accepted that NSW laterites were fossil soils and that they should be seen as the parent material to the soil profiles now found on them. They also claimed that the laterites had a characteristic profile of three horizons: a pisolitic, laminated, or massive surface horizon of iron oxides, over a mottled zone, which passed into a pallid zone at depth. They discussed the genesis of this profile and accepted that it was created by a fluctuating water table or seasonal saturation which no longer applied, but they also noted that the existence of a laterite was not prima facie evidence of either a previous peneplain or a tropical climate. Their attempted introduction of the German term ‘ortstein’ to describe iron pisoliths in stone layers of podsolic soils, which was not consistent with European or American use of the word, was not adopted. Hallsworth and Costin (1953) suggested that the Sydney laterites were of Miocene age, that Monaro laterites were Pliocene, and that ‘ortstein’ profiles were Pleistocene or Recent. Evidence supporting any of these claims was weak. However, Faniran (1971) accepted them and applied the Miocene age to the laterite profile at Terrey Hills and to lateritic ironstones that he claimed were evidence of the former extent of full laterite profiles on the Hornsby Plateau. He applied the Pliocene age to ferricretes (his term) formed on Nepean Valley alluvium. Faniran’s work accepted the explanations of duricrusts presented by Dury (1969, 1971).

Paton and Williams (1972) showed that the very meaning of the word laterite had been so misused globally that it no longer had any value and suggested that it should be abandoned. This view was supported in Australia by Bourman (1989) and Eggleton and Taylor (1999) who proposed that the term ferricrete would be more acceptable as it carried fewer genetic connotations.

Why has there been so much debate about these different soils? There are four main reasons.

1. Almost all the research focussed on the soil profile (a vertical slice comprising horizons that were believed to be genetically related), as the object of interest that needed to be explained, classified, and mapped. This focus limited consideration of the three-dimensional nature of soil materials in the landscape and almost ignored the role of plants and animals in soil formation.
2. Few of the earlier Australian workers had the opportunity to see overseas profiles and relied on written descriptions and black and white photographs.
3. Profile nomenclature frequently changed and with every revised classification, fewer researchers appreciated the nuances of meaning embodied in the plethora of old and updated terms, which themselves were often difficult to understand.
4. Few of the many genetic models invoked in soil formation have ever proceeded beyond hypotheses and have rarely been adequately tested.

Research at Macquarie University

The nature and distribution of profile types i.e., podsols, podsolics, and laterites were explored in the KGR by researchers at Macquarie University over four decades from the 1970s. The impetus for this work came with the appointment of T.R. Paton to the School of Earth Sciences and his development of teaching units in pedology. Paton had extensive soil survey experience overseas and in the late 1960s was engaged in survey work in south-eastern Queensland with CSIRO, Division of Soils. One of the outcomes of that work was Thompson and Paton (1980) which was the first coherent account of the genesis of texture contrast soils on hill slopes. That paper and an initial soil formation model (Paton 1978) directed much of the research effort in the Hawkesbury Sandstone environments of northern Sydney. The most important studies from Macquarie and a summary of their findings follows.

Podsols and their vegetation

Much of the soils teaching at Macquarie was based on field work and in the process of locating good sections one unexpected find was a strongly developed podsol profile (Northcote principal profile form Uc2.35) in a sand pit at Ingleside (since destroyed). Although Walker (1960) had mentioned the occasional presence of podsols in his Commodore Series no locations were known in the sandstone country. Several profiles were later found in small basins in the upper valleys of the sandstone landscapes, adjacent to hanging swamps, and on alluvial benches in the lower valleys. These are now included in the Oxford Falls and the Deep Creek soil landscapes (Chapman and Murphy 1989). A considerable variation was found in the degree of development of the podsol from shallow profiles with soft pans to deep profiles with thick, intensely bleached A_2 horizons, and complex, convolute, double pans; the bleached A_2 horizon and the pans being essential characteristics of the profile. Buchanan (1980) and Buchanan and Humphreys (1980) found 28 podsol sites on the Lambert Peninsula. Most were between two and five hectares in extent and carried different shrub communities with *Ceratopetalum gummiferum* being conspicuous and other common species being *Banksia serrata, Xanthorrhoea arborea*, and *Xylomelum pyriforme*. Trees of *Angophora costata*, *Corymbia gummifera*, and *Eucalyptus globoidea* were often present but the sites were too small to deal with the trees statistically. *Eucalyptus haemostoma,* a common tree on adjacent non-podsol soil, was rarely found on podsols.

The biochemical processes by which podsols are formed are understood. These profiles occur in relatively inert quartz sands where individual sand grains carry a yellowish coating of iron oxides and hydroxides. Active organic molecules enter the soil from leaf drip or exudates from proteoid roots (Sawkins et al. 2011). This solution interacts with the sand, stripping the iron coating, moving through the profile as an iron/organic complex, and depositing pans at depth. This is believed to be a mechanism by which the plants can access the small amount of phosphorus locked on the iron oxides. Informal experiments by undergraduate students leaching aqueous extracts from leaves and bark of *Ceratopetalum gummiferum* and *Angophora costata* through columns of podsol subsoil (C horizon) demonstrated that bleaching and pan formation could be replicated on a small scale in a matter of days and it was apparent that those species at least played a significant role in podsol formation. Another variable was expected to be time and some late Pleistocene dates were obtained from fragmentary charcoal recovered from C horizons (Mitchell 1975). This program was discontinued because of insufficient sample numbers and doubts about the methodology. It is an approach that would be worth revisiting using single grain OSL dating rather than ^{14}C.

Podsolics, surface processes, and bioturbation

Given the abundance of red and yellow podsolic profiles described in the sandstone landscape, several studies were initiated to test Thompson and Paton's (1980) model and to discover what processes were involved in creating the texture contrast and how the clear to sharp boundaries between A and B horizons were formed.

Mitchell (1975) confirmed that the A horizon of a texture contrast profile was a separate body (stratum) by tracing one downslope over B horizons formed in situ from volcanic breccia at the base of Peats Crater in Muogamarra Nature Reserve (see Paton et al. 1995 for details). Mitchell speculated that the process involved in creating the mobile A horizon was sheet erosion. Bishop (1976) extended this work to show that the A horizon over varied Triassic rocks and their weathering products was also a separate stratum and that the stone layer often found between A and B horizons in these profiles had a definable downslope distribution. Bishop thought that some sort of soil creep process may have been involved in creating the sequence.

Soil erosion on sandstone slopes, particularly after bushfires had long been a matter of concern, to the extent that Lamy and Junor (1965a, 1965b) believed that frequent severe fires in KCNP played a significant role in stripping soil, damaging vegetation, and that they threatened the very existence of the National Park as a protected area. In the next six decades that threat has not happened and although fire management has changed, the question can be asked whether there were other factors involved in slope stability that had not been observed.

Figure 48. Litter dam and micro-terrace formed by rainwash lying on sandstone outcrop. This feature demonstrates the mobility of the biomantle. Flow is from right to left; scale is 10 cm long.

Many researchers have attempted to measure rates of soil loss after fire with highly variable results. These efforts have been summarized by Atkinson (2012), but it was not until the work of Blong et al. (1982) that it was seen that there were natural checks on the slope where the formation of litter dams and micro-terraces (Figure 48) stabilised the surface mantle and encouraged vegetation recovery (Mitchell and Humphreys 1987). Soil erosion after most fires was limited to a pulse of surface sediment movement over short distances between litter dams at any one point on a slope. Close examination of the nature of this movement revealed that sheetwash and rain splash erosion as studied under laboratory conditions was much less important in moving sediment than rain wash, that is, turbulent sheet flow, agitated by falling raindrops.

Litter dams did not prevent the export of fines (silt/clay) from the surface 20 to 30 mm of soil as the first runoff events after fire carried this as suspended load. The litter dams did limit the total movement of sand. Other factors in this relationship were fire intensity, fire frequency, soil water repellence, slope angle, rainfall intensity, and recovery time since the fire (Tulau 2015). It is likely that at the time of their study, Lamy and Junor (1965a, 1965b) were not aware of the existence of litter dams and thus had not taken their slope protection role into account.

Gould (1998a, 1998b) expanded work on micro-geomorphic forms with observations in the Lane Cove Valley after fires in 1994. By mapping a small sandstone bench (3-19^{o} overall slope) in detail, and determining the complexity of surface flow paths, she identified six repeating micro-geomorphic elements each of which behaved slightly differently in terms of overland flow and sediment transfer.

The elements were as follows.

- Litter dams and micro-terraces (sensu Mitchell and Humphreys 1987).
- Boulder dams.
- Joint crevice fans.
- Mossy ledges.
- Ephemeral drainage lines.
- Rock overhangs.

Gould found that the key to limiting erosion was the dense mat of surface feeding roots in the partially burnt and unburnt plant litter. These roots were present in both uniform sandy soil and in texture contrast soil and were identified as proteoid roots that could be linked to individual *Banksia serrata* growing on the site. Root mats were as much as 150 mm thick in some litter dams but were almost entirely absent from ephemeral drainage lines, and there was a strong correlation between the presence of proteoid roots and observed soil water repellence. Gould concluded that the water repellent root mats were making a large contribution to runoff generation, but they also bound the surface mantle so effectively that erosion of what appeared to be a highly susceptible sand, was minimised.

Monitoring of erosion on another sandstone slope in the Woronora catchment after the wildfires of 2000 confirmed Gould's observations of micro-geomorphic forms and that near surface water repellence was important in generating runoff even from small rainfall events. However, it was also noted that water could by-pass the water repellent layer and saturate the A_2 horizon by passing down larger cracks and voids adjacent to rocks and larger roots. This uneven distribution of soil water plus the addition of runoff from rock surfaces probably has important effects on plant growth, and perhaps species distribution, which deserves further study.

In another post fire study, Howell et al. (2006) sought links between soil water repellence, the formation of litter dams, and seed germination. Results showed that water repellence varied spatially, and that fire was not the only cause of this phenomena as fungi and proteoid roots were also involved. Botanists and plant ecologists have known of the existence of cluster rootlets particularly in the family Proteaceae for some time (Bellgard 1991) and generally equated them with mycorrhizal fungi in serving a similar role in nutrient and/or water scavenging in harsh environments. As studies multiplied, proteoid roots were found in an increasing number of plant genera and were seen to be most abundant in the surface layers of nutrient poor soils. Studies on chemical exudates (Veneklaas et al. 2005) on 57 species of *Banksia* in Western Australia showed that they all possessed proteoid roots that exuded a range of carboxylates, predominantly citrates. Citrates are known to effectively liberate phosphorus when it is bound on iron and aluminium in the soil and thus the presence of proteoid roots was recognised as playing a role in soil chemistry.

Lamont (2003) showed that proteoid roots vastly increased the volume of soil explored, thus making them much more efficient in accessing water and nutrients and at the same time intimately binding individual soil particles as noted by Gould (1998a, 1998b). These pioneering studies were undertaken in iron rich soil (lateritic sandplains and laterite breakaways) in semi-arid Western Australia and Pate et al. (2001) suggested that the co-occurrence of Proteaceae and laterite may have a causative relationship. This observation deserves study in NSW.

Macquarie researchers also turned their attention to the role of surface and near surface excavation and mounding of mineral soil (Figure 49) by invertebrates (ants, earthworms, cicada, and termites) and vertebrates such as echidna, and lyrebirds. Studies attempting to establish rates of soil turnover (bioturbation) were presented by; Humphreys (1981); Humphreys and Mitchell (1983); Adamson et al. (1983); and Cowan et al. (1985). The measured rates were surprisingly high and quite sufficient to turn over the entire thickness of A horizons in only centuries.

Figure 49. Active ant mounds casting subsoil material on top of surface litter. Most of this mound will be moved in the next rainfall. Scale is 10 cm long.

By combining both the erosion processes and the bioturbation studies a suite of processes turning over the topsoil and exposing it to irregular rain wash was recognised as being responsible for the genesis of the mobile surface mantle (a biomantle sensu Johnson 1990). These combined processes also explained the sharp A/B horizon boundary, the burial and transport of clasts in the stone layer, and downslope changes in sand grain size.

Laterite

Following Paton and Williams (1972) criticism of the laterite concept, Hunt et al. (1977) reviewed the nature of the ‘type profiles’ at Terrey Hills and lateritic ironstones on the Lambert Peninsula. Contrary to claims by Faniran (1971), iron oxides were found to be readily available in the Hawkesbury Sandstone and abundant in some beds near the top of the sequence. Therefore, seeking external sources of iron from shales or volcanic rocks to form laterites as Faniran had done, was unnecessary. Hunt et al. (1977) found that the Terrey Hills profile was formed on Hawkesbury Sandstone rather than shale as Burges and Beadle (1952) had tried to demonstrate. Bourman (1989) challenged this claim but was unable to view the base of the profile which was visible to Hunt et al. The widespread distribution of alleged lateritic ironstone clasts across the plateau as evidence of the former more extensive distribution of laterite was challenged when the lithology and distribution of the clasts themselves were examined. They were identified as stone layers in the biomantle that could be physically traced to various bedrock sources of iron cemented sandstone or shale. Both Hunt et al. (1977) and Bourman (1989) agree there is no merit in continuing the case for a hypothesised Miocene peneplain and tropical climate for any of these materials.

Several questions about the genesis of these ferricretes remain. One direction for research would be to follow up on the work on Western Australian laterites (Verboom and Pate 2006; Sawkins et al. 2011). Another would be to examine contemporary movement of iron in the sandstone landscape. Iron minerals are not in short supply in the sandstone landscape and their mobilisation can be mediated by several biospheric pathways all of which should be further examined. For example, Bourman (1989) noted the presence of ferrihydrite staining in soil water seepage zones along roadsides and identified ‘bog iron ore’ in one location at Terrey Hills. Small bacterial iron flow structures are frequently found in sandstone rock overhangs where there is regular water seepage. Buchanan (1980) described flocculant masses of iron bacteria and organic matter as much as 50 cm thick in creeks and swamps on the Lambert Peninsula which elsewhere is a precursor to the formation of bog iron, and observation of an exposed stone layer in a soil seepage zone being actively cemented by ferrihydrite (Figure 50) all show that iron solution and deposition is occurring the landscape today.

Is it possible that the KGR's ferricretes began as bog irons? Such places are quite different from where the ferricretes are now found as indurated profiles on the ridge crests. If there is any merit in this extreme suggestion, then outcrops like the Terrey Hills ferricrete could still be ancient, but rather than being remnants of a planation crust, they may be examples of topographic inversion.

Figure 50. Seepage zone precipitating ferri-hydroxide and cementing sandstone gravel, KCNP. Scale is 10 cm long.

Development of a new model of soil formation

Humphreys and Mitchell (1983), Mitchell (1988), Humphreys (1994), and Paton et al. (1995) summarised the hill slope processes and their pedological effects in a new soil genesis model (Figure 51) that changed the existing concept of podsolic soils as mature profiles that had taken tens of thousands of years to form (Walker 1962) They could now be seen as active soils in which the biomantle could be less than a millennium old, and the profiles were effectively time transgressive.

The model applies to all soils on hillslopes regardless of whether or not they exhibited a texture contrast between horizons, and biomantles could be identified in soils in virtually all environments (Mitchell 1988). This model enabled a new approach to soil survey in which soil materials were first identified and then placed in their landscape context using stratigraphic interpretation. It should be no surprise that this approach, although more explicit, is essentially identical to that used by Chapman and Murphy (1989).

Soil materials were defined by Chapman and Murphy (1989) in the original publication as 'recognisable three-dimensional soil entities which have a degree of homogeneity, and lateral continuity. Soil materials are not necessarily defined by soil formation processes or position within a profile and although they usually correspond with soil horizons other materials such as introduced fill, regolith, or unconsolidated alluvium may also qualify.'

In other words, some soil material may be identifiable horizons formed by pedogenic processes, but other materials are better regarded as strata if their distribution can be

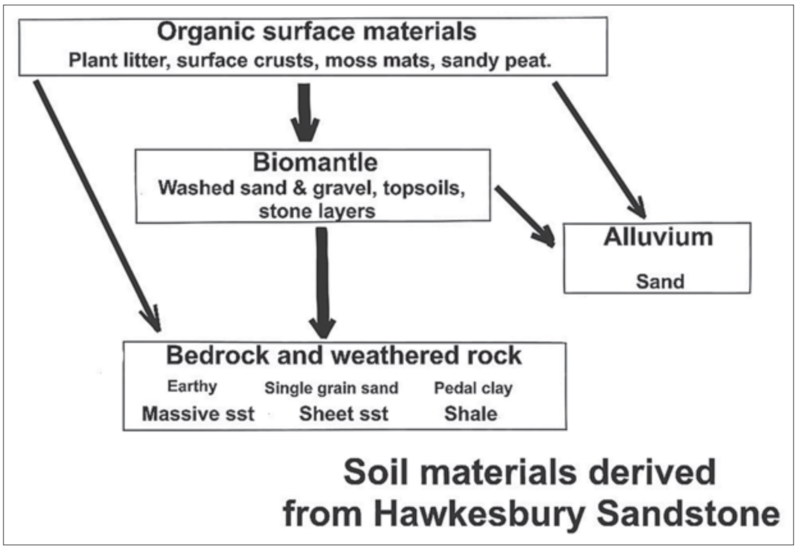

Figure 51. Soil material model applicable to the Hawkesbury Sandstone landscape. Width of the arrows reflects the frequency of the relationship, each box may be treated as a stratum although sometimes the boundaries are difficult to identify.

shown to obey stratigraphic principles (Krumbein and Sloss 1963) the most useful of which are as follows.

1. Principle of cross cutting relationships – the independence of a layer (stratum) may be demonstrated by its persistence over two or more substrates.
2. Principle of superposition – younger materials are deposited on, or incised into, older materials.
3. Principle of included fragments – fragments of pre-existing materials are normally only included in younger materials.

In any soil landscape there are inevitably complications in the applications of these principles for three reasons i.e.,

1. The degree of mixing between layers and the resulting gradational boundaries can make it difficult to identify some strata.
2. Some pedological horizons (podsol pans for example) may be superimposed on strata and obscure the stratigraphy.
3. There can be considerable lateral change in the fundamental properties of a single stratum such as downslope fining that may be challenging to interpret. However, these can be treated as facies (variants) of a stratum.

Stratigraphic links between soil materials can be seen in Chapman and Murphy's schematic diagrams although they are not explicitly acknowledged. Other work in the same landscapes identified some materials not listed by Chapman and Murphy (1989) and allowed all known materials to be assembled into four linked sets that create the explanatory model of soil material genesis and distribution shown in Figure 51.

This model identifies four process and soil material sets with an emphasis on stratigraphic interpretation and acknowledgment of the effects of surface movement processes (erosion, size sorting, and deposition), along with the mixing of materials by plants and animals (bioturbation). This model has been widely and successfully applied in other Australian environments (e.g., Unger et al. 1996).

All the hillslope materials found in the Hawkesbury Sandstone Landscape consist of a litter layer, an active biomantle (topsoil), in situ weathered subsoils and intact rock. The process and material sets are as follows.

1. An organic surface layer mainly composed of plant litter in various stages of decomposition. Surface feeding roots are abundant in the decomposing litter. Active bioturbating organisms, particularly ants, deposit mounds of excavated mineral soil on the surface of the litter which is redistributed in subsequent rains with finer particles being exported from the slope environment. The litter may include concentrations of charcoal from past wildfires. In swamps the organic layer can grade into a sandy peat through a gelatinous mat of iron oxides, algae, and bacteria. The layer can also include somewhat ephemeral moss mats and soil crusts of algae or lichen. It is important to recognise that litter is an active layer that can move downslope independently of other materials except when the vegetation cover is very dense.
2. A biomantle (Johnson 1990) which may include several facies such as an active rain splash layer of single grain sand and charcoal, or surface gravels. The biomantle is usually loamy sand-sandy loams, or grey-brown or yellow fragile earthy sands, which are designated as A_1 and A_2 horizons. Charcoal fragments are abundant, bioturbation patterns (burrows and other fabrics) are usually visible, fine grained mica and graphite flakes derived from Hawkesbury Sandstone bedrock are rare because their platy shape allows them to be easily exported. The soil surface often reveals micro-geomorphic forms such as litter dams when the vegetation cover has been reduced. Plant feeding roots are largely confined to this layer. Parts of the biomantle may vary in their physical properties such as grain size and layer thickness in different slope positions.
3. At the base of the biomantle stone layers of iron cemented sandstone or shale clasts, quartz pebbles, and sandstone boulders are found. Bishop et al. (1980) found that in cases where the stones were platy there was a tendency for them to be imbricated and for individual clasts to dip downslope at steeper angles than the slope itself. Individual lithologies may sometimes be traced upslope to bedrock sources.
4. A suite of bedrock materials weathered in situ and grading downward to firm rock. These are the normal subsoils and the lithological base of most soil profiles. They have firm earthy or pedal fabrics

depending on the clay content of the weathered rock involved. Colours vary with drainage condition i.e., red, yellow, drab brown, and often mottled. Charcoal fragments are absent, fine grained mica and graphite flakes are common and confirm the in-situ nature of this material. Stone layers may occur in deeper parts of this layer composed of indurated bedrock layers which normally lie parallel to bedrock structures. Sandstone or shale rock fabric becomes more evident toward the base of the layer. In the Hawkesbury Soil Landscape three types of bedrock produce different weathering products. Massive sandstone tends to produce slightly clayey subsoils with earthy fabrics, sheet sandstone produces cleaner sand and rock debris, and the lens-like bodies of shale produce blocky pedal clay.

5. Alluvial sands are often interbedded with charcoal layers in depositional sites such as swamp margins or creek alluvium, whereas fine grained mica and graphite flakes are absent. Older deposits on stream terraces or benches lack clear bedding, show increased levels of bioturbation, and may be overprinted with pedological features such as mottling, and iron or organic pans. These materials form the basis of separate soil landscapes such as Deep Creek and Oxford Falls.

Conclusions

Focusing only on the soil materials and processes seen in Hawkesbury Sandstone landscapes facilitated closer observation and improved understanding that led researchers at Macquarie University to discriminate between two soil profiles, podsolic and podsols with respect to their morphology and genesis. Review of the contentious laterite profiles supported the preference for referring to these as ferricretes and has opened the way to potential research topics that may better elucidate their origin. By consolidating this work through the recognition of discrete soil materials rather than profiles, and by adopting a stratigraphic approach to soil landscapes, a new genetic model of soil evolution and distribution was developed and presented in an award-winning text by Paton, Humphreys, and Mitchell (1995).

Most previous studies failed to consider the role of the biosphere and the importance of geomorphic processes. These topics were explored by researchers at Macquarie University and enabled the most recent soil survey to break away from the constraints of the soil profile to present a more comprehensive picture of the distribution of discrete bodies of soil material across the landscape.

VERTEBRATE FAUNA OF THE KGR (J.B. Walsh)

The fauna of the expanse of country encapsulated by the KGR is intricately expressed as the living story of geology. The sandstones and shales of the Sydney Basin Bioregion have driven the evolution of many endemic flora and fauna species (Couper and Hoskin 2008). Within the boundaries of the KGR, the predominant geology belongs to the Narrabeen Group, the Hawkesbury Sandstone, and the Wianamatta Group. The varying habitat requirements and life histories of fauna are dictated by the floristic structure of an area which is directly caused by aspect, climate and most importantly, geology. Within the study area there are a total of over 500 tetrapod species comprised of 350+ birds, 47 reptiles, 87 extant mammals, and 23 extant amphibians.

