PERGAMON

Quaternary International 103 (2003) 41–55

The shaping of Sydney by its urban geology

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Abstract

Sydney's surface geology of Hawkesbury Sandstone capped with Wianamatta Shale has produced poor soils but good building material. The topography, derived from the subaerial erosion and extensive dissection of the Permian/Triassic sedimentary strata of the Sydney Basin, has been the strongest constraint on the city's growth. Steep-sided valleys carved out of sandstone plateaux forced the direction of settlement along the flatter interfluves, and in recent decades out onto the tectonic depression of the Cumberland Plain to the west. Holocene marine transgression flooded the eastern incisions of the eroded mass, producing some of the few safe anchorages on the southeast Australian coast, as well as bedrock-controlled zeta-curved coastal beaches. Some of the geological disadvantages have turned into advantages over time. The sterility of the skeletal sandstone soils made farming difficult, but has allowed much of the native vegetation to be retained for conservation and recreation. Coastal quartz sand deposits produced equally infertile soils but provided pure sand fill for Sydney's many attractive beaches, along with industrial uses. The depth of underlying coal deposits discouraged early mining within the city boundaries, to the ultimate benefit of residential development, while tectonic stability reduced complications for infrastructure engineering works.

1. Introduction

Geological influence on the development of Sydney is centred on the distribution and uses of the two dominant sets of Permian/Triassic surface rocks (Figs. 1 and 2), the shales of the Wianamatta Group and the sandstones of the Hawkesbury and Narrabeen Groups (Scheibner, 1996; Fig. 3), with some input from the relatively small local accumulations of Quaternary sediments (Roy, 1983, 1994; Fig. 4). Tertiary sediments are insignificant (Herbert, 1983). The products of Mesozoic volcanism in the form of a scattering of small dykes and diatremes are also limited, but of more importance.

2. Extent of Sydney

Sydney at present occupies the peninsulas between Port Hacking and Broken Bay and their hinterlands, and a growing portion of the Cumberland Plain (Fig. 2). The bays, harbours and estuaries around which the original city was built give Sydney its distinctive character. However, beyond coastal and estuarine Sydney, new development has spread into the basin of the Cumberland Plain to the west (Figs. 4–6), where over half the population now live. The radial arms of Greater Sydney reach out 50 km to the foot of the escarpment that marks the edge of the Blue Mountains, the uplifted western segment of the Sydney Basin.

The CBD and older parts of the city lie on a low plateau on the central part of the basin's edge, bordered by rugged and barren sandstone plateaux to north, south and, eventually, the west, with sea to the east (Figs. 1 and 2). These plateaux surround the lowlands of the Sydney Basin, the Cumberland Plain (Figs. 3 and 6). Geology has been a strong influence in channelling the city's growth westward, away from the constriction of the dissected sandstone landscape, and towards flat, accessible land. Parramatta, once a separate and rival town, is now at the demographic centre of Greater Sydney. The one other possible direction for residential expansion would involve the conversion of some of the Botany Basin lowlands (Fig. 4) from their present use by the petro-chemical industry and transport nodes.

3. History of settlement and future development

The deepwater access of Port Jackson attracted the first colonial settlement in 1788. However, the skeletal

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PII: S1040-6182(02)00140-4

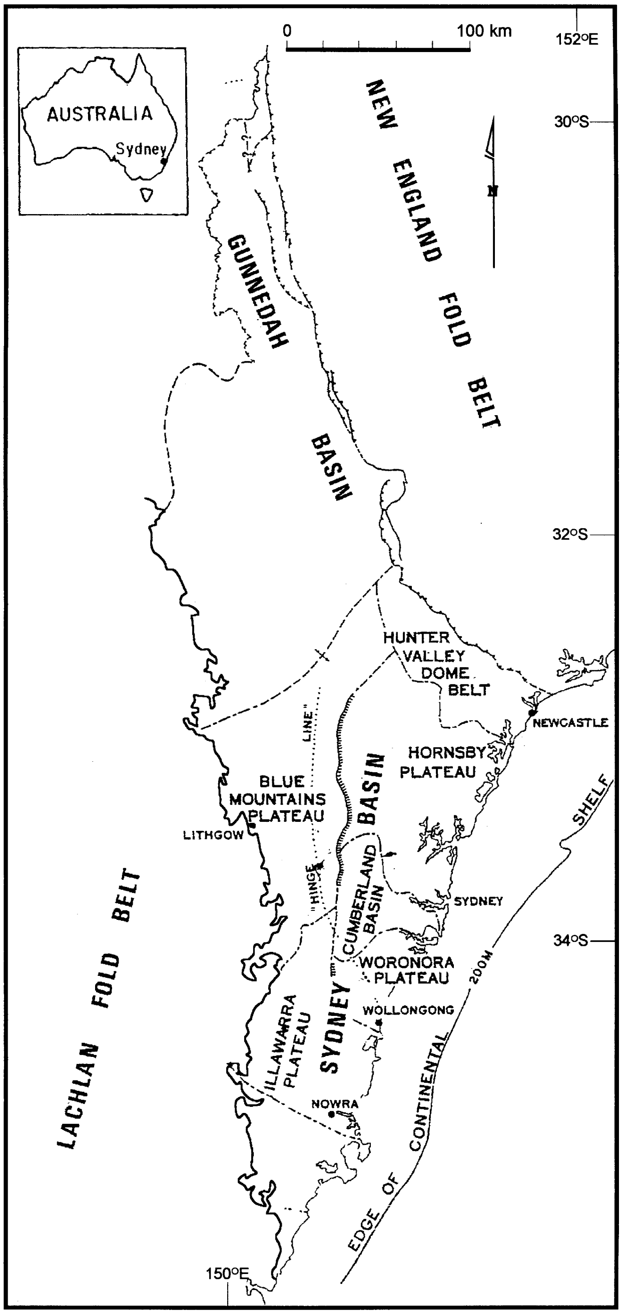


Fig. 1. Southern arm of the Sydney–Gunnedah–Bowen Basin, showing the relationship of the surrounding plateaux to the central lowland of the Cumberland Basin.

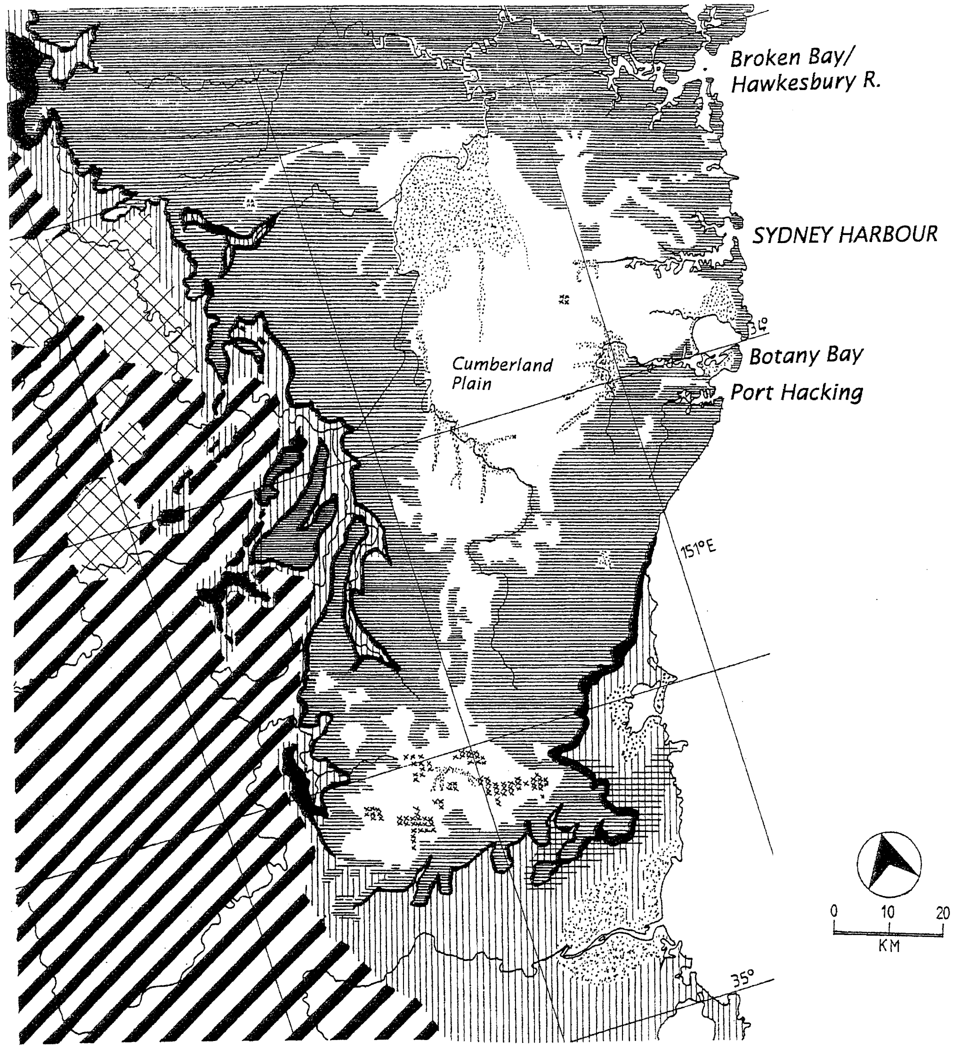
sandy soils around the original anchorage at Sydney Cove were so poor (despite the presence of clear water running from a hanging swamp in the capping shale) that the first occupants were driven within a year to settle the head of the marine inlet 20 km upstream at Parramatta (Fig. 7), where the shale and alluvium provided marginally better soils.

