PART 3

A THUMBNAIL ENGINEERING GEOLOGY OF THE TRIASSIC ROCKS OF THE SYDNEY AREA

1. INTRODUCTION

This Part presents a summary of the engineering geology of the rocks of the area covered by Figure 3.1, an area extending from Port Hacking to Gosford and westwards to Camden, Warragamba Dam and Kurrajong. The area falls within the Sydney Basin, a broad zone of subsidence comprising dominantly sedimentary rocks.

It is suggested that this document may be useful for engineering students as a starting point for geotechnical practitioners in the Sydney area.

A proper geological framework is necessary for the presentation of engineering data and the writer, not being a geologist, has culled the framework from a number of excellent publications by specialists in Sydney Basin geology.

The area is covered by a series of geological maps, namely:

Sydney 1:100,000 and associated Notes published 1983
Penrith 1:100,000 and associated Notes published 1991
Gosford 1:100,000
St. Albans 1:100,000
Wollongong & Port Hacking 1:100,000 and associated Notes published 1986

The geology of the area is covered in detail in numerous publications, but for ease of reference, and in terms of the level of information relevant to engineering, the interested reader should refer to:

- The Geology of New South Wales, Packham (Ed), 1969
- Notes on the Sydney and Penrith 1:100,000 Sheets (9030 and 9130)
- Engineering Geology of the Sydney Region, Pells (Ed), 1985

2. STRATIGRAPHY AND PETROLOGY OF THE TRIASSIC

Rock engineering works in the Sydney region relate largely to the Triassic sandstones and shales that underlie most of the metropolitan area. The underlying Permian rocks are of great importance around the margins of the Triassic because of the important coal seams. However, geotechnical facets relating to coal mining are beyond the scope of this presentation and therefore the Permian units are not discussed here.

Geologists present the Triassic stratigraphy in four major divisions, namely:

- Wianamatta Group
- Mittagong Formation
- Hawkesbury Sandstone
- Narrabeen Group

The distributions of these formations are shown in Figure 3.1 and it can be seen that the Mittagong Formation is quite insignificant compared with the other three. The Hawkesbury Sandstone is quite consistent across the region but the Narrabeen and Wianamatta change in character, both from the south to north and towards the west. The result is that geologists have defined and named different stratigraphic subdivisions in these Groups (particularly in the Narrabeen Formation) according to location. Tables 1 and 2 summarise the major subdivisions and show the currently viewed correlations as set out in the Notes accompanying the Sydney, Penrith and Wollongong/Port Hacking 1:100,000 geological sheets. However, as illustrated in Figure 3.2 and pointed out by Herbert (1980), certain stratigraphic subdivisions cannot be correlated across the Basin. Thus, sandstone bodies in the Wianamatta represent point bar deposits and cannot be correlated. The *Potts Hill Sandstone Member* occurs only at Potts Hill and cannot be equated with sandstone at a similar stratigraphic level in the Razorback Range.

Table I
Subdivisions of the Narrabeen Group

Southern and Central	West of Parramatta	North of Hawkesbury River
• **Gosford Sub-Group** - *Newport Formation* - *Garie Formation*	- *Burralow Formation*	- *Terrigal Formation*
• **Clifton Sub-Group** - *Bald Hill Claystone* - *Bulgo Sandstone* - *Stanwell Park Claystone* - *Scarborough Sandstone* - *Wombarra Claystone* - *Coal Cliff Sandstone*	- *Wentworth Falls Claystone* - *Banks Wall Sandstone* - *Mt York Claystone* - *Burra-Moko Head Sandstone* - *Caley Formation*	- *Patonga Claystone* - *Tuggerah Formation* - *Tuggerah Formation* - *Munmorah Conglomerate* - *Dooralong Shale*

Table II
Subdivisions of Wianamatta Group

Central Area	West of Parramatta	South of Port Hacking
(Absent)	• Bringelly Shale - *Potts Hill Sandstone*	• Bringelly Shale - *Mt Hercules Sandstone* - *Razorback Sandstone*
(Absent)	• Minchinbury Sandstone	• Minchinbury Sandstone
• Ashfield Shale - *Mulgoa Laminite* - *Regentsville Siltstone* - *Kellyville Laminite* - *Rouse Hill Siltstone*	• Ashfield Shale - *Mulgoa Laminite* - *Regentsville Siltstone* - *Kellyville Laminite* - *Rouse Hill Siltstone*	• Ashfield Shale - *Mulgoa Laminite* - *Regentsville Siltstone* - *Kellyville Laminite* - *Rouse Hill Siltstone*

As can be seen from Table I, the greatest potential confusion from the engineer's viewpoint relates to the Narrabeen Group. Brannagan (1985) summarises the problem succinctly when he states:

> *"... the lack of persistent time or rock markers has made detailed correlation and reconstruction of the sedimentary history of the basin quite difficult. Separate systems of nomenclature have been used in various parts of the basin - in particular for the Narrabeen Group ..., and the nomenclature can be regarded at present as a tangled web which needs considerable ingenuity to untangle. Care is consequently needed to ensure what rock unit is being discussed in a particular publication."*

Summaries are given in the following sub-sections of only those sub-units of the Narrabeen that relate directly to geotechnical engineering in the Sydney area, namely:

- Newport formation
- Terrigal Formation
- Garie Formation
- Bald Hill Claystone
- Patonga Claystone
- Bulgo Sandstone
- Stanwell Park Claystone

In the traditional geological manner the various formations and units of the Triassic are dealt with in order of decreasing age (i.e. from the bottom up).

2.1 Narrabeen Formation

2.1.1 Stanwell Park Claystone

This is a lenticular unit which extends from Port Kembla to at least north of Manly but fades out to the west of Campbelltown. It attains a thickness of about 80m near Sutherland and, according to the Notes on the 1:100,000 Wollongong Sheet, comprises three main claystone intervals and two sandstone intervals.

The claystone is chocolate and mottled chocolate/grey near the top of the unit, grading into olive green and grey. They are comprised primarily of illite, mixed layer clays and chlorite with some smectite.

The sandstones are lithic and range from fine to coarse grained and conglomeratic in places. A fence diagram for this unit is presented in NSW Geological Survey Bulletin 22 covering the area south of Sutherland.

The unit becomes progressively more sandy towards the west until it becomes indistinguishable from the overlying Bulgo Sandstone - representing a change of facies rather than progressive thinning.

At the site of the proposed Avon Tunnel, some 15km west of Port Kembla, the unit is about 4m thick, while some 4.5km offshore of North Head (Sydney) the thickness is greater than 10m.

The main relevance of this unit to geotechnical engineering in the Sydney area is that where it has been tunnelled through between Sydney and Wollongong, problems have developed over a long period, ostensibly due to swelling of the claystone.

It should be noted that the siltstone/claystones in this unit constitute part of a group of so called red beds that are found at various stratigraphic levels in the Narrabeen Group. These red beds include:

- siltstone/claystone horizons in the Bulgo Sandstone and the Tuggerah Formation north of the Hawkesbury
- Bald Hill Claystone
- Patonga Claystone
- Mount York Claystone
- Wentworth Falls Claystone

Although the materials in these red beds look similar in hand specimen, their mineralogy is quite variable as is discussed further in relation to the Bald Hill Claystone.

2.1.2 Bulgo Sandstone

The Bulgo Sandstone is the thickest unit of the Narrabeen Group in the southern part of the Sydney Basin, reaching a maximum thickness of some 260m. The top of this unit is 160m below sea level at North Head, where it has a thickness of about 200m, and is more than 200m below sea level at Bondi.

The formation is exposed at Long Reef Point where the top few metres appear at low tide. Its main significance for engineering works in the Sydney area has been in the ocean outfall tunnels at North Head, Bondi and Malabar.

The unit consists of thickly bedded and laminated sandstone beds with intercalated siltstone and claystone bands ranging from fractions of a metre to greater than 10m.

In the ocean outfall tunnel at Malabar the Bulgo comprised about 68% fine to coarse sandstone and some pebble conglomerate, with the balance being siltstone and claystone. Petrographic analysis of one sandstone sample from the Malabar outfall gave the following:

Quartz	30%
Felspar	18%
Chlorite	2%
Mafic volcanic fragments	3%
Other volcanic fragments	30%
Sedimentary fragments	3%

At the ocean outfall tunnel at North Head (18 km north of Malabar) six sandstone specimens were analysed, with the following mean composition:

Quartz	15%
Felspar	12%
Chert	14%
Volcanic fragments	20%
Sedimentary fragments	8%

The six specimens were reasonably similar and the petrographic description included the following:

> *"This is one of the most compositionally diverse rocks that is possible in nature in that it is a complex mix of chemically, mineralogically and tectonically contrasting fragments and crystals held together by an abundant unusual cement that probably owes its origin to somewhat elevated thermal conditions."*

The above detailed descriptions are included here to make the point that the Bulgo Sandstone is a complex and diverse formation for which it is not reasonable to assign blanket engineering parameters. The sandstones in the formation are complex and there is a substantial proportion of claystone and siltstone. It is worth noting that the report on the 1982 drilling for the ocean outfalls included the following comment:

> *"After storage core samples of some siltstones and fine sandstone of the Bulgo Sandstone were found to disintegrate to 10mm fragments. This deterioration was more severe than that occurring in the Bald Hill Claystone/"*

The top quarter to one third of the Bulgo contains numerous discontinuous chocolate coloured claystone interbeds which tend to confuse the definition of the boundary with the overlying Bald Hill Claystone. The latter is generally regarded as an essentially continuous sequence of chocolate claystone.

2.1.3 Bald Hill Claystone

This is an extensive red bed unit which is readily recognisable from south of Port Kembla to the Hawkesbury River. Its thickness ranges from:

- 15m at type section at Bald Hill
- 80m at Sutherland
- 80m at Malabar (at shoreline the top surface is 170m below sea level)
- about 100m at Bondi (top surface 120m below sea level)
- 65m at North Head (top surface 140m below sea level)
- 18m at Long Reef Point where the full unit is exposed in the cliff face

The unit outcrops from Long Reef to Bilgola before dipping below sea level. Discontinuous red beds occur in the Terrigal Formation north of the Hawkesbury and may correlate with the Bald Hill Claystone.

It is typically a massive chocolate brown to red brown kaolinitic claystone with silty and sandy grey and mottled grey-brown zones. It contains minor laminated and thinly bedded siltstones and sandstones ranging in thickness from fractions of a metre to 3m.

Bembrick states that the mineralogy of the Bald Hill Claystone is unique to the red beds of the Sydney Basin. It consists predominantly of kaolinite (50% to greater than 75%), with haematite as the principal "contaminant". Quartz and felspar may be present in minor quantities, but are frequently absent. This mineralogy means the Bald Hill Claystone does not swell, and while slaking does occur on exposure, this is not significant and, for example, caused no problems in the ocean outfall tunnels at North Head and Bondi.

It is worth noting that the Wentworth Falls Claystone, which is correlated time-wise with the Bald Hill, comprises 10% to 20% quartz and includes a significant proportion of well-ordered illite as well as minor felspar.

2.1.4 Patonga Claystone

The type section for the Patonga Claystone is the depth interval 237m to 373m in a borehole (Windeyers) drilled in the parish of Patonga on the Hawkesbury River.

The unit comprises interbedded red-brown and grey-green claystone and siltstone with some sandstone. The sediments are commonly colour mottled and/or churned. The relatively high proportion of oxidised iron and an abundance of desiccation cracks suggests that these red beds were formed in a well drained and oxidising floodplain.

The Patonga Claystone outcrops north of Gosford and is therefore not of particular relevance to the region covered in this book. However, it is included here because it appears to be more reactive than the Bald Hill Claystone and has been implicated in a number of slope instability problems north of Gosford (Fell, MacGregor, Williams and Searle, 1987).

2.1.5 Garie Formation

This formation is pretty well insignificant from the engineering viewpoint but is included here because it forms one of the best marker horizons in the southern Sydney Basin. South of Sydney, in the area of the 1:100,000 Wollongong and Port Hacking sheet, it consists of up to 3m of cream, clay-pellet kaolin rock which forms prominent outcrops immediately above the Bald Hill Claystone (BHC). Except for the lack of haematite, the mineralogy is very similar to the underlying BHC.

In the Sydney area it outcrops in the headlands north of Long Reef.

2.1.6 Terrigal Formation

The Terrigal Formation is the dominant foundation material in the Gosford area. Its time equivalent south of the Hawkesbury River is the Newport Formation. It attains a maximum thickness of about 210m and has been divided into seven fine grained and six coarse grained units as shown in Figure 3.3. It forms the major portions of the headland exposures from Box Head through Maitland Bay and Avoca to the skillion at Terrigal.

The sandstones and siltstones have similar properties to those of the Newport Formation discussed below.

2.1.7 Newport Formation

The Newport Formation refers to an interbedded shale and sandstone sequence occurring above the Bald Hill Claystone (and Garie Formation) and below the Hawkesbury Sandstone. It outcrops and forms the foundation material for much of the area of development north of Long Reef where it has been associated with hillside instability problems.

It has a thickness of about 50m at Bungan Head. All three decline tunnels for the ocean outfalls at North Head, Bondi and Malabar passed through the full Newport sequence. The measured thicknesses and levels of the formation at shoreline at these locations were:

North Head	50m, base at 90m below sea level
Bondi	120m, base at 130m below sea level
Malabar	85m, base at 75m below sea level

The Newport Formation passes gradationally upwards from the Garie Formation and the upper boundary is frequently interbedded with the overlying Hawkesbury Sandstone. In such cases the boundary is difficult to define because the sandstones are very similar.