The diverse geological formations in this area from coastal lagoons to rugged Hawkesbury Sandstone escarpments provide many opportunities for an impressive diversity of life to flourish. The extent of rock outcrops plays a significant role in shaping animal distributions. The red-crowned toadlet (*Pseudophryne australis)*, the endemic rockwarbler (*Origma solitaria*), broad-headed snake (*Hoplocephalus bungaroides*), and broad-tailed gecko (*Phyllurus platurus*), are all icons of the Bioregion with distributions entirely limited by presence of sandstone. In addition, the structurally diverse heathlands, and woodlands of the KCNP are well-known to host exceptional diversity in both flora and all tetrapod classes (Lunney et al. 2010; DECC 2008). As a result of a high diversity of habitats and flowering eucalypts within the KGR, a staggering 28 honeyeater species (representing some 40% of the species recorded in Australia) have been recorded including the critically endangered regent honeyeater (*Xanthomyza phrygia*) and the vulnerable, black-chinned honeyeater (*Melithreptus gularis*). In winter, the KGR comes alive with nomadic honeyeaters that continuously travel along the Great Dividing Range in the never-ending search for flowering eucalypts. This plant-pollinator mutualism is a common theme with many nectivorous birds and mammals relying upon flowering plants for food and plants relying upon animals for pollination.

Throughout spring and summer, herpetofauna (i.e., reptiles and amphibians) are active and obvious, in both good numbers and diversity. Briefly during late summer, as red bloodwoods (*Corymbia gummifera*) flower profusely, masses of grey-headed flying foxes (*Pteropus alecto*) descend upon the characteristic sandstone woodlands and heathlands of the KGR, after leaving their day roosts across Sydney. By day, noisy friarbirds (*Philemon corniculatus*) undertake a similar mission. The important levels of genetic variation in plants generated by long-distance pollinators such as the grey-headed flying fox and noisy friarbird enhance the resilience of vegetation communities and increase the communities' capacity to withstand or adapt to external pressures such as a changing climate (Kremer et al. 2012).

Resulting from the unpredictable weather patterns that Australia experiences, the behaviour of fauna is dictated by physical and chemical triggers and hence this behaviour is never the same two years in a row. This extreme variability in weather has driven Australian fauna to have remarkable physiological, behavioral, and structural adaptations (Marder et al. 2003; Roberts and Edwards 2018). In more stable climates, these triggers can be predicted year after year to the specific day that an organism will become active or migrate etc. When considering population dynamics, Australian fauna is in a constant 'dance' with the climate; in good wet seasons within the Sydney Basin, the short-term conditions dictate that most species will have an abundance of resources and therefore optimal breeding conditions. Contrastingly, severe droughts such as the Millennium Drought can cause significant short-term population reductions. These climactic oscillations are reflected in fauna abundances and distributions at a point in time. Over millennia, climactic conditions are a key driver in speciation (Cooper et al. 2011; Rix et al. 2015).

Fauna of coastal heathlands and dry sclerophyll woodlands

Reptiles

Within the KGR, reptiles include lizards, snakes, and turtles. Across the highest elevation and larger bench escarpments within the area, many species will congregate around the complex and numerous basking and sheltering options. Escarpments offer caves, overhangs, gnammas, crevices, canyons, post-rockfall habitat, and more. As such, the KGR has significant diversity and abundance of herpetofauna especially considering its location as part of Australia's largest city. Every spring, reptiles of many species emerge in search of prey following prolonged periods of dormancy, known as brumation. This dormancy is characterised by lowered metabolism, heart rate, and energy demands to survive the potentially lethal winters (Ultsch 1989; Holden et al. 2021).

Lizards

All Australian lizard families - dragons, legless lizards, skinks, monitors, and geckos are represented within the study area by multiple species. The elegant snake-eyed skink (*Cryptoblepharus pulcher*) can be seen efficiently navigating logs, rock faces, and any vertical or even upside-down terrain. They are well adapted to life on the edge of escarpments and subsequently to the derived escarpments of older suburbs that utilise coarse brick and unpainted fences. Within any deep horizontal gaps on escarpments with multi-layered rock, Cunningham's skinks (*Egernia cunninghami*) can be found living in small family groups with members of mixed ages and can live to

Figure 52. Terrestrial termite mound nest of the heath monitor (*Varanus roserbergi*) with recent termite reconstruction.

be almost 30 years old (Brown 2012). All along the top of these escarpments and within the surrounding heathland and dry sclerophyll woodland, the boldly patterned copper-tailed skink (*Ctenotus taeniolatus*) is a common but urban-intolerant species. They are part of a large genus of skink that is only represented in the Sydney Basin by three species, out of 106 species represented in Australia. Throughout the dense leaf litter found in the heathland and woodland that surrounds escarpments, both dark-flecked (*Lampropholis delicata*) and pale-flecked sun skinks (*Lampropholis guichenoti*) are abundant, making the most of the available invertebrate 'buffet.' The life history of the vulnerable heath monitor (*Varanus rosenbergi*) is one that revolves around terrestrial termite mounds (Figure 52). Another icon of Sydney coastal heathlands and dry sclerophyll woodlands, the heath monitor finds a stronghold within the KGR. Adult monitors will lay their eggs in terrestrial termite mounds like many reptiles to capitalise on the warm, stable temperatures, increased humidity, and physical protection from egg predators (Figure 52) (Riley et al. 1985; Carter 1992; Kirshner 2016). The eggs are laid in late February or early March and are incubated over winter before hatching in October.

Figure 53. Broad-tailed gecko (*Phyllurus platurus*); a Sydney Basin endemic foraging below a tongue orchid (*Dockrilla linguiformis*).

Upper escarpments are good places for the four species of native gecko in Sydney – broad-tailed gecko (*Phyllurus platurus*) and thick-tailed gecko (*Underwoodisaurus milli*) – to call home with the broad-tailed gecko being a Hawkesbury Sandstone endemic and frequently inhabiting anything from rainforest boulder fields to suburban garages, weaving its way into the human story (Figure 53). In addition, Burton's Legless Lizard (*Lialis burtonis*) and the Common Scaly-foot (*Pygopus lepidopodus*) are two species from the family Pygopodidae which are a kind of legless gecko. They have vestigial hind legs, a fleshy tongue, and the ability to lick clean the clear spectacles that cover their lidless eyes (Wilson and Swan 2021).

Another 'legless lizard' is the three-toed skink (*Saiphos equalis)* which wakes to forage at sunset with reduced limbs, moving in a snake-like manner. Conversely, this is a species of skink and unrelated to the legless geckos of *Pygopodidae*. One fascinating breeding biology trait is they are known to lay eggs in coastal areas such as the KGR and give birth to live young in colder upland regions such as the Blue Mountains (Figure 1).

Finally, one lizard species that has significantly declined in abundance and distribution within the Sydney Basin is the eastern bearded dragon (*Pogona barbata*). This species (Figure 54) was still patchily distributed within Northern Sydney half a century ago, however is now confined to larger expanses of bushland that are free from the impact of urbanisation. There are still occasional sightings of this species in Ku-ring-gai Chase NP (pers. obs., Walsh 2022; ATLA 2022).

Figure 54. Eastern bearded dragon (*Pogona barbata*) basking on an overcast 22^{o} C day overlooking Coal and Candle Creek in KCNP. A very infrequently seen species in the coastal parts of the Sydney Basin.

Snakes

There are 14 terrestrial snake species recorded within the KGR and several vagrant sea snake species. The gentle warmth provided by spring sunshine lures many snake species to bask including eastern brown snake (*Pseudonaja textilis*), red-bellied blacksnake (*Pseudechis porphyriacus*), tiger snake (*Notechis scutatus*), yellow-faced whip snake (*Demansia psammophis*), death adder (*Acanthophis antarcticus*), diamond python (*Morelia spilota*), marsh snake (*Hemiaspis signata*) and common tree snake (*Dendrelaphis punctulatus*). However, not all snake species bask, and many are either adapted to tolerate cooler conditions or are attracted to sources of warmth that are residual or independent of the sun. Many snake species within the KGR are partly or wholly nocturnal with all locally recorded species displaying some nocturnality when conditions dictate.

As the daylight fades, a different suite of snakes emerges. On a warm spring night including anything as low as 16^{o} C, the golden-crowned snake (*Cacophis squamulosus*), brown tree snake (*Boiga irregularis*), bandy bandy (*Vermicella annulata*), blackish blind snake (*Anilios nigrescens*), diamond python and marsh snake may all be active. In contrast, on a hot summer night, the fastest striking snake in the world, the death adder, tiger snake and eastern brown snake may all be active at night (Figure 55).

Figure 55. Both red and grey morph, common death adders (*Acanthophis antarcticus*) are abundant but infrequently seen in the coastal heathlands and coastal dry and wet sclerophyll forests of the GeoRegion.

Freshwater turtles

Two species of native freshwater turtle have been recorded within the KGR, the eastern snake-necked turtle (*Chelodina longicollis*) being the most common, with just a few more few recent records, including from the Warriewood Wetlands, of the short-necked Murray River turtle (*Emydura macquarii*). Both are members of the reptilian family Chelidae, a Gondwanan turtle family in which the head and neck are folded sideways under the shell when the animal is alarmed instead of being directly withdrawn. They both rely on freshwater environments and are often found basking on logs and rocks within waterways, lakes, dams, or ponds of the KGR. They are also sometimes sighted on ridgetops and roads when on the move from one waterhole to another, and unfortunately are often the subject of roadkill.

The snake-necked turtle feeds on aquatic invertebrates, gastropods, tadpoles, and small fishes while the Murray River turtle is an omnivore and feeds on copious amounts of water plants and algae as well as invertebrates. Foxes, roadkill, and drought are their main threats. The North American red-eared slider turtle (*Trachemys scripta elegans*) has also been found in the Sydney region, probably because of people releasing imported pets into local waterways, though there are no records of it yet occurring within the KGR.

Amphibians

Almost all frog species in the study area are exclusively active at night with occasional calls and periods of wakefulness during the day. Most activity is focused around spring and early summer but as always, each species has its own preferred conditions and months of activity. Some species are peak-winter breeders, but this is rare locally, limited to the whistling tree frog (*Litoria verreauxii*). Like reptiles, every spring many amphibian species awake out of their dormancy, which is known as aestivation (Carvalho et al. 2010; Storey and Storey 2011). Travelling from the headwaters of a creek downstream, a repeatable pattern displays itself in the biota present. Initially, the surrounding woodland and heathland begins to form ephemeral and slow-flowing channels. Shallow basins begin to appear that have significantly dense and compacted leaf litter. Only a few metres down from the headwaters of such a feature the red-crowned toadlet (*Pseudophryne australis*) will usually be detected. From here on, as the channel begins to incise into the surrounding land, pooling, obvious channeling and overflow points are common with thick leaf litter periodically distributed. A similar density of red-crowned toadlets will remain along these first order streams until water becomes more permanent with decreasing elevation. Any first order streams that contribute to the primary waterway are habitat for this species which is both vulnerable and a Sydney Basin endemic (Figure 56). Because of Australia's unpredictable climate, the *Pseudophryne* genus which includes the southern corroboree frog has co-evolved some interesting ways to deal with this situation (Tyler 1994; Thumm and Mahony 2002). Eggs are laid year-round therefore taking into consideration unpredictability of rain (Figure 57). However, there is still an extremely low recruitment rate with one study recording only three out of 1,000+ tadpoles surviving until adulthood, therefore making any recovery difficult from pollution or from a drought event.

Figure 56. A particularly boldly marked Red-crowned toadlet (*Pseudophryne australis*) from the Middle Creek Catchment.

Figure 57. Red-crowned toadlet eggs from the Deep Creek Catchment.

For 1st, 2nd, and 3rd order streams travelling down the escarpment the habitat generally opens or increases in stream width and remains dense. In these light-filled, warmer and water abundant spots, different frogs dominate. Open rocky dry sclerophyll forest provides breeding habitat for wallum rocket frogs (*Litoria freycineti*), green stream frogs (*Litoria phyllochroa*), common eastern froglet (*Crinia signifera*), and the vulnerable giant burrowing frog (*Heleioporous australiacus*), as well as for two species of spiny crayfish (*Euastacus spinifer* and *Euastacus australiensis*) within these clear pooling waters. The giant burrowing frog is a large frog that lives in woodland, heathland, and dry and wet sclerophyll forest (Figure 58). The species lives on deep sand beds and creates a burrow to aestivate in until conditions are favourable. The frog lays eggs in small pools of water or slow flowing creeks of the highest water quality. Depending on water temperatures, it can often take over one year for tadpoles to metamorphose into frogs. Incredibly, male giant burrowing frogs have been recorded wandering more than 500 m from breeding sites and spend time in distinct non-breeding habitat well away from waterbodies (Penman et al. 2008).

Figure 58. Giant burrowing frog (*Heleioporous australiacus*) recently emerged from burrow on Lambert Peninsula.

Birds

The KGR is home to 300+ species of bird, almost one-third of all species recorded in Australia. Such complexity of habitats arising from proximity to the coast has resulted in phenomenal bush-bird, wetland, shorebird, and seabird diversity. The relative high density of people acting as observers has also allowed for regular citizen science surveying. Some of the more unique birds of the Sydney Coastal Heathlands and Sydney Dry Sclerophyll Woodlands include the southern emu-wren (*Stipiturus malachurus*), brush bronzewing (*Phaps elegans*), chestnut-rumped heathwren (*Calamanthus pyrrhopygius*), white-throated nightjar (*Eurostopodus mystacalis*), pheasant coucal (*Centropus phasianinus*), painted button-quail (*Turnix varius*), wedge-tailed eagle (*Aquila audax*), little eagle (*Hieraaetus morphnoides*), and the Sydney Basin endemic rockwarbler (*Origma* *solitaria*). The rockwarbler is inextricably linked to the Hawkesbury Sandstone of the Sydney Basin, and it does not occur anywhere outside of that. Its closest relatives live in the ancient rainforests of Papua New Guinea (Norman et al. 2018). In summer, this bird lives and often nests in the habitat of 'coachwood/lilly-pilly/water gum gallery rainforest in sandstone gullies.' Here, the birds are protected from the harsh summer sun. The sandstone boulder creek beds provide refuge thanks to the accompanying gallery rainforest. Then in winter, when temperatures are cooler and days more overcast, rockwarblers feel confident to explore upper exposed ridges, rocky shorelines, and all manner of sandstone outcrops. The first recorded roost site of a rockwarbler was discovered by the author within a sandstone overhang near Akuna Bay in KCNP in December 2018 (Figure 59).

Figure 59. Roosting rockwarbler (*Origma solitaria*) near Akuna Bay in KCNP.

In late September and early October, the summer migrants arrive. They consist of birds that spend time chasing a near constant temperature of ~30^{0}C by wintering in North Queensland and migrating south to NSW to breed in the summer. These species occur in good numbers in the productive feeding grounds surrounding the Hawkesbury River. They include the leaden flycatcher (*Myiagra rubecula*), satin flycatcher (*Myiagra cyanoleuca*), sacred kingfisher (*Todiramphus sanctus*), dollarbird (*Eurystomus orientalis*), pacific koel (*Eudynamys orientalis*), channel-billed cuckoo (*Scythrops novaehollandiae*), common cicada bird (*Coracina tenuirostris*), white-throated gerygone (*Gerygone olivacea*), rufous whistler (*Pachycephala rufiventris*), and white-throated nightjar (*Eurostopodus mystacalis)*.

In late summer/early autumn, flowering red bloodwoods (*Corymbia gummifera*) form a significant feeding resource within the landscape and one that influences animal behavior patterns in coastal New South Wales. This abundant resource attracts a stream of noisy friarbirds (*Philemon corniculatus*) – a large honeyeater with a distinct bald black head – and smaller numbers of other nomadic honeyeaters and other nectarivores that are on a northward passage only to return in large numbers again in a few more months. As the red bloodwoods peak in flower, most of the summer migrants have returned northwards once more. As late autumn and winter approaches it is peak honeyeater season. At this time of year on an early morning walk along the Waratah, Chiltern or Gibberagong Trails within the KCNP, up to 15 species of honeyeater are likely to be observed. These are the eastern spinebill (*Acanthorhynchus tenuirostris*), Lewin's honeyeater (*Meliphaga lewinii*), yellow-faced honeyeater (*Caligavis chrysops*), yellow-tufted honeyeater (*Lichenostomus melanops*), noisy miner (*Manorina melanocephala*), little wattlebird (*Anthochaera chrysoptera*), red wattlebird (*Anthochaera carunculate*), fuscous honeyeater (*Ptilotula fusca*), scarlet honeyeater (*Myzomela sanguinolenta*), New Holland honeyeater (*Phylidonyris novaehollandiae*), white-cheeked honeyeater (*Phylidonyris niger*), white-eared honeyeater (*Nesoptilotis leucotis*), white-naped honeyeater (*Melithreptus lunatus*), brown-headed honeyeater (*Melithreptus brevirostris*), noisy friarbird (*Philemon corniculatus*), and in addition tawny-crowned honeyeater (*Gliciphila melanops*), little friarbird (*Philemon citreogularis*), crescent honeyeater (*Phylidonyris pyrrhoptera*), black-chinned honeyeater (*Melithreptus gularis*), and regent honeyeater (*Anthochaera phrygia*) have all been seen multiple times in the KGR.

Mammals

The same red bloodwoods that feed noisy friarbirds by day in February host a similar yet different frenzied feeding event by night. Large numbers of grey-headed flying foxes occasionally mixed with other species such as little red (*Pteropus scapulatus*) and black flying fox (*Pteropus alecto*) (pers. obs., Walsh 2019, 2021) descend en masse to these profusely flowering eucalypts, travelling long distances from all over Sydney to feed on this seasonal resource. This includes remnant street trees and remnant red bloodwoods on private property. However, within the larger patches of continuous bushland such as KCNP, the local specialist and urban intolerant inhabitants take advantage of the opportunity too. Within these continuous patches of habitat, species such as feathertail glider (*Acrobates pygmaeus*), sugar glider (*Petaurus breviceps*) (Figure 60), eastern pygmy possum (*Cercartetus nanus*), common ringtail possum (*Pseudocheirus peregrinus*), common brushtail possum (*Trichosurus vulpecula*), brown antechinus (*Antechinus stuartii*), and more turn their attention to the

Figure 60. Sugar Glider (*Petaurus breviceps*) from the Endangered Swamp Sclerrophyll Forest of Warriewood Wetlands.

Figure 61. Eastern pygmy possum (*Cercartetus nanus*) on *Grevillea buxifolia* at Lambert Peninsula.

bloodwoods. By night, the vulnerable and until recently infrequently recorded eastern pygmy possum spends much of this early part of the year feeding on invertebrates, old-man banksia flowers (*Banksia serrata*) and red bloodwood blossom (Tulloch and Dickman 2006). In the last 20 years, survey techniques have improved using natural material 'hollow log' nest boxes and camera traps, as prior to this they were a poorly researched species. However, finding eastern pygmy possum by spotlight over much of the year in the Sydney Coastal Heathlands, and Sydney Coastal Dry Sclerophyll Forests (Figure 61) is successful. They occur throughout the KGR in a variety of other habitats although in lower density in wetter habitats and their movements are resource dependent. Some other important feeding resources of the eastern pygmy possum explain why the study area is so well known for its significant population of this species. These include invertebrates, *Allocasuarina distyla, Banksia ericifolia*, *Banksia oblongifolia*, *Banksia marginata, Eucalyptus haemostoma, Eucalyptus camfieldii, Angophora hispida*, and *Lambertia formosa*. All the above are prolific within certain areas of the KGR.

Being so rare in NSW and at its northern limit, perhaps the most significant mammal that occurs in the heathland and dry sclerophyll forest of the area is the southern brown bandicoot (*Isoodon obesulus*). This species is listed as Endangered in both NSW and nationally and is at its northern limit in KCNP (DECC 2006). Invasive predators such as the red fox (*Vulpes vulpes*) and feral domestic cat (*Felis catus*) coupled with changed fire regimes have caused significant declines in this species across NSW where it is rare, range restricted, and difficult to survey. They are more specific in their habitat requirements than the long-nosed bandicoot (*Perameles nasuta*) and within NSW require heathlands or dry/wet sclerophyll forests with heathy understorey on sandy soil (Dowle 2012). Whilst habitat that superficially fits this description is widespread there are few records of the southern brown bandicoot in recent times indicating a troubled future and the widespread reality of pest species and too frequent burning. They feed upon a variety of foods including ants, beetle larvae and plant material. Seeds and the fruit-bodies of hypogeous fungi are eaten on a seasonal basis (Braithwaite 1995; Claridge et al. 1991). Increased funding for further survey and research, and implementation of more refined fire regimes will encourage activities such as small-scale mosaic burning to protect habitat features including logs, *Xanthorrhoea* spp. skirts and the low and dense shrub cover required by the southern brown bandicoot.

In the last decade, the plight of the koala (*Phascolarctos cinereus*) in NSW and Queensland has been increasingly publicised through the national media. Simultaneously, government policy has lacked adequate protection for trees and vital koala habitat with legal protections frequently being removed. There are few koalas left in Sydney with the largest population in South Sydney around Campbelltown/Heathcote constantly under threat from car strikes, dog attacks, and housing development. Historically, there were large populations of koalas in the KGR at Barrenjoey Peninsula, Deep Creek, Middle Creek, Mullet Creek, Cottage Point, and West Head. The largest and most well-known of all of these was on the Barrenjoey Peninsula where up until the late 1970s residents of Avalon, Clareville, and surrounds would frequently see koalas in their backyards and community spaces (Smith and Smith 1990). Unfortunately, now that the Barrenjoey population is no longer extant, the koalas that do persist within the KGR are rarely discussed and are perceived to be locally extinct by many. Since the year 2000, sporadic records from throughout KCNP and adjacent areas indicate that a population is persisting despite having small population size and no formal surveying (Smith and Smith

2000). It would be desirable for koala detector dogs to be used in all bushland areas greater than 10 ha in size within the Northern Beaches, Ku-ring-gai, and Hornsby Councils to determine the location and size of the remaining koala population. Then compensatory planting of grey gums could be conducted throughout KCNP and Garigal National Park to improve future food resources and change fire regimes in target areas for reduced intensity of fire. The favoured food of koalas locally is grey gum (*Eucalyptus punctata*) which is commonly found on escarpments and slopes where Narrabeen Group shales are more exposed. The second most favoured food resource is scribbly gum (*Eucalyptus haemastoma*) which grows on sandy soils and the third is swamp mahogany (*Eucalyptus robusta*), a wetland species. Along the Koolewong Track at West Head impressive examples of tall grey ironbark (*Eucalyptus paniculata*) occur on igneous rock. Koalas have frequented this area in the past and scats have been observed as recently as 2021. The most recent record of a koala in the KGR was of a male heard calling by the author in April 2022.

A comparable situation applies to the platypus (*Ornithorhynchus anatinus*) with only a few older records for the KGR from Narrabeen Lagoon, Manly Dam and Pittwater catchments. The alteration of its freshwater habitat through inappropriate fire regimes, sedimentation, and urbanisation contributing to poor water quality is likely to be responsible for their reduction or demise.

On the other hand, the other Australian monotreme, the echidna (*Tachyglossus aculeatus*) remains reasonably common in the KGR. It is not often seen but feeding scrapes in ant nests and termite mounds reveal its presence.

Wet sclerophyll, rainforest, and wetlands

As suggested by this heading, these three habitats provide something that dry sclerophyll and heathland lack, i.e., abundant water. As such, there are marked differences in the ecology of these places despite occurring so close together. There are a multitude of different habitats found in wet bushland from the many habitats around Narrabeen Lagoon to Warriewood Wetlands, Cockle Creek, Deep Creek, Middle Creek, Lover Jump Creek, McCarrs Creek, Bangalley Headland, Barrenjoey Headland, and many unnamed valleys and creeks throughout the KCNP.