The "altogether barren, peculiarly romantic landscape" (Young and Young, 1988) of the sandstone country nonetheless has a species-rich and dense cover of vegetation (hence the naming of "Botany Bay" by Cook and Banks in 1770; Parkinson, 1773). Annual rainfall is high (~1100 mm) but variable, and the climate humid subtropical maritime (Cfa) in Koppen's classification (Sturman and Tapper, 1996).

Despite its beginning as a penal settlement, Sydney quickly grew as a trading base for the South Seas and a transit port for inland resources. Its 19th century prosperity and democracy promoted the growth of extensive low-density suburbs that sprawled along the radial transport routes. These followed the shale interfluves and level surfaces of the plateau land to the south and west of Sydney Cove (Stretton, 1989). Industry crowded around the harbour at first, but then expanded out to the flat swampy land around Botany Bay and the upper Parramatta River.

Industry, transport, housing, recreation and commerce have all competed for the small stock of accessible level land. The constraints have been accentuated by a change in the city's nature and function from the raw industrial/trading outpost of the past to an increasingly important financial and services centre. Population increased steadily but not dramatically from under one million in 1901 to two million by 1950, and reached almost four million (3,997,321) in the just-released 2001 Census results (Australian Bureau of Statistics, 2002: http://www.abs.gov.au). Of the present four million people, 31% were overseas-born, compared to a national average of 20%. The four-fold increase in population over a century has been accommodated by a disproportionately large 20-fold increase in built-up area, from ca. 80 km^2 in 1901 to ca. 1600 km^2 in 2001. This spatial expansion has been largely driven by a persistent preference of families for owner-occupied free-standing bungalows with a surrounding garden, despite the equally persistent disapproval of many urban planners (Stretton, 1989; Forster, 1995). Expansion over the last 50 years has encouraged the development of multiple major subcentres or hubs of retail and industry, described by Forster (1995) as a complex set of overlapping "labour sheds", while the pre-existing labour shed of the old CBD has still managed to retain much of its overall dominance. A current government-supported urban consolidation drive has only partially checked the rate of suburban sprawl: families continue to prefer generous open space in which to raise children, while a reverse migration of singles and smaller households has repopulated the inner city. Contrary to official expectations, even migrant families from high-density Asian cities tend to move outwards to enjoy cottage life as they move up the economic and social ladder. The pattern of a huge, sprawling, car-dependent Sydney seems set, despite the exhortations of social engineers and planners (Forster, 1995).

The new population, dominated by those clustered around finance and services industries, tends to see



GEOLOGY OF THE SYDNEY REGION

Symbol	Geological Period or Era	Age of rocks	Rock type	Significance for settlement
	Tertiary and Quaternary	30 m.y. to the present	Alluvium	Excellent agricultural soils in some places.
	Tertiary	About 30 m.y	Volcanic rocks, mainly basalt	Good soils for agriculture.
	Triassic	About 180 m.y.	Wianamatta series mainly shales	Fair grazing soils. Easy paths where remnants lie over Hawkesbury sandstone in elevated terrain.
	Triassic	About 220 to 200 m.y.	Narrabeen Series and Hawkesbury sandstone. Hard sandstones with small shale layers.	Skeletal soils and deeply incised terrain. Unsuitable for grazing or agriculture
	Permian	about 230 m.y.	Coal measures. Soft shales and coal seams.	Easily eroded causing formation of cliffs in overlying sandstones.
	Permian	About 250 m.y.	Shoalhaven series sandstones and shales and Gerringong volcanics.	Lowest rocks of the Sydney Basin. Fair to good grazing soils
		FLOOR OF SYDNEY BASIN		
	Paleozoic	More than 280 million years	Kanimbla Batholith. Igneous intrusion of granite.	
	Paleozoic	More than 230 million years	Folded strata of the Lachlan Fold Belt. Sedimentary and metamorphic rocks	

Fig. 2. Generalised geology of the Sydney Region, and its significance for settlement and urban expansion. Note how Sydney is almost encircled by a wide zone of barren skeletal soils of the Sandstone units. Cultivation is restricted to the small patches of alluvium, and pasture to the alluvium and shales. Deep dissection of the sandstone plateaux by steep-sided gorges and valleys has always presented a major land communication problem. The belt of dense fire-prone sclerophyllous bushland that covers the rugged sandstone country creates both a major fire hazard and a major recreational asset. The so-called "sandstone curtain" separates Sydney geologically, psychologically and politically from inland agricultural Australia (adapted from Cunningham, 1996, pp. 36–37).

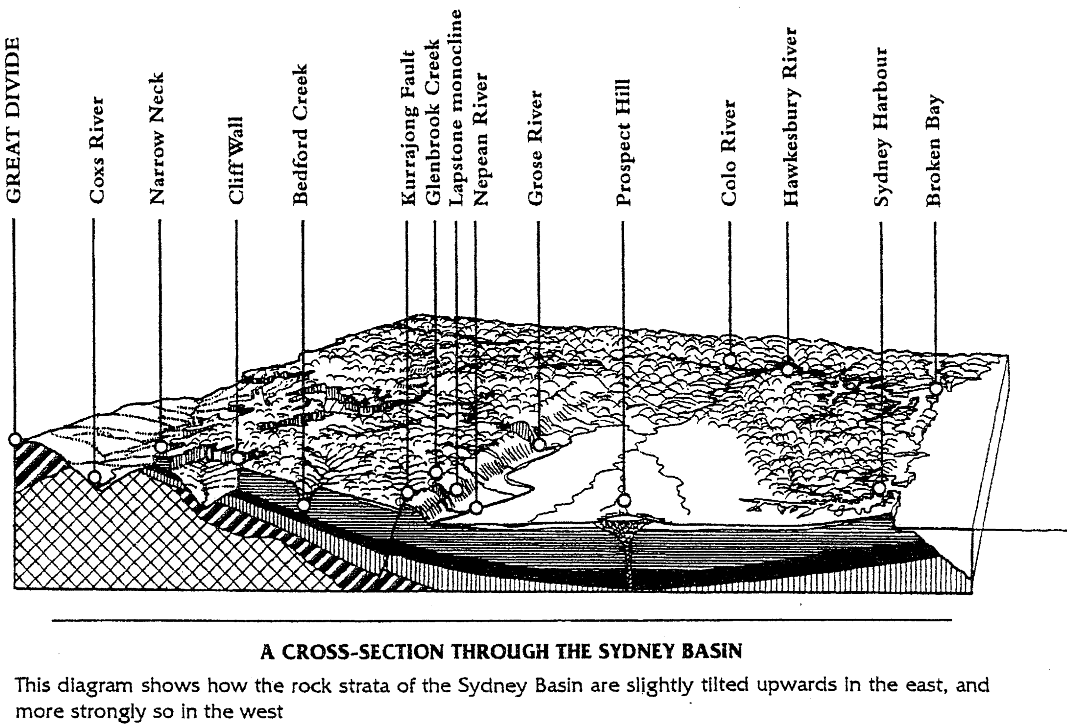


Fig. 3. Cross-section through the Sydney Basin, from west to east. Note how the rock strata of the basin are slightly tilted upwards in the east, and more strongly so in the west, with the escarpment associated with the Lapstone Monocline forming a high barrier. Comparing the diagram with Fig. 2, it can be seen how most of the sediment carried out of the uplands is trapped on the outer edge of the Cumberland Plain, thus keeping the estuaries of these rivers relatively unsilted with deep channels. The continental shelf is less than 50 km wide. (adapted from Cunningham, 1996).

preservation of lifestyle and residential amenity as major imperatives. This has had the result of driving an advance of affluent suburbs into the rugged bush and broken sandstone country, which in turn drives a demand for bigger and more expensive infrastructure development (freeways, bridges, sewerage, etc.) in the most difficult terrain around Sydney, until the western barrier blocks further expansion. This has forced suburban expansion to the southwest corridor of Campbelltown, where a narrow gently sloping ramp leads to the Southern Tablelands and Canberra, hedged in between the broken relief of the Blue Mountains on one side and the Woronora/Illawarra plateau on the east (Fig. 2). The so-called "sandstone curtain" of rugged, essentially uninhabitable country around Sydney served well as the ultimate prison wall in the early days of the colony. It still effectively separates Sydney from the rest of Australia, politically and psychologically as well as physically.

