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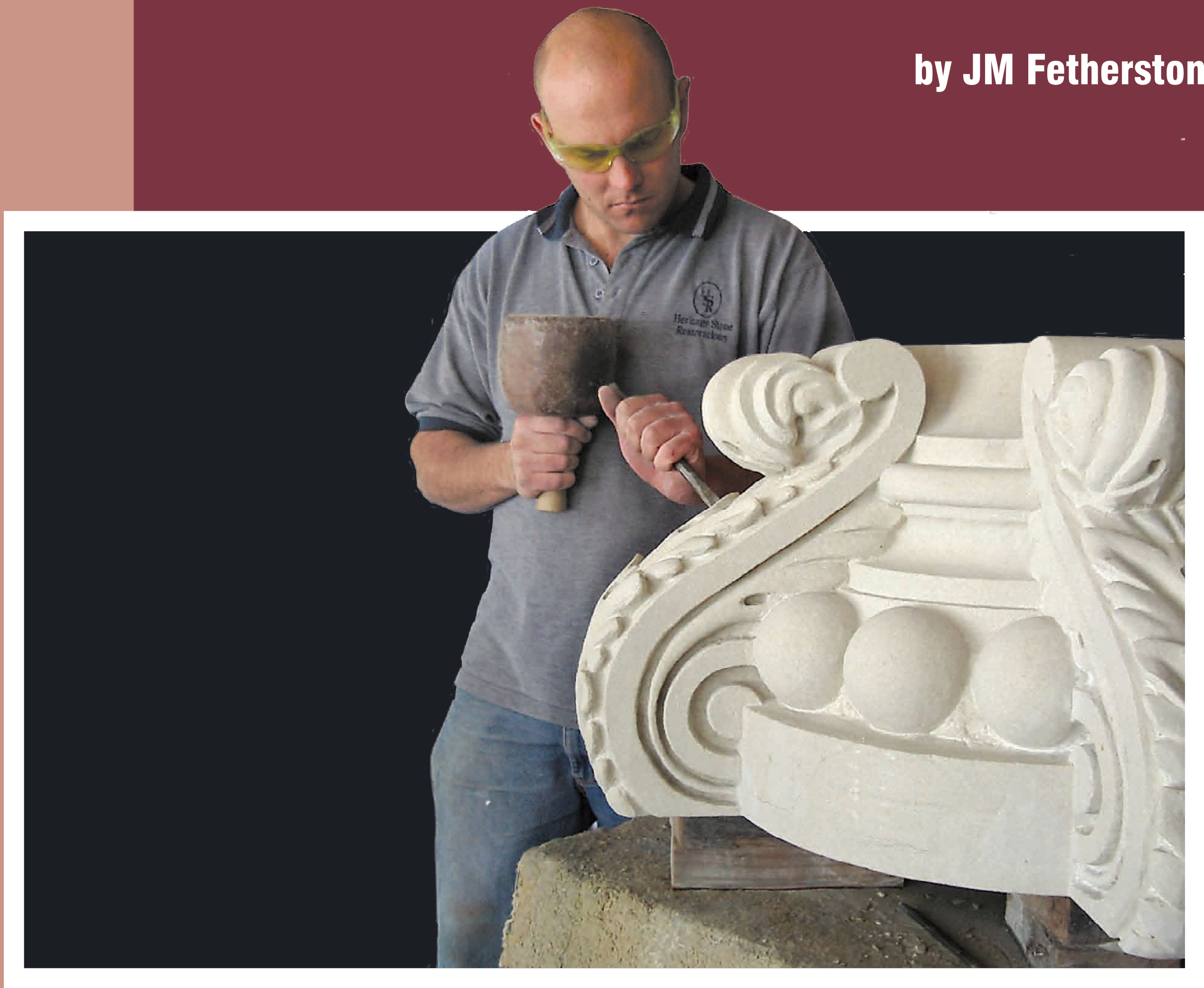
Department of
Industry and Resources

DIMENSION STONE IN WESTERN AUSTRALIA

Volume 1

INDUSTRY REVIEW AND DIMENSION STONES OF THE SOUTHWEST REGION

by JM Fetherston



Geological Survey of Western Australia

DIMENSION STONE IN WESTERN AUSTRALIA

VOLUME 1

INDUSTRY REVIEW AND DIMENSION STONES OF THE SOUTHWEST REGION

FRONTISPIECE

Saint Patrick's Basilica, Fremantle. Constructed between 1900 and 1916, the walls are blocks of Tamala Limestone, and the spires, flying buttresses, window dressings, and main entrance are carved from Donnybrook Sandstone