Reptiles

The stable temperature, abundance of water and structural complexity of an environment shaped by water produces a high biomass of skinks and frogs allowing reptiles to thrive. Wetland and Sandstone Gallery Rainforest habitat provide a home for red-bellied black snakes (*Pseudechis porphyriacus*). These mainly feed upon frogs but also eat mammals, birds, and reptiles opportunistically (Cogger 2018). They are locally abundant in suitable habitat all over the KGR but are an uncommon find away from water.

Figure 62. Gully Skink (*Saproscincus spectabilis*) from urban backyard in Avalon.

The gully skink (*Saproscincus spectabilis*) (Figure 62) is an interesting species with a disjunct population in Sydney (Wilson and Swan 2021). They are found naturally within the KGR in Sandstone Gallery Rainforest, Littoral Rainforest, and derived rainforest as well as some backyard gardens. This is a poorly documented species that is more widespread in Sydney than previously realised as evidenced by many recent records in the KGR from North Narrabeen, Irrawong Reserve, Avalon Beach, McCarrs Creek, and KCNP.

Amphibians

At the lowest elevations in KCNP where rainforest and wet sclerophyll forest abound, green stream frogs (*Litoria phyllochroa*) call from exposed coachwood (*Ceratopetalum apetalum*) and water gum (*Tristaniopsis laurina*) branches overhanging fast flowing rocky creeks (Figure 63). In small pools on the sides of these creeks the common eastern froglet (*Crinia signifera*) and striped marsh frog (*Limodynastes peronii*) breed when water levels are suitable. In wetland areas prone to slow and seasonal flooding such as Deep Creek, Middle Creek, and Warriewood Wetlands, ‘explosive’ breeders occur. These are frogs that undertake all breeding activity for

Figure 63: Coachwood - lilly pilly - water gum gallery rainforest in sandstone gullies of the Sydney Basin at Cowan Creek; habitat of rockwarbler, broad-tailed gecko, gully skink, red-bellied black snake et al.

only a few nights following heavy rain after prolonged dry periods. These species include the regionally significant dainty tree frog (*Litoria gracilenta*), Tyler's tree frog (*Litoria tyleri*) (Figure 64) and the green tree frog (*Litoria caerulea*). Some other wetland frogs include Peron's tree frog (*Litoria peronii*), the eastern dwarf tree frog (*Litoria fallax*), and the whistling tree frog (*Litoria verrauxii*).

Figure 64. Tyler's tree frog (*Litoria tyleri*) from Warriewood wetlands.

Birds

In the foothills, gullies and below some escarpments, wet sclerophyll and rainforest provides dense habitat for many rainforest specialists. High rainfall, a general absence of fire, and abundant fallen rock along escarpments, headlands, gullies, and waterways provides semi-continuous rainforest habitat within the Northern Beaches for dispersing rainforest species. Post-2000 records on the Northern Beaches of dispersing birds includes white-eared monarch (*Carterornis leucotis*), spectacled monarch (*Symposiachrus trivirgatus*), Torresian imperial-pigeon (*Ducula bicolor*), rose-crowned fruit-dove (*Ptilinopus regina*), superb fruit-dove (*Ptilinopus superbus*), emerald dove (*Chalcophaps indica*), noisy pitta (*Pitta versicolor*), and green catbird (*Ailuroedus crassirostris).* Formerly this corridor extended south towards the Illawarra Region and that facilitated bird migration and dispersal. Once, green cat birds, regent bowerbirds (*Sericulus chrysocephalus*), Wompoo fruit-doves (*Ptilinopus magnificus*), and barred cuckoo shrikes (*Coracina lineata*) were likely to have travelled along the rainforest escarpments from Barrenjoey Headland all through the rainforest gullies to Mona Vale, from there up onto Bayview/Mona Vale/Warriewood Escarpment which can then be followed to Collaroy. These wet habitats, when allowed time without fire, can establish impressive diversity and density allowing more northern NSW avifauna to thrive. Large-billed scrubwren (*Sericornis magnirostra*), superb lyrebird (*Menura novaehollandiae*), satin bowerbird (*Ptilonorhynchus violaceus*), black bittern (*Ixobrychus flavicollis*), rufous fantail (*Rhipidura rufifrons*), wonga pigeon (*Leucosarcia melanoleuca*), and bassian thrush (*Zoothera lunulata*) all reside in these rainforest thickets. The KGR is a stronghold within the Sydney Basin as it provides high-quality roosting habitat for the threatened forest owls namely the sooty owl (*Tyto tenebricosa*), powerful owl (*Ninox strenua*), masked owl (*Tyto novaehollandiae*) (Figure 65), and barking owl (*Ninox connivens*). These species are all listed as vulnerable within NSW.

Figure 65: The KGR supports a significant population of Australian masked owl (*Tyto novaehollandiae*).

Mammals

Australia is becoming a 'biodiversity graveyard,' and that is not truer for any class than mammals. Therefore, the mammal diversity seen now is extremely limited in comparison to 200 years ago, and unimaginably different to 20,000 years ago. An analysis of remains excavated in an Aboriginal midden at Angophora Reserve in Avalon identified a variety of mammal species that are no longer present within the KGR including the brush-tailed rock-wallaby (*Petrogale penicillata*), pademelon (*Thylogale* sp.), red-necked wallaby (*Notamacropus rufogriseus*), common wallaroo (*Osphranter robustus*), long-nosed potoroo (*Potorous tridactylus*), dingo (*Canis familiaris*), and rufous bettong (*Aepyprymnus rufescens*) (McDonald 1992).

The only apex predator still present within the KGR is the spotted-tailed quoll (*Dasyurus maculatus*), which is listed as vulnerable in NSW and endangered nationally. Within the KGR, most records are from the Narrabeen Lagoon and Berowra Creek catchments, with a few older records from the Cowan Creek Catchment. However this is a very rarely recorded species with records occurring only every several years. The spotted-tailed quoll is about the size of a domestic cat with shorter legs and a pointed face. This quoll is a dietary generalist that consumes a variety of medium-weight mammalian prey and requires naturally large home ranges to fulfill its preferences, and even larger home ranges, since prey mammals have significantly declined. They have also been recorded eating carrion and domestic chickens. One individual was found and subsequently caught in a chicken pen in 1993 in the suburb of Elanora Heights. In a confusing turn of events, it was rediscovered two months later in a garage in the inner suburb of Granville (Andrew 2005). If anything, this only shows just how little we know of urban spotted-tailed quolls. Yet again, this species is under surveyed and poorly known in our area but thrives elsewhere in wet sclerophyll forest. (Edgar and Belcher 1995; Menkhorst and Knight 2001).

The rapidity and significance of mammal loss under European management can be appreciated when it is realized that the dingo was still present in KCNP in the 1920s and that the loss of surface feeding small mammals must have had a profound effect on plant litter accumulation, fuel loads, and fire regimes in the last century.

Coastal beaches, cliffs and shore platforms, lagoons, and estuaries

These areas include the northern beaches and associated reefs, coastal cliffs and lagoons and the lower Hawkesbury estuary including Pittwater, Cowan Creek, and Berowra Creek.

Reptiles

The large, sheltered bays, estuaries, and rivers of the KGR provide respite for vagrant individual sea turtles and sea snakes. During winter the water temperature becomes too cold for these species to persist, however during summer and in particularly during tumultuous oceanic conditions, these species can be observed within the KGR.

Four species of sea snake have been recorded within the KGR i.e., yellow-bellied sea snake (*Pelamis platurus*), elegant sea snake (*Hydrophis elegans*), spectacled sea snake (*Disteira kingii*), and Stokes's sea snake (*Hydrophis stokesii*). All species occur as vagrants most often in poor health following east coast storm activity.

Of these four, the yellow-bellied sea snake is the only species to be regularly sighted, with the others being considerably less common.

In addition, four species of sea turtle have been recorded i.e., leatherback sea turtle (*Dermochelys coriacea*), hawksbill sea turtle (*Eretmochelys imbricata*), loggerhead sea turtle (*Caretta caretta*), and green sea turtle (*Chelonia mydas*). The endangered leatherback turtle has been recorded in several locations along Cowan Creek including as far upstream as Bobbin Head. The vulnerable green turtle is the most frequently recorded with records throughout Pittwater annually. The hawksbill turtle is also recorded from Pittwater and along several beaches, whilst the endangered loggerhead turtle has been recorded only from beaches such as Long Reef, Newport, and Palm Beach.

Birds

The lagoons and other substantial waterbodies on the coastal floodplain provide significant refuges for nomadic species during drought. In addition, they support nomadic waterfowl and migratory shorebirds in all manner of conditions. Dee Why lagoon, Long Reef Golf Course, and Long Reef Aquatic Reserve, which combined form a large and continuous expanse of habitat in the south-east of the KGR, has hosted many rare shorebirds and waterfowl over the decades. These include, but are not limited to, letter-winged kite (*Elanus scriptus*), inland dotterel (*Charadrius australis*), oriental plover (*Charadrius veredus*), little curlew (*Numenius minutus*), western sandpiper (*Calidris mauri*), ruff (*Philomachus pugnax*), hooded plover (*Thinornis cucullatus*), marsh sandpiper (*Tringa stagnatilis*), common sandpiper (*Actitis hypoleucos*), Australasian bushlark (*Mirafra javanica*), rufous songlark (C*incloramphus mathewsi*), brown songlark (*Cincloramphus cruralis*), red-chested buttonquail (*Turnix pyrrhothorax*), singing honeyeater (*Gavicalis virescens*), common tern (*Sterna hirundo*), crimson chat (*Epthianura tricolor*), Arctic tern (*Sterna paradisaea*), white-winged black tern (*Chlidonias leucopterus*), bridled tern (*Onychoprion anaethetus*), grey ternlet (*Procelsterna cerulea*), glossy ibis (*Plegadis falcinellus*), yellow-billed spoonbill (*Platalea flavipes*), brolga (*Grus rubicunda*), Australasian bittern (*Botaurus poiciloptilus*), pink-eared duck (*Malacorhynchus membranaceus*), blue-billed duck (*Oxyura australis*), Australian shelduck (*Tadorna tadornoides*), and white-backed swallow (*Cheramoeca leucosterna*) (Hoskin et al. 1991; Birdlife NSW 2022).

The inter-tidal shore platforms present along the Northern Beaches such as at Long Reef, Mona Vale, and Newport provide crucial habitat for rapidly declining migratory shorebirds (Amano et al. 2010; Murray et al. 2018). These birds complete annual migrations from breeding areas in the Arctic to non-breeding areas in Asia and Australasia, with very few and sometimes no stops on this 11,000 km+ journey across the world. Once they arrive in Asia and Australasia in September and October, they spend the summer feeding, enjoying the non-arctic winter temperatures, and stocking up before the return journey in late March and early April. Regular migratory species on these rocky shores include bar-tailed godwit (*Limosa lapponica*), eastern curlew (*Numenius madagascariensis*), grey-tailed tattler (*Tringa breves*), pacific golden plover (*Pluvialis fulva*), red knot (*Calidris canutus*), red-necked stint (*Calidris ruficollis*), ruddy turnstone (*Arenaria interpres*), and whimbrel (*Numenius phaeopus*). Rising sea-levels and disturbance from dogs and humans are key local threats to all these severely threatened species.

As mangroves approach their southern limit, they are reduced in both diversity and size. Whilst Northern Australian mangroves host many endemic fauna species, the mangroves of the Sydney Basin are not yet established long enough for such speciation events. Mangroves are scattered all over the lower Hawkesbury, including the many bays of Pittwater, Cowan Creek, and Berowra Creek, with most stands being relatively small. Careel Bay near Avalon is an exception and as such it provides habitat for the mangrove specialist, mangrove gerygone (*Gerygone levigaster*) that is at its southern breeding limit. This species is colonising further south following the establishment of mangroves. Further, the mangroves of Careel Bay provide roosting habitat for the NSW endangered bush stone-curlew (*Burhinus grallarius*) (NPWS 2003). This species has disappeared from all other sites within the Sydney Basin. Finally, the mudflats and limited salt marsh adjacent to the mangroves at these sites provides habitat for migratory shorebirds that prefer mudflats over rock platforms. However anthropogenic disturbance resulting from dogs accompanying humans or unaccompanied is consistently high in these mudflats and shorebirds are rarely recorded from Pittwater these days.

Along the coast and estuaries various raptors are often seen hunting or nesting in the KGR including the white-bellied sea-eagle (*Haliaeetus leucogaster*), whistling kite (*Haliastur sphenurus*) and nankeen kestrel (*Falco cenchroides*). Occasionally the brahminy kite (*Haliastur indus*), peregrine falcon (*Falco peregrinus*) and osprey (*Pandion cristatus*) are also seen.

Other seabirds including various cormorants (family Phalacrocoracidae), shearwaters (*Ardenna* spp.) some of which have been known to nest in large numbers on Lion Island such as the Wedge-tailed Shearwater (*Ardenna pacificus*), terns and gulls (family Laridae), oystercatchers (*Haematopus* spp.) and the Australasian Darter (*Anhinga novaehollandiae*) are also often seen while feeding, nesting, or resting within the KGR. The little penguin (*Eudyptula minor*) has a small breeding colony on Lion Island within Broken Bay and is often seen feeding in the estuaries of the lower Hawkesbury. Interestingly it also appears as a motif in Aboriginal rock engravings in the KGR and as faunal material in archaeological deposits.

Marine Mammals

The expanse of waterways including both open ocean and sheltered estuaries within the KGR present ideal resting and foraging habitat for wide-ranging cetaceans. Pittwater, Cowan Creek, and the Hawkesbury River have all hosted a variety of threatened marine mammals. Anthropogenic disturbance within the waterways of Pittwater and the Hawkesbury River areas, coupled with significant global cetacean declines and naturally large home ranges, means infrequent records of marine mammals. However, given the extent of Aboriginal rock art featuring whales throughout the KGR, this was no doubt a resting location for multiple whale species on an annual basis and significant occasional food resource for the peoples of this area. Just over a dozen cetacean species have been recorded within the study area including several rarely seen species such as Cuvier's beaked whale (*Ziphius cavirostris*), pantropical spotted dolphin (*Stenella attenuata*), long-finned pilot whale (*Globicephala melas*), and Risso's dolphin (*Grampus griseus*) (ATLA 2022). Humpback whales (*Megaptera novaeangliae*), following the remarkable recovery of global stocks, are a significant tourist attraction along the KGR coastline.

One marine mammal rarely considered within NSW is the dugong. Given the lack of preferred seagrasses within NSW, most individuals are considered vagrants (Allen et al. 2004). Within the KGR there have been two records; one was sighted at Newport beach in 1992 during a significant dispersal event because of flooding impacts upon seagrasses at Hervey Bay (Preen and Marsh 1995), and another near Brooklyn in 1980 (Bionet 2022).

In the north-eastern corner of the KGR at Barrenjoey Headland, there is an Australian fur-seal (*Arctocephalus pusillus*) haul out. The location of this haul out reiterates the abundance and diversity of marine life within the surrounding oceanic and estuarine waters. Further, there are several records of the vagrant leopard seal (*Hydrurga leptonyx*) exist from the beaches of the Northern Beaches LGA (ATLA 2022).

CONNECTION TO COUNTRY - ABORIGINAL SITE TYPES OF THE KGR (R. J. Conroy)

Introduction

The sandstone and shale landscapes of the Sydney Basin including the coast, estuaries, and plateaus, contain some of the richest examples of indigenous occupation and connection to Country anywhere in Australia (Attenbrow 2003). The linkages between Aboriginal site types with the physical features of the Sydney Basin have been investigated in the past by several authors including Attenbrow (2003), McDonald (2008), and Doelman et al. (2015).

Statewide models of potential site distribution, site condition, and conservation status have also been developed using landscape indicators such as terrain factors, soil and vegetation type, distance to water, and geology (Ridges 2010). This chapter describes the different site types which are found in the proposed KGR and their relationship with some of the KGR's natural heritage features.

Topography of the KGR

The KGR occupies a land mass of some 38,400 ha, comprising forest, woodlands, shrubland and cleared and developed areas, some 5,060 ha of estuaries and coastal embayments and approximately 27 kms of coastline (Figure 1).

The KGR samples part of a dissected sandstone plateau known as the Hornsby Plateau, with the highest point registered at the Bywater Trigonometric Station near Cowan at 235 mASL. Only 1% of the area of the KGR is above 220 mASL and only 4% above 200 mASL, while 26% of the KGR sits between 140-180 mASL.

Two major joint directions influence the trend of dykes, ridgelines, and major waterways, one being a NE-SW bearing, which is reflected in the angle of the coastline, Pittwater, Cowan Creek, and Berowra Creek; and a

NW-SE bearing which is reflected in the general alignment of the Lane Cove River, Smiths Creek, and Coal and Candle Creek. Major ridgelines above Cowan Creek and Berowra Creek such as the Govett Range and Lambert Peninsula extend over some 25 kms and have an average elevation of between 200-220 mASL. The Hornsby Plateau rises gradually to the north, as indicated by the profile (A1-A2) over the Govett Range (Figure 66).

Westerly facing slopes are generally longer with a slighter slope angle and with numerous sandstone terraces and benches of 2-5 m in height, while easterly facing slopes are generally shorter and steeper with higher cliffs of 5-15 m in height and are usually populated by large fallen joint blocks (Figure 66. Profile B1-B2).

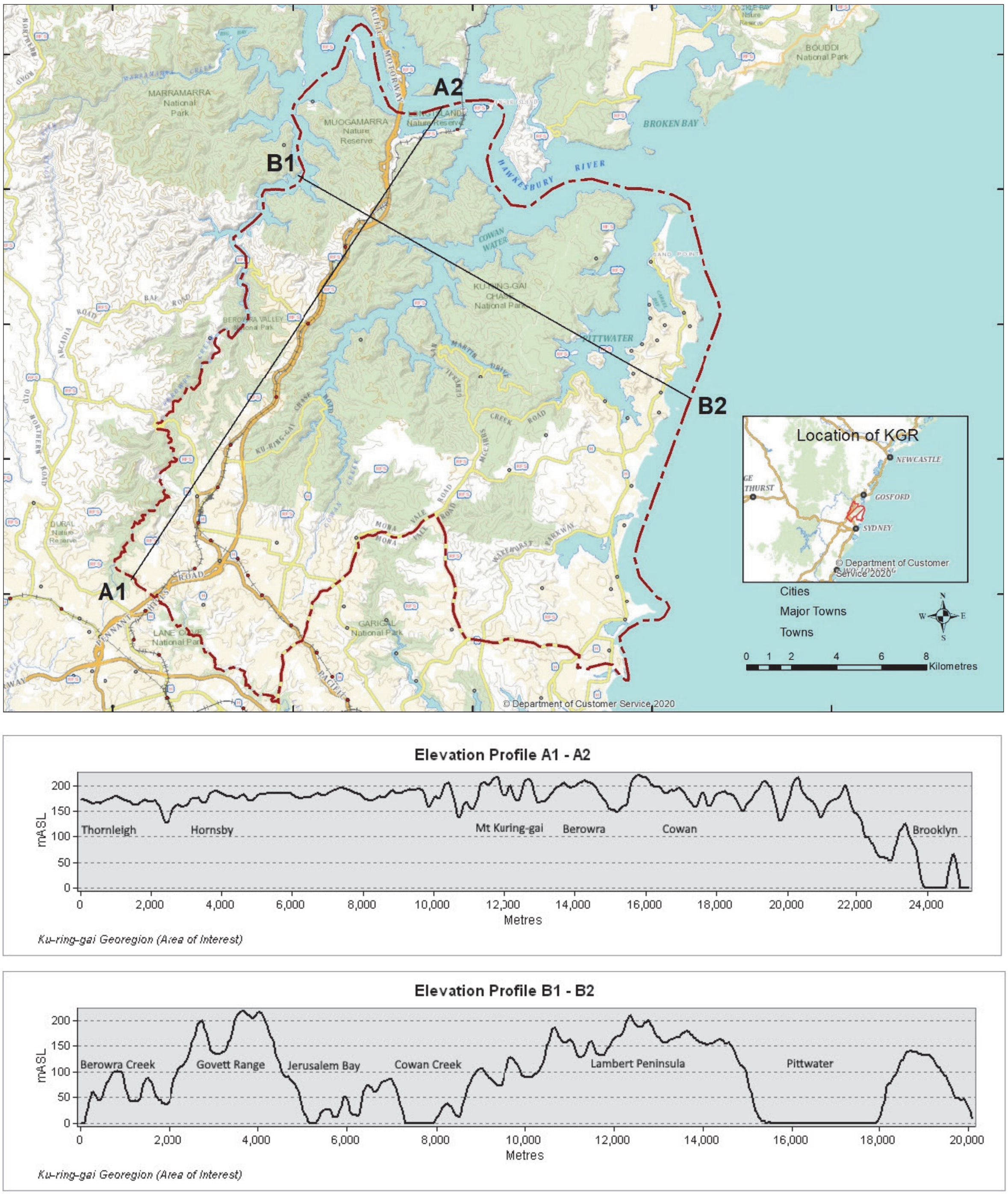

Figure 66. Map of the KGR and geosites with examples of topographic profiles.

Northerly facing aspects comprise about 41% of the KGR, followed by easterly at about 39%, with southerly and westerly aspects evenly distributed at about 34% each. Only 2% of the KGR is relatively flat and without aspect. Gentle slopes of 1-5^o extend over about 33% of the area, while steep slopes of >20^o represent about 8.6% of the KGR.

Aboriginal Site Types

As with other bushland areas in the Sydney Basin, the plateaus, ridges, drowned river valleys, and coastal landscapes of the KGR maintain an extraordinary record of Aboriginal heritage and occupation in this area. Aboriginal occupation within the KGR dates back to at least the Late Holocene some 3-4,000 years B.P. (Attenbrow 2003; McDonald 2008), and for nearby areas such as the Cumberland Plain, as far back as 36-44,000 years (Doelman et al. 2015). This was a period during which generations of coastal Aboriginal people would have been witness to both dramatic changes in the climate and to major fluctuations in ocean and estuary shorelines. Evidence of their use and occupation of this affected landscape has been slowly destroyed or at least hidden, and access to well used travel routes, camp sites, and ceremonial grounds would have similarly been affected.

The Aboriginal clans of the KGR have been named as the Gur-ring-gah to the north and Gai-mariagal to the south (Foley 2001), or alternatively the Garigal to the north, the Gayamaygal to the south and the Darramurragal to the west (Attenbrow 2003). Evidence of their occupation and use of this Country over several millennia survives with 1,424 recorded Aboriginal sites within the area of the KGR (NSW Aboriginal Heritage Information Management System (AHIMS) - valid sites as of 30 November 2021). However, new and updated site records continue to be entered into the records.

A combination of different site types is often recorded as one site within the AHIMS, and when separated into individual site type or site trait locations, a total of some 1,667 Aboriginal site type locations are currently recorded within the KGR, which is a similar proportion to that reported by Attenbrow (2003:48) for the Sydney region. These site types include occupational deposits such as middens and artefact scatters, art in shelters, art on both vertical and horizontal rock platforms, and as various other site types including burials, stone arrangements, modified trees, habitation sites, a recorded fish trap, and axe, spear, and potential seed grinding grooves.