The following notes in relation to the lithology of the Newport rocks are taken directly from the chapter by Herbert in the Notes to the Sydney 1:100,000 Sheet.

> *"A variety of lithologies is present in the Newport/Terrigal Formations which were deposited in a fluvio-deltaic environment. Quartz-lithic sandstone, white when fresh, weathering to grey or orange, was deposited mainly in channel-shaped bodies. Channel sandstones are, in some cases, massive at the base and grade up to medium-scale, cross bedded sandstone. Shale breccia and polynictic pebble conglomerate occur commonly within massive sandstone immediately above a basal erosive surface. Sandstone varies from very fine grained to medium grained. In the field it can be differentiated (not always easily) from quartz sandstone of the Hawkesbury Sandstone by the presence of lithic pebbles, especially red, green and grey chert fragments.*
>
> *Shale and laminite contain a tremendous variety of sedimentary features including macro-cross bedding, slumped bedding, ball and pillow structures, fossil roots, burrows and shrinkage cracks. In places the shale is extremely carbonaceous .... The shale is composed of kaolinite, illite and quartz. The presence of illite differentiates Newport Formation shale from the underlying kaolinitic Bald Hill Claystone and Garie Formation."*

Figure 3.4 gives a summary log of the Newport Formation from the 220m deep borehole NH1 drilled on land for the North Head outfall tunnel. Also included in the summary log is the top of the Bald Hill/Garie and the base of the Hawkesbury.

2.2 Hawkesbury Sandstone

The Hawkesbury Sandstone tends to dominate the Sydney region, both from the viewpoint of engineering structures and the natural topography. This formation thickens from its western and southern outcrop margins in the Blue Mountains and Illawarra and is about 290m thick near the Hawkesbury River.

When viewed in vertical section the Hawkesbury Sandstone may be divided into three facies, namely:

- sheet facies)- 95% of formation
- massive facies)
- mudstone facies - 5% of formation

The **sheet facies** comprises sets of cross-bedded strata bounded by planar sub-horizontal surfaces. The cross-bedded units range in thickness from fractions of a metre to greater than 5m but are typically of the order of a metre. The horizontal surfaces (usually termed bedding planes by geotechnical engineers) give this facies a sheet-like appearance when viewed from a distance. The cross-beds typically dip to the north east, indicating that the Hawkesbury Sandstone was deposited by a fluvial system on a coastal plain with the source rocks being in the Lachlan Fold Belt to the south west. The sandstone of the **sheet facies** tends to be well sorted.

The term **massive facies** was coined "*to convey the gross aspect of this lithosome when viewed from a distance and should not be taken to mean wholly structureless at closer inspection*" (Conaghan). The sandstone is poorly sorted and therefore is fairly homogeneous in grain size, and is typically more friable than the sheet facies in weathered exposures. Frequently, sandstone bodies of this facies have a discordant erosional lower surface and a planar concordant upper surface. Mudstone (or shale) breccia commonly occurs within troughs at or above the basal surface but clasts, and in particular mudchips and mudflakes, can occur dispersed throughout. Petrographic analyses indicate that the massive facies sandstone contains significantly higher proportions of clay and less chemical cement and quartz overgrowth than the sheet facies, which is why there is the characteristic difference in weathering.

Petrographic analyses presented by Standard (1969) indicate that on average the Hawkesbury Sandstone has the following composition:

detrital quartz grains	68%
lithic fragments	2%
felspar	1%
mica	1%
clay matrix	20%
secondary quartz	6%
siderite (iron carbonate)	4%

Analysis by Robson (1978) of 42 samples taken from 16 sites gave:

quartz grains	mean 58.4%, SD 13.0%
rock fragments, felspar, mica	mean 3.5%, SD 2.8%
matrix clay	mean 24.2%, SD 7.1%
secondary silicates	mean 8.4%, SD 4.4%

Scanning electron microscope and electron probe studies reported by Pells (1985) indicate the presence of a secondary potassium aluminium silicate which acts as a cementing agent in the sandstone.

The average composition of the matrix clay is 55% to 75% kaolinite, 20% to 30% illite and the balance mixed-layered clays. It appears that the proportion of kaolinite decreases and illite increases to the south (i.e. towards the source area of the sandstones).

The **mudstone facies** comprises numerous thin mudstone (also termed shale) units with characteristic thicknesses in the range 0.3m to 3m. Occasionally they are thicker than 10m and there is one unit approximately 35m thick near Terrey Hills in Sydney's northern suburbs. Most units of the mudstone exhibit a fairly uniform thickness and appear to be sheet-like, although laterally discontinuous and frequently terminated laterally by erosion surface overlain by **massive facies** sandstone. This sudden lateral termination can make borehole interpolation very difficult. The **mudstone facies** comprises largely dark grey to black, laminated mudstone/siltstone and the thicker units are frequently termed laminite. The material does not swell significantly on exposure but does slake in a similar way to the red bed claystones discussed above. Quartz is usually the most abundant mineral with illite clays up to 30% and variable amounts of kaolinite.

Characteristically, mudstone units overlie sheet facies sandstone with abrupt and conformable relationship, but in some places occupy shallow, channel-like erosional depressions. The units are more abundant in the top quarter of the Hawkesbury Sandstone, particularly towards the east and north east.

2.3 Mittagong Formation

The Mittagong formation was at one time described as "the passage beds" between the Hawkesbury Sandstone and overlying Ashfield Shale and this old description aptly describes its characteristics. It comprises fine grained quartzose sandstone interbedded with dark grey siltstone and laminite. Thickness varies from nil to about 10m, with an average of 2m. It is about 8m thick at Town Hall Station near central Sydney.

Because of its limited thickness and similarity in properties to sandstones and laminite within the Hawkesbury, it has no specific importance from the engineering viewpoint, and for practical purposes can be treated as part of the Hawkesbury.

2.4 Wianamatta Group

From the engineering viewpoint the rocks, residual soils and transported weathered debris of the Wianamatta Group are as important as the Hawkesbury Sandstone. This is because, as shown by Figure 3.1, the Group directly underlies most of the western urban area from south of Campbelltown to Windsor (some 60km north) and eastwards through Liverpool, Parramatta, Ashfield and into the southern part of the CBD area (Sydney University, Central Station etc). It occupies the ridge up which the Pacific Highway runs from North Sydney, through St Leonards, Chatswood and on to Hornsby, also, ridges and areas of high ground through Eastwood, Pennant Hills and Castle Hill.

The stratigraphic subdivision of the Wianamatta has already been presented in Table II. The thickest recorded section is 304m in a borehole at Razorback Mountain some 15km south west of Campbelltown. However, the type section is taken as borehole Blaxland DDH1 which is within the Penrith 1:100,000 Sheet and was used by Herbert (1979) in formulating a revised nomenclature for the Group which is the basis of Table II. The following sub-sections give pertinent information in relation to stratigraphy, structure and petrology of the major units of the Wianamatta which is taken largely from the Notes to the Wollongong and Port Hacking sheet. Figure 3.5 presents a schematic relationship of the units taken from the same publication.

2.4.1 Ashfield Shale

The Ashfield Shale forms the basal unit of the Wianamatta and ranges in thickness up to about 60m. It is the only unit of the Wianamatta of relevance in the heavily developed ridge areas of the northern and north western suburbs and along the Great Western Highway from about Central Station to Parramatta.

It comprises a lower sequence of dark grey to black sideritic claystone and siltstone which grades upwards into a laminite of fine sandstone and siltstone. Four lithological intervals have been defined by Herbert (1979) based on drill core. However, except in some quarry exposures, these members cannot be recognised with any confidence within the rolling topography and deep soils developed on the Wianamatta. The lithological intervals are set out in Table III.

Table III
Subdivision of the Ashfield Shale

Rouse Hill Siltstone	5m to 15m thick dark grey to black siltstone/claystone with abundant siderite rich zones.
Kellyville Laminite	1m to 6m thick laminite, with interbedded sandstone and dark grey siltstone laminae up to about 25mm thick. Sandstone is typically less than 30% of the member.
Regentville Siltstone	Similar to the Rouse Hill Siltstone and between 10m and 20m thick. There is an increase in sandy laminae towards the top, making the upper boundary indistinct.
Mulgo Laminite	15m to 30m thick member similar to the Kellyville Laminite but with a slightly higher average sandstone content which increases to the top where the Ashfield Shale grades into the overlying Minchinbury Sandstone.

Bedding in the Ashfield Shale is close to horizontal although small scale cross bedding occurs in the sandier horizons and inclined bedding up to 30° is reported in the Kellyville Laminite.

The petrology of the Ashfield may be summarised as follows:

Siltstone/Claystone
    Quartz, kaolinite, siderite (10% to 12%), disordered illite, randomly interstratified illite/smectite, minor carbonaceous matter

Sandstone
    Quartz (50% to 70%), calcite, intermediate volcanic lithic fragments

The Ashfield Shale was formerly the major source of raw material for the Sydney brick making industry, with many brick pits in inner suburban areas (e.g. St Peters, St Leonards, Artarmon, Eastwood and Homebush). Because of its high siderite content the unweathered material fires to a dark red colour and may be blamed or praised (depending on your aesthetic viewpoint) for the dark red brick house of much of inner Sydney. Currently less than 10% of brick making clay comes from this formation.

Groundwater in the whole Wianamatta Group is saline and is also hard. Salinity levels range up to 3100 mg/l and it is typically not even suitable for stock watering.

2.4.2 Minchinbury Sandstone

This is a persistent but thin unit (1.5 to 6m, typically less than 3m) which is the lowest significant sandstone unit in the Wianamatta and forms a boundary marker between the Ashfield Shale and Bringelly Shale. It therefore has geological importance but no greater engineering significance than other sandstone units which occur in the overlying Bringelly Shale. the Minchinbury Sandstone comprises up to 70% quartz with significant calcite and volcanic lithic fragments. It has significantly less felspar and more calcite than sandstones in the overlying Bringelly.

2.4.3 Bringelly Shale

The Bringelly Shale was re-defined in the late 1970s to include all Wianamatta sediments above the Minchinbury Sandstone. Thus, substantial sandstone units which may be up to 30m thick but which have limited lateral continuity (being channel or point bar deposits) are now considered as members of the Bringelly Shale. These include:

- Potts Hill Sandstone
- Razorback Sandstone
- Mt Hercules Sandstone

A maximum thickness of about 257m of the Bringelly is preserved at Razorback but, owing to greater post-Triassic erosion in the Parramatta-Sydney area, the unit is virtually restricted to the synclinal structure of the Fairfield Basin where it has a thickness of about 60m at Potts Hill.

The Bringelly displays primarily a regular sequence of alternating claystone, siltstone and laminite with some sandstone and highly carbonaceous claystone and coal. In order of volumetric significance, the lithologies are:

- claystone/siltstone
- laminite
- sandstone
- carbonaceous claystone with coal
- tuff

The lower 30m of the Bringelly is thinly bedded and contains the highest carbonaceous content beds in the Wianamatta. Claystone, siltstone and sandstone beds become thicker above this lower zone.

Claystone/Siltstone

Claystone typically grades into siltstone in sequences up to 15m thick. They are composed primarily of quartzite, kaolinite and micaceous clays with a higher proportion of expandable mixed layer illite/smectite than the underlying Ashfield Shale. Siderite is quite common but not as uniformly distributed as in the Ashfield Shale.

Laminite

This occurs throughout the Bringelly in units typically less than 5m. It comprises varying proportions of quartz-lithic, light grey, fine, micro-cross bedded sandstone and dark grey siltstone. Laminae are typically 10mm to 20mm. Siderite grains and nodules are common as too are carbonaceous plant remains along bedding planes.

Sandstone

The channel sandstones are typically less than 2m thick in the basal 30m zone and above this reach in excess of 6m, rarely up to 16m. An exception is the Mt. Hercules Sandstone (in the Razorback Range) which is up to 44m thick. Angular shale fragments often occur above the basal contacts in a massive medium grained sandstone. There is some conflict in published petrology data but it appears that the sandstones comprise less than 40% quartz, with felspar ranging from 5% to 30% and the balance being clay pellets and a matrix of clay, calcite, chlorite and siderite.

The Bringelly Shale is nowadays the primary source of brick making material in the Sydney area. Its variable siderite content gives rise to a wide variety of fired colours, ranging from cream to red, although economically significant deposits of light-firing material are quite scarce. Some 2 million tonnes of Bringelly Shale is extracted annually in the Sydney region.

3. DISCONTINUITIES

3.1 Bedding

As must be clear from the stratigraphic descriptions in Section 2, the sub-horizontal bedding horizons are the most important type of discontinuity in the Sydney rocks. It would be silly to attempt to make generalised statements about the spacing and nature of these discontinuities other than to note that they include:

- closely spaced laminations (which are planes of incipient failure or parting) in the shales and laminites;
- continuous seams of sandy and silty clay between quite massive beds of fresh sandstone;
- bedding contacts of strength almost equivalent to intact rock, visible only as colour changes.

In the study for the ocean outfall tunnels an attempt was made to categorise the typical bedding conditions in the Hawkesbury, Newport, Bulgo and Bald Hill units. These are given in Table IV.