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Information Centre
Department of Industry and Resources
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Cover photograph:
A banker mason carving an elaborate urn base in white Donnybrook Sandstone from the southwest of Western Australia (photo courtesy Heritage Stone Restorations, and J Mann)

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Dimension stone in Western Australia

Volume 1

Industry review and dimension stones of the Southwest Region

by

JM Fetherston

Abstract

Dimension stone is a natural rock material quarried for the purpose of obtaining blocks or slabs that meet specifications as to size and shape suitable for use as building stone, ornamental stone, and monumental stone. Dimension stones mostly fall into six major commercial categories: granite and metamorphic equivalents, black granite, sandstone, limestone, marble, and slate.

The Southwest Region of Western Australia, within a radius of 300 km from Perth, contains many high-quality and visually attractive dimension stones from the Archean Yilgarn Craton, Proterozoic Leeuwin Complex, and the Phanerozoic Perth and Southern Carnarvon Basins. Localities for all known dimension stones in the region are listed and geological settings examined. Many of these stones have currently found favour with architects, builders, landscape designers, and artisans. These include the spectacular Austral Juperana, a metamorphosed granite ranging from pinkish beige to yellow gold, the Verde Lope granite with its very large pale green and pink crystals, and the beautiful Donnybrook Sandstone, produced in a variety of shades and textures suitable for precision-cut blocks and slabs, and intricate, high-quality carving. Also included is the high-grade Tamala Limestone, extending south from Geraldton through the economically significant outer Perth metropolitan area to the Bunbury area, with operations serving the building block industry.

Estimates for 2003–04 show Western Australia is the largest producer of cut limestone blocks in Australia at over 0.23 Mt valued at approximately A$4.57 million, and the State is now Australia's largest dimension stone producer at almost 0.25 Mt, valued at approximately A$7.81 million.

The history of the use and methods of extraction of dimension stone is discussed, as are technical properties, stone testing, petrography, processing, production trends, current and potential markets for local stone products, and conservation procedures.

KEYWORDS: Western Australia, dimension stone, building stones, ornamental stone, monumental stone, granite, black granite, sandstone, limestone, marble, slate, quartzite, gneiss, physical properties, history, mineral exploration, quarrying, natural resources, mineral economics, stone conservation, Yilgarn Craton, Leeuwin Complex, Perth Basin.

Chapter 1

Introduction

Object and scope

This two-volume Mineral Resources Bulletin on dimension stone in Western Australia is written in response to recent requests from industry for a comprehensive account of the State's known dimension stone resources. Since a publication of this nature has never been produced by the Geological Survey of Western Australia (GSWA), it is timely that such a work is written to illustrate the variety of high-quality dimension stone present in the State. This account of the State's dimension stone resources includes rock types, previous exploration and mining, current quarrying operations, prospects, commercial applications, and marketing. On a wider perspective, issues such as historical applications, physical properties and testing, stone selection, quarrying and processing, production, market trends and substitutes, and weathering and restoration are also discussed. It should be noted that in the text, commercial names for dimension stones are shown in italics.

Accordingly, this publication is for the information of prospectors, geologists, dimension stone processors, architects, civil engineers, landscape designers and others interested in the current prospectivity, quarrying and processing of the spectacular dimension stones present in the State. It is also intended to serve in future years as a reference compilation of the State's current dimension stone resources for explorers and developers who may wish to take advantage of new niche market situations both in Australia and abroad, and as a source of raw material for unique, architecturally designed buildings, monuments and landscape designs specifying Western Australian dimension stone.

Volume 1 contains an account of the definition of dimension stone, suitable rock types, physical properties and mode of occurrence, followed by historical applications for dimension stone both in Australia and abroad. Stone selection, resource estimation and quarry design, quarrying and processing operations, production, market trends and substitutes, and weathering processes and stone restoration are then examined. The final chapter is a detailed account of the dimension stone resources of the southwest of the State centred on the Perth region. This area includes high-grade limestone and sandstone resources of the Perth Basin, situated mainly on the Swan Coastal Plain, extending southwards from Geraldton in the north, through the economically significant outer Perth metropolitan area, to the Bunbury–Donnybrook area in the south. Also included is the diversity of high-quality granitic, mafic, and metamorphic dimension stone from the Yilgarn Craton, and Leeuwin Complex within a radius of 300 km from Perth.