High concentrations of Aboriginal site types (i.e. >10 sites per km^2) are centered on the Porto Bay, Refuge Bay to The Basin, Berowra Creek, Appletree Bay to Waratah Bay, Smiths Creek, Bilgola Plateau and Elvina Bay to Coal and Candle Creek areas (Figure 67). This relatively high clustering of site types with an Average Nearest Neighbour Ratio of 0.39, is possibly due to recorder survey bias and indicative of areas with easy access or possibly areas that were favoured and often used camp or ceremonial sites, or which were known to supply reliable food and other resources. For example, surveyor William Govett who worked in the Berowra-Cowan area between 1829 and 1834, reported 'The bottom of the ravines, especially where the creeks widen and open to the river, were much frequented by the coast natives; for the wooded sides of the ridges in this neighbourhood, abound with various animals, and the waters below afford a plentiful supply of oysters and other shell-fish' (Attenbrow 2003:47).

AHIMS, which was established in 1971, contains over 100,000 registered sites of Aboriginal culture and heritage significance from across NSW in the form of site cards and archaeological reports. Information includes site location, site type or traits, features, and motifs present, as well as accompanying reports, maps, and photos. These records date from the late 19th century to the present day and have varying degrees of consistency in terms of site survey and nature of the recording and very often will contain a strong accessibility bias, as might be expected in the KGR with its dissected and rugged sandstone landscape and dense shrubby vegetation. Some records are also duplicated in the system or contain well separated sites or multiple site traits combined into the one location record. These issues are gradually being addressed by both professional archaeologists and trained volunteers, as the recording of new sites and updating of AHIMS sites is undertaken using standard templates, guidance notes, and recent technologies.

Although imperfect for the reasons mentioned above, the AHIMS is a comprehensive record of known Aboriginal sites in the area and the substantial number of recorded sites in the KGR represents a good sample on which to make some general assumptions, with appropriate qualification, about the relationship of these sites to the landscapes of the KGR. This relationship was examined using various tools available within the ESRI ArcGIS 10.8.1 software package and available site data for the KGR from AHIMS as of 30 November 2021. Geospatial information was sourced on-line from NSW Spatial Services and from the SEED data portal (NSW SEED 2022). A summary of results for site types within the KGR is presented in Table 3 and further described below.

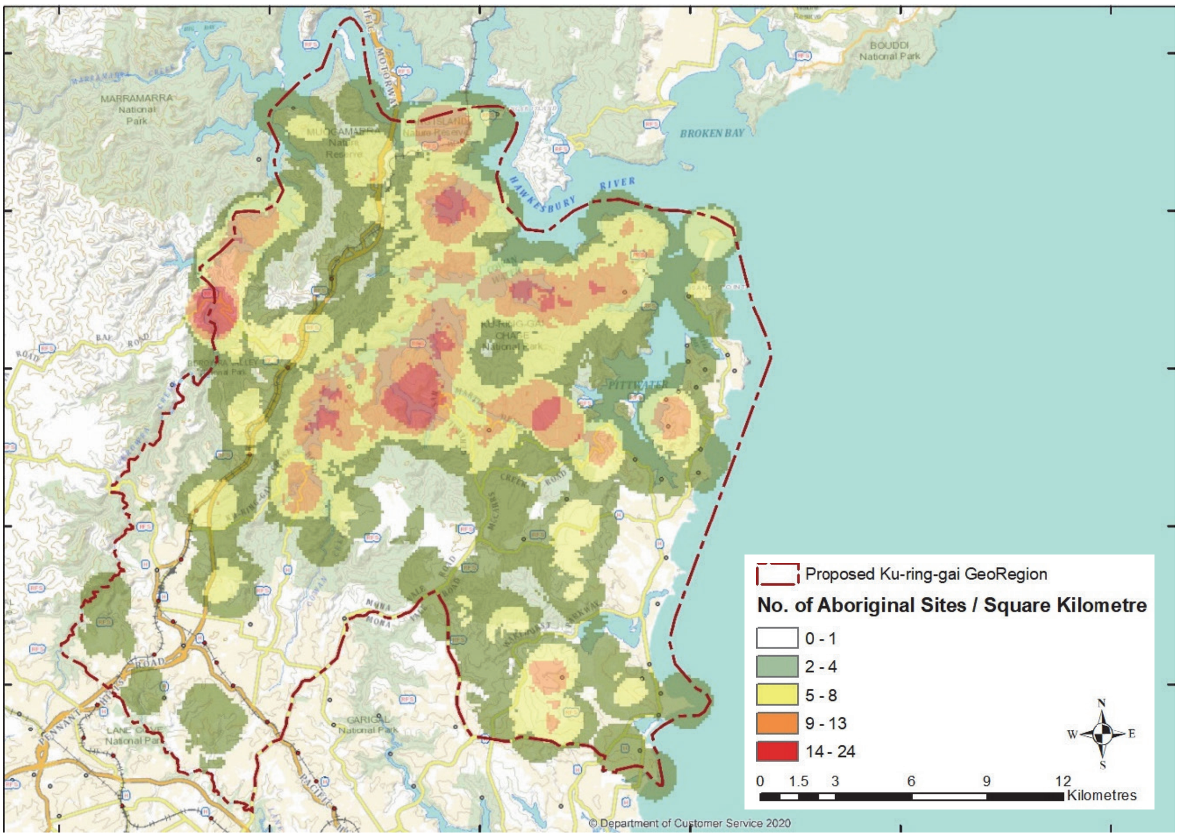

Figure 67. Aboriginal Site Density, KGR.

Ku-ring-gai GeoRegion Site Types	Number of Types		Number in Protected Areas		Elevation mASL		Slope Degrees		Distance to Freshwater (m)		Distance to Estuary/Coast (m)	
	No.	% of Total	No.	% of Total	Average	SD	Average	SD	Average	SD	Average	SD
Rock Engraving	647	38.8%	434	67.1%	120	57	8	6	229	176	815	640
Shelter with Art	389	23.3%	300	77.1%	61	59	16	8	231	215	376	599
Shelter with Midden	166	10.0%	133	80.1%	33	29	16	7	252	258	103	229
Open Deposit	145	8.7%	79	54.5%	27	43	13	7	338	351	126	316
Axe Grinding Groove	111	6.7%	66	59.5%	121	56	9	6	155	165	902	623
Shelter with Deposit	97	5.8%	45	46.4%	57	56	12	7	379	381	513	864
Midden	63	3.8%	37	58.7%	24	36	13	7	376	391	119	297
Stone Arrangement	16	1.0%	11	68.8%	142	24	8	5	137	75	734	489
Burial	11	0.7%	4	36.4%	22	35	11	11	540	456	166	386
Water Hole/Well	8	0.5%	4	50.0%	102	59	8	5	160	181	971	725
Habitation Structure	6	0.4%	3	50.0%	111	46	13	4	630	826	1023	697
Scarred Tree	5	0.3%	0	0.0%	149	41	8	4	286	102	1541	781
Quarry	2	0.1%	1	50.0%	138	33	5	2	399	18	433	145
Fish Trap	1	0.1%	1	100.0%	15	0	5	0	31	0	22	0
Total of Site Types	**1667**	**100.0%**	**1118**	**67.1%**	**82**	**65**	**12**	**8**	**253**	**254**	**541**	**656**

Table 3. Summary of Data on Aboriginal Site Types in the KGR.

Art Sites

The Aboriginal art of the Sydney Basin has been described as a 'simple figurative' style' because of the high level of recognition between the art and the natural features drawn and because the schema is not complicated and contains a minimum amount of detail (McDonald 2008). There are differences between the art forms, with Aboriginal pigment motifs in shelters consisting of both outline and infilled art forms, while the Aboriginal rock engraved motifs are mostly outline with limited examples of infill. The only consistently infilled rock engravings are of culture heroes, some of which are well decorated and carrying ornaments or tools. Unfortunately, because of the tragic and rapid loss of the original artists in the Sydney area post-1788, there are very few reliable interpretations or meanings of the motifs or of their relative significance, though various attempts have been made to understand and/or present that meaning.

Rock Engravings

Rock engravings are the most common site type in the KGR with a total of 647 recorded site type locations of which 67% (n=434) are in protected areas. Most are on large, relatively flat rock surfaces of massive quartz sandstone as described by Mathews (1897:469-470), 'Rock carvings are found in districts abounding in large masses of rock, chiefly of the Hawkesbury series' and '… preference seems to have been given to rocks occupying prominent positions or which were situated in mountain passes along which the natives traveled from one part of their hunting grounds to another. Fine-grained sandstones of a durable character, with tolerably smooth surfaces and in dry situations, appear to have been chosen.' A smaller number of engraved motifs are also found on near-vertical rock surfaces, generally close to and visible from waterways such as Cowan Creek (about 20 sites) and Berowra Creek, with only very few known from near-vertical rock surfaces at higher elevations (e.g., near Topham Trig in KCNP). The near-vertical engravings are sometimes superimposed, with complex in-fill and with motifs that are very relevant to the location, for example the engraved fish, jellyfish, eels, and starfish that are recorded above the Broken Bay shoreline near West Head (Sim 1965) as well as the various koala-like, emu-like, and fish motifs recorded at sites along the Great North Walk near Berowra Waters, including the near-vertical birthing rock and six bream rock engraving sites.

Rock engraving sites in the KGR are found at an average elevation of 120 m ASL ± 57 m with 44% of sites found between 140-180 m ASL and 16% between 0-40 m ASL. Most rock engraving sites have either a northerly (42%) or westerly (37%) aspect, often with commanding views across the Hornsby Plateau and the drowned river valleys of the lower Hawkesbury River; 33% of sites are found on southerly aspects.

Engravings are usually found on the ridgelines and shoulders of higher peaks, but also on seepage zones of terraced upper slopes (e.g., below hanging swamps). In fact, 44% of rock engraving locations are found on slopes of 0-5^{o}, 27% on slopes 6-10^{o}, 24% on slopes of 11-20^{o} and only c.5% on slopes greater than 20^{o}. Most rock engraving sites in the KGR are found in association with the Hawkesbury (46%) or Lambert (28%) soil landscapes. The average distance of rock engravings to the nearest freshwater creek in the KGR is 229 m ± 176 m.

Motifs are usually drawn in conjoined puncture outline and include the following:

- male and female anthropomorphic figures, some with infill;
- culture heroes of Sydney Region Aboriginal groups such as Baiame and Daramulan (McDonald 2008). Engravings of both these figures are relatively large, usually with infill features and usually with a headdress and holding a shield and/or boomerang. Daramulan is thought to be a relative of Baiame. Baiame is often shown in a frontal view with outstretched limbs, while Daramulan is shown in profile mostly with one leg and with an animal-shaped body or head (Figure 68) and is sometimes placed in association with an engraving of an emu (e.g., near the Elvina Trail in KCNP);
- terrestrial animals such as dingoes, macropods, echidnas, koalas, possums, gliders, emus (some with eggs), and other birds such as penguins and shags, goannas and snakes;
- aquatic animals such as whales, dolphins, sharks, various fish species, eels, and jellyfish; and
- tools or ornaments such as shields, clubs, boomerangs, possibly bullroarers, and circles and tracks such as an engraved human footprint (mundoes) and emu and macropod tracks, often with several engraved in a line, suggesting perhaps the importance of the direction of these motifs as indicators of pathways or linkages to other sites as part of storytelling.

The most common motifs in order of abundance are mundoes, fish, macropods, other land animals, and male anthropomorphs (McDonald 2005). In the KGR, these engraved motifs vary in size from about 20 m^2 (e.g., large whales and spirit figures or culture heroes) to less than 0.25 m^2 (e.g., animal tracks, boomerangs, and mundoes) and may sometimes accentuate or drawn near unusual geomorphological features such as natural waterholes or basins, small sandstone pillars, natural arches, whalebacks, tessellated pavement, and large open rock platforms with spectacular views.

Some of these motifs are drawn in profile such as the depiction of Daramulan, terrestrial animals (e.g., emus, echidnas, wallabies, and kangaroos), fish, whales, and dolphins, while others are drawn with front-on

Figure 68. A large, engraved motif on a sandstone bench above Cowan Creek. This motif is believed to represent the culture hero 'Daramulan' holding a boomerang.

view such as people, often with outstretched legs and arms holding tools, as well as anthropomorphic figures and shields. Other motifs are drawn from an elevated view such as goannas, gliders, snakes, eels, boomerangs, mundoes, and animal tracks.

McDonald (2008) found that 11 motifs represented the regional average number at sample sites in the Sydney Basin. Two sites in the KGR near Cowan and Elvina Bay have more than 50 recorded motifs. These two sites are also associated with very unusual sandstone features including an elevated natural basin near Cowan and a large, tessellated rock pavement near Elvina Bay (Branagan 1968); both of which give support to the connection between geoheritage and cultural values. However, most of the recorded rock engraving sites in the KGR known to the author have fewer than 10 motifs.

Given the primary location of the engraved motifs being on ridges and saddles which are set relatively high in the landscape, it is likely that they also were near or along access routes and perhaps some served as 'signposts' or as 'pages in a book'. They may have also been indicative of the presence of a particular resource in the area such as indicated by a school of fish, or a mob of wallabies. Engravings of whales are restricted to the coast and appear to be uniquely concentrated between Broken Bay and Port Hacking (McDonald 2008), a region in which observations of whale migration, or of whales taking safe harbour and where occasional strandings are recorded.

Rock engravings in the KGR are not usually associated with other occupational evidence such as middens and artefact scatters, although they are sometimes associated with other site features such as grinding grooves (8% of engraving sites also have grinding grooves), stone arrangements (ditto 2%), and water channels and/or waterholes (ditto <1%). The average distance of rock engraving locations from the shoreline of estuaries is 815 m ± 640 m. The presence of spirit or culture hero motifs, suggests that these sites may have played a ritual, ceremonial, or storytelling function (McCarthy 1959), particularly at night when fires may have been lit nearby to help illuminate the grooves and highlight or showcase the engraved figures (Clegg 2002).

Shelters with Art

There are 389 recorded sandstone shelters or overhangs with Aboriginal art in the KGR, of which 77% (n=300) are in protected areas. Art in shelters consists of either stencilled, printed, or drawn motifs (Figure 69). Stencilled and printed motifs are thought to be prepared using a mixture of ochre, water, and animal fat, while other motifs are usually drawn with charcoal. Motifs are commonly found on vertical and smooth panels within cavernous, weathered shelters or under overhangs. These shelters are generally shallow and

Figure 69. A shelter with art in the McCarrs Creek catchment. Motifs include handprints, hand stencils, ochre drawings of two wombats, and indecipherable objects with some possibly in charcoal. An old termite tunnel runs vertically down the shelter.

formed at the bottom of sandstone cliff lines and sometimes under large sandstone boulders on colluvial foot slopes. Art within shelters is usually located on the back wall but may also be found on the ceiling and on the inside of the dripline.

Shelters with art within the KGR are generally found relatively close to estuaries such as Cowan Creek and Berowra Waters (i.e., an average distance of 376 m ± 599 m) and to freshwater (ditto 231 m ± 215m). Shelters with art have an average elevation of 61 m ASL ± 59 m and most sites (56%) are found between 0-40 m ASL. A total of 48% of shelters with art are found on the Watagan Soil Landscape and 38% of sites are found on the Hawkesbury Soil Landscape. Shelters with art are found primarily on northerly aspects, i.e., 52% of shelters with art, compared with only 23% of shelters with art recorded from southerly aspects.

Many motifs in the KGR are unidentifiable owing to superimposition, graffiti, age and weathering, and animal and smoke damage. The most common decipherable motif is the hand stencil displayed in either red and white ochre, with both left and right hands and adult and child hands commonly stenciled, and sometimes with handprints and feet also presented. Stencils of fish, clubs, spears, and boomerangs are also common. Drawings and paintings in either charcoal or ochre are of fish, macropods, wombats, koalas, anthropomorphs and other terrestrial mammals, goannas and snakes, shields, bird tracks, circles, and other geometric patterns such as those that may represent fishing nets (E. Keidge NPWS pers. comm), and many of these are drawn in association with hand stencils and handprints. The average number of identifiable motifs per site recorded across the Sydney region is 15.4 (McDonald 2008).

Shelters with art in the KGR vary significantly in size. One of the largest recorded art shelters in the Sydney Basin is within the KGR at North Turramurra and measures 40 mL x 10 mW x 8 mH and contains 91 motifs (McDonald 2008). Others within the KGR include a very large shelter on Long Island which contains 130 motifs, most of which are now largely disfigured by graffiti and smoke damage, but even relatively small shelters such as one near Mackerel Beach with 114 motifs and another near Hallett's Beach with 60 motifs, can contain unusually large numbers of motifs, while other recorded sites may consist of a single hand stencil or a motif which may sometimes be indecipherable.

Shelters with art are often found in association with middens and/or archaeological deposits (i.e., 29% of all shelters with art contain either middens or occupational deposits), with just a few (n=3) also associated with grinding grooves.

Occupational deposit sites

Occupational deposit sites show evidence of human occupation in the form of food remains, stone tools, baked clay etc. and exist as either shell middens, open campsites or artefact scatters and may be found either in the open or within shallow sandstone shelters or overhangs. They are extremely important as they can provide insights into traditional diets, seasonal exploitation, and adaptation to changes in food resources, the use of fire, and changing tool technologies.

Middens are primarily made up of the discarded and accumulated remains of either freshwater or marine shellfish. The proportion of other occupational material in the midden, such as teeth, bone, charcoal, and artefacts, is usually much smaller. Shell middens may be distinguished from natural shell accumulation based on the shell remains being mostly of large edible species, the presence of burnt shells, the locational context, and the presence of other occupational evidence.

Artefact scatters or archaeological deposits are primarily objects such as stone tools and associated flaked material and grinding stones and may also include small amounts of shaped shell and bone, all of which provide evidence of the use of the site by Aboriginal people (OEH 2012). Pieces of stone were sometimes carried from one place to another and used for grinding and sharpening implements or for food preparation (Figure 70).

There are 471 midden and/or archaeological deposit sites recorded within the KGR with 263 (56%) of these located within sandstone shelters or overhangs and 208 (44%) located on open sites. A total of 62% (n = 294) of all occupational deposit sites are located within protected areas.

Figure 70. Possible grinding stone in association with an open midden on Cowan Creek. These stones were very portable and were often carried between occupation sites.

Open deposit and midden sites have an average elevation of 27 m ASL ± 43 m and 24 m ± 36 m respectively, while deposits and middens within shelters have an average elevation of 57 m ASL ± 56 m and 33 m ASL ± 29m respectively, indicating both open and closed archaeological deposits in the KGR, naturally being near resource rich shorelines and waterbodies. Open and sheltered deposit sites are also located primarily on northerly aspects (52% and 53% respectively) and are least likely to be located on southerly aspects (23% and 25% respectively).

The KGR has a high density of recorded occupational deposit sites which given the extent of estuarine shoreline and ready availability of fish and shellfish is to be expected. For example, Guthrie and Kohen (2005) reported an extra-ordinarily high density of occupational deposits (Figure 71) in the Cowan Creek catchment (8.5 sites/km^2).

Surface examinations of the midden deposits in this area suggest that the hairy mussel (*Trichomya hirsuta*) and Sydney rock oyster (*Saccostrea glomerata*) were a favoured food resource in the area. Other species that have been identified in lesser amounts within the deposits include the whelk (*Pyrazus ebeninus*), Sydney cockle (*Anadara trapezia*), and spiny oyster (*Chama fibula*), all of which preserve relatively well in the deposit.

Most of the shell middens (i.e., 70%) in Cowan Creek that were recorded by Guthrie and Kohen (2005) displayed a deposit depth >30 cm, while some, such as an open deposit near Duffys Wharf, are large at some 800 m^2 and up to two metres deep in places. The easy access and proximity to both permanent fresh drinking

Figure 71. A very large and open occupation deposit covering an area of about 800 m2 near Duffys Wharf.

Figure 72. A closed shelter with midden on Cowan Creek.

water and a rich estuarine resource in Cowan Creek probably explains the location and size of this site type (Figure 72). Unfortunately, many of these deposits were also the target of early 19th Century lime burners and were consequently damaged or destroyed.

There are two important excavated shelters in the KGR, one at Great Mackerel Beach (3,670 ± 150 B.P.) and another within the Angophora Reserve at Avalon (1,890 ± 130 B.P.), each of which provides an excellent record of occupation and use of the area during the late Holocene. Both sites provide evidence of cultural tradition such as burial practices, seasonal use patterns, food resources, tool tradition and use, and the local fauna which existed at the time.

For example, 5,715 stone artefacts were recovered from the deposit at Angophora Reserve, which were primarily composed of quartz (54.5%), but also indurated mudstone (13.5%), veined chert (11.3%), and chert (7.7%), with small amounts of quartzite, silcrete, black fine grained volcanic rock, granite, fine grained basic igneous rock, siltstone, and other material. Worked bone (possibly bone points) and shell artefacts (possibly scrapers) were also uncovered.

The Great Mackerel Beach shelter also contained 428 artefacts of quartz and indurated mudstone, 4.7 kg of shell material including fishhooks, faunal remains, and a minute quantity (0.5 g) of white pipeclay.

Grinding grooves

Grinding groove sites are thought to be used either for modifying or sharpening tools, such as hafted stone axes or spear points, or for food preparation. There are 111 recorded grinding groove sites recorded in the KGR, 59% (n = 66) of which are found in protected areas. Attenbrow (2003) reported that nearly all hatchet grinding grooves in the Sydney Region are found on Hawkesbury Sandstone which provided an abrasive quartz rich surface on which to sharpen the axe head or spear point.

Grinding groove sites (Figure 73) are usually found on slightly sloping rock surfaces with an average slope of 9 ^{o} ± 6 ^{o}, and usually where freshwater seeps across the rock surface. They are also sometimes found in association with waterholes, natural basins (gnammas), and/or 'engineered' water channels. Grinding groove dimensions recorded at several sites in the West Head area averaged 24 cmL ± 8.5 cm, 7 cmW ± 2.1 cm and 12 mmD ± 7 mm (n = 13).

Grinding groove sites in the KGR are usually found in association with rock engravings (i.e., 49% of grinding groove sites also have engravings recorded), while a few (6%) are found in association with shelters with art, middens and/or archaeological deposits. 75% of grinding groove sites are found on slopes of <10^{o}. The average elevation of grinding groove sites is 121 mASL ± 56 m, with most grinding groove sites (57%) found between 130-180 mASL and most recorded with a northerly aspect (56%).

Figure 73. Grinding grooves found in a seepage zone and adjacent to a rock gnamma, near Elvina Bay.

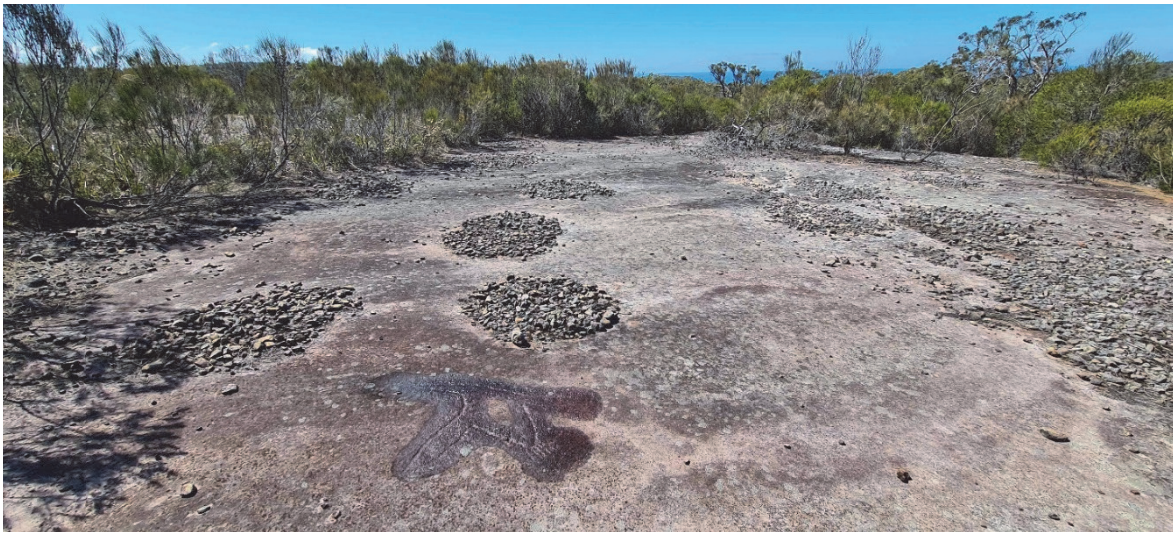

Figure 74. Stone arrangement and associated engraving of a penguin or shag not far from a large whale engraving on a ridge above Pittwater.