Table IV
Generalised Bedding Descriptions

Unit	Bedding Spacing	Description
Hawkesbury Sandstone	0.3m to 5m, average 2m	Continuous, planar, typically clean but with characteristic clay seams in the upper 30m
Newport Formation	0.1m to 2m, average 1m in sandstones, 0.3m in siltstones	Continuous, planar, clean and rough, infrequent clay seams
Bulgo Sandstone	0.5m to 5m in sandstones, 0.1m to 0.3m in claystones	Continuous, planar, clean with occasional crush zones, infrequent seams
Bald Hill Claystone	0.1m to 1m, typically 0.3m	Undulose, rough but with frequent clay seams

3.2 Joints

Orientation and Spacing

Information on joint orientations and spacings has been gained from the following sources:

(i) Studies conducted by McElroy & Probert (1976), Beavis (1978) and Coffey & Partners (1980) undertaken in connection with the enquiry into mining under stored waters

(ii) Mapping, undertaken as part of this study, of exposures of the Hawkesbury Sandstone and Narrabeen Group at North Head, Long Reef and Bondi

(iii) Mapping undertaken by Coffey & Partners in connection with the design of Mangrove Creek Dam (1976) and the Mt Colah/Berowra Freeway (1981)

(iv) Mapping undertaken by Dr. J. Huntington (CSIRO, Pers. Comm.) in rocks of the Sydney area

(v) Borehole logs from offshore and onshore drilling for the ocean outfall tunnels

(vi) Investigation by SMEC (1979) for the Eastern Suburbs railway tunnels

(vii) Mapping undertaken for the Sydney Harbour Tunnel

The results of the above studies are summarised in Table V.

Table V
Joint Orientations in Hawkesbury Sandstone and Narrabeen Formation Rocks

Location	Rock Unit	Major Joint Orientations	Comment
Illawarra Plateau	Hawkesbury Sandstone	Trends 005°, 055°, 105° & 155°	Air photo interpretation
Illawarra Plateau	Hawkesbury Sandstone	Trends 005°, 045°, 115° & 160°	Air photo interpretation
Illawarra Plateau	Hawkesbury Sandstone	Trends 020° & 090°	Field mapping
Illawarra Plateau	Hawkesbury Sandstone	Trends 055°, 105° & 155°	Air photo interpretation
Mt Colah-Berowra	Hawkesbury Sandstone	Strike 010° ±20° Dip 90° ±5°	Field mapping[x]
Sirius Cove	Hawkesbury Sandstone	Trend 035° to 040°	Field mapping
Cremorne Point	Hawkesbury Sandstone	Trend 025°	Field mapping
Sydney Railway Tunnels	Hawkesbury Sandstone	Set 1 strike 025° ±10° Dip 75°E to 90° Set 2 Strike 110° ±15° Dip 75°S to 90°	Field mapping
North Head	Upper Hawkesbury Sandstone	Set 1 Strike 025° ±5° Dip 75° to 90°E Strike 205° ±5° Dip 85° to 90°W Set 2 Strike 285° ±10° Dip 75° to 90°W Strike 105° ±10° Dip 85° to 90°S	Field mapping. Sets 1 and 2 are an orthogonal set. Dominant set is Set 2.
North Head	Lower Hawkesbury Sandstone	Set 1 Strike 210° ±10° Dip 70° to 90°W Strike 030° ±10° Dip 80° to 90°W Set 2 Strike 120° ±10° Dip 65° to 85°S	Field mapping. Sets 1 and 2 are an orthogonal set.
Bondi Headland	Hawkesbury Sandstone	Set 1 Strike 105° ±5° Dip 90° ±10° Set 2 Strike 010° ±5° Dip 90° ±10° Set 3 Strike 050° ±5° Dip 95° ±10° Set 4 Strike 130° ±5° Dip 90° ±10°	Field mapping. Sets 1 and 2 are an orthogonal set. Sets 3 and 4 are an orthogonal set.
Illawarra Plateau	Newport Formation	Trends 020° and 090°	Field mapping
Collaroy Beach	Newport Formation	Trends 040° and 320°	Field mapping
Long Reef	Newport Formation	Trends 035° and 335°, minor 285°	Field mapping
Long Reef	Newport Formation	Set 1 Strike 020° ±5° Set 2 Strike 100° ±5° Both dip 90° ±10°	Field mapping. Sets 1 and 2 are an orthogonal set.
Illawarra Plateau	Bald Hill Claystone	Trends 13° and 90°	Field mapping
Long Reef	Bald Hill Claystone	Set 1 Strike 075° ±5° Dip 90° ±5° Set 2 Strike 170° ±5° Dip 90° ±10° Set 3 Strike 150° ±5° Dip 90° ±10° Set 4 Strike 015° ±5° Dip 90° ±10° Set 5 Strike 080° Dip 25°S (minor)	Field mapping. Sets 1 and 2 are an orthogonal set.
Illawarra Plateau	Bulgo Sandstone	Trend 002°, 103°, 095° & 103°	Field mapping

NOTE:

1. All joint orientations are with respect to true north.
2. Upper and Lower Hawkesbury Sandstone refer to joint measurements recorded at the cliff top and cliff base of North Head.

*Average orientations have been presented from highly variable data at numerous sites.

Based on the data summarised in Table V it is considered that a good starting point for work on sites in the Sydney area is the joint set definitions given in Table VI.

Table VI
Generalised Joint Sets in the Sydney Area

Rock Unit	Orientation	Joint Sets (excluding bedding partings)			
		Set 1	Set 2	Set 3	Set 4
Hawkesbury Sandstone	Strike	025° ±10°*	110° ±10°	150° ±10°	050° ±5°
	Dip	90° ±15°	90° ±15°	90° ±10°	90° ±10°
Newport Formation	Strike	025° ±10°*	105° ±10°*	150° ±10°	
	Dip	90° ±10°	90° ±10°	90° ±10°	
Bald Hill Claystone	Strike	080° ±10°*	350° ±10°*	015° ±10°*	330° ±10°
	Dip	90° ±15°	90° ±15°	90° ±15°	90° ±15°
Bulgo Sandstone	Strike	010° ±10°	100° ±10°	Minor trend at 140°	
	Dip	90° ±10°	90° ±10°		

*Dominant sets

Joint spacing assessments have been made in the main from mapping of cuttings and natural exposures where weathering and stress relief may have induced closer than average spacings. Therefore, the data given here may be conservative in relation to excavations in fresh rock.

Data on joint spacings have been taken from McElroy & Probert (1976), Coffey & Partners (1976, 1978, 1980), Beavis (1978) and SMEC (1979). Observations of spacings in the Hawkesbury Sandstone are summarised in Table VII.

Table VII
Joint Spacing in Hawkesbury Sandstone

Location	Joint Spacing (m)	
South Head	Shales	average 0.2
	Sandstones (2-10m beds)	5-10
	Sandstone with shale (1-4m beds) range 1-5m	3
F3 Freeway Mt Colah to Berowra	Joints terminating within beds or at bedding partings	1-20+
	Joints which cut across or truncate along bedding partings	≅5-10
Southern Catchment Area	3-4 to 30-40	average 7-15
Eastern Suburbs Railway	Sub-horizontal joints and partings	<0.025-6+
	Steeply dipping joints	<0.025-30+
	(NE striking steeply dipping joints average 0.3-1.5)	
North Head Water Pollution Control Plant	Joints continuous through several beds	3-10
	Joints terminating within beds	0.5-3
	Faulted zone	0.05-0.3

The data in Table VII give average spacings but it should be noted that the joints can occur in swarms. One well known swarm in the Sydney CBD area runs from near Town Hall through Martin Place to the Man-O-War steps near the Opera House. Another swarm runs from near Luna Park in a NNE direction through the Warringah Expressway.

In the Newport Formation, spacings in the shaly units range from 0.2m to 3m, while in the sandstones they range from 1m to 5m. Probert (1976) suggests a typical spacing for the whole formation of 1m to 3m. Beavis (1978) suggests that spacing of joints is often approximately equal to bed thickness.

Data available on spacings in the Bald Hill Claystone is summarised in Table VIII, while that for the Bulgo Sandstone is in Table IX.

Table VIII
Joint Spacings in Bald Hill Claystone

Location	Joint Spacing (m)
Southern catchment area	Typically <2m with average ≈1m
Long Reef	Range 0.1m to 1m but up to 5m. Average of 0.5m

Table IX
Joint Spacings in Bulgo Sandstone

Location	Joint Spacing (m)
Southern catchment area - mine data	2m to 13m with average of 4m
Southern catchment area - cuttings	0.5m to 3m

Continuity

As discussed in Part 2 of this article, it is the writer's opinion that joint continuity is frequently more important than orientation and spacing.

Good information on continuity within the Sydney area was obtained by MacGregor in a study for proposed mining under the reservoirs inland of Wollongong (Coffey & Partners, 1980). He inspected exposures in the clifflines around Sydney, by helicopter, boat and foot, to assess vertical continuity of the dominant near vertical joints in the Narrabeen Formation. His conclusions have been of value in many projects in the Sydney area and may be summarised as follows:

(i) More than 70% of joints are confined within sedimentary beds and have vertical continuity of 1m to 3m.

(ii) 10% to 15% cross several beds of the same rock type (e.g. sandstone) but terminate at depositional changes (e.g. a shale bed). These have vertical continuities of 3m to 8m.

(iii) Less than 2% of joints cross the whole formation - these have vertical continuities of 100m or more.

On a small scale, mapping of the vertical joints in the Hawkesbury Sandstone in the 35m deep cavern of the Opera House parking station (Figure 3.8) gave the following information:

(i) Joints had a horizontal continuity typically greater than 150m (see Figure 3.8).

(ii) About 80% of joints terminated against major bedding horizons within 6m to 8m of the rock surface.

(iii) About 10% of joints had a vertical continuity greater than 15m.

(iv) No joints extended the full 35m depth of the excavation.

3.3 Folding and Faulting

Gentle folding and faulting of the Sydney Basin occurred contamporaneously with sediment deposition in the Permian and Triassic and continued through the Tertiary with tectonically related faulting and joint formation. The main structures of the region are shown in Figure 3.9.

The fold axis of the Hornsby Plateau strikes at about 20°, i.e. sub-parallel to the coastline. It is postulated that there is an anticline axis about 7 km offshore and therefore the rocks in the vicinity of the ocean outfall tunnels at North Head, Malabar and Bondi dip at up to 10° to the west - but typically about 6°. In the central business district the rocks dip to the west at about 10°.

A warp structure which runs in the vicinity of Castle Hill Road has resulted in dips in the Wianamatta Shales up to 8° or more to the south west. This has resulted in several areas of natural land instability in that part of Sydney (Fell, 1989).

As pointed out by Branagan (1985) there has been little systematic study of faulting in the Sydney region, although he does describe several faulted areas.

Large scale faulting is absent but significant small scale faulting is encountered in the Wianamatta Shales in St. Leonards and Chatswood and in exposures in brick pits in the St. Peters area. It is reasonable to expect small scale faults in these shales anywhere in the Wianamatta. However, these faults are usually of limited continuity (i.e. typically less than 10m).

Observations of the Narrabeen rocks (Newport Formation and Bald Hill Claystone) at Long Reef show that many of the faults exposed in the Bald Hill are not vertically continuous through the overlying Newport Formation. These normal faults have occurred contemporaneously with sedimentation and many fault planes tend to be healed and tight. These faults have strikes of 330° to 015° and dip east and west at 38° to 65°.

At Long Reef, two faults show continuity through the Newport boundary. These are of similar orientation to a fault at North Head in the Hawkesbury Sandstone, striking 280° and dipping 80° to the north.

4. ROCK MASS PERMEABILITY

A substantial amount of packer permeability testing was undertaken in the deep boreholes drilled both on land and offshore for the ocean outfall tunnels. Table X gives a summary of all the results.

From the statistical viewpoint the design value from a population of permeability values is the geometric or log mean value. The following values are thus obtained (taking a recorded 0μL value as 0.01μL):

Hawkesbury Sandstone	0.02µL
Newport Formation	0.03µL
Bald Hill Claystone	0.2µL
Bulgo Sandstone	0.6µL

These geometric mean values illustrate well the generally tight nature of the rocks in the metropolitan area. However, experiences with shaft sinking through the Triassic rocks in the southern coalfields (Fawcett and Rose, 1978; White, 1978) showed that significant inflows of water may be anticipated through isolated zones within the Hawkesbury Sandstone but that the Narrabeen Group is generally tight. The zones of high permeability within the Hawkesbury Sandstone appear to be so discrete and isolated that they may be missed in exploratory boreholes.

Table X
Rock Mass Permeability Data

Stratigraphic Unit	Lugeon Value (µL)	Length of Borehole (m)
Hawkesbury Sandstone	0.01	194
	0.5	24
	1	6
	25	12
Newport Formation	0.01	288
	0.5	77
	1	6
	3	6
	8	6
	10	6
	14	6
Bald Hill Claystone	0.01	139
	0.5	153
	1	62
	2	46
	5	6
	9	5
	12	6
	37	5
Bulgo Sandstone	0.01	11
	0.5	205
	2	20
	37	8
	37	7

NOTES:

1. Field recorded values of 0µL are taken as 0.01µL for computational purposes.
2. Field values recorded as <1µL are taken as 0.5µL.

5. ROCK MASS CLASSIFICATION

The Rock Mass Ranking system published by Bieniawski (see Bieniawski, 1993) includes a good form for summarising geotechnical data belonging to a particular structural group. While there is always a danger in generalisation, the summaries which were prepared in this form for the ocean outfall tunnels provide a useful basis for the initial assessment of underground works in the Sydney area. These summaries are presented in Tables XIa to XId for the Hawkesbury, Newport, Bald Hill and Bulgo formations.