4. Geological development

The Sydney Basin is the southernmost part of the larger Sydney–Gunnedah Basin (Bembrick et al., 1973; Fig. 1), a narrow ~1000 km long structure between the Palaeozoic New England Fold Belt to the north, and the Lachlan Fold Belt to the west and south that extends well into Queensland (Scheibner, 1996; Fig. 1). The Sydney Basin was filled by Permian and Triassic sediments deposited unconformably on a basement of the Lachlan Fold Belt (Leitch, 1974; Figs. 2 and 3). The eastern margin of the Basin terminates at the edge of the continental shelf, where late Cretaceous rifting and the opening of the Tasman Sea (Hayes and Ringis, 1973) initiated the present drainage and erosion pattern.

Sydney Basin strata are relatively undeformed, and may be described as a layer cake of horizontally-bedded sandstones capped with shale, underlain with coal measures and older sandstones, with a scattering of minor volcanic plugs and intrusions outcropping mainly on local erosion fronts. There is an average 2000 m depth of fill (Scheibner, 1996). Across an approximate 200 km × 200 km area that represents the Sydney Basin, the strata have sagged in the middle and inclined gently upwards towards the edges (Fig. 3). The lowest strata are the 300–900 m thick sequences of sandstones and shales of the Shoalhaven series (Herbert and Helby, 1980; Scheibner, 1996). Above the Shoalhaven Series (which are exposed on the outer edges of the Basin; Fig. 2) are the coal bearing strata of the Illawarra and Newcastle series (~300 m thick), and over these in turn are the Narrabeen Series consisting of shales and

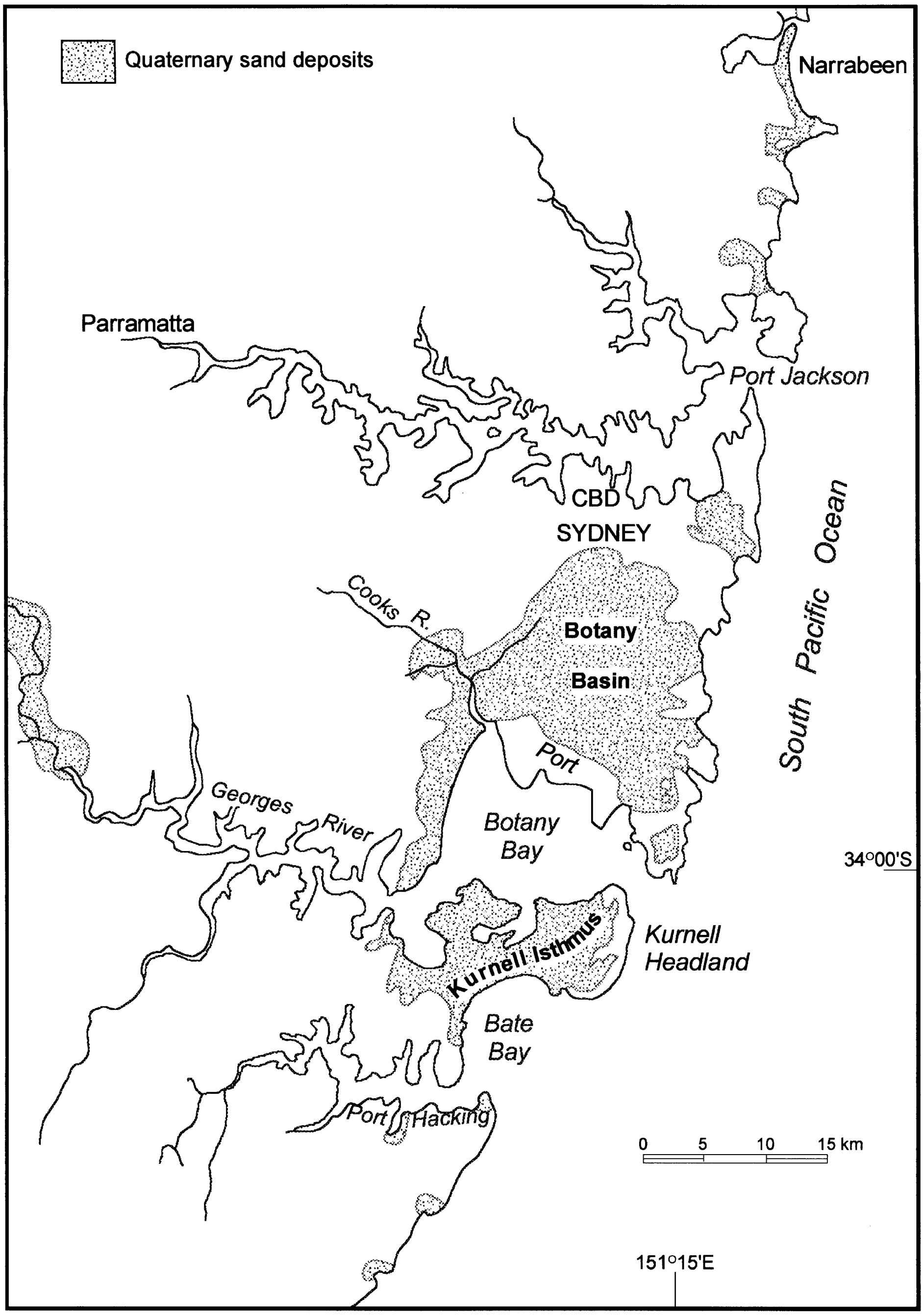


Fig. 4. Main Quaternary sand sediments in the Sydney region. A large proportion of Sydney's industrial infrastructure is concentrated on the flat land of the Botany Basin, where Quaternary sediments are between 10 and 30 m deep. This puts it at risk in the event of a moderate-sized earthquake similar to the nearby 1989 Newcastle earthquake, and suggests some vulnerability to sea-level fluctuations.

massive sandstones (300–500 m in width). Above the Narrabeen Series are the quartz sandstones and minor shales of the Hawkesbury Group, capped by the thinner strata of the Wianamatta Group of dominant shales with some sandstones. These two series are smallest in volume, but being uppermost in the strata they dominate the surface area of the Sydney region (Figs. 2 and 5).