Quarries

Quarries are sites where stone and ochre materials have been extracted and used as raw material in the manufacture of tools or to produce pigment for art or body decoration. Stone tool quarry sites are often recognised by the extent of flaking and battering of rock and the presence of partially shaped and discarded objects such as rock cores. Cone-like shapes on the ventral surface of a rock core (i.e. bulbs of percussion) are tell-tale signs that the rock was struck and deliberately fractured by another hard object. Only two recorded quarry locations are recorded in the KGR.

Volcanic dyke and diatreme exposures such as those that exist along the coast at Barrenjoey Headland and Long Reef and creek line exposures at Hornsby and Thornleigh may have provided raw material for these purposes. More likely, these materials may have been sourced from more regional locations such as from silcrete and cobblestone sites at Plumpton Ridge and Rickabys Creek on the Cumberland Plain (Doelman et al. 2015) and possibly traded locally in exchange for coastal resources. For example, axe head blanks such as those observed by early colonisers in Broken Bay and on Long Island are likely to have originated from cobblestone gravels found along the banks of the Nepean/Hawkesbury River and its palaeochannels (Corkhill 2005).

Habitation sites

Habitation sites are places where evidence of structures constructed by Aboriginal people have been found, either for temporary or long-term shelter, and may include historic camps of contemporary significance. Smaller structures may make use of natural materials such as branches, logs and bark sheets or manufactured materials such as corrugated iron to form shelters. Archaeological remains of a former structure may also be evident such as chimney/fireplace, raised earth building platform, excavated pits, rubble mounds etc.

The most common form of a preserved habitation site is those found in rock shelters, overhangs or caves formed by fallen sandstone slabs, however timber and brush shelters are also known from historic accounts and accounts of a village or camp on the shores of both Pittwater (E. Keidge NPWS pers. comm.) and Narrabeen Lagoon (Foley 2001) are known but not recorded in AHIMS as such. Only six habitation structures have been recorded in the KGR, three of these (50%) are found in protected areas. Recorded habitation sites have an average elevation of 109 mASL ± 47m.

Stone arrangements

There are 16 recorded stone arrangements (Figure 74) within the KGR of which 93% are located between 110-180 mASL. Sitting high in the landscape at an average elevation of 142 mASL ± 24m, is perhaps indicative of their ceremonial, directional or sign-posting purpose. Stone arrangements typically take circular forms, but other forms such as stone cairns and erect pillars are also known elsewhere in NSW (OEH 2012).

Although difficult to distinguish from non-Aboriginal structures of similar appearance, the co-location or proximity of stone arrangements with rock engravings and occupation shelters gives some suggestion and confidence as to their origin and perhaps purpose.

Waterholes and water channels

There are some sites within the KGR which are good examples of the manipulation of water by Aboriginal people using weirs or drains. These sites appear to have been constructed to better exploit water resources, such as capturing or diverting the seepage from hanging swamps, and many such sites are usually found associated with grinding grooves and/or rock engravings (Figure 75). These channels appear to be constructed in the same way that rock engravings are made (i.e., conjoined puncture). There are eight waterhole or water channel sites recorded in the KGR.

Fish traps

A fish trap is a modified area along a watercourse or on an intertidal shore platform where fish were trapped for short-term storage and gathering (OEH 2012). Fish traps that survive today are very few, but those that have been recorded are usually constructed of stone and are sites where fish could be easily speared, netted, or poisoned.

Only one recorded fish trap exists in the KGR being in the lower part of the Cockle Creek catchment and located near some engraved figures and a shelter with a midden and art. Foley (2001) refers to permanent fish traps being common in the estuaries and lagoons of the area and being used seasonally for the procurement of fish resources such as flathead (*Platycephalus bassenis)* and mullet (*Mugil cephalus*).

Figure 75. Engraved water channels near a gnamma with two grinding grooves.

Modified trees

Modified trees, such as scarred trees or carved trees, are trees with evidence of Aboriginal bark marking or extraction. Scarred trees are trees where bark has been cut from the trunk for use in the production of shields, canoes, burial shrouds, containers, or for foot holds. Carved trees are where there has been intentional carving of the wood of the tree to form a permanent marker to indicate ceremonial use/significance of a nearby area, these carvings may act as territorial or burial markers (OEH 2012). While scarred trees are the more likely type of modified tree to be found in the KGR, they may often be damaged or destroyed due to ageing, lightning strikes, insect damage, and bushfires.

Scarred trees are generally recognisable with the scar being more-or-less regular in shape with parallel sides and with slightly pointed or rounded ends. The scar usually stops well above ground level and there is an absence of branch scars or tree knots. Sometimes there is evidence of stone or steel axe cuts, and the tree is usually identified as an old Australian native. There are five scarred trees recorded in the KGR, not including Figure 76 and there are no recorded carved trees.

Burials

Aboriginal people used cremation and/or burial to dispose of their dead, typically within shelters, middens, sand dunes and campsites but other methods are also known (Attenbrow 2002). There are 11 recorded burial sites within the KGR, not including two relatively recent repatriation or reburial sites, which have since been declared as Aboriginal Areas (Table 4).

Only four (36%) of these recorded sites are located within a protected area, 64% have a northerly aspect and most (63%) are located on the foot slopes and depositional environments associated with the Watagan, Narrabeen, Newport, and Erina soil landscapes.

Burials have an average elevation of 22 mASL ± 35 m. Unfortunately, it is likely that many records of previously discovered burial sites are unrecorded with many sites being disturbed and material being relocated several times. For example, one AHIMS record of a burial site which is recorded high within a cliff-side shelter, and which contained skeletal material of an adult male, was most likely relocated, and reassembled from a nearby beach, perhaps during or prior to WWII, and has since been relocated again.

The burial sites in the KGR are extremely significant and culturally sensitive. They are usually found accidentally following the exposure of skeletal material either in dune systems after heavy storms, or because of coastal building or utility excavations, archaeological digs and following erosion of sediments from rock shelters. Burial places are known along the coast from Palm Beach to Narrabeen.

The discovery of 'Narrabeen Man' because of Energy Australia cabling works, is significant as it is possibly the oldest known record of a ritualistic killing (McDonald et al. 2007) in Australia. The skeletal material of Narrabeen Man was dated at 3,700 B.P. and was found disarticulated and partly burnt with 14 spear barbs of silcrete, quartzite, and quartz, near the burial. Two such barbs were found embedded within the spine. Natural processes were thought to have buried this individual rather than burial by deliberate internment.

The Angophora Reserve burial site at Avalon is also one of the most significant in the KGR. It was estimated that the remains of five or possibly six individuals were found in the shelter, including an adult female which was fully articulated and buried with an Aboriginal baby about six months old; two Aboriginal children between the ages of three and five; and one, but possibly two other adults (McDonald 1992).

Archaeological evidence suggests that coastal Aboriginal people buried their dead in midden deposits, both in the open and in shelters and some with hardened ash caps above them, suggesting a cremation process (McDonald 1992).

Figure 76. This turpentine (*Syncarpia glomulifera*) near West Head Lookout in KCNP is a possible scarred tree as it is a species that is sometimes recorded for taking bark to form a canoe.

Aboriginal places

Aboriginal Places are sites that are of special significance to Aboriginal people in NSW. They can be of spiritual, historical, social, educational, or of resource utility significance. These places range from small ceremonial sites to large natural features such as mountains or lagoons. When a significant place is declared an Aboriginal Place, it is protected under the National Parks and Wildlife Act 1974. Aboriginal objects and places can be on either public or private land, and do not change the tenure of the land. It is an offence under the Act to damage or destroy these places.

Four special sites in the KGR have been declared as Aboriginal Places, two of which are repatriation (i.e., reburial) sites which are located on the foreshores of Pittwater and Berowra Creek. These repatriation sites are sites where Aboriginal skeletal material has been returned from museum, university or other collections and is ceremonially reburied on the Country from which they are believed to have been taken.

Two other Aboriginal Places (APs) have been declared with the agreement of private landowners in the Belrose (Moon Rock AP) and Cromer areas (Cromer Heights Rock Engravings and Shelter AP). Both sites are significant ceremonial and/or storytelling sites (Pittwater Online News 2020).

Aboriginal areas

An Aboriginal Area is an area which is managed as a protected area by the NPWS under the National Parks and Wildlife Act 1974. The KGR contains a dedicated Aboriginal Area at Mt Ku-ring-gai (0.6 ha) which protects an outstanding set of Aboriginal engravings (Figure 77). McCarthy (1959) considered this site to be an important ritual group of engravings reflecting images of Daramulan with his two wives and other figures including a large number of mundoes or footprints (45), being ‘the longest and largest yet recorded’. However, the figure probably depicts Baiame, a culture hero, together with female figures and various other motifs including a basket, fish, animal tracks, and the mundoes which are engraved over some 200 m along a narrow rock ledge (OEH 2017). There are commanding views to the west across Calna Creek and the catchment of Berowra Creek.

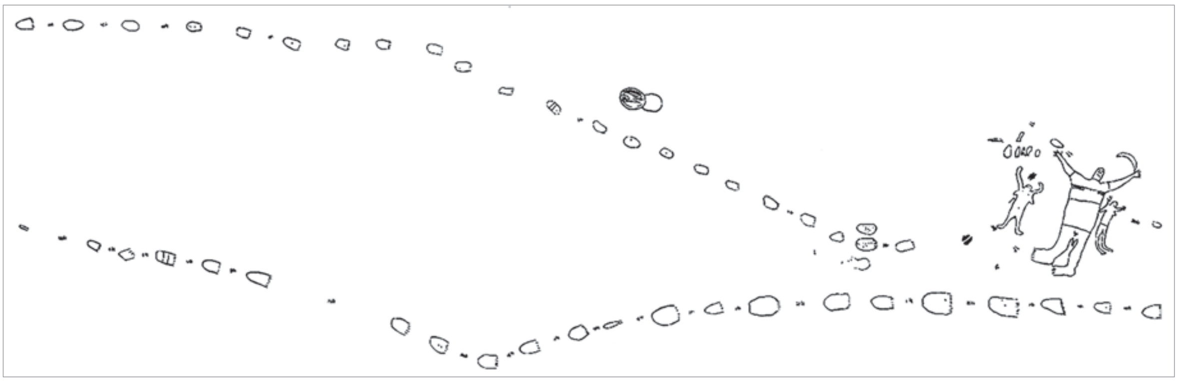

Figure 77. McCarthy’s (1959) recording of the Mt. Ku-ring-gai engraving site.

Site Types/Traits	Berowra Valley NP	Garigal NP	Ku-ring-gai Chase NP	Lane Cove NP	Long Island NR	Mount Kuring-gai AA	Muogamarra NR	Total
Axe Grinding Groove	2	1	50				13	66
Burial/s			4					4
Fish Trap			1					1
Habitation Structure			2				1	3
Midden	2		22		2		10	36
Open Deposit	1		67		9		2	79
Quarry			1					1
Rock Engraving	14	13	375	1		2	29	434
Shell					1			1
Shelter with Art	14	4	249		7		26	300
Shelter with Deposit	5		23	1	11		5	45
Shelter with Midden	2		110		6		15	133
Stone Arrangement			8				3	11
Water Hole/Well			4					4
Total	**40**	**18**	**916**	**2**	**36**	**2**	**104**	**1118**

Table 4. Number of Aboriginal site types within NPWS managed protected areas.

Site conservation

The protection and conservation of Aboriginal sites has been an ongoing challenge for both land managers and Aboriginal people, however there is promise arising from several recent initiatives within the KGR aimed at improving site identification and management and improving engagement and ownership by Aboriginal people in conserving their cultural heritage.

Without such intervention these site types will not be with us forever. They are all slowly degrading over time, particularly with more intense weather patterns and with development pressure. Accelerated degradation of many sites is also occurring due to recreational activities including the impacts of boat wash, graffiti and disturbance in shelters, unsupervised marking or highlighting of engravings and the construction of unauthorised tracks and trails. Natural hazards such as storms, floods, and bushfires (Figure 78), are also having a significant impact and are being compounded by the effects of climate change (Lambert 2007; Lambert and Welsh 2011; Mackay 2016).

Figure 78. Exfoliation of sandstone near an engraving site at West Head following a bushfire.

Since 1969, Aboriginal sites and Aboriginal Areas have received statutory protection in NSW. In the KGR, many site types (67%) are also well conserved within protected areas (Tables 3 and 4). More recently the legislation in NSW was amended to change the emphasis from a 'knowingly destroy' onus of proof with emphasis on the prosecution proving intent to damage or destroy, to one in which the defendant needs to demonstrate due diligence to avoid prosecution for damaging or destroying an Aboriginal site. Within the KGR there are examples of sites which have been either:

- unknowingly damaged (e.g., construction of The Basin Trail, KCNP in 1967 or thereabouts);
- knowingly damaged following post-development approval (e.g., at Quarter Sessions Road, Westleigh in 1984); or
- when well-intentioned management of sites has subsequently created considerable damage (e.g., burning of the boardwalk over the Echidna site at West Head, KNP resulting in considerable damage to the motifs).

Greater care is now being taken to better conserve sites which involves partnerships between land managers, local government, and Aboriginal community groups such as the Metropolitan Aboriginal Lands Council, the Aboriginal Heritage Office Guringai Tribal Link, and the Tribal Warrior Association. This is being implemented in the following ways within the KGR;

- interpretive and cautionary signposting of sites, which raises awareness of their location and significance e.g., at The Basin and Resolute engraving sites (Figure 79);
- undertaking heritage impact surveys and assessments as part of the development approval process e.g., the Mona Vale Road upgrade in 2021/2022.
- highlighting art on promoted visitor sites to reduce foot traffic impacts, the risk of graffiti and careless marking of grooves e.g., various engravings at West Head;
- appointment and training of site caretakers such as the volunteer program managed by the Aboriginal Heritage Office, noting that this Office is a joint initiative by Lane Cove, North Sydney, Willoughby,

Ku-ring-gai, Strathfield, and the Northern Beaches Council to protect Aboriginal heritage in these areas (https://www.aboriginalheritage.org/);

- removing overhanging vegetation and heavy litter adjacent to sites to minimise the risk of bushfire smoke and radiation damage prior to prescribed burns;
- reducing nearby erosion and removal of sediments from sites; and
- regulating or removing foot, bike, and vehicle traffic over sites to reduce the impacts recreational use e.g., installation of stone barriers and fire-proof walkways and relocation of tracks.

Figure 79. The Basin Engraving Site, KCNP, a significant site co-operatively managed by the NPWS and the Metropolitan Local Aboriginal Land Council. The site also has important geoheritage values i.e., it is a large tessellated pavement site.

Other key considerations

While no systematic archaeological survey has been carried across the whole KGR, it is likely that there are many more sites which are yet to be captured within the AHIMS. This is demonstrated by the number of new sites that enter the system each year. There is also a need to update recorded sites so that site type, site location and other site information is consistently recorded, though this is laborious and would require significant investment.

The Aboriginal rock art in northern Sydney has been previously recommended for inclusion onto the National Heritage List (McDonald and Clayton 2016). This was on the basis that the area contains excellent examples of rare motifs such as the large images of Baiame and Daramulan, a rare example of an emu nesting with eggs, a rare example of a kangaroo hunt, and rare engravings of female figures in association with ancestral beings. Also highlighted in this report was the significance of the many occupation deposits and rock art in the region which have potential to provide information on Aboriginal occupation of the area during the Holocene and their adaptation to environmental change. More recently, the rock art sites within the KGR have been included for priority assessment by the Australian Heritage Council, as part of a proposed Sydney Cultural Crescent Rock Art National Heritage Listing (DAWE 2022).

This close association between significant Aboriginal site features and the landscapes of the area, combined with the fact that many of the Aboriginal sites in the KGR are also promoted for education and tourism, adds diversity and value to the understanding, appreciation, and enjoyment of visiting the proposed KGR geosites and traversing the proposed geotrails in the area, and further demonstrating the strong linkage that exists between geotourism and cultural heritage (Olsen and Dowling 2018).

GEOTRAIL DEVELOPMENT WITHIN THE KGR (D.F. Robson)

Geotrail development within the KGR will foster visitor understanding about the geology and landscapes which shape the geomorphological character of the region. It will showcase accessible and well-known 'visitor friendly' geological locations, and many hitherto undiscovered landscapes for tourists to enjoy, as well as enabling visitors to understand the relationship of rocks to flora and fauna and Aboriginal culture, thus enriching their visits to the KGR. This can be achieved in an entertaining and educational way to create an early interest in geology and the environment for children and their parents. Not only will residents benefit, but more visitors will be attracted to the region leading to greater tourism expenditure.

What are Geotrails?

Geotrails are journeys that offer the advantages of:

- relating directly to the tourism experience linking destinations particularly of geological or geographical interest;
- having universal appeal, and do not compete with or impact on land management/access issues;
- being relatively easy to establish and representing a cost-effective means of enhancing regional development;
- forming logical journeys linking accommodation destinations where available;
- melding the geological heritage features of a region with a cohesive story; and
- incorporating the biodiversity and cultural components of the region through which the geotrail traverses.

Geotrails not only link natural landscapes, wilderness, and protected areas, but also include human modified environments like quarries, road sections and urban settings. Geotourism argues that to fully understand and appreciate the environment, visitors firstly learn about the Abiotic (non-living) elements of climate, landscape, geology, and soils, as these determine the distribution of Biotic (living) elements of animals and plants. Both components influence the cultural landscape of how people inhabited the area in the past, as well as how they live there today. These become the key ABC (Abiotic, Biotic, Cultural) elements of geotourism/geotrails, which provides a cohesive approach to interpreting natural areas.

Examples of established geotrails

In NSW over recent years, the Geological Survey of New South Wales (GSNSW) has developed in conjunction with Councils, universities, and community groups, three outstanding geotrails (https://www.regional.nsw.gov.au/meg/community/geotrails)

- the Newcastle Coastal Geotrail linking 14 geosites along about 10 km of coastal walk from near Newcastle CBD at Nobbys Beach in the north, to Glenrock State Conservation Area to the south;
- the Port Macquarie Coastal Geotrail covering about 4 km of coastline from Port Macquarie CBD south to the Sea Acres National Park which was proposed at the 2010 NSW Linnean Society Symposium held in Port Macquarie (Robinson and Percival 2011); and
- geotrails of the Warrumbungle National Park, which were proposed at the 2018 NSW Linnean Society Symposium held in the neighbouring township of Coonabarabran and later completed, recently captured in a video production of the Department of Regional NSW (DRNSW 2021).

These geotrails are supported with smartphone apps as virtual tours and provide a unique and interactive experience for visitors, school groups, and local communities.

Proposed geotrails within the KGR

The six proposed KGR geotrails are well connected by public transport, major roads and existing tracks and trails, and are being developed in partnership with the NPWS and the three Councils. This project is being driven by a Steering Committee that includes several past and present members of the Geotourism Standing Committee of the GSA and is one of the pilots of the National Geotourism Strategy (NGS) to establish a framework of high quality, sustainable geotrails nationwide. Those proposed geotrails link interesting geosites that have cohesive geological/landscape stories in places that were already known, easily accessed, and frequently visited. Their establishment will of course be subject to review by the land managers having regard to a range of issues including funding, visitor safety and parking etc.

Proposed Long Reef geotrail, Northern Beaches

The Northern Beaches Council is considering whether an existing walk around the perimeter of Long Reef Headland could be adapted as a geotrail. The walk, which is visited by over 4,000 school children and many individuals annually, is very well known for its inter-tidal ecology and is serviced by regular guided walks from the Coastal Environment Centre (CEC) at North Narrabeen. The Long Reef Headland geotrail includes about seventeen geosites around the base of the headland. With the existing information signage that focuses on the biology of the intertidal zone, this experience will be enhanced by including interpretive data (in the form of QR Codes or a dedicated App) about the geology of the headland which contains geological features of international interest (Figure 80). Sites include a volcanic dyke, significant trace fossil burrows, and the discovery of fossilised bones and footprints of a Labyrinthodont. These features reveal the nature of the Triassic environment and how the headland and shore platform provide habitat for the diverse species living today. It also shows several aspects of human history such as Aboriginal land use, fishing, shipwrecks, copper staining that attracted early prospecting, and conservation (Martyn 2018). At the southern end of the geotrail, Long Reef Beach fronts Dee Why Lagoon and is an example of Ice Age legacy and active coastal change. A narrated video with drone footage has been produced to explain these concepts to the public.

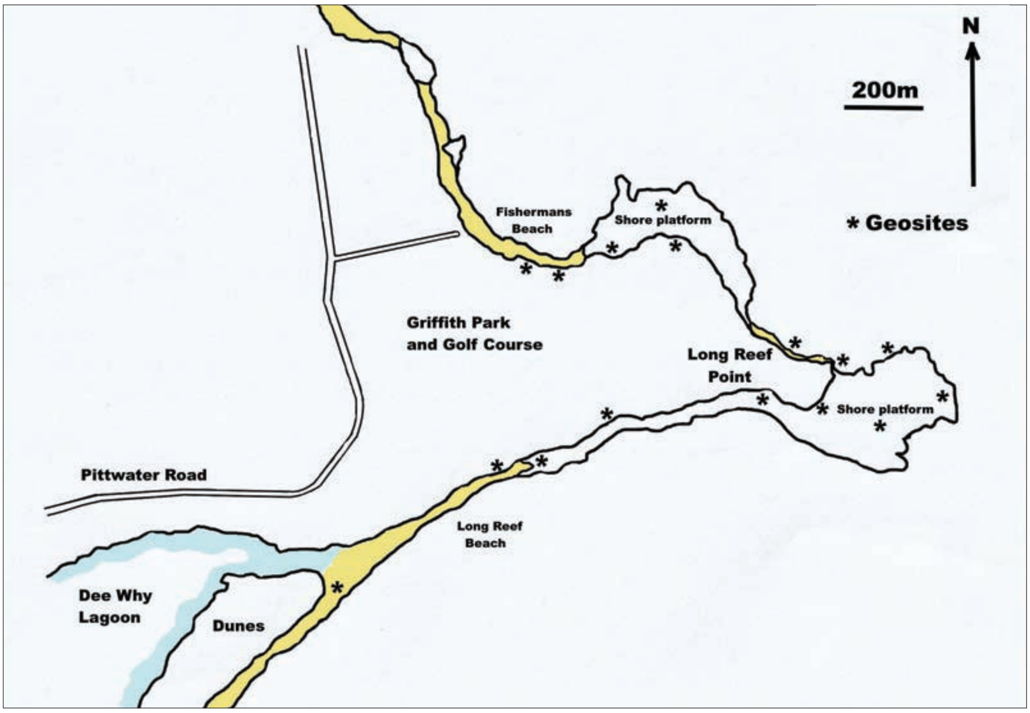

Figure 80. Map of proposed Long Reef Headland Geotrail.