A simple classification system for the sandstones and shales of the Sydney region was prepared by a sub-committee of the Australian Geomechanics Society in 1978 primarily for foundation design purposes (Pells et al, 1978). This system has become widely used by the Sydney geotechnical fraternity and has found application as a communication and evaluation tool in problems other than rock foundations. It has also found application in areas far from Sydney but having similar geology. A summary of this system, presented in a form which can be readily copied and laminated to give a pocket sized field guide, is given in Attachment A immediately after the references.

6. STRESS FIELD

A very good summary of available data on the natural stress field is given by Enever Walton & Windsor (1990) and need not be repeated here. For near surface work, say down to about 100m, the writer currently adopts the following regime:

$$\sigma_1 = \sigma_{NS} = 1.5 + 1.2\sigma_V \text{ MPa}$$
$$\sigma_2 = \sigma_{WE} = 0.8 + \sigma_V \text{ MPa}$$
$$\sigma_3 = \sigma_V = 0.024H \text{ MPa}$$

where σ_V = vertical stress

σ_{NS} = horizontal stress oriented approximately 20^0 east of true north

σ_{WE} = orthogonal to σ_{NS}

7. MATERIAL PROPERTIES

In an overview article like this, one is faced with a dilemma when it comes to the presentation of engineering properties. Space and time do not permit the inclusion of all data which are readily available on just strength and deformation parameters, let alone the information which could be gleaned from consultants and government organisations. On the other hand, including nothing would substantially diminish the value of this presentation.

I have therefore chosen to present some information which is broadly valid, together with references where further data can be obtained. However, a clear warning must be sounded that geological variability dictates that site specific measurements must always be made.

TABLE XIA
ROCK MASS DATA - HAWKESBURY SANDSTONE

GEOLOGICAL DESCRIPTION

SANDSTONE, quartzose with matrix clay to 20%, medium to coarse grained, but with intraclasts and interbeds of mudstone

MAJOR GEOLOGICAL FEATURES

Sandstone occurs in sheet and massive facies with the former being characterised by strong cross-bedding generally dipping at $>20^o$ and trending N to E. The massive beds exhibit some cross-bedding but are characterised by irregular, grossly discordant lower surfaces in the form of channel structures. Shaley siltstone beds occur in beds up to 6m thick.

DEGREE OF WEATHERING (AS1726-1981)

Fresh	Slightly W	Moderately W	Completely W	Seams & Crush Zones
80%	18%	1%	1%	0.6m in 12.5m of core

ROCK SUBSTANCE STRENGTH (AS1726-1981)

<2 MPa	2 to 6 MPa	6 to 20 MPa	20 to 60 MPa	>60 MPa
			χ = 31 MPa s = 13 MPa	Occasional strength values to 65 MPa have been measured

ROCK MASS PERMEABILITY DATA

µL	Length of Borehole	
0.01	194m	Geometric Mean = 0.02µL
0.5	24m	
1	6m	
25	12m	

HYDROSTATIC HEAD	REGIONAL STRESS FIELD
	Assume $\sigma_1 NV = 2.5\sigma_v$ $\sigma_h \omega E = 1.5\sigma_v$

JOINT SETS

Source of Information: References 10, 11, 14, 15

Set 1	Set 2	Set 3	Set 4
Bedding	Tension	Tension Dykes and faults associated with this set	Tension

ORIENTATION OF JOINT SETS (True North)

	Set 1	Set 2	Set 3	Set 4
Dip	0-5^{o}W	$90^o \pm 15^o$	$90^o \pm 15^o$	$90^o \pm 10^o$
Strike	0^o	$25^o \pm 10^o$	$110^o \pm 10^o$	$150^o \pm 10^o$/ $50^o \pm 10^o$

EFFECTIVE JOINT SPACING (m)

References 4, 15

Set 1	Set 2	Set 3	Set 4
0.3 to 5.0m Overall >3m	1 to 3m in swarms but overall >3m	>3m	>3m

CONDITION OF JOINTS

Set 1	Set 2	Set 3	Set 4
Planar, generally clean but with occasional clay seams, continuous	Planar, generally rough & clean with fresh to slightly weathered joint wall rock. Continuity 1 to 5m	Planar, generally rough & clean with fresh to slightly weathered joint wall rock. Continuity 1 to 5m	Planar, generally rough & clean with fresh to slightly weathered joint wall rock. Continuity 1 to 5m

RQD

Of 148m logged	90%	with RQD > 90%
	5%	with RQD >50% <75%
	5%	with RQD <25%

TABLE XIB
ROCK MASS DATA - NEWPORT FORMATION

GEOLOGICAL DESCRIPTION

Light to dark grey, interbedded and interlaminated, quartzose and lithic, fine to medium grained sandstones and siltstones and also grey-white, poorly bedded, medium grained quartzose sandstones

MAJOR GEOLOGICAL FEATURES

Beds range in thickness from 10mm to 7m. The interbedded coarser sandstones are current bedded with rare carbonaceous and micaceous laminae.

DEGREE OF WEATHERING (AS1726-1981)

Fresh	Slightly W	Moderately W	Completely W	Seams & Crush Zones
99.7%	0.3%			1.18m in 105m of core

ROCK SUBSTANCE STRENGTH (AS1726-1981)

<2 MPa	2 to 6 MPa	6 to 20 MPa	20 to 60 MPa	>60 MPa
			Offshore: $\chi = 52.0$ MPa $s = 15.4$ MPa Onshore: $\chi = 45.9$ MPa $s = 16.5$ MPa	Note - 6 of the 26 tests gave values >60 MPa Highest 80 MPa

ROCK MASS PERMEABILITY DATA

µL	Length of Borehole
0.01	288m
0.5	77m
1 to 8	18m
10 to 14	12m

Geometric mean = 0.03µL

HYDROSTATIC HEAD	REGIONAL STRESS FIELD
	Assume $\sigma_h NS = 2.5\sigma_v$ $\sigma_h \omega E = 1.5\sigma_v$

JOINT SETS

Source of Information: References 10, 11, 14

Set 1	Set 2	Set 3	Set 4
Bedding	Tension	Tension	Tension

ORIENTATION OF JOINT SETS (True North)

	Set 1	Set 2	Set 3	Set 4
Dip	0-5°W	90° ± 10°	90° ± 10°	
Strike	0°	25°± 10°	105° ± 10°	

EFFECTIVE JOINT SPACING (m)

References 4, 10, 11

Set 1	Set 2	Set 3	Set 4
0.1 to 2.0m 1m in sandstones 0.3m in siltstones	0.2 to 1.0m in siltstones (variable) 1.0 to 3m in sandstones	0.2 to 1m in siltstones (variable) 1 to 3m in sandstones	

CONDITION OF JOINTS

Set 1	Set 2	Set 3	Set 4
Planar, clean and rough, infrequent clay seams. Continuous	Planar, rough & fresh joint wall rock. Continuity 1 to 5m	Planar, rough & fresh joint wall rock. Continuity 1 to 5m	

RQD

Of 344m logged	90%	with RQD 90%
	9%	with RQD 75% <90%
	1%	with RQD 50% <75%

TABLE XIC
ROCK MASS DATA - BALD HILL CLAYSTONE

GEOLOGICAL DESCRIPTION

Massive chocolate-brown to red-brown, kaolinitic claystone with silty and sandy grey and mottled grey-brown zones. Minor interbedded and laminated siltstones and fine to coarse sandstones.

MAJOR GEOLOGICAL FEATURES

The claystones tend to be massive, with the interbedded siltstone/sandstone units ranging from 0.1m to 3m. A significant proportion of the jointing appears to be associated with compaction and relict soil structures associated with the depositional cycles. Faults with some clay gouge dipping at 45° may be anticipated, with spacings of the order of hundreds of metres; sub-horizontal shear zones with spacings of the order of 20m. The rocks in this sequence deteriorate rapidly on exposure to the atmosphere.

DEGREE OF WEATHERING (AS1726-1981)

Fresh	Slightly W	Moderately W	Completely W	Seams & Crush Zones
99.9%		0.5m in 385m of core		7.92m in 3.45m of core

ROCK SUBSTANCE STRENGTH (AS1726-1981)

<2 MPa	2 to 6 MPa	6 to 20 MPa	20 to 60 MPa	>60 MPa
		Lowest offshore value 11.5 MPa Onshore (North Head) $\chi = 8.1$ $s = 0.9$	Offshore $\chi = 30.8$ MPa $s = 13.5$ MPa(21)	Highest offshore value 65 MPa

ROCK MASS PERMEABILITY DATA

μL	Length of Borehole
0.01	139m
0.5	153m
1 to 2	108m
5 to 12	17m
37	5m

Geometric mean = 0.2μL

HYDROSTATIC HEAD	REGIONAL STRESS FIELD
	Assume $\sigma_h NS = 2.5\sigma_v$ $\sigma_h \omega E = 1.5\sigma_v$

JOINT SETS

Source of Information: References 10, 11, 14

Set 1	Set 2	Set 3	Set 4
Bedding partings not well developed	Tension?	Tension?	Depositional compaction and relict features

ORIENTATION OF JOINT SETS (True North)

	Set 1	Set 2	Set 3	Set 4
Dip	0.5°W	90° ± 15°	90° ± 15°	15 to 75°, steeper in upper grey zone, flatter near base of claystone beds. Data insufficient to define strike
Strike	0°	80° ± 10°	350° ± 10°	

EFFECTIVE JOINT SPACING (m)

References

Set 1	Set 2	Set 3	Set 4
0.1 to 1m Overall 0.3m	0.3 to 1m Overall 0.5m	0.3 to 1m Overall 0.5m	50mm to 0.5m where developed

CONDITION OF JOINTS

Set 1	Set 2	Set 3	Set 4
Undulose, rough, fresh joint wall rock, frequent clay seams, continuous	Planar, tight, clean, fresh joint wall rock. Continuity ≈2m but some greater	Planar, tight, clean, fresh joint wall rock. Continuity ≈2m but some greater	Planar, rough, striated but numerous polished slickensided, not continuous

RQD

Of 340m cored	77%	with RQD >90%
	13%	with RQD >75% <90%
	8%	with RQD >50% <75%
	2%	with RQD >25% <50%

TABLE XID
ROCK MASS DATA - BULGO SANDSTONE

GEOLOGICAL DESCRIPTION

Massive to laminated, white to grey-green and brown, fine to very coarse grained sandstones with siltstone laminations and bands and occasional claystone layers. The sandstones may be current bedded with dips to 30°. The siltstone and claystone beds generally vary from 0.1 to 2m but there are claystone members to 12m.

MAJOR GEOLOGICAL FEATURES

Crush zones and minor faulting dipping from 25° to 70° may be anticipated at a vertical spacing of the order of 20m. Also occasional bedding plane crush zones.

DEGREE OF WEATHERING (AS1726-1981)

Boreholes NO1, NO3, MO3, NO4B

Fresh	Slightly W	Moderately W	Completely W	Seams & Crush Zones
100%				10.14m in 312m of core

ROCK SUBSTANCE STRENGTH (AS1726-1981)

<2 MPa	2 to 6 MPa	6 to 20 MPa	20 to 60 MPa	>60 MPa
	lowest value 18.8 MPa	Lowest value 18.8 MPa	Offshore: $\chi = 33$ MPa $s = 15.3$ Onshore: $\chi = 39$ MPa $s = 20.4$ Gordeaux Tunnel $\chi = 55$ MPa	Highest value 75.6 MPa

ROCK MASS PERMEABILITY DATA

µL	Length of Borehole	
0.01	11m	Geometric mean = 0.6µL
0.05	205m	
2	20m	
17 to 57	15m	

HYDROSTATIC HEAD	REGIONAL STRESS FIELD
	Assume $\sigma_h NS = 2.5\sigma_v$ $\sigma_h \omega E = 1.5\sigma_v$

JOINT SETS

Source of Information: References 10, 11, 14

Set 1	Set 2	Set 3	Set 4
Bedding	Tension	Tension	

ORIENTATION OF JOINT SETS (True North)

	Set 1	Set 2	Set 3	Set 4
Dip	0 to 5°	90° ± 10°	90°± 10°	Minor trend at 140°
Strike	0°	100° ± 10°	10° ± 10°	

EFFECTIVE JOINT SPACING (m)

References 4, 10

Set 1	Set 2	Set 3	Set 4
0.5 to 5 in sandstones	2 to 15m Average ≈4m	2 to 15m Average ≈4m	

CONDITION OF JOINTS

Set 1	Set 2	Set 3	Set 4
Planar, clean, occasional crush zones, infrequent seams (spacing >20m)	Planar, clean, fresh wall rock. Continuity >>2m but some greater	Planar, clean, fresh wall rock. Continuity >>2m but some greater	

RQD

Overall, of 360m cored	78%	with RQD >90%
	18%	with RQD >75% <90%
	3.5%	with RQD >50% <75%
	0.5%	with RQD >25% <50%

7.1 Narrabeen Group

7.1.1 Bulgo Sandstone

Core from the outfall tunnel boreholes was tested by both the Water Board and the University of New South Wales. The results are summarised in Table XII.

Table XII
Unconfined Compressive Strength
Bulgo Sandstone - Ocean Outfall Tunnels

Testing Authority	No. of Specimens	Unconfined Compressive Strength MPa		
		Range	Mean	Std Deviation
Water Board	18	8 to 56	33.0	15.3
Unisearch	8	19 to 76	39.0	20.4

Thirteen specimens from two boreholes were tested from the Avon Tunnel site. Testing included measurement of unconfined compressive strength, Brazilian tensile strength and Young's modulus. The results are summarised in Table XIII.