5. Rock types and their importance to Sydney's development

5.1. Hawkesbury Sandstone

Hawkesbury Sandstone dominates Sydney through its outcropping and exposure in cliffs, outcrops and cuttings, although the uppermost Wianamatta Shale strata actually amount to a larger area of the urban

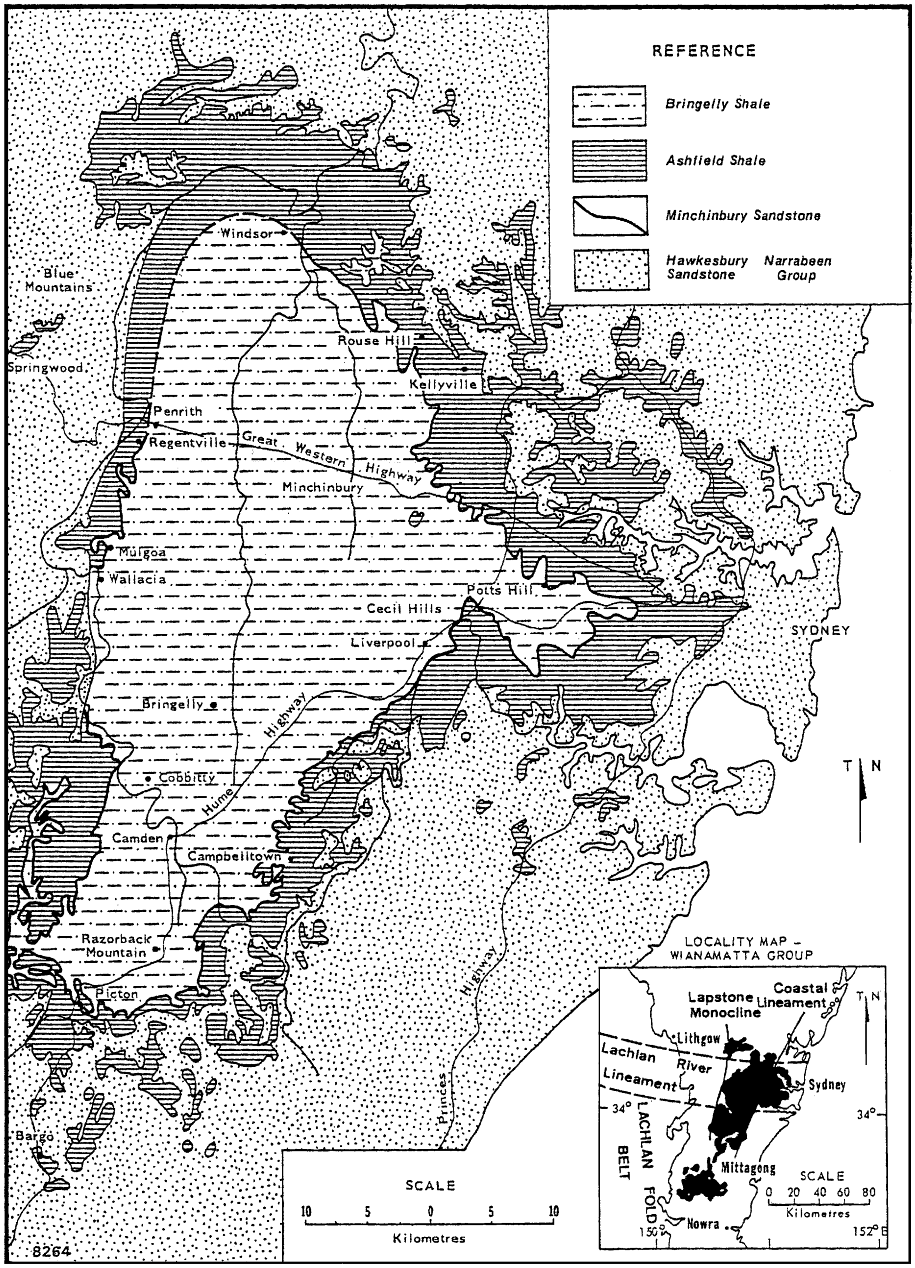


Fig. 5. Relationship of the surface Wianamatta Shales to the Sandstone units. Other minor rock types have been removed for clarity. Note how the residual shales peter out as islands on the high ground on the periphery, but fill the lowland of the Cumberland plain in the centre. Transport routes and suburban development were forced to follow the flat shale country on the ridgelines at first, and avoid the sandstone gullies. In recent years, development has spread over the Cumberland Plain, and up onto the shale corridors of the highlands. Expansion into the dissected sandstone country is fraught with difficulties—Sydney is effectively confined by topography.

surface (Figs. 2 and 5). It is made up of quartz sandstone with minor shale lens and conglomerates. It completely underlies Sydney, thickening to almost 300 m at its northern end at the Hawkesbury River (Fig. 2) (Herbert and Helby, 1980). Iron oxides mobilised by deep weathering have stained much of the stone in yellows and reds. It produces a high-quality, easily accessible, and attractively coloured building stone. High sea cliffs and freeway cuttings provide dramatic and highly coloured stratigraphic cross-bedding displays, and many harbour cliffs have been used as a surface for several thousand years of Aboriginal art. The high detrital quartz grain content produces soils of marked infertility, but it also breaks down to produce coloured sands of fine quality for many purposes.

5.2. *Wianamatta Group shales*

The Middle Triassic Wianamatta Group shales, which are the youngest and therefore the topmost rock

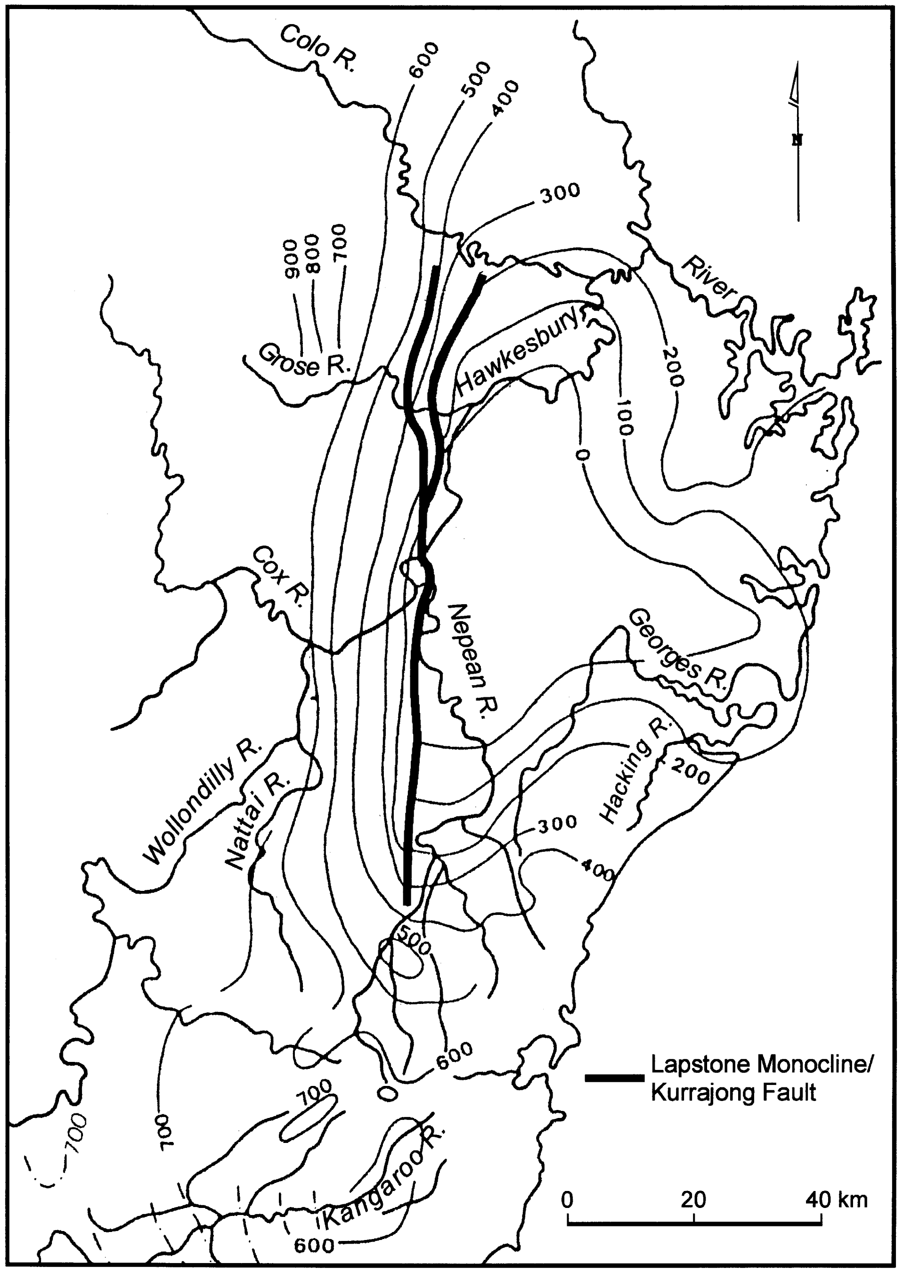


Fig. 6. Structural contours of the Sydney Basin, with Tertiary and Quaternary deposits removed. Note that the depression of the Cumberland Basin forms a natural atmospheric sink, receiving pollution from the eastern city and cold air drainage from the highland to the west (the Blue Mountains).