Proposed Browns Field geotrail, Ku-ring-gai

Ku-ring-gai Council region already has several trails in the Hawkesbury Sandstone hillslopes and Wianamatta shale caps from which a geology/landscape story can be readily incorporated to provide a more cohesive and informative visitor experience. The proposed Browns Field geotrail that lies off Campbell Drive about 1 km east of the Sydney Adventist Hospital in Wahroonga includes 16 potential geosites which are easily accessible and are interconnected around Browns Field, the now cleared parkland in the centre of the Fox Valley diatreme (Figure 81). Sites show highly weathered outcrops of fine to medium grained, quartz-poor fragmental volcanic rocks interlayered with much finer grained bedded rocks of possible crater-lake sediments. Entrained Permo-Triassic wall rock clasts are common with outcrops of intensely weathered volcanic breccia showing lithological evidence such as those observed in Cooper Crescent. Fine grained bedded clastic rocks are sliced up by a steeply dipping fault zone, with blocks of Hawkesbury Sandstone. The rainforest on the Cooper Crescent outcrop is rich and diverse and includes some very uncommon species for this botanical region such as the giant stinging tree (*Dendrocnide excelsa),* blue quandong (*Elaeocarpus grandis)*, river oak (*Casuarina cunninghamiana*), corkwood (*Endiandra sieberi*), pencil cedar (*Polyscias murrayi)*, native tamarind (*Diploglottis australis)*, white bolly gum (*Neolitsea dealbata),* featherwood (*Polyosma cunninghamii),* and kangaroo fern (*Microsorum pustulatum)* (Martyn 2018).

Figure 81. Map of Browns Field, Wahroonga.

Proposed Sheldon Forest geotrail, Ku-ring-gai

The existing Sheldon Forest walking track just south of the Turramurra shops is already a popular walking track. Adding a story of geology and landscapes would add more interest to this track as it meanders through the beautiful bushland of Sheldon Forest, along ridge tops, through open forest on the hill slopes and down to the creek side. Sheldon Forest is of high conservation status because it contains some of the last remnants of the endangered ecological communities, i.e., Sydney Turpentine-Ironbark Forest and Blue Gum Forest (https://www.krg.nsw.gov.au/Things-to-do/Bushwalking-tracks/Sheldon-Forest-Track).

Proposed Bicentennial Park dolerite dyke geosite, Ku-ring-gai

The main cliff face backing the small central oval in Bicentennial Park, West Pymble, was originally a quarry face. A narrow, vertical, east-west striking dolerite dyke (Figure 82) cuts the Hawkesbury Sandstone towards the southern end of the face (Martyn 2018; Branagan and Packham 2000).

The sandstone up to 2.0 to 5.0 m away from both contacts has been recrystallised to quartzite, quartz having replaced the native ferrous carbonate cement as an overgrowth to the quartz sand grains. Samples of this sandstone were analysed in 1948 and show that quartz has locally been recrystallised to a high temperature polymorph of platy silica known as tridymite (Osborne 1948). This crystal form implies the intrusion of the dolerite occurred under low pressures and heated the adjacent sandstone to temperatures in the range of approximately 870 to 1,470^{0} C.

Proposed diatremes geotrails and geosites, Hornsby

Hornsby Council is fortunate to have the former Hornsby quarry available for development of a parkland for community use. The quarry is of international significance as it exposes a large diatreme composed of

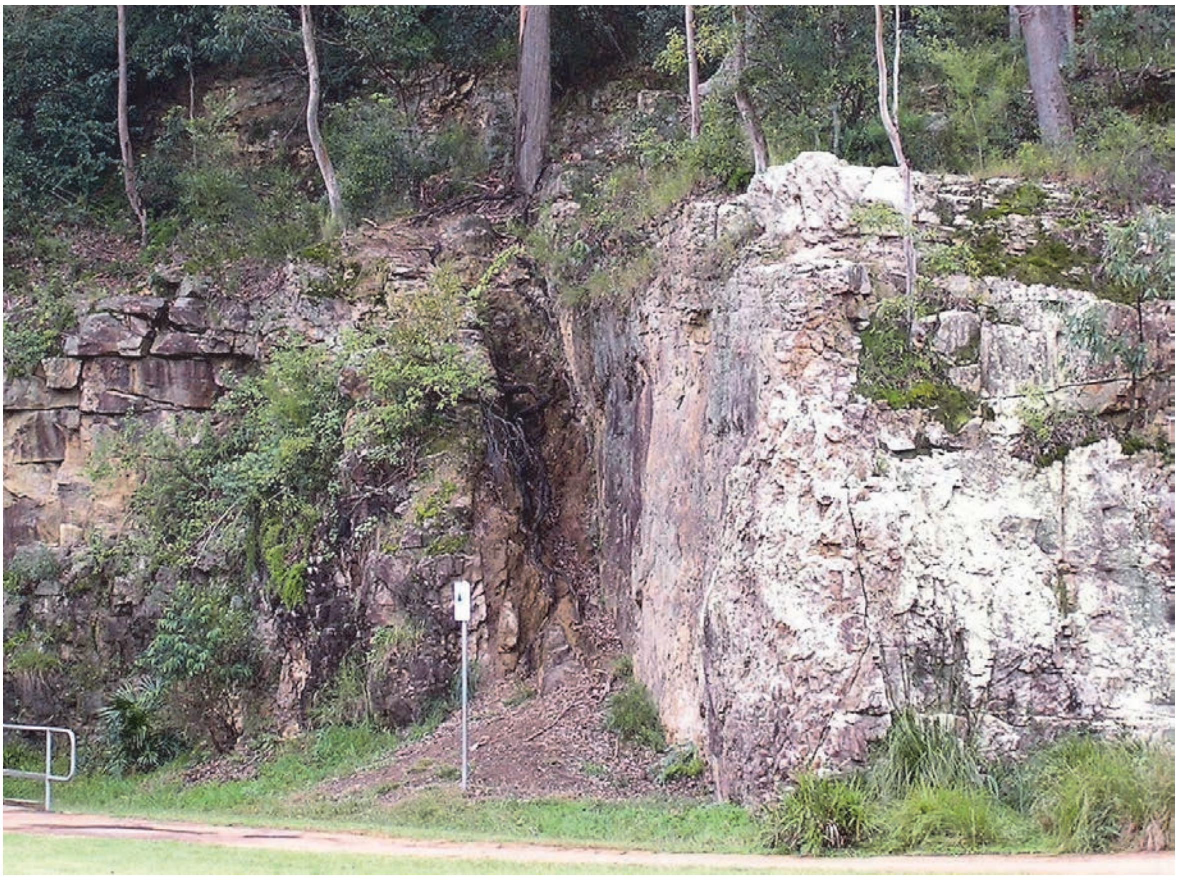

Figure 82. Dyke outcrop in an old quarry face at Bicentennial Park, West Pymble.

rocks injected through Sydney Basin sediments, complete with volcanic features visible at many scales, with post-volcanic features related to magma and gas extrusion at various depths, and with different host rocks. Council has committed resources over the next 12 months to redevelop the former quarry into a prime tourist destination as Hornsby Park. By combining the Hornsby diatreme with the nearby Thornleigh diatreme, which can be accessed along an existing walking track that follows Larool Creek, they could both form part of a future 'Sydney Volcanics Geotrail.'

Proposed West Head geotrail, KCNP

The West Head Road or associated walking tracks on the Lambert Peninsula could be the basis of a suitable geotrail to illustrate the integrated nature of the landscape of the Hornsby Plateau.

The proposed West Head geotrail travels along West Head Road from the intersection of General San Martin Drive to West Head Lookout (Figure 83). The 12 km trail runs roughly north-south along the upper surface of the Hawkesbury Sandstone covering nine accessible geosites within the KCNP. Information about these geosites could be disseminated through brochures, information boards, a phone application, and QR codes. There are numerous excellent photo points, plentiful and varied wildflowers at any time of the year and opportunistic viewing of fauna, particularly birds. Some sites lead to well exposed shale beds crosscut by a sandstone channel where both sheet facies and massive facies sandstone are present. Elsewhere, siderite/ironstone layers in the shale can be traced to form stone lines in the soil mantle that have been incorrectly described as detrital 'laterite.' Where a soil profile is evident the surface layer can be seen to be formed from sandstone weathering products showing the importance of the biomantle as a discrete soil material. Several sandstone platform sites show extensive tessellated pavements (Branagan 1968), numerous vegetation islands and significant Aboriginal rock engravings.

At West Head at the northern end of the geotrail, there are magnificent views over Pittwater to Barrenjoey and over the mouth of the Hawkesbury River to Lion Island. In clear view in the cliffs is a full sequence of the Hawkesbury Sandstone above the Narrabeen Group sedimentary rocks and the drowned valley reflects the effects of post-glacial sea level rise and the geomorphic history of Pittwater and the Palm Beach isthmus. Opportunities to interpret and reflect on the effects of volcanic intrusion on soil development and vegetation and the related links to both Aboriginal and European occupation and use of area are also available.

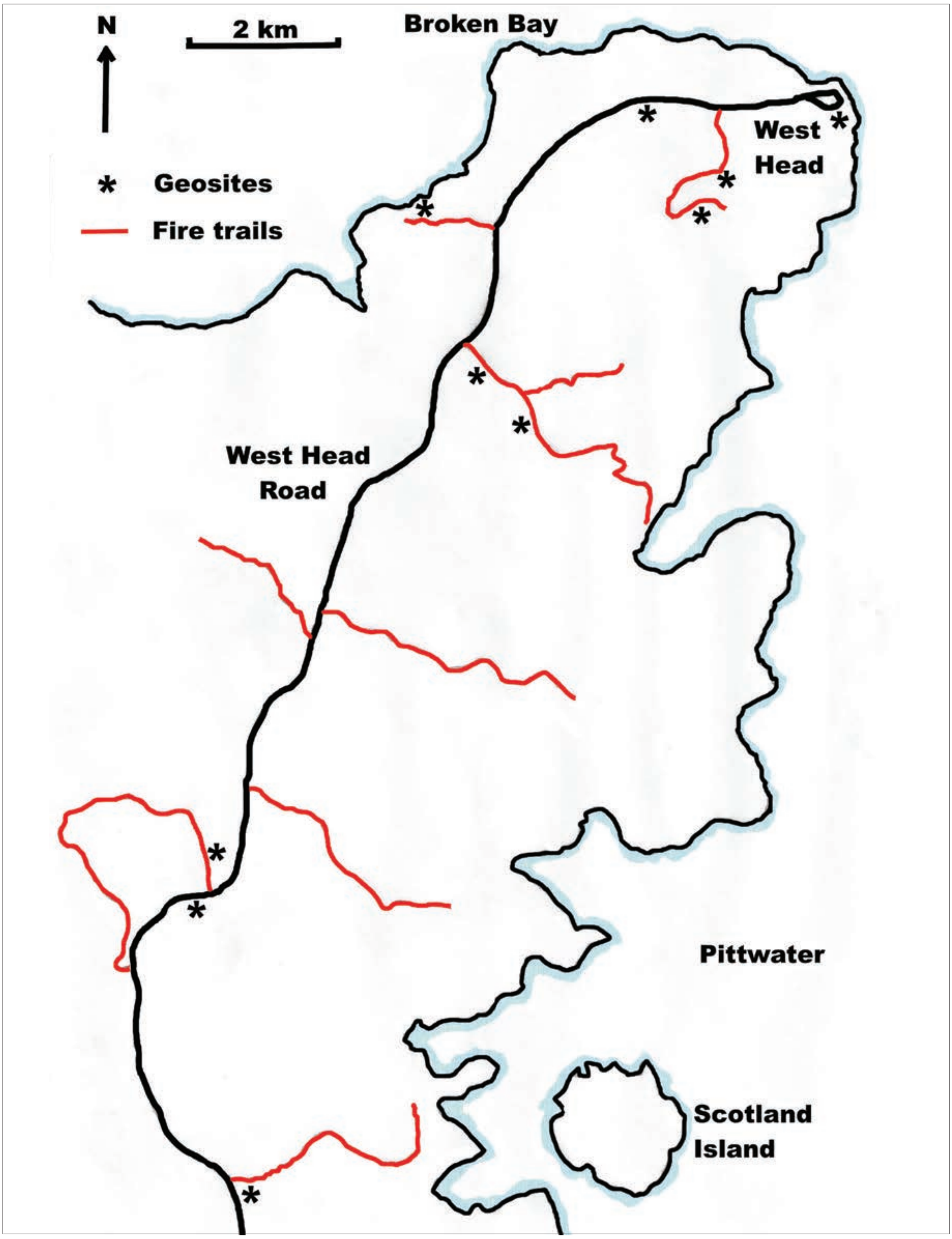

Figure 83. Map of proposed West Head geotrail.

CONCLUSION – FUTURE POTENTIAL OF THE KGR AS AN ASPIRING UNESCO GLOBAL GEOPARK (A.M. Robinson)

In Australia, a GeoRegion can be considered as a defined area of natural and cultural heritage which highlights outstanding geoheritage features (i.e., geosites) around which geotrail and potential geopark projects can be developed. Two GeoRegion projects (one of which is the KGR) are now being developed within Australia as pilots under the auspices of the NGS), an initiative of the Australian Geoscience Council (AGC 2021).

The KGR is currently being assessed with the long-term intentions of it being nominated as an Aspiring UNESCO Global Geopark. This is of course subject to community consultation and support, and State and Australian Government approval to be sought over the next few years. The establishment and development of the KGR and its associated geosites and geotrails represents a significant first step in realising this aspiration.

Having regard to the hitherto unsuccessful history of geopark development in Australia (Robinson 2022), the NGS recognises that any geopark proposal should, in the initial stages of project conceptualisation, adopt a nomenclature which removes reference to the word ‘geopark’ and focuses instead on communicating the concept of a ‘GeoRegion’. This approach offers the opportunity for proponents within Australia using the language of GeoRegions to explore various alternative options for geotourism, which are not hampered by notions of a single tenure and regulatory approach. These would strongly focus on the establishment of themed geotrails which link geoheritage sites, some of which may already have been established as geological ‘monuments’ or recognised in state or national geoheritage registers. From an UNESCO evaluation perspective, this approach also serves to establish a status of a ‘de facto’ geopark, a pre-requisite for any Aspiring UNESCO Global Geopark nomination (UNESCO Global Geoparks 2022).

As a NGS pilot project, it is envisaged at some future time, a final report with recommendations will need to be prepared by a designated proponent (structured as an incorporated management entity) for initial submission to the NSW State Government. This report will no doubt need to include final support sought from the GSNSW, planning and environment agencies, and other state and federal government agencies responsible for land and resource management. In the case of the KGR, it is axiomatic that the project has the backing of the three Councils embracing the area, as well as the NPWS as the major manager of public land (KCNP and other protected areas) in the KGR to ensure that visitor impacts are responsibly managed.

As the initiating proponent, FOKE has been seeking recognition of the significant natural and cultural heritage values as exemplified by the wide range and number of identified geosites that exist within the KGR. In NSW nearly 100 geosites have already been identified statewide (Cartoscope 2018), but these are generally widely scattered rather than being relatively concentrated within a localised GeoRegion.

D. Robson (above) has discussed the key ABC (Abiotic, Biotic, Cultural) elements that apply to recognition of geotrails within a GeoRegion. The geology and geomorphology, mantled by the soil profiles, provides the foundation for vegetation communities that are also in part controlled by proximity to fresh and saltwater and microclimatic conditions. In turn the fauna of the region is dependent on the vegetation for protection, habitat, and food resources. Likewise, the original Aboriginal inhabitants of the land fully utilised its abiotic and biotic elements in their daily lives, as recorded in the wealth of sites detailed in this paper. In the concluding remarks to the evaluation of the KGR, it is appropriate to briefly review each of its salient elements.

Salient Elements of the KGR

Abiotic

In understanding the geology of the KGR, J. Martyn (above) has argued that it is important to consider the depositional position of the Permo-Triassic Sydney Basin which lay around 5 to 10^{o} south of where Macquarie Island sits today, with widespread glaciation of its continental hinterland a big part of its Permian history. The abundant ice-rafted glacial dropstones of the South Coast Permian are part of this story. The Permian coal measures were compacted from peat laid down in boreal rather than tropical swamp forests, and red beds like the Triassic Bald Hill Claystone clearly had a different origin to the hot desert setting of British Triassic red beds.

The Sydney Basin evolved as the foreland basin of an alpine mountain front, deepening sharply against the rising New England Fold Belt to the north, like the trough in front of an ocean swell, with its sediments fanning out and flattening to the south-west and south over the worn-down Lower Palaeozoic basement rocks of the Lachlan Fold Belt. It captured a strong influx of sediment from the rising fold belt. In Late Permian to Early Triassic times, volcanoes of shoshonitic composition lay to the east, pouring out lava flows and ash clouds that locally put a strong imprint on the sediments.

The end-Permian global extinction event at 252 million years was triggered by massive eruptions in far-away Siberia that profoundly changed the climatic conditions, abruptly terminating coal seam formation.

The KGR draws on all these influences. The classic geology of the Narrabeen Group along the Northern Beaches coastline features rocks like Bald Hill Claystone that formed from the in-situ weathering of riverine debris washed in from the shoshonitic volcanic ranges. The Newport Formation of coastal cliffs like Avalon and Bungan Head carries conglomerate bands sourced almost certainly from several hundred kms to the north, in an active mountain belt in what is now the New England part of NSW.

The thick quartz lithic sandstones and interlayered laminites today support endangered littoral rainforest and the beautiful Pittwater Spotted Gum Forest of the Pittwater shoreline, both floral highlights of the KGR. The 230 m thick, quartz-rich Hawkesbury Sandstone that overlies the Newport Formation and underpins the extensive tablelands of KCNP, is the braid plain deposit of a massive river system, with distant catchments extending to what is now Antarctica. Its preserved ancient land surface is florally rich and diverse, ranging from woodlands and shrublands to upland swamps. KCNP's drowned valley coastline is a classic of its type and a local scenic wonderland (Figure 84), a theme which echoes the perspective of Trueman (1938) who proposed, 'everyone interested in countryside, how it has taken shape, why it presents us with the varied beauties of mountain and woodland, river valleys and fertile meadows, is, if often unconsciously, appreciating its geology'.

Assessment so far of the abiotic attributes of the KGR has also highlighted evidence of Jurassic volcanic activity within the Sydney Basin, in particular the outstanding diatreme geosite at the former Hornsby Quarry. Development of this feature as the centrepiece of the new Hornsby Park will ensure that this example of world class geoheritage is protected and becomes available for public education and enjoyment through the development of geotrails and other geotourism activities.

Figure 84. A waterfall in Refuge Bay, Cowan Waters. A popular boating destination which offers both geological, geomorphological (e.g., examples of massive sandstone, flooded river valley and knickpoint), and cultural heritage (i.e., Aboriginal, exploration and naval history values) promotional opportunities.

The geomorphic feature of drowned valleys highlights the impact of substantial, post-glacial sea level rise in the Pleistocene Epoch of the Quaternary Period.

Currently over 50 geosites within the KGR have been identified as being very worthy of visitation. The GSA has proposed a practical process for identifying suitable geosites/geotrails with subsequent detailed assessment to be followed for any selected geosites for geotrail development. Other geosites might be identified as of sensitive cultural/geoheritage significance and are not developed for geotrails. So far, it has been proposed that geotrail development (based on six localities supported by the three Councils and the NPWS) within the KGR will provide a basic understanding of the geology and landscapes which shape the character of this region.

Whereas the study of soil landscapes is often overlooked in geoheritage investigations, this is certainly not the case for the KGR which is shaping up as a significant laboratory for future soil research in the science of pedology. P, Mitchell (above) has outlined fundamental work already carried out in the region, involving the recognition of discrete soil materials rather than profiles, and development of a new genetic model of soil evolution and distribution by adopting a stratigraphic approach to soil landscapes as a definitive feature of Holocene geology. He has also argued that most previous studies failed to consider the role of the biosphere and the importance of geomorphic processes.

Geology is a major influence and control on vegetation in the KGR. There are many other abiotic influences, especially terrain and microclimate, including distance or protection from the exposed, windy coast, but then geology's influence on terrain also has a critical downstream effect on microclimates.

Biotic

Vegetation communities in the KGR range from northern warm temperate rainforests and North Coast wet sclerophyll forest in areas of richer soil or sheltered gullies to coastal headland heaths, maritime grasslands directly on the coast and estuarine mangroves, saltmarsh, and sea grass meadows. Sydney coastal dry sclerophyll forests and Sydney coastal heaths come in many forms that frequently intergrade and complement each other as the broad ridgetops give way to sloping and often steeply eroded hills. As such, these classes dominate much of the area with large continuous stands in KCNP. Whilst there is infinite variation in form because of fire history, aspect, topography, and recent climactic conditions, these vegetation classes show consistent traits of high structural diversity.

As shown by J. Walsh (above), distribution of the diverse fauna of the KGR is closely related to vegetation communities and therefore geomorphology, soils, and underlying geology. The multitude of diverse vegetation communities present within the KGR is responsible for the diversity of fauna.

There are few places within Australia where such diversity and species richness are evident as in the KGR, rivalling the likes of Kakadu National Park. Internationally recognised for its impressive wildlife watching opportunities, the KGR excels. With over 300 bird species recorded in this relatively small area, it is home to some impressively rare and diverse species.

Despite having lost many species locally over the past 200 years since European settlement, there is so much left to learn and conserve. Moreover, in enjoying a coastal interface, there exists a plethora of marina fauna (including migrating birdlife and visiting marine mammals, as well as other marine fauna), many of which are captured in the art and occupational deposits of Aboriginal peoples over many thousands of years.

Cultural – Aboriginal

In discussing the Aboriginal heritage of the KGR, R. Conroy (above) affirms that this evidence of the original inhabitants adds immeasurable value to our understanding, appreciation, and enjoyment of its natural and cultural heritage. R. Conroy has demonstrated that there is strong connection between the various Aboriginal site types with the landscapes of the KGR, influenced by geology, aspect, elevation and slope, and associated landforms.

While most site type locations are found within the protected areas of the KGR, R. Conroy has noted that the ongoing conservation of sites is challenged by ongoing residential development and by the construction and upgrade of roads and utilities, bushfire, and recreational activity impacts.

Cultural – climate change impacts

Finally, whilst the evidence of past climate change both in the geological and cultural heritage record has been discussed, the paper has also described in detail, based on skillful application of drone technology, the geomorphic processes that are taking place along the eastern coastal boundary of the KGR and the real and substantive impact on local residential communities.

R. Conroy (pers. comm.) has observed that climate change is also expected to accelerate both physical and chemical weathering processes in the future, as well as cause the inundation of low elevation sites, putting further pressure on the future conservation of Aboriginal sites such as occupational deposits which are likely to hold information regarding Aboriginal lifestyles, particularly throughout the Holocene - the later epoch of the Quaternary.

By exploring the links between the area's geological heritage and other natural, cultural, and intangible heritage, the potential nomination of the KGR as an Aspiring UNESCO Global Geopark will create an unrivalled opportunity to study the effects of past and current climate change on natural and cultural heritage in an outdoor, natural history museum. Furthermore, it will provide local communities with the knowledge to mitigate and adapt to the potential effects of future climate change.