Table XIII
Test Results - Bulgo Sandstone
Avon Tunnel

	Range	Mean
Bulk Density - t/m^3	2.37 to 2.72	2.58 (11)
Moisture Content %	1.7 to 6.3	4.0 (15)
Unconfined Compressive Strength MPa	6 to 56	36.2 (13)
Brazilian Tensile Strength MPa	2.7 to 4.9	3.5 (11)
Young's Modulus GPa	6 to 19	11.4 (6)

NOTE: Bracketed numbers indicate number of specimens tested

During excavation of the ocean taps (short tunnels connecting the main tunnel to the sea bed risers) at North Head and Malabar, a substantial amount of strength, cuttability and petrographic testing was undertaken.

Thirty-nine core samples of fine to medium grained lithic sandstone were tested at North Head and 70 at Malabar. The UCS results are summarised in Table XIV.

Table XIV
Ocean Taps

Parameter	North Head	Malabar
UCS (MPa)		
mean	40.9	72.4
SD	14.7	32.4
Moisture Content (%)		
mean	3.5	2.9
SD	0.5	0.9
Dry Density (t/m^3)		
mean	2.4	2.5
SD	0.1	0.1

At Malabar the ocean taps passed through an interlayered sequence of sandstone, siltstone and claystone, with sandstones typically comprising more than 60% of the sequence. The sandstones included some surprisingly strong material. Four specimens gave strengths of greater than 125 MPa. These had moisture contents of between 1.6% and 1.7% and dry unit weights of 2.57 t/m^3.

The relationship between UCS and moisture content from the ocean tap data is given in Figure 3.10 and suggests that the Malabar and North Head results all belong to the same population, notwithstanding the higher strength at Malabar.

7.1.2 Bald Hill Claystone

Core from the offshore boreholes for the outfall tunnels was tested immediately after recovery by the Water Board. The results may be summarised as follows:

Number of samples	21
Mean unconfined compressive strength	30.8 MPa
Standard deviation	13.5 MPa
Range	10.8 MPa to 65.0 MPa

Two samples were tested from one of the boreholes drilled for the proposed Avon Tunnel and both gave a strength of 21 MPa. The bulk densities of the two samples were 2.77 t/m^3 and 2.65 t/m^3 at moisture contents of 3.5% and 3.1%. Brazilian tensile strengths of 4.4, 2.1 and 1.3 MPa were measured.

Tests conducted by Bhattacharyya for the Water Board in connection with the Enquiry into Mining Under Stored Waters gave the following results:

Mean unconfined compressive strength	39 MPa
Strain to failure	3.3 to 4.4 millistrain
Mean tensile strength	2.3 MPa

I am not aware of any durability testing of the Bald Hill Claystone but from observations of exposures and experience in the outfall tunnels it is clear that the material does not swell significantly and slaking is a slow process.

7.1.3 Newport Formation

Extensive testing was conducted at the Mangrove Creek damsite and Table XV gives data from two of the boreholes, one at the dam and one at the quarry.

The results in Table XV show the sensitivity of the strength of these sandstones and siltstones to the degree of saturation.

Modulus values were measured on four specimens of sandstone and silty sandstone and the results are summarised in Table XVI.

At the site of the proposed Avon Tunnel (see Figure 3.1) the Newport Formation has a thickness of only about 6m. It consists of grey siltstone/shale and laminated siltstone/sandstone with a bed of sandstone 0.3m to 3m thick in the middle to upper part. Tests on a single specimen gave:

Bulk density	2.57 t/m^3
Moisture content	2.1%
Unconfined strength	78 MPa
Brazilian strength	4.4 MPa

Table XV
Test Data from the Mangrove Creek Damsite (Newport Formation

Rock Type	Dry Density t/m3	Unconfined Strength	
		Dry MPa	Wet MPa
Sandstone, moderately weathered	2.11	27	9
Sandstone, slightly weathered	2.04	33	9
Sandstone, highly weathered	2.03	24	22
Sandstone/siltstone, slightly weathered	2.30	39	-
Sandstone, slightly weathered	2.26	54	16
Sandstone, slightly weathered	2.23	52	16
Sandstone, highly weathered	2.30	39	25
Sandstone, moderately weathered	2.27	38	27
Sandstone, fresh	2.23	54	32
Sandstone/siltstone, fresh	2.55	103	40
Sandstone, fresh	2.22	46	26
Sandstone, fresh	2.35	62	34
Siltstone, fresh	2.24	51	29
Siltstone, fresh	2.41	74	27
Siltstone, fresh	2.39	86	32
Siltstone/claystone, fresh	2.60	118	34
Sandstone, fresh	2.26	59	32
Sandstone, moderately weathered	2.09	26	14
Sandstone, moderately weathered	2.20	59	29
Siltstone, fresh	2.69	99	29
Sandstone, fresh	2.28	62	29

Table XVI
Modulus Values of Narrabeen Rocks from Mangrove Creek Damsite (saturated)

Material	Unconfined Strength MPa	Young's Modulus MPa
Sandstone	34	5700
Sandstone	39	9900
Siltstone	28	8500
Siltstone	35	22500

A summary of the UCS tests on the Newport rocks from the ocean outfall tunnels is given in Table XVII.

Table XVII
Unconfined Compressive Strength
Newport Formation - Ocean Outfall Tunnels

Testing Authority	No. of Specimens	Unconfined Compressive Strength MPa		
		Range	Mean	Std Deviation
Water Board	12	28 to 80	49.7	13.5
Unisearch	13	21 to 74	45.6	16.9

7.2 Hawkesbury Sandstone

Substance, Strength and Deformation Properties

A reasonably large amount of information on the engineering properties of the Hawkesbury Sandstone is given in Pells (1985) and therefore only summaries of key properties are given here.

Figure 3.11 presents strength and modulus measurements on samples of fresh and slightly weathered material from a broad range of sites. It can be seen that saturated UCS values mostly lie in the range 20 MPa to 40 MPa and seldom exceed 45 MPa. Both strength and stiffness are affected by the degree of saturation, as illustrated by the data in Table XVIII. Strength is always reduced but the effect of saturation, or conversely drying, on stiffness is variable.

Table XVIII
Comparison of Dry and Saturated Moduli
of Hawkesbury Sandstone

Location	Material (all medium grained)	Tangent Modulus @ $0.5\sigma_c$		Ratio Es/Ed	Ratio $\frac{\text{Dry Strength}}{\text{Wet Strength}}$
		Dry Ed (MPa)	Saturated Es (MPa)		
Bondi	Massive, fresh	13.8	8.1	0.59	0.45
Waterloo	Laminated, fresh	10.3	11.0	1.07	0.69
Waterloo	Bedded, fresh	11.6	8.7	0.75	0.59
Kirribilli	Laminated, SW	4.8	5.0	1.04	0.61
Kirribilli	Thin bedded, SW	12.0	8.4	0.70	0.55
Fr Forest	Thin bedded, MW	12.7	8.6	0.68	0.57
Elizabeth St	Thin bedded, fresh	11.7	13.9	1.19	0.68

The triaxial strength parameters are not of particular relevance to most engineering projects but as a matter of record it is worth noting the following test data:

Peak strength of intact sandstone $c' = 2$ MPa to 6 MPa
$\phi' = 41^{o}$ to 53^{o}

Peak strength of clean rough joints $c' = 1$ MPa to 4 MPa
$\phi' = 33^{o}$ to 36^{o}

As broad guides the relationships between UCS and both Point Load Index (I_{s50}) and Brazilian tensile strength (σ_t) results are as follows:

UCS = (15 to 30) I_{s50}
(use 20 I_{s50} as field guide)
UCS = (12 to 15) σ_t

Creep behaviour is discussed in Pells (1985) and usually is not an issue in tunnelling projects, although significant creep settlements were recorded above the cavern of the Sydney Opera House underground parking station.

For foundation design it is suggested that the long term modulus be taken as about 70% to 80% of the short term value. However, as significant uncertainties exist regarding the ratio of insitu mass modulus to laboratory measured values it is the writer's opinion that this reduction for creep effects is rather academic in most cases.

Hardness, Cuttability and Abrasivity Data

Much specialised testing has been done for evaluating rock excavation characteristics for projects such as the ocean outfall tunnels, the Sydney Harbour Tunnel (SHT) and the Blue Mountains sewer tunnels. It is not feasible to include all the data here and I have chosen to summarise, in Tables XIX and XX the SHT data as being reasonably typical of the Hawkesbury. These tables include data on material ranging from moderately weathered through to fresh (see also Figure 3.11).

Table XIX
Summary of Test Data from North Side SHT
(saturated specimens)

Property	Unit	No of Tests	Range	Mean	Std Deviation
UCS	MPa	55	10 to 46	24.5	78
S-wave velocity	m/sec	10	1100 to 2170	1560	300
P-wave velocity	m/sec	10	2000 to 3340	2710	420
NCB cone indentor		55	0.95 to 3.74	2.06	0.9
Specific energy	MJ/m^3	3	6.8 to 10.3	8.5	2.0
Cutter wear	mg/m	3	6.8 to 8.1	7.5	0.6
Shore hardness		10	13 to 19	16.2	30
Goodrich cuttability		10	200 to 650	362	142
Goodrich wear No.		10	11.3 to 16.7	13.1	2.0
Cherchar abrasiveness		10	2.0 to 5.8	3.9	1.5
Durete abrasivity		10	9 to 45	17.3	10.2

Table XX
Summary of Test Data from Overwater and South Side SHT (all on saturated samples)

Property	Unit	No of Tests	Range	Mean	Std Deviation
UCS	MPa	43	11 to 37	22.9	7.8
NCB cone indentor		36	0.4 to 4.7	1.55	1.0
Specific energy	MJ/m3	7	9.6 to 13.9	11.4	1.5
Cutter wear	mg/m	7	1.6 to 5.0	3.3	1.3
Abrasive wear	mg/m	8	0.9 to 1.2	1.07	0.1
Goodrich drillability		6	100 to 380	240	110
Goodrich wear No.		6	12.6 to 31.5	20.4	8.3
Cherchar abrasiveness		6	2.1 to 6.3	4.0	1.4
Durete abrasivity		6	4.5 to 31.0	21.0	10.5

Mass Modulus Values

Pile load test results, plate test data and monitoring of building settlements suggest that insitu modulus values for different classes of Hawkesbury Sandstone (see Pells et al, 1978 for definition of the classes) may be taken as per Table XXI.

Table XXI
Insitu Deformation Moduli

Sandstone Class	Insitu Modulus	
	As Ratio of Unconfined Strength (E/q_u)	Probable Range (MPa)
1	90-100 (90)	2000-4000 (2500)
2	80-90 (80)	1000-2000 (1500)
3	60-80 (70)	400-800 (600)
4	30-60 (40)	100-400 (200)
5	N/A	40-200 (80)

NOTE: Numbers in brackets are suggested for design purposes.

Measurements of movements around deep basements in typically Class III or better sandstone in the Sydney CBD have indicated that the mass modulus is typically in the range of 2000 MPa to 3000 MPa. This at least partially represents an unloading modulus and probably explains why the range is at the high end of the values given in Table XXI.

Roof sag and subsidence calculations for the Opera House parking cavern were based on the following moduli based on pressuremeter testing:

6m to 8m of Class II sandstone in roof:	E = 1500 MPa
35m depth of Class I/II sandstone to base of cavern	E = 3500 MPa

Actual settlements were very close to the predictions (Pells, Mikula & Parker, 1993), indicating these modulus values to be quite appropriate.

7.3 Wianamatta Shales

As discussed in Section 2 of this Part, the Wianamatta Shales contain a wide variety of materials ranging from claystones to medium grained sandstones. However, the most important materials from the engineering viewpoint are the Ashfield and Bringelly Shales, for which useful data is given by Won (1985).

Figure 3.12 reproduces the UCS data presented by Won and shows that, while mean strengths are in the range 25 to 35 MPa, both the Ashfield and Bringelly Shales contain significant amounts of material with UCS in the range 50 to 80 MPa.

A very useful analysis of UCS data from weathered and fresh Wianamatta Shales is given by Ghafoori, Airey & Carter (1993). This showed a good correlation between UCS and natural moisture content as shown in Figure 3.13. They demonstrate therefore that a reasonable prediction of UCS may be obtained using the equation:

$$\mathrm{UCS} = 60e^{-0.415m}\ \mathrm{MPa} \qquad \ldots\ 7.3(i)$$

where m = moisture content as %

Won (1985) presents data which shows that laboratory core modulus values lie in the range 30 to 130 times E. Therefore, if one adopts a multiplier of 60 for design purposes, one may take:

$$E = 3600e^{-0.415m}\ \mathrm{MPa} \qquad \ldots\ 7.3(ii)$$

The fresh shales show minor slaking characteristics and are not significant problem rocks with regard to durability, either when exposed in cuttings or in tunnels.