geologically, occupy both high- and low-lying country (Fig. 4), due to the depression of the Cumberland Basin. They cover the low plateau west of Sydney's central business area, and underlay a large part of the inner western and southern suburbs, as well as capping the ridges of northern Sydney. The shales are associated with level, stable ground readily accessible by transport routes. For this reason they carry the bulk of Sydney's buildings, and their moderately fertile soils supported widespread orchards and grazing in earlier days. The principal surface cover of the Wianamatta Group shales is from Sydney westwards to Penrith (Fig. 5), north to Windsor, and south to Picton, reaching a maximum thickness of 240 m in the south

The Wianamatta Group consist of three formations (Herbert and Helby, 1980; Herbert, 1983) the basal Ashfield Shale, the overlying Minchinbury Sandstone, and the uppermost Bringelly Shale. The Minchinbury Sandstone has only very limited outcrops to the west of Sydney. Bringelly Shale also survives only in ridge-top patches, most of it preserved in the higher country to the northwest of the city. The deep soils produced from this shale once supported an important orchard industry in the northwest suburbs from which, in the

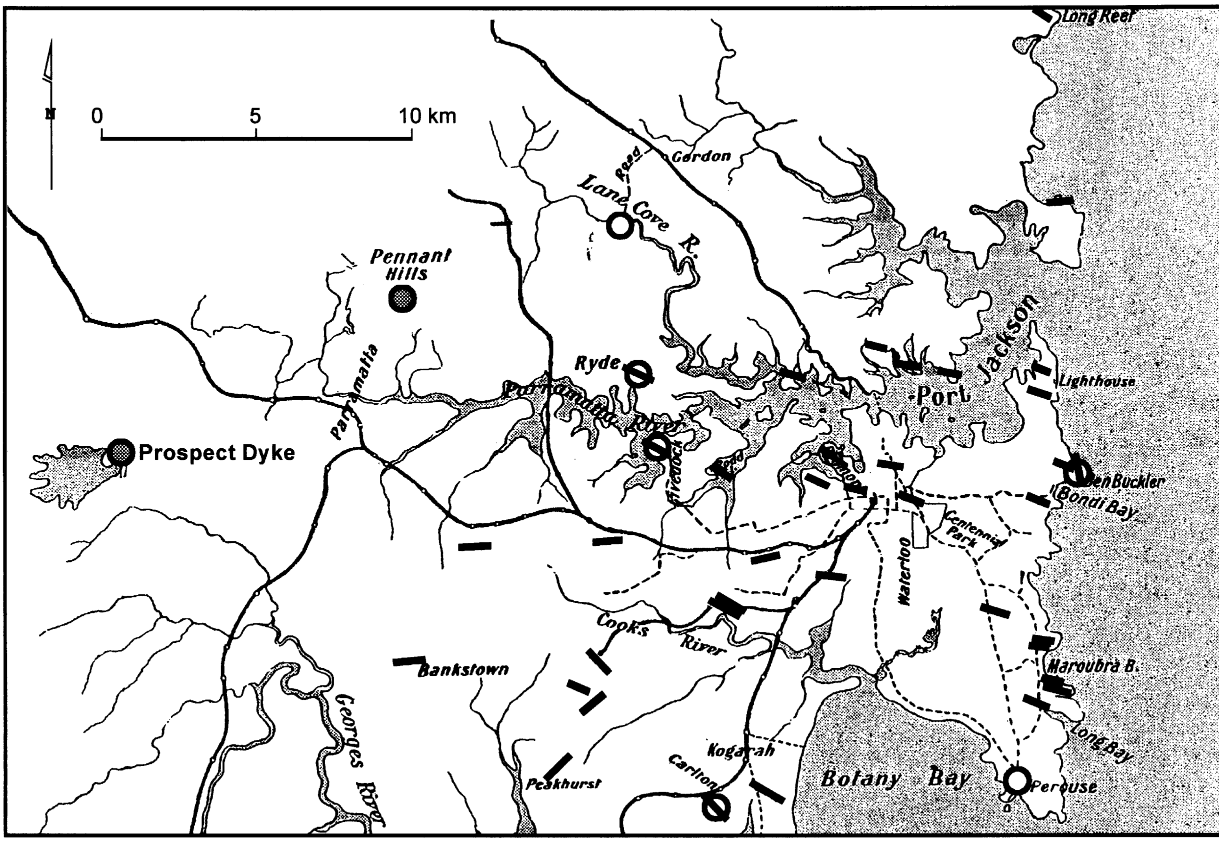


Fig. 7. An 1899 (Curran) chart of volcanic dykes and outcrops around Sydney, many of which have now disappeared under urban development.

19th century, the Granny Smith apple originated. It was also the focus of an influential nursery and gardening culture that became central to the lifestyle of a 20th century suburban Sydney based on detached houses on spacious blocks. Produce from home gardens was very important part of the informal economy from 1788 up to and after 1945, and established the particular characteristics of Australian suburbia. In contrast to much of American suburbia, this included formidable paling (wooden slat) fencing, which existed partly to protect valuable vegetable and fruit crops from pilfering, but possibly more to keep official eyes away from unofficial and unregulated backyard production of various kinds. While those blocks remained on shale soils they could emulate old world styles of gardening: when suburban dwellers moved onto the more barren but species-rich sandstone after the 1950s, and prosperity made them less dependent on garden produce, they began a widespread movement to domesticate the native flora as garden cultivars (Haworth, 1995).

The Ashfield Shale, the most extensive in the Sydney urban area, weathers to a brightly coloured clay from which was produced the red brick and tiles of the bungalows of the older suburbs. From its inception much of Sydney became a town of sandstone and brick, in contrast to most other European colonial settlements of this period.

The base of the shales extends below sea level in the subdued watershed separating the three main river catchments of the Sydney area (Georges, Parramatta, and Hawkesbury-Nepean Rivers), around the volcanic dyke of Prospect Hill (Fig. 7). Much of the ground water extracted from the shales is saline (Curran, 1899; Old, 1942), a consequence of the marine origin of many of the shale measures. As this is also the area of western Sydney where urban expansion is greatest, urban salinity has become an increasing problem in recent years.

5.3. Coal measures

Further down the sequences underlying Sydney, but at some depth (> 300 m), are black coal measures. The coal measures are mostly mined 50–100 km south, west, and north of the city, where the strata come closer to the surface than in Sydney. Because of this the heavy polluting industries, such as steel works and smelters, have been located outside of Sydney in satellite towns. The coal under Sydney, which presents no real difficulties to mine, has remained untouched, much to the benefit of residential life.

5.4. Igneous rocks

Basaltic lava outcrops in the Sydney region are relatively small (Herbert, 1983), with basalt confined to the base of most diatremes. Discovery of dykes during brick pit excavation (Percival, 1985) suggests that there may be more concealed under the Wianamatta Group shales, but as with most aggregate sources suburban growth makes future access and exploitation difficult. A large volcanic dyke at Prospect, 15 km west of the city centre, has provided most of the coarse aggregate for road and rail construction.

5.5. Quaternary sediments

Where are the products of erosion of this Permian/Triassic block? Tertiary sediments are rare (Herbert, 1983), and even Quaternary sediments are restricted (Fig. 4). Apart from a few limited sediment sinks in the inland Cumberland Basin, and a thin sediment layer in the estuaries, the largest body of sediment is mobile: the coarser quartz sands which have been moved out to the narrow continental shelf, and back and forth during the Quaternary oscillations of sea level. The inner limit forms the beaches and sand dunes of the littoral zone. The finer silts derived from the Wianamatta shales have accumulated in bayhead estuarine swamps, and in the deltaic facies of the main estuaries (Roy, 1994).

One accumulation, mixing both Quaternary sand and silt, lies to the east and south of the city in the Botany Bay basin (Fig. 4). This site has provided much of the sand for the building of Sydney, in structures as well as for glass making and other specialised industries (Herbert, 1983). The north Botany sediments served as an aquifer supplying town water for many years. Most of the sand deposits of the Botany/Kurnell area have been exhausted after 210 years of intensive development. There has been some attempt to survey the use of offshore deposits, but this has met with strong public opposition.