ACKNOWLEDGEMENTS

Lead author, Bob Conroy, acknowledges the dedicated support, guidance, and encouragement of each of his co-authors i.e., John Martyn, Ian Percival, Peter Mitchell and John Illingsworth, Jayden Walsh, Ursula Bonzol, David Robson, and Angus M Robinson. The latter was also responsible for the coordination and synthesis of all the individual contributions into one coherent paper. A special mention is made to the work of John Martyn in preparing an overview of the unpublished natural and cultural heritage account of the KGR. That document was instrumental in gaining early support for the GeoRegion concept from government agencies through the work of the KGR Steering Committee. Appreciation is also made for the provision of data from the Aboriginal Heritage Information System.

John Martyn acknowledges that much of the fieldwork and study for his section came about in the preparation of his book 'Rocks and Trees' published by the community environmental group STEP Inc. and is grateful for their past and continuing support. He also thanks the researchers who over the decades have published so much on the geology of the Sydney Basin – too many to mention individually but their key geological references represented a superb background resource.

Ian Percival is grateful to Armstrong Osborne, John Martyn, and Peter Mitchell for discussion on various aspects of the geological setting and formation of the diatreme. Photographs for Figures 28 and 29 were supplied by Armstrong Osborne. Craig Clendinning (Planning Manager, Hornsby Shire Council, responsible for redevelopment of the former quarry site into Hornsby Park), is thanked for facilitating a site visit in June 2020.

Peter Mitchell gives credit to the ideas and leadership of Professor T.R. Paton for his contribution on soils. He records that numerous Macquarie University staff and students participated in the collaborative research and teaching that explored the topics discussed in this paper, with some of the work being supported by university research grants.

Unless labelled otherwise, all other Figures and Tables are those of the authors.

REFERENCES

Adamson, C.L. and Taylor, G.H. (1976). Hornsby and Peats Ridge aggregate quarries. *25th International Geological Congress Guidebook*, Excursion **14B**, 12.

Adamson, D. Selkirk, P.M. and Mitchell, P.B. (1983). The role of fire and lyrebirds in the sandstone landscapes of the Sydney Basin. Aspects of Australian sandstone landscapes. (Eds. R.W. Young and G.C. Nanson) *Australian and New Zealand Geomorphology Research Group Special Publication* **1**, 81-93.

AdaptNSW (2022). Managing the effects of sea level rise. www.climatechange.environment.nsw.gov.au/managing-effects-sea-level-rise

AGC (2021). https://www.agc.org.au/geoscience-in-australia/geotourism

Allen, S., Marsh, H. and Hodgson, A. (2004). Occurrence and conservation of the dugong (Sirenia: Dugongidae) in New South Wales. *Proceedings of the Linnean Society of New South Wales* **125**, 211-216.

Amano, T., Székely, T., Koyama, K., Amano, H. and Sutherland, W.J. (2010). A framework for monitoring the status of populations: An example from wader populations in the East Asian–Australasian flyway. *Biological Conservation* **143**, 2,238–2,247. https://doi.org/10.1016/J.BIOCON.2010.06.010

Andrew, D. (2005). Ecology of the tiger quoll (*Dasyurus maculatus*) in coastal New South Wales, MSc thesis, School of Biological Sciences, University of Wollongong. https://ro.uow.edu.au/theses/686/

Andrews, E.C. (1924). Volcanic breccia from Hornsby. *New South Wales Department of Mines, Annual Report for 1923*, 80**.**

ATLA (Atlas of Living Australia) (2022). https://biocache.ala.org.au/occurrences/search?q=lsid:urn:lsid:biodiversity.org.au:afd.taxon:25b7606b-0b61-4f2d-967e-9c5c210fe332#tab_mapView

Attenbrow, V. (2003). 'Sydney's Aboriginal Past. Investigating the archaeological and historic records.' University of New South Wales Press Ltd, Sydney.

Barron, L. and Barron, J. (2001). Photographs, geology, and petrology of Hornsby Diatreme. *Geological Survey of New South Wales, Report* **GS 2001/226**, 29 pp.

Beadle, N.C.W. (1953). The edaphic factor in plant ecology with a special note on soil phosphates. *Ecology* **34**, 426-428.

Beadle, N.C.W. (1954). Soil phosphate and the delimitation of plant communities in Eastern Australia. *Ecology* **35**, 370-375.

Beadle, N.C.W. and Burges, A. (1949). Working capital in a plant community. *Australian Journal of Science* **11**, 207–208.

Bellgard, S.E. (1991). Mycorrhizal associations of plant species in Hawkesbury Sandstone vegetation. *Australian Journal of Botany* **39**, 357-364.

Bembrick, C.S., Herbert, C., Scheibner, E. and Stuntz, J. (1973). Structural subdivision of the New South Wales portion of the Sydney – Bowen Basin. *Quarterly Notes Geological Survey of New South Wales* **11**, 1-13.

Benson, W.N. (1911). The volcanic necks of Hornsby and Dundas near Sydney. *Journal and Proceedings of the Royal Society of New South Wales* **44**, 495-555.

Benson, D. and Howell, J. (1994). The natural vegetation of the Sydney 1:100,000 map sheet. *Cunninghamia* **3**, 677-787.

Bionet (2022). https://www.environment.nsw.gov.au/AtlasMapViewerApp/index.html

Birdline NSW (2022). http://eremaea.com/BirdlineArchive.aspx?Birdline=2&From=20060601&To=20221113

Bishop, P.M. (1976). An investigation of soil materials in the Patonga-Pearl Beach area. BA Honours thesis, Macquarie University.

Bishop, P.M., Mitchell, P.B. and Paton, T.R. (1980). The formation of Duplex soils on hillslopes in the Sydney Basin, Australia. *Geoderma* **23,** 175-189.

Blong, R.J.M., Riley, S.J. and Crozier, P. (1982). Sediment yield from runoff plots following bushfire near Narrabeen Lagoon, New South Wales. *Search* **13**, 36-39.

Bourman, R.P. (1989). Investigations of ferricretes and weathered zones in parts of southern and southeastern Australia – A reassessment of the Laterite concept. PhD thesis, University of Adelaide.

Braithwaite, R.W. (1995) Southern Brown Bandicoot (*Isoodon obesulus*), 176-177 in Strahan, R. (ed.) 'The Mammals of Australia'. Reed Books, Chatswood.

Branagan, D.F. (1968). A tessellated platform. Ku-ring-gai Chase, N.S.W. *Journal and Proceedings of the Royal Society of New South Wales* **101**, 129-133.

Branagan, D.F. and Packham, G.H. (2000). 'Field Geology of New South Wales 2000.' Third Edition, 109-110. New South Wales Department of Mineral Resources, Sydney.

Breckwoldt, R. (1988). 'The dirt doctors. A jubilee history of the Soil Conservation Service of New South Wales.' Soil Conservation Service of New South Wales.

Brown, D. (2012). 'A Guide to Australian Skinks in Captivity.' Reptile Keeper Publications, Burleigh Heads.

Buchanan, R.A. (1980). The Lambert Peninsula, Ku-ring-gai Chase National Park. Physiography and the distribution of podzols, shrublands and swamps, with details of the swamp vegetation and sediments. *Proceedings of the Linnean Society of New South Wales* **104**, 73-94.

Buchanan, R.A. and Humphreys, G.S. (1980). The vegetation on two podzols on the Hornsby Plateau, Sydney. *Proceedings of the Linnean Society of New South Wales* **104**, 49-71.

Burges, A. and Beadle, N.C.W. (1952). The laterites of the Sydney District. *Australian Journal of Science* **14,** 161-162.

Byrnes, J.G. (1973). Sedimentary dyke at St Michael's Cave. *Geological Survey of New South Wales, Report* **GS 1973/053**, 2 pp.

Byrnes, J.G. (1982). Accretionary lapilli formed at three Jurassic volcanoes near Sydney. *Geological Survey of New South Wales, Report* **GS 1982/127**, 7 pp.

Campbell, L.M., Conaghan, P.J. and Flood, R.H. (2001). Flow-field and palaeogeographic reconstruction of volcanic activity in the Permian Gerringong Volcanic Complex, southern Sydney Basin, Australia. *Australian Journal of Earth Sciences* **48**, 357-375.

Carr, P.F. (1998). Subduction related Late Permian shoshonites of the Sydney Basin, Australia. *Mineralogy and Petrology* **63**, 49–71.

Carter, D.B. (1992). Reproductive ecology of the lace monitor (*Varanus varius*) in southeastern Australia. PhD thesis, Australian National University, Canberra. 164 pp.

Cartoscope, (2018). 'Geotourism Map – Geological Sites of New South Wales.' 2nd Edition.

Carvalho, J.E., Navas, C.A. and Pereira, I.C. (2010). Energy and water in aestivating amphibians. *Progress in Molecular and Subcellular Biology*, **49**, 141-169.

Chapman, G.A. and Murphy, C.L. (1989). 'Soil landscapes of the Sydney 1:100,000 sheet.' Soil Conservation Service of New South Wales.

Chapman G.A., Murphy C.L., Tille P.J., Atkinson G. and Morse R.J. (2009). 'Soil landscapes of the Sydney 1:100,000 Sheet.' 4th Edition. New South Wales Department of Environment, Climate Change and Water, Sydney.

Charman, P.E.V. and Murphy, B.W. Eds. (1991). 'Soils their properties and management. A soil conservation handbook for New South Wales.' Sydney University Press.

Claridge, A.W., McNee, A., Tanton, M.T. and Davey, S.M. (1991). Ecology of Bandicoots in undisturbed forest adjacent to recently felled logging coupes: a case study from the Eden woodchip agreement area. *Conservation of Australia's Forest Fauna* (Lunney, D. ed), 331-345. The Royal Zoological Society of New South Wales, Mosman.

Clegg, J. (2002). Recent Research at Elvina Track Rock Platforms. *Australian Association of Consulting Archaeologists Inc. Newsletter* **90**, 17-19.

Cogger, H.G. (2018). 'Reptiles and amphibians.' CSIRO Publishing.

Conaghan, P.J. (1980). The Hawkesbury Sandstone: gross characteristics and depositional environment. A guide to the Sydney Basin. Eds. C. Herbert and R. Helby. *Geological Survey of New South Wales Bulletin* **26**, 188-253.

Conaghan, P.J. and Jones, J.G. (1975). The Hawkesbury Sandstone and the Brahmaputra: a depositional model for continental sheet sandstone. *Journal of the Geological Society of Australia* **22**, 275-283.

Cooper, S.J.B., Harvey, M.S., Saint, K.M and Main, B.Y. (2011). Deep phylogeographic structuring of populations of the trapdoor spider (*Moggridgea tingle Migidae*) from southwestern Australia: evidence for long-term refugia within refugia. *Molecular Ecology* **20**, 219–236.

Corbett, J.R. (1969). 'The living soil: the processes of soil formation.' Geography Teachers' Association of New South Wales.

Corkery, R.W. (1980). Weathering of Hawkesbury Sandstone shale lenses – implications for ceramic evaluation. *Quarterly Notes Geological Survey of New South Wales* **41**, 1-9.

Corkhill, T. (2005). Sourcing stone from the Sydney region: A hatchet job. *Australian Archaeology* **60**, 41-50.

Couper, P. and Hoskin, C. (2008). Litho-refugia: the importance of rock landscapes for the long-term persistence of Australian rainforest fauna. *Australian Zoologist* **34**, 554–560.

Cowan, E.J. (1993). Longitudinal fluvial drainage patterns within a foreland basin-fill: Permo-Triassic Sydney Basin, Australia. *Sedimentary Geology* **85**, 557-577.

Cowan, J.A., Humphreys, G.S., Mitchell, P.B. and Murphy, C.L. (1985). An assessment of pedoturbation by two species of mound building ants, (*Camponotus intrepidus*) (Kirkby) and (*Iridomymex purpureaus*) (F. Smith). *Australian Journal of Soil Research* **22**, 98-108.

Crawford, E.A., Herbert, C., Taylor, G., Helby, R., Morgan, R. and Ferguson, J. (1980). Diatremes of the Sydney Basin. in Herbert, C. and Helby, R. (Eds.), A Guide to the Sydney Basin. *Geological Survey of New South Wales Bulletin* **26**, 294-325.

Damiani, R.J. (1999). Giant temnospondyl amphibians from the Early to Middle Triassic Narrabeen Group of the Sydney Basin, New South Wales, Australia. *Alcheringa* **23**, 87-109.

Davis, W.M. (1899). The geographic cycle. *Geography Journal* **14**, 481-504.

DAWE (2022). Finalised Priority Assessment Lists for the National and Commonwealth Heritage Lists. Department of Agriculture, Water, and the Environment. Canberra. https://www.awe.gov.au/parks-heritage/heritage/places/priority-assessment

DECC (2006). Recovery plan for the southern brown bandicoot (*Isoodon obesulus*). New South Wales Department of Environment and Climate Change, Hurstville. https://www.environment.nsw.gov.au/-/media/OEH/Corporate-Site/Documents/Animals-and-plants/Recovery-plans/southern-brown-bandicoot-isoodon-obesulus-recovery-plan.pdf

DECC (2008). Rapid fauna habitat assessment of the Sydney Metropolitan Catchment Management Authority Area (CMA). New South Wales Department of Environment and Climate Change, Hurstville. https://majorprojects.planningportal.nsw.gov.au/prweb/PRRestService/mp/01/getContent?AttachRef=MP10_0052%2120190814T044834.377%20GMT

Dehghani, M.H. (1994). Sedimentology, Genetic Stratigraphy and Depositional Environment of the Permo-Triassic Succession in the Southern Sydney Basin, Australia. PhD thesis, Department of Geology, University of Wollongong.

Delpit, S., Ross, P. and Hearn, B.C. (2014). Deep-bedded ultramafic diatremes in the Missouri River Breaks volcanic field, Montana, USA: 1 km of syn-eruptive subsidence. *Bulletin of Volcanology* **76**, art. 832, 22 pp. DOI: 10.1007/s00445-014-0832-8

de Strzelecki, P.E. (1845). 'Physical description of New South Wales and Van Diemen's Land, accompanied by a geological map, sections and diagrams, and Figures of the organic remains.' Longman, Brown, Green, and Longman, London.

Doelman, T., Webb, J., Williams, A., May, J. and Barry, F. (2015). Paleochannels and Patches: A Geoarchaeological Assessment of Silcrete Sources in the Cumberland Plain, Eastern Australia. *Geoarchaeology: An International Journal* **30**, 495–510.

Dowle, M. (2012). A comparison of two species of bandicoots (*Perameles nasuta* and *Isoodon obesulus*) influenced by urbanisation, population characteristics, genetic diversity, public perceptions, stress, and parasites. PhD thesis. Macquarie University, Sydney.

DRNSW (2021). Video production of the Warrumbungle National Park Geotrails https://www.youtube.com/watch?v=_V1oZeqdUg0

Dury, G.H. (1969). Rational descriptive classification of Duricrust. *Earth Science Journal* **3**, 77-86.

Dury, G.H. (1971). Relict deep weathering and duricrusting in relation to the palaeoenvironments of middle latitudes. *The Geographical Journal* **137**, 511-522.

Edgar, R. and Belcher, C. (1995). Spotted-tailed Quoll (*Dasyurus maculatus*), 67-69 in Strahan, R. (ed.) 'The Mammals of Australia.' Reed Books, Sydney.

Edye, J.A., Murphy, C.L., Chapman, G.A., Milford, H.B., McGaw, A.J.E., Macleod, A.P. and Simons, N.A.

(Undated). What's in a landscape? Describing natural resources with soil landscapes. http://www.regional.org.au/au/gia/21/714edye.htm

Eggleton, R.A. and Taylor, G. (1999). Some selected thoughts on laterite. New approaches to an old continent. (Eds G. Taylor and C.F. Pain), *Proceedings of the Third National Regolith Conference*, 209-226.

Embleton, B.J., Schmidt, P.W., Hamilton, L.H. and Riley, G.H. (1985). Dating volcanism in the Sydney Basin: evidence from K-Ar ages and paleomagnetism. In Sutherland, F.L., Franklin, B.J. and Waltho, A.E. (eds), 'Volcanism in Eastern Australia.' *Geological Society of Australia, Special Publication.* **1,** 59-72

Facer, R.A. and Carr, P.F. (1979). K-Ar dating of the southeastern Sydney Basin. *Journal of the Geological Society of Australia* **26**, 73–80.

Faniran, A. (1971). The parent materials of Sydney laterites. *Journal of the Geological Society of Australia* **18**, 159-164.

Farman, R.M. and Bell, P.R. (2020). Australia's earliest tetrapod swimming traces from the Hawkesbury Sandstone (Middle Triassic) of the Sydney Basin. *Journal of Paleontology* **94**, 966-978.

Fergusson, C.L. (2006). Review of structure and basement control of the Lapstone Structural Complex, Sydney Basin, Eastern New South Wales. Hutton, A.C. and Griffin, J. (Eds.). *Proceedings of the Thirty Sixth Sydney Basin Symposium on advances in the study of the Sydney Basin.* University of Wollongong, 45–50.

Fielding, C.R., Frank, T.D., Birgenheier, L.P., Rygel, M.C., Jones, A.T. and Roberts, J. (2008). Stratigraphic imprint of the Late Paleozoic Ice Age in eastern Australia: a record of alternating glacial and nonglacial climate regime. *Journal of the Geological Society* **165**, 129-140.

Foley, D. (2001). Repossession of our Spirit. Traditional owners of northern Sydney. *Aboriginal History Monograph* **7.** Aboriginal History Inc. Canberra.

Gibson, D.L. (2007). Potassium-argon ages of late Mesozoic and Cainozoic igneous rocks of Eastern Australia. *CRC LEME Open File Report* **193**; Geoscience Australia.

Glen, R.A. (2005). The Tasmanides of eastern Australia. *Geological Society, London Special Publication,* **246,** 23-96.

Gould, S.F. (1998a). Proteoid root mats bind surface materials in Hawkesbury Sandstone biomantles. *Australian Journal of Soil Research* **36,** 1,019-1,032.

Gould, S.F. (1998b). Proteoid root mats stabilise Hawkesbury Sandstone biomantles following fire. *Australian Journal of Soil Research* **36**, 1,033-1,043.

Griffin, W.L. and O'Reilly, S.Y. (1986). The lower crust in eastern Australia: xenolith evidence. The Nature of the Lower Continental Crust. (Eds J.B. Dawson, D.A. Carswell, J. Hall and K.H. Wedepohl). *Geological Society, London Special Publication* **24**, 363-374.

Guthrie, F.B. (1898). Notes on the Soils of County Cumberland. *The Agricultural Gazette of New South Wales* **9**, 481-487. Government Printer, Sydney.

Guthrie, S. and Kohen, J. (2005). Water views: Water-based survey methods. *Australian Archaeology* **60**, 16-23.

Hallsworth, E.G. and Costin, A.B. (1953). Studies in pedogenesis in New South Wales; IV, The ironstone soils. *Journal of Soil Science* **4**, 24-46.

Hallsworth, E.G., Costin, A.B. and Gibbons, F.R. (1953). Studies in pedogenesis in New South Wales. VI. On the classification of soils showing features of podzol morphology. *Journal of Soil Science* **4,** 241-56.

Hamilton, L.H. (1970). The volcanic necks of Sydney. *Bulletin volcanologique* **34**, 738-739.

Helby, R. and Morgan, R. (1979). Palynomorphs in Mesozoic volcanoes of the Sydney Basin. *Geological Survey of New South Wales Quarterly Notes* **35**, 1-15.

Hencher, S.R. and Knipe, R.J. (2007) Development of rock joints with time and consequences for engineering. *Proceedings of the 11th congress of the International Society for Rock Mechanics* **1**, 223–226.

Herbert, C. (1983). Igneous Rocks, 93-113. 'Geology of the Sydney 1:100,000 Sheet, 9130' (Ed C. Herbert). Geological Survey of New South Wales.

Herbert, C. and Helby, R. (Eds.) (1983). A Guide to the Sydney Basin. *Geological Survey of New South Wales Bulletin* **26**.

Holden, K.G., Gangloff, E.J., Gomez-Mancillas, E., Hagerty, K. and Bronikowski, A.M. (2021). Surviving winter: Physiological regulation of energy balance in a temperate ectotherm entering and exiting brumation. *General and Comparative Endocrinology* **307**, 113758, https://doi.org/10.1016/j.ygcen.2021.113758

Hoskin, E.S., Hindwood, K. and McGill, A.R. (1991). 'The birds of Sydney, County of Cumberland, New South Wales, 1770-1989.' Surrey Beatty.

Howell, J., Humphreys, G.S. and Mitchell P.B. (2006). Changes in soil water repellence and its distribution in relation to surface microtopographic units after a low severity fire in eucalypt woodland, Sydney. *Australian Journal of Soil Research* **44**, 205-217.

Humphreys, G.S. (1981). The rate of ant mounding and earthworm casting near Sydney, New South Wales. *Search* **12**, 129-131.

Humphreys, G.S. (1994). Bioturbation, biofabrics, and the biomantle an example from the Sydney Basin. Soil micromorphology: studies in management and genesis. (Eds. A.J. Ringrose-Voase and G.S. Humphreys) Elsevier, Amsterdam 421-436.

Humphreys, G.S. and Mitchell, P.B. (1983). A preliminary assessment of the role of bioturbation and rainwash on sandstone hillslopes in the Sydney Basin. Aspects of Australian Sandstone Landscapes. (Eds R.W. Young and G.C. Nanson), 66-80. *Australian and New Zealand Geomorphology Group Special Publication.*

Humphreys, G.S., Raven, M.D. and Field, R.J. (2004). Wood-ash stone in *Angophora costata* (Gaertn.) J. Britt. following Sydney bushfires. *Australian Forestry* **67**, 39-43.

Hunt, P.A., Mitchell, P.B. and Paton, T.R. (1977). 'Laterite profiles' and 'lateritic ironstones' on the Hawkesbury Sandstone. Australia, *Geoderma* **19**, 105-121.

Isbell, R.F. (1992). A Brief History of National Soil Classification in Australia since the 1920's. *Australian Journal of Soil Research* **30**, 825-842.

Isbell, R.F. (2021). 'The Australian Soil Classification. National Committee on Soil and Terrain.' CSIRO Publishing, Melbourne. 3rd edn.

Jensen, H.I. (1912). The Soils of New South Wales Sydney*, Science Bulletin Department of Agriculture, New South Wales* **8**, 1-14.

Johnson, D.L. (1990). Biomantle evolution and the redistribution of earth materials and artifacts. *Soil Science* **149**, 84-102.

Joplin, G.A. (1968). 'A Petrography of Australian Igneous Rocks.' Second Edition. (Angus and Robertson: Sydney), 125 (xenoliths), 128-129 (petrography 'coal'), 142 (peridotites).

Kear, B.P. (2009). *Proterosuchid archosaur* remains from the early Triassic Bulgo Sandstone of Long Reef, New South Wales. *Alcheringa* **33**, 331-337.

Keith, D.A. (2004). Ocean shores to desert dunes: the native vegetation of New South Wales and the ACT. New South Wales Department of Environment and Conservation, Hurstville.

Keith, D.A. and Simpson, C.C. (2010). Vegetation Formations of New South Wales (version 3.0). A seamless map for modelling fire spread and behaviour. Final Report to the Rural Fire Service. New South Wales Department of Environment and Climate Change, Hurstville. https://datasets.seed.nsw.gov.au/dataset/vegetation-classes-of-nsw-version-3-03-200m-raster-david-a-keith-and-christopher-c-simpc0917

Kirshner, D.S. (2016). Notes on nesting behaviours of heath monitors (*Varanus rosenbergi*) Mertens 1957, in the Sydney region. *Proceedings of the Interdisciplinary World Conference on Monitor Lizards. Pranakhon Rajabhat University, Bangkok,* 105-121.