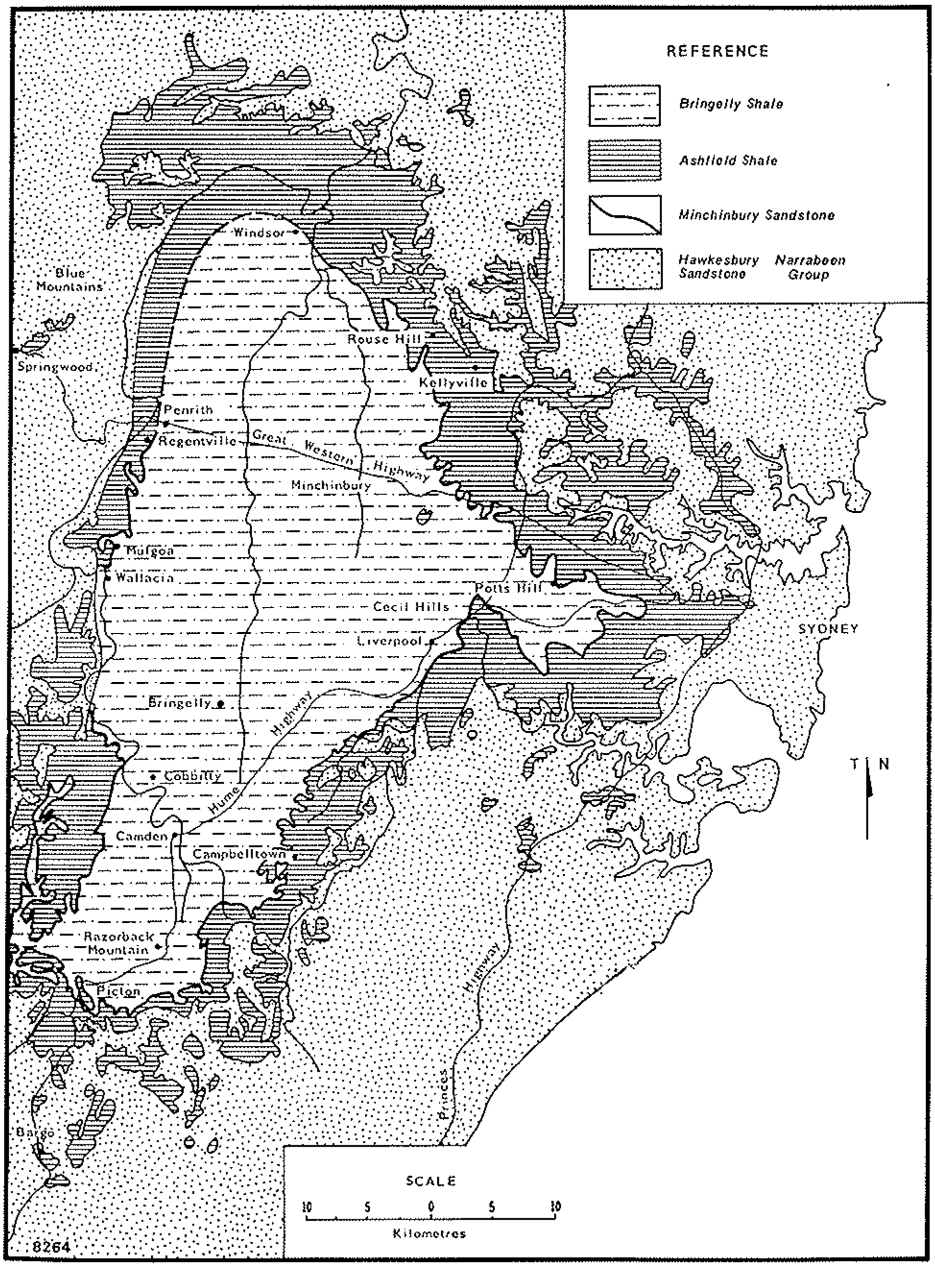
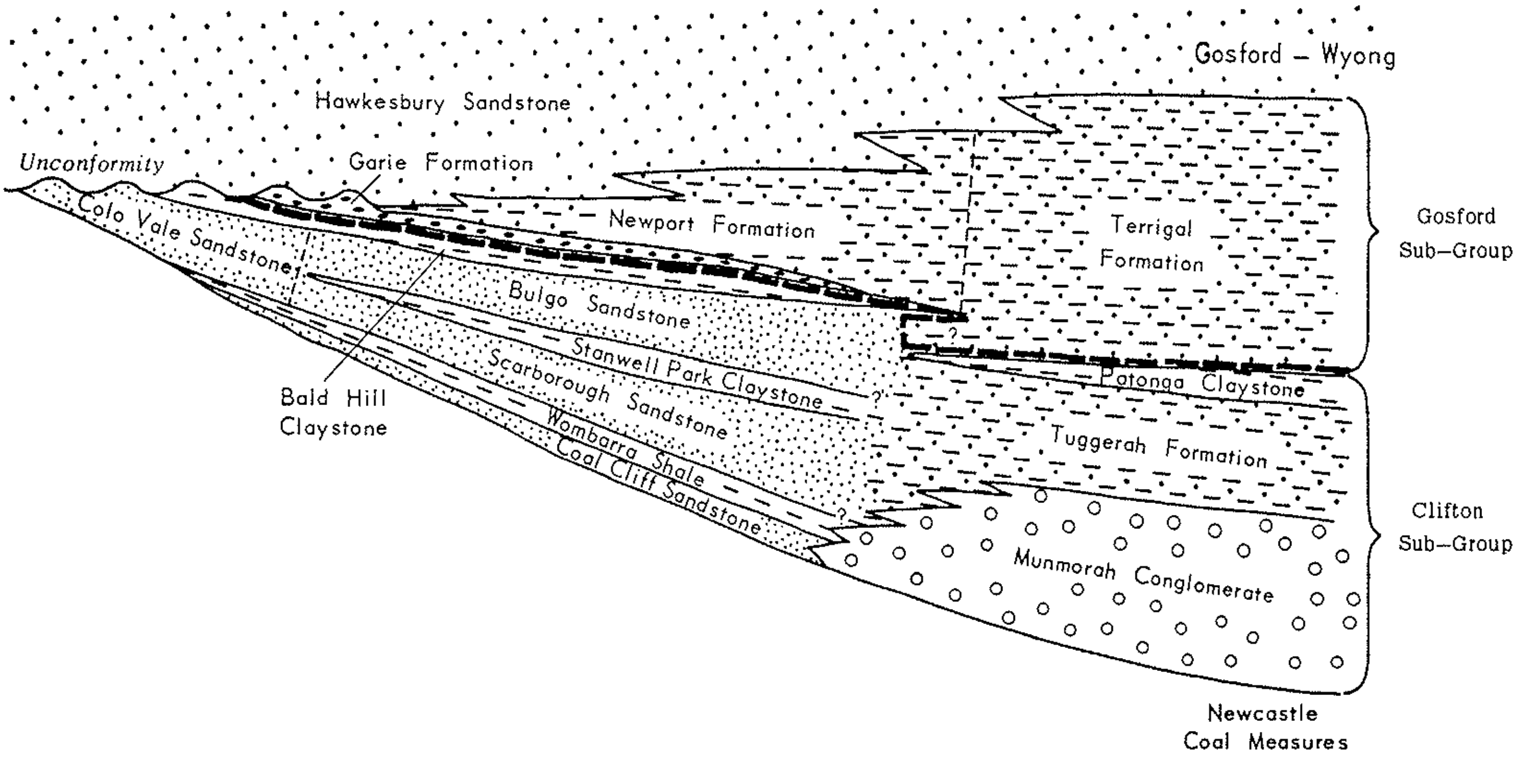
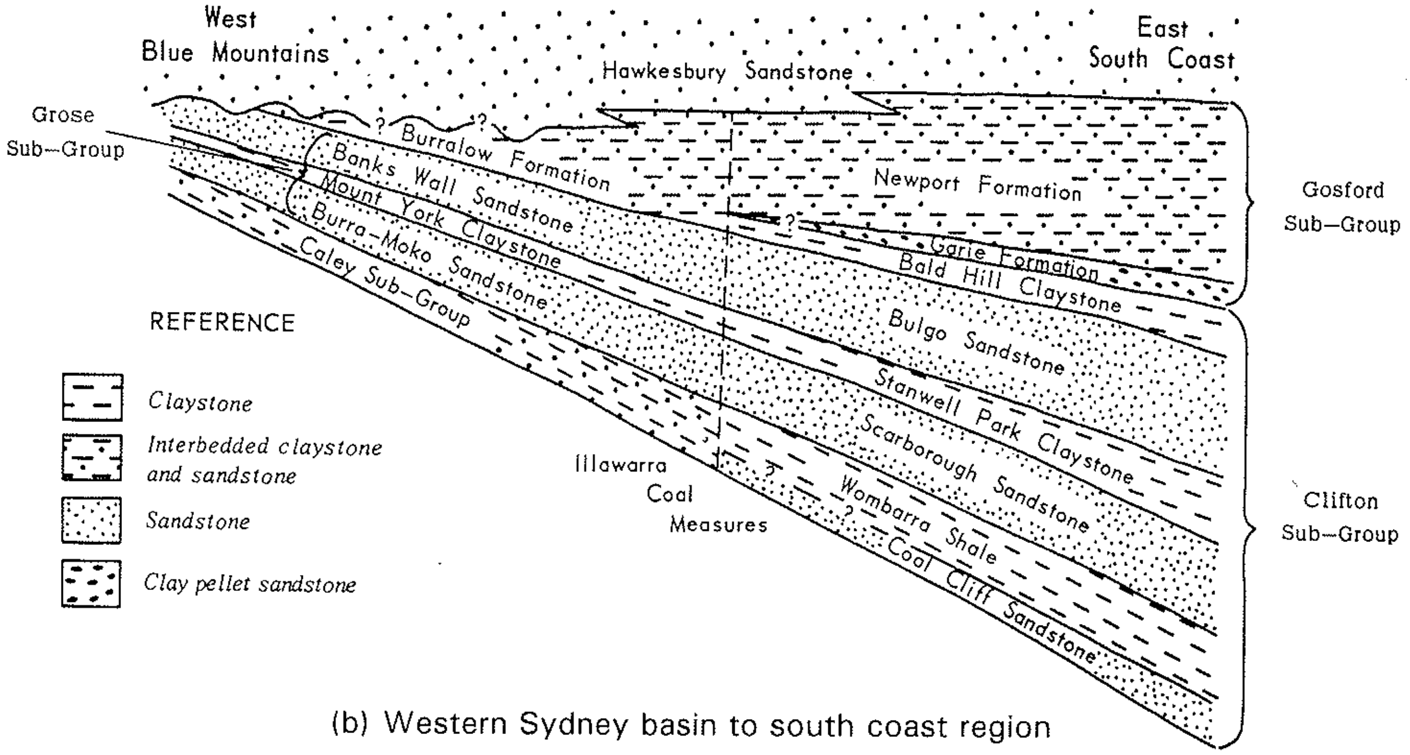


FIGURE 3.1 : TRIASSIC GEOLOGY OF THE SYDNEY REGION
(from Bulletin 25 of Geological Survey of NSW)



(a) South coast to Gosford district



(b) Western Sydney basin to south coast region

FIGURE 3.2 : NOMENCLATURE OF NARRABEEN GROUP
(from Herbert 1970)