The extensive Aboriginal shell middens that once lined the estuaries were used long ago to make lime mortar. The finer silts around Botany Bay, particularly those around the mouth of the Cooks River, were one of the few areas of soil close to the CBD of sufficient fertility to support market gardens, even though the original settlement site was moved in 1788 from Botany Bay to Sydney Harbour because of a judgement that the soils around the bay were poor (Collins, 1798). Gravels are also scarce in reasonable proximity to Sydney, the nearest big deposit being the Quaternary gravels of the Nepean River 50 km to the west. While there are some thin layers of conglomerate in the Sydney Sandstone measures, there is little rock overall that can weather into hard pebbles. Only those rivers that rise outside the Sydney Basin can deliver sizeable quantities of worn gravels. The greatest concentration of commercial gravel has accumulated on the plain where the Nepean river system runs out of the Blue Mountains, bringing detritus from the rocks of the Lachlan Fold Belt far to the west and south (Figs. 1 and 2). The Nepean gravel deposit, though extensive, has now been largely exhausted, and the building of the Warragamba Dam upstream on the Wollondilly River (Fig. 5) has prevented any replenishment. There are some untapped deposits of Tertiary gravels in the Cumberland Basin to the west of Parramatta (Herbert, 1983), but they will be lost to suburban encroachment unless they are reserved soon.

5.6. Soils

Soil type in the Sydney area is closely related to the underlying lithology, modified by geomorphic position (Herbert and Helby, 1980). As has been noted, the rocks of the Sydney area produce poor soils, both in structure (e.g., sandy and skeletal) and in geochemistry. Even the better soils formed on Wiannamata Shale are deficient in phosphorus, though these soils can be of some depth. The soils on the Wianamatta Shales are mediocre, but far better than the skeletal soils of the surrounding sandstone country. The dissected sandstone country has, however, proved invaluable as a water harvesting and storage area, with the deep valleys making good reservoirs, the catchments free of farming and habitation, and the slope of the country allowing gravity feed most of the way to Sydney.

The sandstone-based soils cannot maintain pastures, either natural or exotic. In the pre-automotive age, grass was of course a necessity to feed pack animals. To the extent that early Sydney was encircled by barren sandstone country, an escape route to the interior could only be along the islands of Wianamatta Shale on the ridgelines, which alone in the highlands could sustain sufficient grassy pastures to support horses and bullocks (Cunningham, 1996). This was one of the reasons that it took 25 years for explorers to breach the barrier to the west, despite the fact that the Blue Mountains Plateau is not particularly difficult to explore on foot.

The most extensive area of good soils is the fertile Quaternary alluvia of the Hawkesbury River floodplain in the Windsor—Richmond district. First settled in 1795, they saved the infant colony from starvation (Collins, 1798), and have been a significant source of Sydney's food supply ever since. Floods have prevented extensive suburban development. One other small area of good soils was mentioned above, around the mouth of the Cooks River and other parts of the north Botany basin (Fig. 6), which throughout the late 19th and early 20th century was intensively cultivated by Chinese gardeners and from which they were able to supply much-needed fresh vegetables to the crowded slums of inner Sydney (Fitzgerald, 1987). This was the area originally recommended as a suitable site for settlement by Captain James Cook, in his original survey in 1770, because of its supposed good workable soils (Parkinson, 1773). It is a curious fact that the site was rejected by the Royal Navy officers of the First Fleet in 1788 because of its allegedly poor, infertile soils, with much scathing criticism of Cook's agricultural expertise (Collins, 1798; Tench, 1996). Cook was also a sailor and Navy officer of course, but he was the son of a Yorkshire agricultural labourer, and from his early life experience on the Humber estuary he was probably better qualified to make a judgement about the potential of estuarine soils. The later Chinese gardeners mixed the surface sand with the abundant backswamp peat, built barriers against salt water incursion, added the city's night soil and, with their own hard labour, went some way towards rehabilitating Cook's judgement. The First Fleet officers were besmitten by the maritime potential of Sydney Harbour (Collins, 1798), but they and the other settlers were to pay dearly in the first years for the lack of good agricultural land within immediate distance of Sydney Cove (Clark, 1963). The decision to relocate with naval access as the dominant priority was a fateful one for the future economic direction of the new town: Melbourne was to become the agricultural entrepot of inland Australia (there is no significant natural physical barrier separating Melbourne from the inland, in contrast to Sydney), whereas Sydney had to learn rapidly to survive by maritime trade, particularly the opening up of the resources of the South Seas for whaling and sealing. Indeed, some of the first beneficiaries of the foundation of Sydney were the Yankee traders and whalers from Nantucket, who were provided with a convenient base from which they could exploit the resources of the newly discovered sub-Antarctic waters (Clark, 1963).

6. Structural development

Subaerial erosion has acted on a sedimentary block that has been fairly stable for most of its post-depositional existence, that is, for over 150 million years (Wellman, 1987). The southeast coast of Australia, that includes the edge of the Sydney Basin, represents one side of the continental rift associated with the opening of the Tasman Sea, 80–100 million years ago (Veevers, 1986). This rifting took place along the northeast–southwest structural lines of the underlying basement. Most of the major physical features of the Sydney region are aligned along this direction: the continental shelf, the coast, the major river systems, and the Lapstone Monocline (Fig. 1), as well as offshore synclines (Warner, 1998).

The last major uplift, of the western segment of the sediments of the Sydney Basin block (the Blue Mountains Plateau; Fig. 1), occurred sometime before 30 Ma (Bishop et al., 1982). Cutting across the sedimentary measures, the Lapstone Monocline (also referred to as the Lapstone Structural Complex: Branagan and Pedram, 1990) is a prominent, scarp-forming structural complex that divides the region between the $\sim$1000 m high plateau of the Blue Mountains to the west, and the lowlands of the Cumberland Plain to the east, with Sydney situated on the eastern rim of the plain as it lifts up gently towards the ocean. The basinal form of the Sydney basin has been exaggerated by the effects of the movement involved in the formation of the Lapstone Monocline (Fig. 3). This has had consequences for Sydney's recent expansion westward, as the Cumberland Plain suffers from a number of environmental problems related to its negative topography and associated micro-climate. The basin tends to act as an atmospheric sink for pollutants blown by onshore winds from the main part of Sydney. As well as these imported pollutants, cold air drainage from the nearby mountains traps locally produced pollutants, and produces severe winter frosts, while summer temperatures can be between 5°C and 10°C hotter than coastal Sydney (Bureau of Meteorology: http://www.bom.gov.au/). Parts of the Cumberland Plain receive considerably less rain than surrounding higher areas (Campbelltown has only 800 mm a year compared to the Sydney CBD average of 1200 mm). It is, however, largely free of the severe bushfire risk that is such a hazard elsewhere in the Sydney region. This is because almost all its natural vegetation has been stripped (White, 2000), and this lack of tree cover further exacerbates the effects of local climate extremes. Salinity is a problem in parts of the subregion (Charman and Murphy, 1991), and some of the heavy clay soils in the southern part of the Basin have a tendency to slip after heavy rain (C. Cunningham, pers. comm.).

7. Landforms derived from different lithologies

The disposition of the two main surface rock types, Hawkesbury Sandstone and its capping rock, the Wianamatta Shales (Fig. 5), have had a particularly strong influence on the direction of the city's growth, firstly in the effect that coping with the distinctive landforms had on building and engineering work and, secondly, in the qualities of the soils and building resources derived from the two contrasting rock types.

Hawkesbury Sandstone landforms are the product of the removal by erosion of the covering shale. Wianamatta Shale landforms, by contrast, are usually relatively uneroded interfluves. Sandstone slopes tend to erode as a stepped series of rock outcrops alternating with regolith-covered benches. Apart from some mass movement along joint lines, the slopes are generally stable (but see Chesnut, 1983, for exceptions). The more level plateau tops have been generally preferred to the sandstone slopes for most building. The only other flat lands around Sydney are sediment-filled estuarine bayheads and littoral strips, but these are limited in area and vulnerable to flooding. The Narrabeen Sandstone (like all the sandstone groups a mixture of massive sandstone with some lenses of shale) outcrops in the northern and southern extremities of Sydney's suburbs. It is more erodible than the Hawkesbury group, and tends to be undercut by rapid denudation of the shale beds to form unstable cliffs (Herbert and Helby, 1980), so is less suitable for development.