Kotze, G.P. (2007). An assessment of rockfall frequency for the coastal cliff lines of Pittwater local government area, Sydney. *Australian Geomechanics* **42**, 213–219.

Kremer, A., Ronce, O., Robledo-Arnuncio, J.J., Guillaume, F., Bohrer, G., Nathan, R., Bridle, J.R., Gomulkiewicz, R., Klein, E.K., Ritland, K., Kuparinen, A., Gerber, S. and Schueler, S. (2012). Long-distance gene flow and adaptation of forest trees to rapid climate change. *Ecology Letters* **15**, 378–392.

Krumbein, W.C. and Sloss, L.L. (1963). 'Stratigraphy and sedimentation.' W.H. Freeman and Co., San Francisco.

Kurszlaukis, S. and Fulop, A. (2013). Factors controlling the internal facies architecture of maar-diatreme volcanoes. *Bulletin of Volcanology* **75**, 761-773.

Lambert, D. (2007). 'Introduction to Rock Art Conservation.' Cultural Heritage Division, New South Wales Department of Environment and Climate Change, Sydney.

Lambert, D. and Welsh, B. (2011) Fire and Rock Art. *Rock Art Research* **28**, 45-48.

Lamont, B.B. (2003). Structure, ecology, and physiology of root clusters – a review. *Plant and Soil* **248**, 1–19.

Lamy, D.L. and Junor, R.S. (1965a). An erosion survey in the Ku-ring-gai Chase and adjoining catchment. Part 1. Survey of the Cowan water and Cockle Creek catchments. *Journal of the Soil Conservation Service of New South Wales* **21**, 94-110.

Lamy, D.L. and Junor, R.S. (1965b). An erosion survey in the Ku-ring-gai Chase and adjoining catchment. Part 2. Survey of the western catchments of Cowan Creek. *Journal of the Soil Conservation Service of New South Wales* **21**, 159-174.

Leeper, G.W. (1943). The classification and nomenclature of soils. *Australian Journal of Science* **6**, 48-51.

Leeper, G.W. (1954). The classification of soils - an Australian approach. *Transactions of the 5th International Congress on Soil Science, Leopoldville* **4**, 217-226.

Leishman, M.R. (1990). Suburban Development and Resultant Changes in the Phosphorus Status of Soils in the Area of Ku-ring-gai, Sydney. *Proceedings of the Linnean Society of New South Wales* **112**, 15-25.

Little, I.P. and Storrier, R.R. (1954). A soil survey of the Municipality of Ku-ring-gai. *New South Wales Department of Agriculture Bulletin* **1**.

Lorenz, V. (1973). On the formation of maars. *Bulletin volcanologique* **73**, 183-204.
Lorenz, V., (1975). Formation of phreatomagmatic maar-diatreme volcanoes and its relevance to kimberlite diatremes. *Physics and Chemistry of the Earth* **9**, 17-27. L.H. Ahrens, J.B. Dawson, A.R. Duncan and A.J. Erlank (Eds). Pergamon Press, Oxford, and New York.
Lunney, D., Hutchings, P. and Hochuli, D. (2010). 'The natural history of Sydney.' Royal Zoological Society of New South Wales, Mosman.
Marder, J., Withers, P. and Philpot, R.G. (2003). Patterns of cutaneous water evaporation by Australian pigeons. *Israel Journal of Zoology* **49**, 111-129.
Mathews, R.H. (1897). Rock Carvings and Paintings of the Australian Aborigines. *Proceedings of the American Philosophical Society* **36**, 466-478.
Mackay, R. (2016). Heritage: Climate change. Australia state of the environment 2016, Australian Government. Department of the Environment and Energy, Canberra.
Martyn, J.E. (2018).' Rocks and Trees: A photographic journey through the rich and varied geology, scenery, and flora of the Sydney region.' STEP Inc., Turramurra, 311 pp.
McCarthy, F.D. (1959). Rock engravings of the Sydney-Hawkesbury District (Part 2): some important ritual groups in the County of Cumberland. *Records of the Australian Museum* **24**, 203-215.
McDonald, J. (1992). The Archaeology of the Angophora Reserve Rock Shelter (or helping the Police with their enquiries). *Environmental Heritage Monograph Series* **1**. New South Wales National Parks and Wildlife Service, Sydney.
McDonald, J.J. (2005). Salvage excavation of Human Remains at Ocean and Octavia Streets. Narrabeen. https://www.aacai.com.au/product/salvage-excavation-of-human-skeletal-remains-at-ocean-and-octavia-streets-narrabeen-2008-01-01/
McDonald, J.J. (2008). Dreamtime superhighway: an analysis of Sydney Basin rock art and prehistoric information exchange. *Terra Australis* **27**. ANU E Press.
McDonald, J. and Clayton, L. (2016). Rock Art Thematic Study. Report to the Department of the Environment and the Australian Heritage Council. Centre for Rock Art Research and Management, University of Western Australia. https://www.awe.gov.au/parks-heritage/heritage/ahc/publications/rock-art-thematic-study
McDonald, J.J., Donlon, D., Field, J.H., Fullagar, R.L.K., Brenner-Coltrain, J., Mitchell, P.B. and Rawson, M (2007). The first archaeological evidence for death by spearing in Australia. *Antiquity* **81**, 887-885.
McKenzie, N., Isbell, R., Brown, K. and Brown, D. (2004). 'Australian soils and landscapes: an illustrated compendium.' CSIRO Publishing.
Menkhorst, P. and Knight, F. (2001). 'A Field Guide to the Mammals of Australia.' Oxford University Press, Melbourne.
Metcalfe, J., Crowley, J.L., Nicoll, R.S. and Schmitz, M. (2015). High-precision U-Pb CA-TIMS calibration of Middle Permian to Lower Triassic sequences, mass extinction and extreme climate-change in eastern Australian Gondwana. *Gondwana Research* **28**, 61–81.
Mitchell, P.B. (1975). The Muogamarra diatremes: An integrated study of the physical environment. BA Honours thesis. Macquarie University.
Mitchell, P.B. (1988). The influence of vegetation, animals, and micro-organisms on soil processes. (Ed. H.A. Viles) 'Biogeomorphology,' 43-82.
Mitchell, P.B. and Humphreys, G.S. (1987). Litter dams and microterraces formed on hillslopes subject to rain wash in the Sydney Basin, Australia. *Geoderma* **39**, 331-357.
Morgan, R. (1974). Triassic microfloras from the clastic dyke of St. Michaels Cave, Avalon, Sydney Basin. *Geological Survey of New South Wales, Report* **GS 1974/362**, 2 pp.
Morgan, R. (1976). Palynological age determinations on material from the Hornsby volcanic breccia. *Geological Survey of New South Wales, Report* **GS 1976/378**, 3 pp.
Morgan, R. (1977). Six palynological determinations from the Hornsby and Erskine Park volcanic necks. *Geological Survey of New South Wales, Report* **GS 1977/007**, 2 pp.
Morgan, R. (1978). Jurassic and Triassic microfloras from some volcanic necks in the Sydney Basin. *Geological Survey of New South Wales, Report* **GS 1978/115**, 3 pp.
Morrison, M. (1904). Notes on some of the dykes and volcanic necks of the Sydney district. *Records of the Geological Survey of New South Wales* **7,** 241-281.
Murphy, C.L., Macleod, A.P., Chapman, G.A., Milford, H.B., McGaw, A.J.E., Edye, J.A. and Simons, N.A. (2022). New South Wales state soil landscape mapping program and derivative products. http://www.regional.org.au/au/gia/21/681murphy.htm
Murray, N.J., Marra, P.P., Fuller, R.A., Clemens, R.S., Dhanjal-Adams, K., Gosbell, K.B., Hassell, C.J., Iwamura, T., Melville, D., Minton, C.D.T., Riegen, A.C., Rogers, D.I., Woehler, E.J. and Studds, C.E.

(2018). The large-scale drivers of population decline in a long-distance migratory shorebird. *Ecography (Copenhagen)* **41**, 867–876.

Nashar, B. (1967). 'Geology of the Sydney Basin.' Jacaranda Press: Brisbane.

Norman, A.R. (1986). A structural analysis of the southern Hornsby Plateau, Sydney Basin, New South Wales. MSc thesis, University of Sydney, 308 pp.

Norman, J.A., Christidis, L. and Schodde, R. (2018) Ecological and evolutionary diversification in the Australo-Papuan scrubwrens (*Sericornis*) and mouse-warblers (*Crateroscelis*), with a revision of the subfamily *Sericornithi*nae (Aves: Passeriformes: Acanthizidae). *Organisms Diversity and Evolution* **18**, 241–259.

Northcote, K.H. (1960). A factual key for the recognition of Australian soils. CSIRO Australia, Division of Soils, *Divisional Report* **4,** 60.

Northcote, K.H. (1979). 'A Factual Key for the Recognition of Australian Soils.' Rellim Technical Publications, Glenside, South Australia. 4th Edn.

Northern Beaches Council (2022). Understanding the Collaroy seawall challenge. https://www.northernbeaches.nsw.gov.au/council/news/understanding-collaroy-seawall-challenge

NPWS (2003). Draft Recovery Plan for the Bush Stone-curlew *Burhinus grallarius*. https://www.environment.nsw.gov.au/-/media/OEH/Corporate-Site/Documents/Animals-and-plants/Recovery-plans/bush-stone-curlew-burhinus-grallarius-recovery-plan-050301.pdf

NSW Government (1979). Coastal Protection Act. https://legislation.nsw.gov.au/view/html/inforce/2015-06-04/act-1979-013#statusinformation

NSW SEED (2022). The Central Resource for Sharing and Enabling Environmental Data in New South Wales. Sydney. https://live.seed.nsw.gov.au/about-seed

Och, D., Offler, R., Zwingmann, H., Braybrooke, J. and Graham, I. (2009). Timing of brittle faulting and thermal events, Sydney region: Association with the early stages of extension of East Gondwana. *Australian Journal of Earth Sciences* **56**, 873-887.

OEH (2012). Guide to completing the AHIMS Site Recording Form. New South Wales Office of Environment and Heritage, Sydney. https://www.environment.nsw.gov.au/research-and-publications/publications-search/guide-to-completing-the-ahims-site-recording-form

OEH (2013). The Native Vegetation of the Sydney Metropolitan Area. Volume **1**: Technical Report. Version .0. Office of Environment and Heritage, New South Wales Department of Premier and Cabinet. https://www.environment.nsw.gov.au/surveys/VegetationSydMetro.htm

OEH (2017). Glossary of Terms used in Soil and Landscape Science. New South Wales Office of Environment and Heritage. https://www.environment.nsw.gov.au/-/media/OEH/Corporate-Site/Documents/Land-and-soil/soil-landscape-science-glossary-terms-170525.pdf

OEH (2017). Statement of Management Intent: Mount Ku-ring-Gai Aboriginal Area. New South Wales Office of Environment and Heritage. Sydney. https://www.environment.nsw.gov.au/research-and-publications/publications-search/mount-kuring-gai-aboriginal-area-statement-of-management-intent

Olsen, K. and Dowling, R. (2018). Geotourism and Cultural Heritage. *Geoconservation* **1**, 37-41.

Osborne, G.D. (1948). Note on the occurrence of tridymite in metamorphosed Hawkesbury Sandstone at Bundeena and West Pymble, Sydney District. *Journal and Proceedings of the Royal Society of New South Wales* **82**, 309–311.

Pate, J.S., Verboom, W.H. and Galloway P.D. (2001). Co-occurrence of Proteaceae, laterite and related oligotrophic soils: coincidental associations or causative inter-relationships? *Australian Journal of Botany* **49**, 529–560.

Paton, T.R. (1978). 'The formation of soil material.' Allen and Unwin, London.

Paton, T.R., Humphreys, G.S. and Mitchell, P.B. (1995). 'Soils. A new global view.' Yale University Press.

Paton, T.R. and Williams M.A.J. (1972). The concept of laterite. *Annals of the Association of American Geographers* **62**, 42-56.

Penman, T.D., Lemckert, F.L. and Mahony, M.J. (2008) Spatial ecology of the giant burrowing frog (*Heleioporus australiacus*): implications for conservation prescriptions. *Australian Journal of Zoology* **56**, 179–186.

Percival, I.G. (1979). The geological heritage of New South Wales. A report prepared for the Australian Heritage Commission and the Planning and Environment Commission of New South Wales, July 1979. *Geological Survey of New South Wales, Report* **GS 1979/420**, 153-156.

Percival, I.G. (1985). 'The geological heritage of New South Wales, Volume 1.' New South Wales National Parks and Wildlife Service, Sydney.

Pitt, R.P.B. (1968). Petrological Study of Kurrajong Heights (A.O.G./Exoil) No.1 Well, Sydney Basin, New South Wales. *Bureau of Mineral Resources Geology and Geophysics,* **Record No. 1968/81**, 31.

Pittwater Online News (2017). Avalon Beach North Headland Indian Face 'Falls': An Everchanging Coastline. https://www.pittwateronlinenews.com/Avalon-Beach-North-Headland-Indian-Face-Falls-2017.php

Pittwater Online News (2020). Cromer Heights Rock Engravings and Shelter Officially Declared a Significant and Important Aboriginal Place. January 26 - February 1, 2020: Issue 435. https://www.pittwateronlinenews.com/Cromer-Indigenous-Sacred-Site-Formal-Listing-2020.php

Pittwaterpathways (2022). Headland series. https://www.youtube.com/user/pittwaterpathways/playlists

Pittwaterpathways (May 2022). Complex cliff failure at Long Reef. https://www.youtube.com/watch?v=E4WTq18ZQoc

Preen, A. and Marsh, H. (1995). Response of dugongs to large-scale loss of seagrass from Hervey Bay, Queensland, Australia. *Wildlife Research* **22**, 507-519.

Prescott, J.A. (1931). The soils of Australia in relation to vegetation and climate. *Council for Scientific and Industrial Research Bulletin* **52**.

Prescott, J.A. (1944). A soil map of Australia. *Council for Scientific and Industrial Research Bulletin* **177.**

Retallack, G.J. (1980). Late Carboniferous to Middle Triassic megafossil floras. Herbert, in C. and Helby, R. (Eds.), A Guide to the Sydney Basin. *Geological Survey of New South Wales Bulletin* **26**, 383-430.

Retallack, G.J. (1999). Postapocalyptic greenhouse paleoclimate revealed by earliest Triassic paleosols in the Sydney Basin, Australia. *Geological Society of America Bulletin* **111**, 52–70.

Rickwood, P.C. (1985). Igneous intrusives in the greater Sydney area. Engineering geology of the Sydney region. (Ed P.J.N. Pells), 215-307. (A.A. Balkema: Rotterdam).

Ridges, M. (2010). Aboriginal Sites Decision Support Tool (ASDST). Statewide product outline and technical summary. Department of Environment, Climate Change and Water NSW, Sydney.

Riley, J., Stimson, A.F. and Winch, J.M. (1985). A review of squamata ovipositing in ant and termite nests. *Herpetological Review* **16**, 38-43.

Rix, M.G., Edwards, D.L, Byrne, M., Harvey, M.S., Joseph, L. and Roberts, J.D. (2015). Biogeography and speciation of terrestrial fauna in the south-western Australian biodiversity hotspot. *Biological Reviews of the Cambridge Philosophical Society* **90**, 762–793.

Roberts, J.D. and Edwards, D. (2018). The Evolution, Physiology and Ecology of the Australian Arid-Zone Frog Fauna. Lambers, H. (eds) 'On the Ecology of Australia's Arid Zone'. Springer, Cham. https://link.springer.com/chapter/10.1007/978-3-319-93943-8_7

Robinson, A.M. (2022). The History of Geopark Development in Australia, A New Way Forward. *Geoconservation Research* **5**, 89-107.

Robinson, A.M. and Percival I.G. (2011). Geotourism, Geodiversity and Geoheritage in Australia – Current Challenges and Future Opportunities. *Proceedings of the Linnean Society of New South Wales* **132**, 1-4.

Roy, P.S. (1983). Cliff erosion rates in the South Sydney region, Central New South Wales coast. *Quarterly Notes Geological Survey of New South Wales* **50**, 8-11.

Runnegar, B. (1980). Biostratigraphy of the Shoalhaven Group. Herbert, C. and Helby, R. (Eds.), A Guide to the Sydney Basin. *Geological Survey of New South Wales Bulletin* **26**, 375-382.

Sawkins, D., Verboom, W.H. and Pate, J.S. (2011). Native vegetation in Western Australia is actively involved with soil formation. *Department of Primary Industries and Regional Development, Western Australia, Digital Bulletin* **4823**.

Short, A.D. and Woodroffe, C.D. (2009). 'The coast of Australia.' Cambridge Univ. Press

Sim, I.M. (1965). Records of the Rock Engravings of the Sydney District: Nos. 138-145. *Mankind* **6** (6), 275-287.

Simpson, C. (2002). Wyatt, Annie Forsyth (1885–1961). Australian Dictionary of Biography, National Centre of Biography, Australian National University.

Smith, P. and Smith, J. (1990). Decline of the urban Koala (*Phascolarctos cinereus*) population in Warringah Shire, Sydney. *Australian Zoologist* **26**, 109-129.

Smith, P. and Smith, J. (2000). Management Plan for threatened fauna and flora in Pittwater. Report to Pittwater Council. P. and J. Smith Ecological Consultants, Blaxland. https://www.researchgate.net/publication/341099324_Management_Plan_for_Threatened_Fauna_and_Flora_in_Pittwater_report_to_Pittwater_Council

Stace, H.C.T., Hubble, G.D., Brewer, R., Northcote, K.H., Sleeman, J.R., Mulcahy, M.J. and Hallsworth, E.G. (1968). 'A Handbook of Australian Soils.' Rellim Technical Publications: Glenside, S.A.

Standard, J.C. (1969). The Sydney Basin - Hawkesbury Sandstone. The Geology of New South Wales. (ed. G.H. Packham). *Journal of the Geological Society of Australia* **16**, 407-415.

Stephens, C.G. (1962). 'A Manual of Australian Soils.' CSIRO, Melbourne.

Storey, K.B. and Storey, J M. (2012). Aestivation: signaling and hypometabolism. *Journal of Experimental Biology* **215**, 1,425-1,433.

Strahler, A.N. (1957). Quantitative analysis of watershed geomorphology. *Transactions of the American Geophysical Union* **38**, 913-920.

Sutherland, F.L. (1995). 'The volcanic Earth.' University of New South Wales Press, Sydney.

Taylor, G.H. (1976). The process of breccia emplacement. Adamson, C.L. and Taylor, G.H. Hornsby, and Peats Ridge aggregate quarries. *25th International Geological Congress Guidebook, Excursion* **14B**, 10-12.

Thomas, J. and Benson, D.H. (1985). Vegetation survey of Ku-ring-gai Chase National Park. Unpublished, National Herbarium of New South Wales.

Thompson, C.H. and Paton, T.R. (1980). Texture differentiation in soils on hillslopes of southeastern Queensland. *CSIRO Division of Soils Report* **53**.

Thomson, V.P. and Leishman, M.R. (2004). Survival of native plants of Hawkesbury Sandstone communities with additional nutrients: effect of plant age and habitat. *Australian Journal of Botany* **52**, 141–147.

Thumm, K. and Mahony, M.J. (2002). Evidence for continuous iteroparity in a temperate-zone frog, the red-crowned toadlet (*Pseudophryne australis*) (Anura: Myobatrachidae). *Australian Journal of Zoology* **50**, 151-167.

Trueman, A.E. (1938). 'Geology and Scenery in England and Wales.' Pelican Books.

Tulau, M.J. (2015). 'Fire and Soils. A review of the potential impacts of different fire regimes on soil erosion and sedimentation, nutrient and carbon cycling, and impacts on water quality and quantity.' NSW Office of Environment and Heritage 2016.

Tulloch, A.I. and Dickman, C.R., (2006). Floristic and structural components of habitat use by the eastern pygmy-possum (*Cercartetus nanus*) in burnt and unburnt habitats. *Wildlife Research* **33**, 627–637. doi: 10.1071/WR06057.

Tyler, M.J. (1994). 'Australian Frogs. A Natural History.' Reed Books, Sydney.

Ultsch G.R. (1989). Ecology and physiology of hibernation and overwintering among freshwater fishes, turtles, and snakes. *Biological Reviews* **64**, 435–515.

UNESCO Global Geoparks (2022). https://en.unesco.org/global-geoparks/how-to-become-geopark

Unger, C., Mitchell, P. and Nisbett, H. (1996). A new approach to soil survey applied to a mining feasibility study in the wet-dry tropics. *Australian Journal of Soil and Water Conservation* **9**, 16-21.

USDA (2014). 'Keys to Soil Taxonomy.' 12th edn. USDA-Natural Resources Conservation Service, Washington DC.

Veevers, J.J., Belousova, E.A., Saeed, A., Sircombe, K., Cooper, A.F. and Read, S.E. (2006). Pan-Gondwanaland detrital zircons from Australia analysed for Hf-isotopes and trace elements reflect an ice-covered Antarctic provenance of 700–500 Ma, TDM of 2.0–1.0 Ga, and alkaline affinity. *Earth-Science Reviews* **76**, 135–174.

Veneklaas, E.J., Lambers, H. and Cawthray, G. (2005). Root exudates of *Banksia* species from different habitats – a genus-wide comparison. http://aff.org.au/results/grant-summaries/aff-lambers-banksia/

Verboom, W.H. and Pate, J.S. (2006). Bioengineering of soil profiles in semiarid ecosystems: the 'phytotarium' concept, a review. *Plant and Soil* **289**, 71–102.

Wade, R.T. (1935). 'Triassic Fishes of Brookvale New South Wales'. British Museum of Natural History, London, 89 pp.

Walker, P.H. (1960). A soil survey of the County of Cumberland, Sydney region. *New South Wales Department of Agriculture. Soil Survey Unit, Bulletin* **2**.

Walker P.H. (1962). Terrace chronology and soil formation on the south coast of New South Wales. *Journal of Soil Science* **13**, 178-186.

Water Research Laboratory, UNSW 2016. https://www.wrl.unsw.edu.au/video/drone-survey-of-catastrophic-cliff-failure-at-north-head

Webb, J. (2004). 'Eccleston Du Faur, Man of Vision'. Deerubbin Press, Berowra Heights.

White, J.D.L. and Ross, P.-S. (2011). Maar-diatreme volcanoes: A review. *Journal of Volcanology and Geothermal Research* **201**, 1-29.

Whitehouse, J. (2016). Beacon Hill Shale Quarry Sydney, New South Wales. Geologic insights into its strikingly preserved Triassic fossil assemblage, 26 pp (unpubl.). https://www.academia.edu/24223101/Beacon_Hill_shale_quarry_Sydney_New_South_Wales_Australia_Geologic_insights_into_its_strikingly_preserved_Triassic_fossil_assemblage

Wilshire, H.G. (1961). Layered diatremes near Sydney, New South Wales. *Journal of Geology* **69**, 473-484.

Wilshire, H.G. and Binns, R.A. (1961). Basic and ultrabasic xenoliths from volcanic rocks of New South Wales. *Journal of Petrology* **2**, 185-208.

Wilson, S.K. and Swan, G. (2021). 'A complete guide to reptiles of Australia.' 6th edition. Scoresby, Victoria.

Woolnough, W.G. (1927). Presidential address. Pt 1. Chemical criteria of peneplanation. Pt II. The duricrust of Australia. *Journal and Proceedings of the Royal Society of New South Wales* **61**, 17-53.

World Reference Base (2015). World reference base for soil resources – international soil classification system for naming soils and creating legends for soil maps. IUSS Working Group WRB. *World Soil Resources Reports* **106**. FAO, Rome.