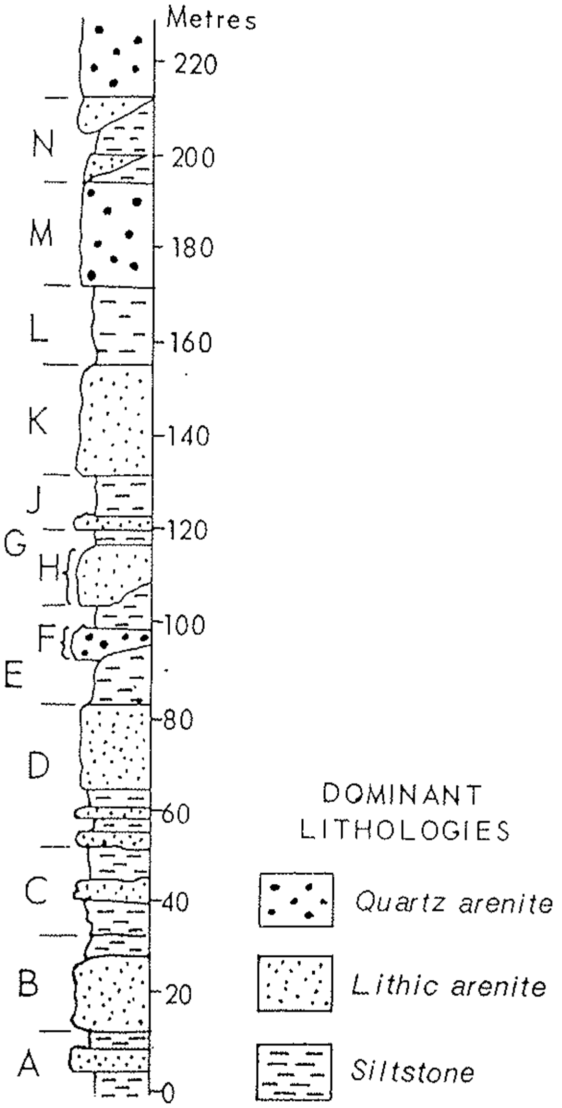


FIG.3.3 SIMPLIFIED VERTICAL PROFILE OF TERRIGAL FORMATION

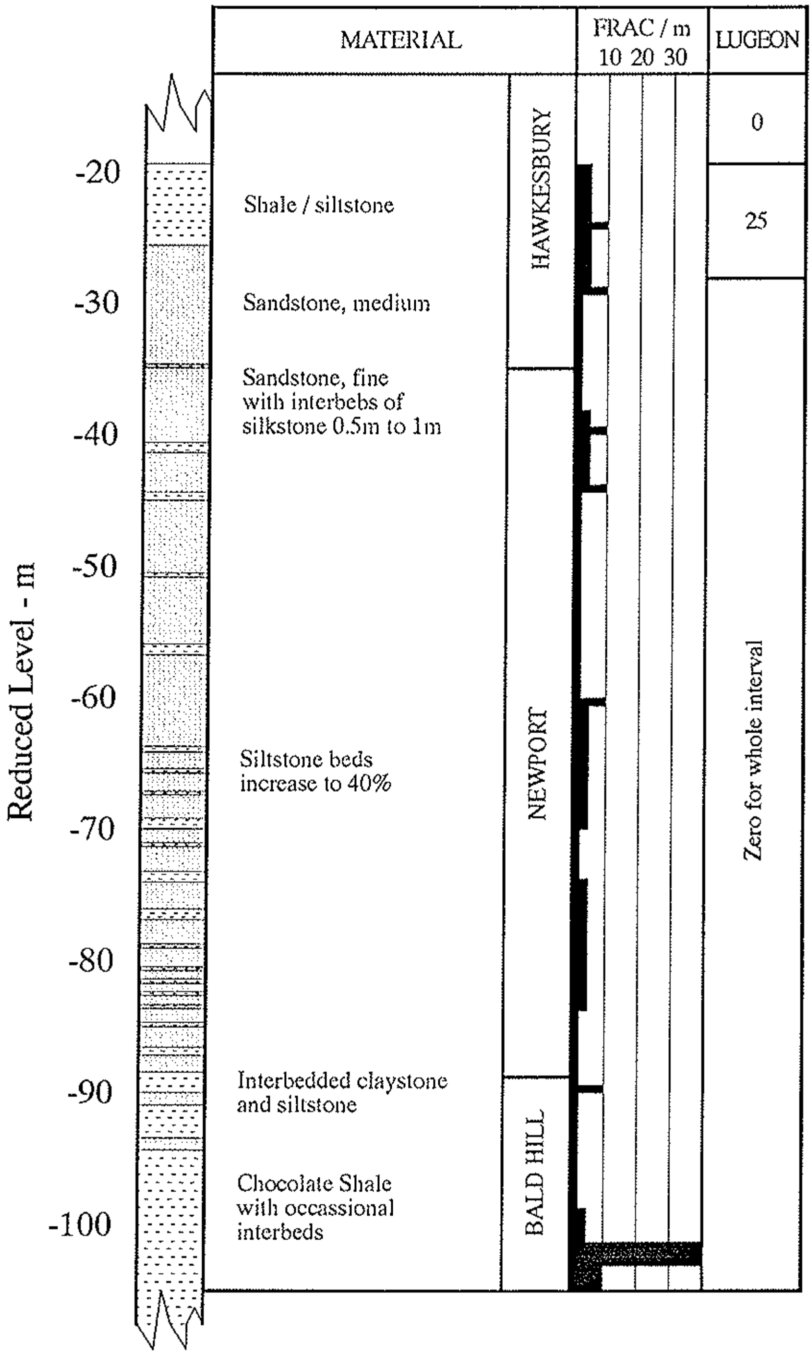


FIG.3.4 SUMMARY OF BOREHOLE NH1 AT NORTH HEAD

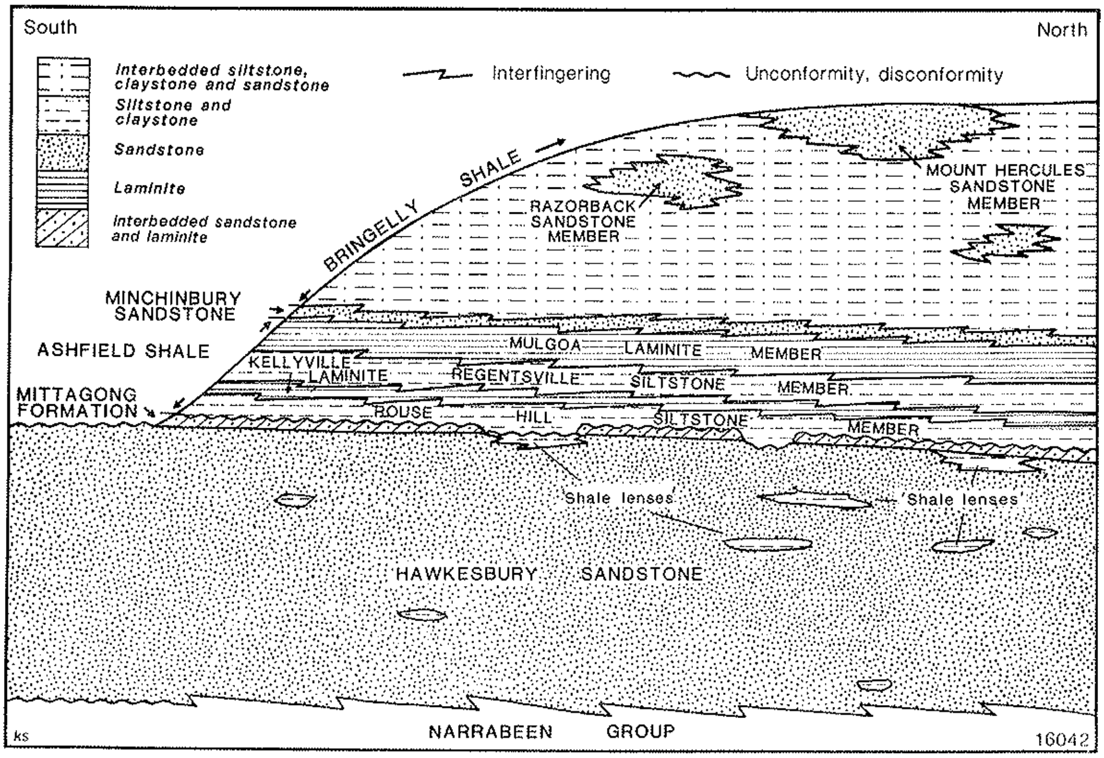


FIGURE 3.5 : UNITS OF THE WIANAMATTA GROUP
(from Geology of the Wollongong & Port Hacking sheets)