8. Coastal Sydney

The continental shelf off Sydney is exceptionally narrow (Fig. 1), straight, and exposed to swell conditions. Up to 2 m high tides flush the estuaries (Fig. 4). The low long-term erosion rates of the region (Roy and Boyd, 1996), producing denudation rates during the Cenozoic as slight as 5 m Ma^{-1} (Gale, 1992, and references therein), as well as the relatively small catchments of some of the estuaries, have reduced the potential for infill in the Sydney estuaries (thus preserving deepwater frontages), compared to the rapid filling of estuaries further south which have more erodible rock in their catchments (Roy, 1984). Sedimentation rates in the estuaries since 1788, while initially high, have returned to close to their pre-European levels of under 1 mm a^{-1} in most places over the last century (Haworth, 2002). The coast is structurally controlled, and exposed to high-energy waves, which have reworked quartz sand into a series of zeta-curve beaches separated by high, sandstone-cliff headlands (Fig. 4). The 87 km long shoreline from Broken Bay to Port Hacking (Fig. 2) has 61 km of rocky coast, and most of the remainder is made up of quartz sand beaches set between rocky headlands (Short, 1999). Cliffs are up to 70 m in height, with extensive rock platforms at the base. Sand moves from south to north around the headlands to feed the 37 coastal beaches. Sand grain size and quantity is in balance with the beach orientation and the energy of the prevailing southeast swell (Roy, 1983).

The ocean beaches are in a real sense the social heart of Sydney, supporting a tourist-friendly beach culture of marine sports and hedonism. Socially, they are the equivalent of the squares or plazas of the old world and, in sharp contrast to the USA, all beaches are public commons managed by local government.

The rate of denudation of the Hawkesbury Sandstone is extremely slow by world standards (Herbert and Helby, 1980; Gale, 1992), so much so that the coast has only retreated ~30 km from the edge of the continental shelf (Fig. 1) in the ~70 Ma since rifting in the Late Cretaceous (Hayes and Ringis, 1973). Some of the limited Tertiary sediments found in the Sydney region are thought to be estuarine facies from the Pliocene deposited close to the present coastline (Herbert, 1983), indicating very little net coastline retreat in several million years.

9. Estuarine Sydney

Nomenclature of the Sydney estuaries is confused by the habit of giving different sections of the one system separate names. The Hawkesbury River/Broken Bay/Pittwater complex to the north is a single interconnected estuarine system, with the Nepean River and its many large tributaries flowing into it (Fig. 2). Despite its large catchment and discharge, it has deepwater anchorage near its mouth. The steepness of the surrounding slopes and poor land access have discouraged port development. The Port Jackson/ Sydney Harbour/ Parramatta River estuarine system (Figs. 2, 4 and 7) is south of the Hawkesbury. It has the smallest catchment and a limited fluvial input, hence it has the deepest and most silt-free harbour. Until recently it has been the preferred port, being both sheltered and deep, with low surrounding hills. The Botany Bay/Cooks River/Georges River estuarine complex is 5–15 km south of Port Jackson. It has much more extensive mud basins in the central parts of its estuaries as a result of a much larger catchment and sediment supply.

Botany Bay occupies a subbasin in which an amount in the order of 2×10^9 m^3 of Quaternary alluvium has accumulated (Fig. 4), largely from the continental shelf (Roy and Crawford, 1981), but also from the shale-rich catchment of the Cooks River (Fig. 4). Although the bay has had problems with shoals and exposure, it has been extensively dredged in recent years to become the busiest port in Sydney, handling 70% of Sydney's shipping turnaround (Sydney Ports Authority: http://www.sydports.com.au/home.asp). The southernmost estuarine complex, comprising Bate Bay/Port Hacking/Hacking River, has a comparatively small catchment. Its central arm is partially obstructed by large deposits of marine sand shoals (Roy, 1994) and the discharge of the Hacking River is too limited to flush this marine tidal delta, hence the estuary is only used by small to medium craft.

Taylor (1958) speculated that Port Jackson had been stripped of its tributaries as a consequence of river capture by the Hawkesbury/Nepean and the Georges Rivers. Explanations for the seemingly anomalous drainage patterns of Sydney's rivers (Fig. 6) have sparked much controversy (for instance, Ollier and Pain, 1994; Bishop, 1986). The stream pattern of sharp right-angled change of direction from north to east may be partly explained by the interaction of the two common joining angles of the Hawkesbury Sandstone, the dominant joints trending east–west between 90° and 125°, and north–south between 5° and 35° (Scheibner, 1996). One important consequence of the "dog leg bends" in both the Georges and the Hawkesbury/Nepean rivers as they cross the Cumberland Plain is that they have encouraged the deposition of the only substantial patches of alluvium anywhere in the Sydney district, trapping sediment from the surrounding highlands in the lowest parts of the Basin. This has supported both farming and sand extraction industries in these areas above the inland tidal limit, and also slowed the rate of sedimentation in the lower estuaries and so maintained relatively deep estuarine waters. The substrates of the lower Georges River estuary, for instance, appear to derive largely from local sources in adjacent Wianamatta Shales, with only limited input from marine sands, and sporadic contributions from the upper catchment (Haworth, 2002).

10. Geological hazards

Sydney's tectonic stability (Bryant et al., 1988), and lack of volcanism, is taken for granted. However, even passive continental margins are subject to some seismic risk, with a 5.5 Richter scale quake predicted every 40 years for the Sydney area (Chesnut, 1983). There may also be some risk from far-off volcanic events, such as tsunami-generating undersea eruptions (Bryant et al., 1992). Coastal subsidence has been measured (Murray-Wallace and Belperio, 1991), but it is at too slow a rate to be of practical concern. Certain models of hydro-isostatic rebound (e.g., Lambeck and Nakada, 1990) have predicted a marked tectonic adjustment for the south-east Australian coast associated with the sea-level change of the Holocene, but other evidence (e.g., Haworth et al., 2002) suggests that this will not be significant. There are no faults in the immediate Sydney area, but the Kurrajong Fault 50 km to the west is possibly active (Chesnut, 1983). Generally, geological risk is low, but there are high risks from geological features combined with other factors, such as climate or vegetation, some of which will be described below.

10.1. Seismic

Despite general stability, southeast Australia is one of three moderately seismically active areas on the continent (for instance, Cotton, 1923). There have been two earthquakes greater than 5.5 on the Richter scale within 120 km of Sydney in the last 30 years. One, the Newcastle earthquake of 1989 (Schneider, 2001), caused extensive damage and loss of life, partly because this city is built on deep Tertiary and Quaternary sediments at the mouth of a large river. By contrast, most of central and western Sydney is built on hard sandstone: however, much of the eastern suburbs is built on unconsolidated aeolian and fluvial sediments. The Botany Bay Basin, which includes part of the east Sydney area, has a high concentration of petro-chemical works and large civil engineering structures. So although Sydney as a whole is not in a high seismic risk area, the concentration of industrial infrastructure on the Botany Bay sediments means that even a relatively small earthquake (magnitude ~ 6.5 on the Richter scale) has been calculated to be potentially catastrophic for the Australian economy (Schneider, 2001).

10.2. Slope and erosion hazards

A common hillslope form in the sandstone valleys of the Sydney region is that of alternating sandstone outcrops and regolith-covered benches. For the purposes of building, this has proved a stable foundation, particularly where the line of bedding rather than jointing controls weathering. Where jointing is pronounced in the sandstone layers, clay lenses between sandstone bedding create the potential for rock glides and topples (where an entire joint-bounded block is displaced), although there are a number of causes put forward to account for joint-bound sandstone displacement (Young and Young, 1992). Water seeping through the sandstone may also be impeded by clay lenses, and be redirected to cliff lines where it may trigger slope instability. Despite these problems on sandstone, mass movement has only been common on the limited areas of deep clays on weathered Ashfield Shale (Chesnut, 1983), particularly on steep slopes in the northwest of Sydney. The Northern Peninsula, where the erodible Narrabeen Series outcrops and undermines the overlying Hawkesbury sandstone, is also a moderate risk area for slope failure and cliff collapse. As this is well known, most development has been kept away from any potentially risky zone. Soil slumping has been a particular problem on slopes in the Wianamatta Series in the newly developed Campbelltown area in the southwest (C. Cunningham, pers. comm.). Overall, however, a saying among local engineers "Sydney Sandstone is very forgiving" emphasises the general lack of risk. The sandstone has proved particularly useful for allowing, with few engineering problems, the tunnelling of underground railway and freeway routes, and also extensive underground sewage tunnels. These last have allowed the transfer of much of the city's sewage against the lay of the land in three major west–east tunnels to ocean outfalls, now extended several kilometres out to sea. The effect of the sewage on the ecology of the generally nutrient-deficient waters of the Tasman Sea has been dramatic, supporting colonies of endangered Albatross and other large scavenger species, which are attracted from all parts of the southern ocean (Low, 2002).