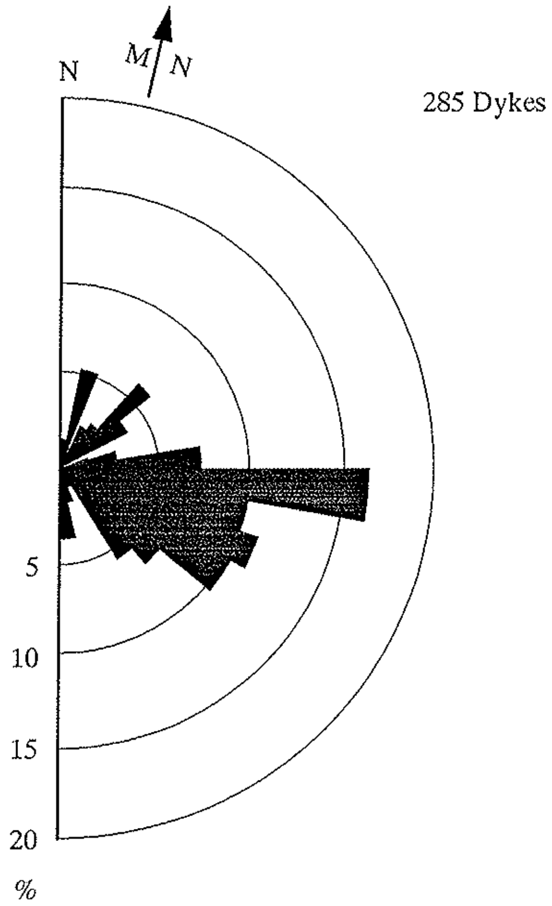


FIG.3.7 ROSE DIAGRAM OF STRIKE DIRECTIONS OF 285 DYKES IN GREATER SYDNEY REGION

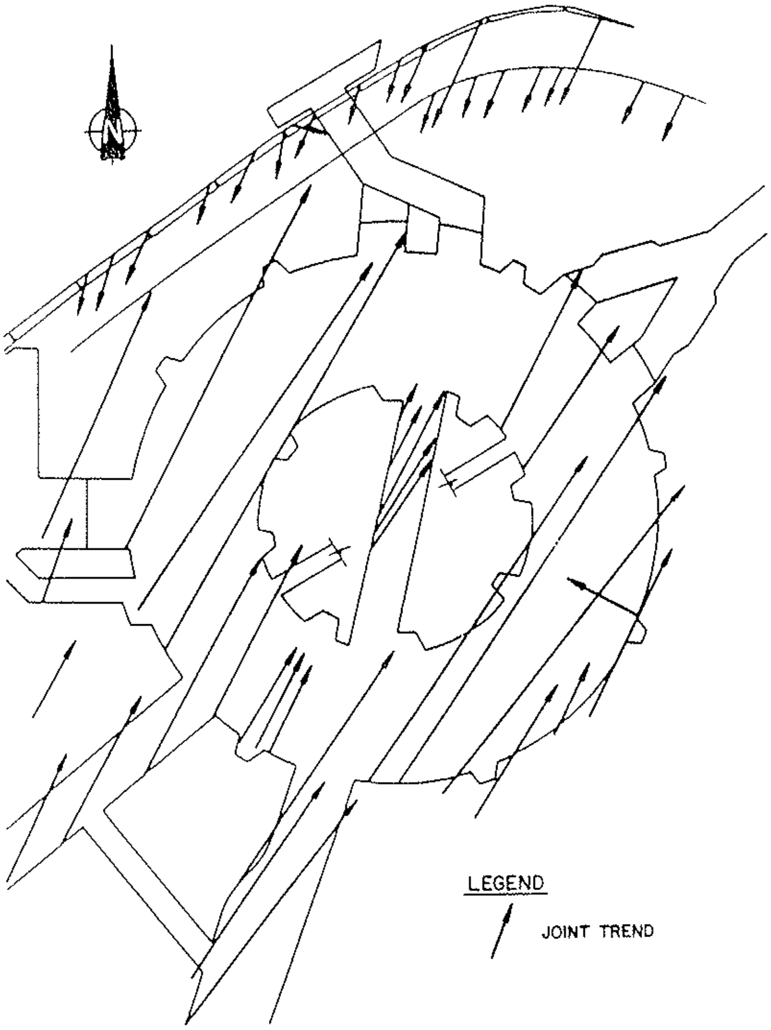


FIG.3.8 JOINTS MAPPED AT OPERA HOUSE PARKING STATION

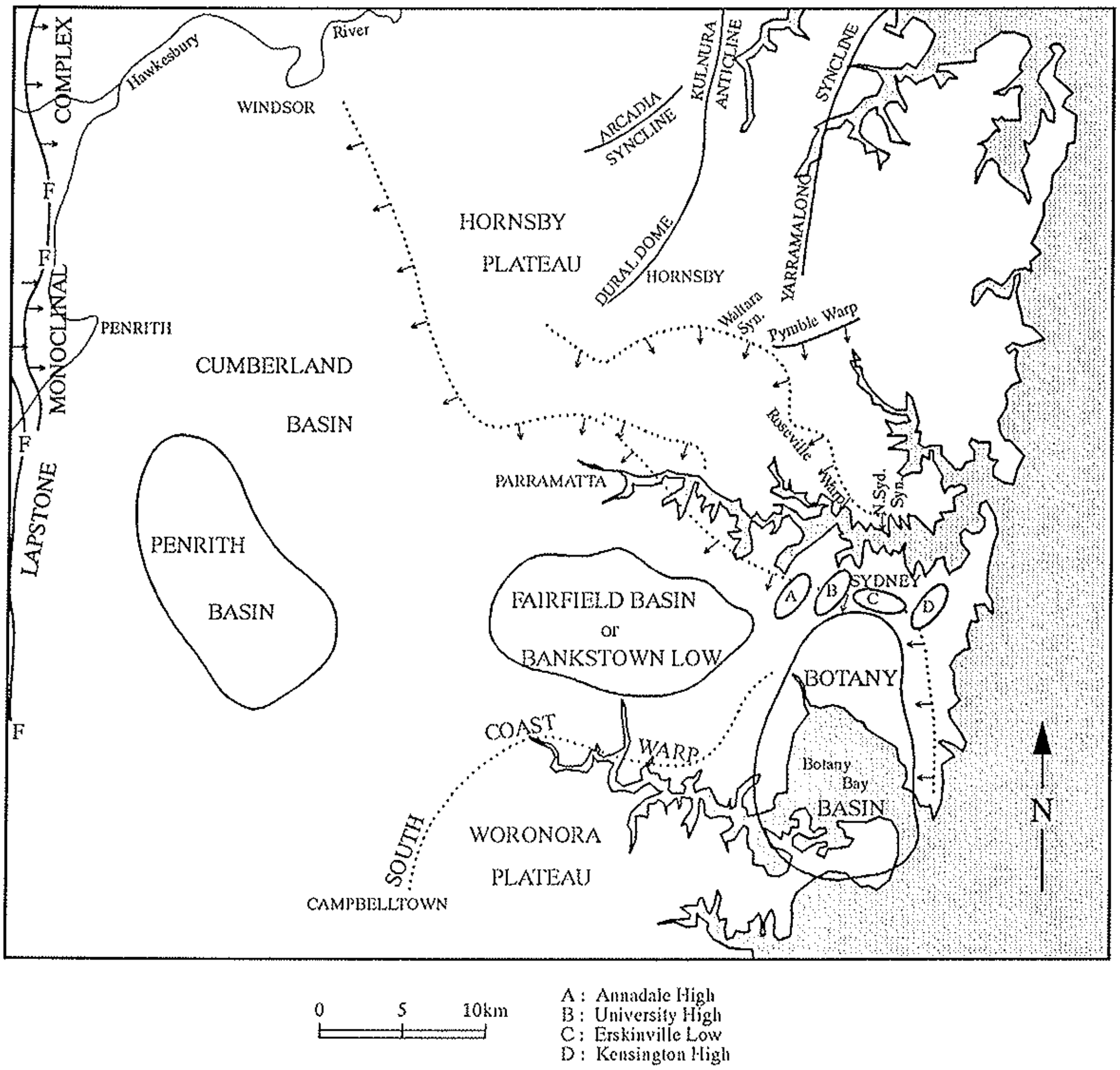


FIG.3.9 MAJOR STRUCTURAL FEATURES OF THE SYDNEY AREA

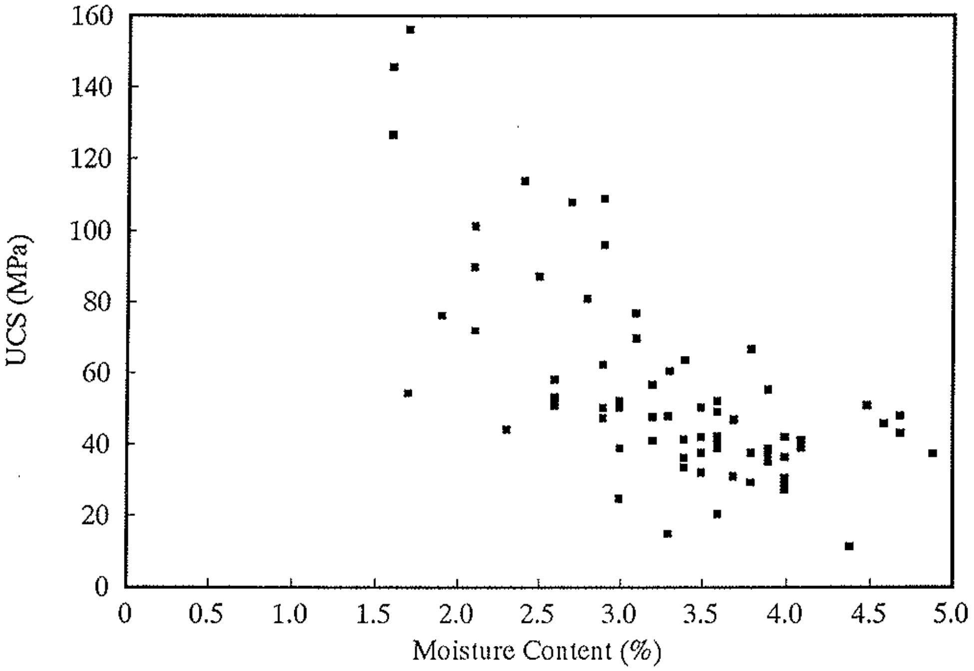


FIG.3.10 UCS RESULTS FROM BULGO SANDSTONE (FRESH) AT OCEAN TAPS FOR MALABAR AND NORTH HEAD

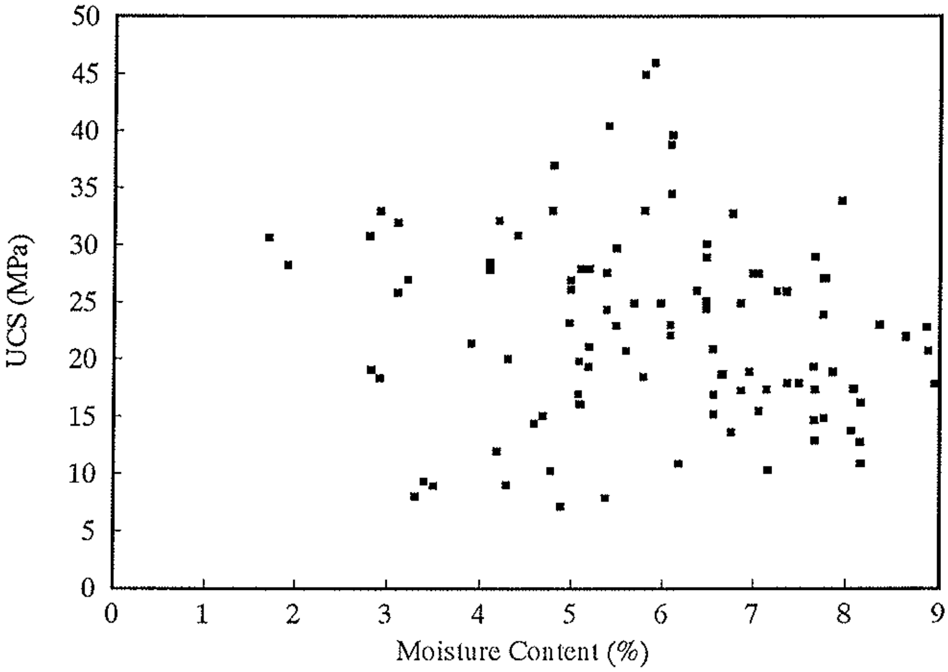
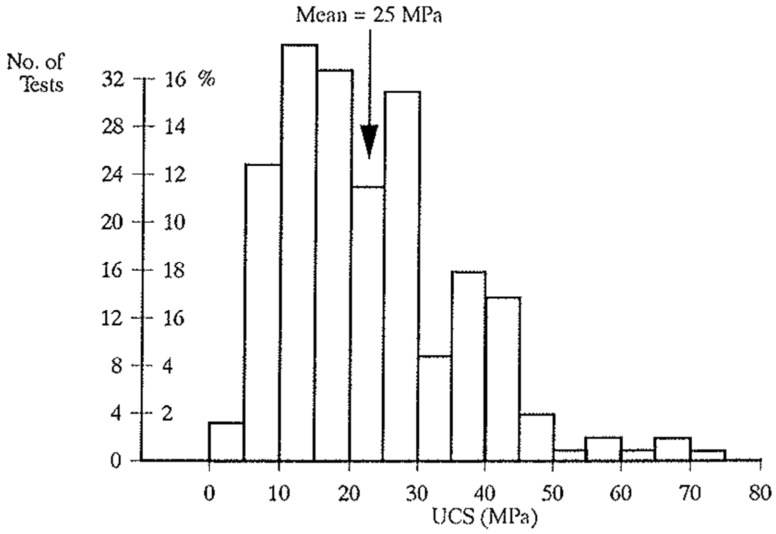
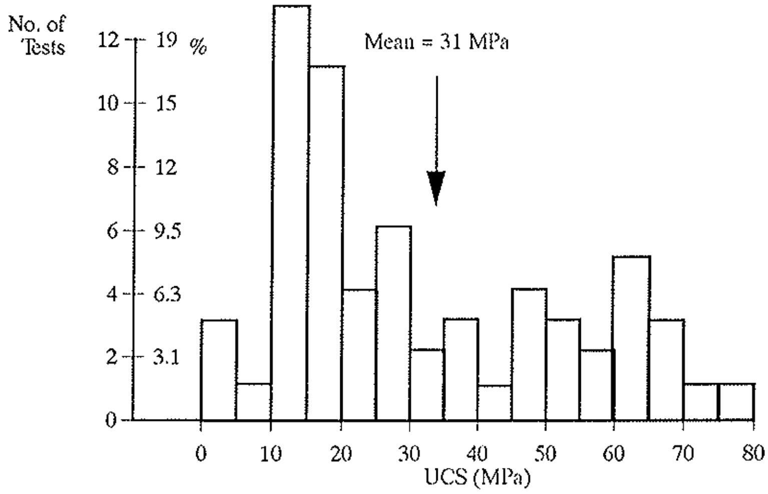


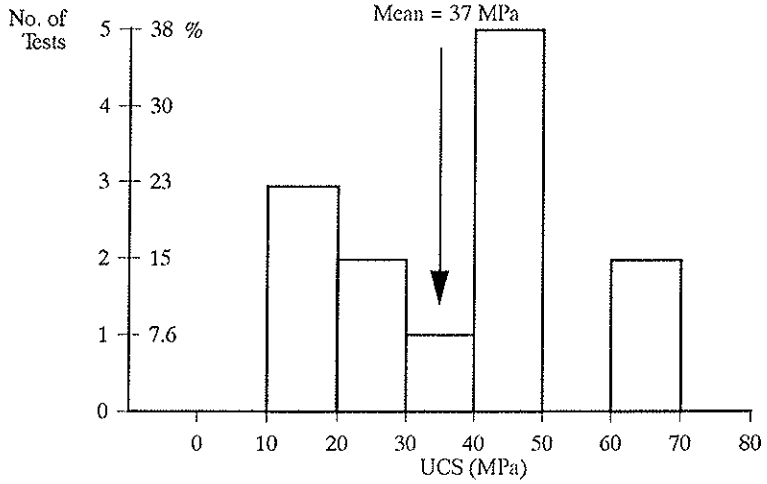
FIG.3.11 UCS TESTS ON HAWKESBURY SANDSTONE FROM HARBOUR TUNNEL (INCLUDES HW TO FRESH MATERIAL)



Ashfield Shale (grey, fresh)



Bringelly Shale (shales and siltstones)



Bringelly Shale (fine grained sandstone)

FIG.3.12 UCS DATA FOR WIANAMATTA GROUP ROCKS
(from Won, 1980)

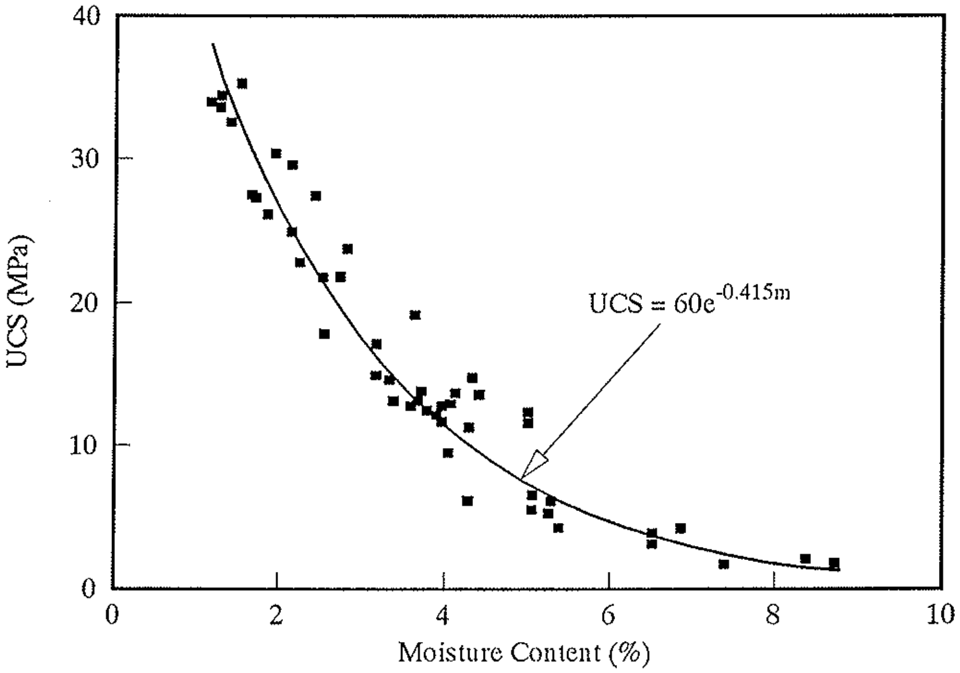


FIG.3.13 RELATIONSHIP BETWEEN UCS AND MOISTURE CONTENT FOR ASHFIELD SHALE
(From Ghafoori et al)

ENGINEERING CLASSIFICATION OF SHALES AND SANDSTONES IN THE SYDNEY REGION - A SUMMARY GUIDE

(from Pells, Douglas, Rodway, Thorne, McMahon, 1978)

The classification system is based on rock strength and defects using three parameters as set out below. The lowest rating of any one factor defines the class.

CLASSIFICATION FOR SHALE

Class	Unconfined Compressive Strength qu (MPa)	Fracturing	Allowable Defects
I	<16	slightly fractured	2%
II	7 to 16	fractured	4%
III	2 to 7	fractured to highly fractured	8%
IV	not normally measurable	highly fractured or fragmented	25%
V	not normally measurable	highly fractured or fragmented	-

CLASSIFICATION FOR SANDSTONE

Class	Unconfined Compressive Strength qu (MPa)	Fracturing	Allowable Defects
I	>24	slightly fractured or unbroken	1.5%
II	12 to 24	slightly fractured	3%
III	7 to 12	fractured	5%
IV	2 to 7	fractured	10%
V	not normally measurable	highly fractured or fragmented	-

FRACTURING

The terms relate to spacing of natural fractures in NMLC, NQ and HQ diamond drill cores and have the following definitions:

Fragmented:	Core is comprised primarily of lengths less than 20mm and mostly of widths less than the core diameter (RQD <10).
Highly Fractured:	Core lengths are generally less than 20 to 40mm with occasional fragments (RQD 10 to 40).
Slightly Fractured:	Core lengths are generally 300 to 1000mm, with occasional longer sections and occasional sections of 100 to 300mm (RQD >70).

ALLOWABLE DEFECTS

Defects are defined as sub-horizontal clay seams, fragmented zones or highly weathered joints and the tolerances suggested in the tables relate to a defined zone of influence. For pad footings, the zone of influence is defined as 1.5 times the least footing dimension. For socketed footings, the zone includes the length of the socket plus a further depth equal to the width of the footing. For tunnel or excavation assessment purposes the defects have been assessed over a length of core of similar characteristics.

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