Weathering of sandstone outcrops produces numerous caverns, or rock overhangs, covering an average 11% of a typical Sydney sandstone cliff face (Young and Young, 1988). These feature intricate honeycomb weathering on cave walls and ceilings. On coastal cliffs, the erosion of cavernous forms is exacerbated by marine action. Massive collapsed sandstone visors are common in parts of the Sydney coast (Baker and Haworth, 1997). The salt-laden air of the coast also increases weathering and the erosion potential. Of even greater effect are periodic storms that have moved 1000 tonne boulders to cliff tops 50 m above sea level (Sussmilch, 1912). Occasional tsunamis are also thought to be a risk to coastal areas, but only on millennia timescales (Bryant et al., 1992). There is also a possibility of damage from rising sea levels. Gordon (1988) has shown from the long-term tide gauge record at Sydney Harbour that there has been a 2 mm per year rise in the last 60 years. The pattern of fluctuation up and down over the 200 year record points to real rather than relative changes in sea level, and major coastal subsidence is therefore ruled out as a cause, as Murray-Wallace and Belperio (1991) also demonstrated. If the recent rise continued or was accelerated by global warming effects, the concentration of industrial infrastructure in the lowlands around Botany Bay basin would be at risk, particularly the international airport. However, a deepening of the water in the shoal areas of the upper estuaries, which are for the most part narrowly confined between sandstone slopes, would probably have a positive effect by improving navigation.

10.3. Fire hazard

The greatest hazard that may be traced to geological causes, though at one remove, is that of bushfires. Sydney is surrounded by an arc of rugged, inaccessible country with a high but very variable rainfall zone, ranging from 800 to 1200 mm per year in various parts of the region, with similar variations from year to year: (Sturman and Tapper, 1996). A sclerophyllic endemic vegetation association has developed in response to the extreme conditions of low fertility and minimum structure soils, and this *Eucalyptus*-dominated bushland has been left largely intact on the barren sandstone ridges and gullies around the city. In wet years dense vegetation builds up, which in dryer years creates a fuel load that explodes in catastrophic fires. Any strengthening of the El Nino Southern Oscillation (ENSO) effect, which is thought by some to have occurred in the last few decades (Sturman and Tapper, 1996), would with its more rapid alternation of drought and high rainfall periods exacerbate fire risk. The rapid building up of biomass in the wet phase creates the conditions for intense fires in the dry phase of the ENSO cycle. Both fire intensity (dependent mostly on fuel load) and fire frequency might, therefore, be expected to increase with a strengthened ENSO. However, the effects of any putative climate change on fire hazard would probably be insignificant compared to the risk already created by urban subdivision in inappropriate locations (Cunningham, 1998). Not only have houses and whole suburbs been situated in the middle of one of the most fire prone vegetation types in the world, but preferred housing sites on the tops of steep ridges with panoramic views represent the most at-risk locations, as fires gather intensity burning uphill, and the steeper the slope the greater their destructive power (Cunningham, 1984). The local topography of ridge and valley is generally aligned in a north–south direction following the regional basement structure, which also maximises the fire potential of the prevailing dessicating winds from the inland. A combination of geologic, bio-geographic, and climatic factors puts Sydney in the focus of one of the world's most extreme fire plume hazards (Pyne, 1991; Cunningham, 1984, 1998) and cultural choices have exacerbated the hazard.

10.4. Floods

In Sydney proper, there is little large-scale flood hazard because of its generally elevated situation, but on the Quaternary sediment areas of the Hawkesbury-Nepean and Georges Rivers (Fig. 2) there is a long-recorded history of disastrous flooding. This is exacerbated by their position at the point where steep tributary streams disgorge onto the plain from the surrounding higher ground (Fig. 6). Fortunately, most of this land has not been developed for housing, but retained for agriculture or recreation. Some reclaimed land in the Botany Basin (Fig. 4) and in the estuarine bayheads is also at risk of flooding, but as the main land uses in these areas is either recreation or industry, the risk is controllable. The general hardening of the urban surface, combined with the high intensity of Sydney's summer rain storms (Sturman and Tapper, 1996), has increased the risk of flash floods in some newly urban areas, particularly where high tides can block the release of storm water. However, Sydney's urban planning and development controls are relatively sophisticated and proactive and, combined with the overall low level of geological hazard, any real risk would be confined to infrequent high-magnitude events affecting limited areas.

11. Overall effect of geology on settlement pattern

The sandstone around the original port provided a stable base and on-site material for the large buildings and structures. The shale that covered the sandstone in the higher areas provided deep weathered clays to manufacture the bricks for the suburbs and, as it was a remnant of the original plateau surface, it provided the necessary flat land on which to build housing estates easily and inexpensively. The dendritic pattern of gullies and gorges incised deeply into the sandstone has made surface land transport extremely difficult, requiring large bridges, ferries, or long detours along ridge lines. In pre-automobile times public transport and poorer housing clung closely to the ridgelines, as few could afford to walk up from the gullies every day to get to work. For over 100 years much of the rugged sandstone country was left unsettled, even close to the centre of the city, while the more level shale country was fully occupied. The skeletal soils of the sandstone were equally useless for farming, so while the shale soils were cleared early for pasture the sandstone gullies were largely left under their native bush. Post WW11, the formally shunned sandstone slopes became the preferred habitat of the well-to-do. Previously worthless land was valued for its water views and romantic natural ambience, while escalating prices forced poorer inhabitants further westward along the bland flatness of the shale deposits (SPA, 1968). Thus Sydney displays a striking example of a geological boundary marking a sharp socio-economic divide, which is growing more extreme as urban consolidation and immigration concentrate still more newcomers on the older sites.

12. Conclusion

The sequence of geologic control of Sydney's fate can be summarised:

(1) The great age and duration of Australia's stable landscapes allowed the accumulation of a high proportion of quartz sands to dominate the Narrabeen and Hawkesbury measures in the Sydney Basin. The sorting was so effective that a hard, sterile sandstone with little matrix was produced. This eroded only very slowly to produce thin, skeletal, nutrient-deficient soils.

(2) In compensation for the poor soils, this same quartz sand made for unusually clean marine and river water, and pure sand beaches. Its slow erosion from bedrock has kept the estuaries largely unsilted during the Holocene highstand, and open to shipping.

(3) The thin overlay of shale produced slightly better soils. However, where fluvial and marine erosion mobilised the products of these shales, mud basins and shoaled estuaries resulted, and some mass wasting occurs on the steeper clay slopes.

(4) The structure of the Sydney Basin, with its depressed centre in the Cumberland Plain, served to trap much of the fluvial load as alluvium, upstream from the estuarine inlets. This produced some tolerably good agricultural land, though limited in area, at the tidal limit of the Georges, Parramatta, and Hawkesbury Rivers. The Cumberland Basin also represents a bad-air drainage sink. As Sydney expands westward into the basin increasing amounts of pollutants will be available to blow westwards with the onshore winds. The escarpment associated with the Lapstone Monocline traps the pollutants driven by the coastal breezes.

(5) It can be argued that Sydney has reached its limits as determined by topography and geology. Any further extension will be into either topographically difficult or high-risk zones, e.g., the Hawkesbury floodplain on its northwest edge, and the bushfire-prone ridges to the north, west and south. The dissected nature of this arc of rugged country also means big development costs in terms of transport infrastructure.

Overall, tectonic stability is probably the biggest advantage its geology has given Sydney, along with the useful products of the underlying basin lithology, from coal to industrial quality clay and the many benefits of clean sand.

Acknowledgements

The author thanks Cliff Ollier and Chris Cunningham for reading an earlier version, and Chris Cunningham for permission to use maps and diagrams from his book "The Blue Mountains Rediscovered: Beyond the Myths of Early Australian Exploration", and also for his expertise on bushfire hazard, Judith Burns for her experience as a working engineer in the Sydney Region, and Dixson Library (Armidale) for use of their rare book section of early colonial journals. Graphic work was either created or adapted by Mike Roach of UNE Cartography.

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