Volume 2 will contain a detailed description of the dimension stone resources in the south of the State, more than 300 km from Perth, in the Yilgarn Craton, Albany–Fraser Orogen, and Bremer Basin. In the State's central west and northwestern regions, dimension stone is described from the Yilgarn and Pilbara Cratons, Gascoyne Complex, and Edmund, Ashburton, and Southern Carnarvon Basins. In the far north, dimension stone resources from the Hooper and Lamboo Complexes in the Kimberley region, and northern Canning Basin are discussed.

A summary of current dimension stone operations throughout Western Australia including quarrying, stone processing, and applications is given in Fetherston (2004).

Sources of information

Sources of information used in this Bulletin are from both published and unpublished information, supplemented by data gathered on field inspections. Published information is derived from GSWA records, reports, bulletins, annual reports, and geological maps. Other published sources include papers in geoscience journals, conference papers, and articles published in newspapers and dimension stone journals.

Unpublished information is obtained from open-file, statutory reports submitted to the Department of Industry and Resources (DoIR) by various mineral exploration companies. This is supplemented by unpublished data made available by dimension stone producers, and information both local and international available on the internet. Key websites accessed for this Bulletin are listed in Appendix 1.

Dimension stone sampled during field investigations was sourced from stone quarries, prospects and historic sites within the area covered by Volume 1. Except for some historic sites of uncertain location, all sites are assigned grid reference values (MGA values) to assist in site re-location. It should be noted that all sites listed in Volume 1 fall within Australia Zone 50. These sites are also listed in the Department of Industry and Resources online 'MINEDEX' mines and mineral deposits database.

Most dimension stone samples were diamond cut and ground, or polished as reference specimens. These were digitally photographed prior to incorporation in the GSWA Core Library collection at Carlisle in Perth to be made available for inspection by industry and the public. Photographs of most reference specimens are included in Appendix 3. The majority of specimens were also submitted for thin-section preparation and petrographic description. Eight samples from significant dimension stone sources (mainly Tamala Limestone) were selected for chemical oxide analysis for major elements. Petrographic descriptions and chemical analyses are presented in the discussion of dimension stone localities from which these samples were collected.

Abbreviations

A$	Australian dollars
°C	degrees celsius
Fe_2O_3	ferric oxide
fob	free on board
Ga	billion years (age)
g/cm^3	grams per cubic centimetre
GSWA	Geological Survey of Western Australia
K-feldspar	potash feldspar
kg	kilogram
Ma	million years (age)
Mm^3	million cubic metres
μm	micrometre
MPa	megapascal
Mt	million tonnes
Mtpa	million tonnes per annum
P_2O_5	phosphorus pentoxide
ppm	parts per million
t	tonnes
t/m^3	tonnes per cubic metre
tpa	tonnes per annum
USA	United States of America
US$	American dollars

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Assistance provided by many suppliers and retailers to the dimension stone industry is appreciated for the provision of data and high-quality images for publication relating to quarrying, stone processing and marketing. Mr Anthony Stock, Managing Editor Discovering Stone Magazine and Mr Jim Mann, Director of Stone Initiatives and Materials Testing Group Pty Ltd are especially recognized for their contributions.

Chapter 2

Definition, rock types, and physical properties

Definition

Dimension stone has been traditionally viewed as a natural rock usually quarried as blocks or slabs and marketed in a variety of sizes and finishes to suit customer specifications. Accordingly, there are numerous definitions for dimension stone that have been proposed over the years. A relatively recent and more formal definition by Oosterhuis (1999) asserts: 'Dimension stone' is a term defined as incorporating all naturally occurring rock material cut, shaped or selected for use in blocks, slabs, sheets or other construction units of specified size or shape, and employed for exterior or interior parts of buildings, foundations, kerbing, paving, flagging or for other architectural or engineering purposes; dimension stone encompasses 'building stone', 'ornamental stone', and 'monumental stone'.

For this publication the shorter, all-embracing definition proposed by Barton (1968) is preferred. Barton's definition simply states: 'Dimension stone is a natural rock material quarried for the purpose of obtaining blocks or slabs that meet specifications as to size (width, length, and thickness) and shape'.

Rock types

Dimension stone nomenclature is somewhat confusing as scientific names applied to many rock types tend to overlap with names of the broad commercial groups used to describe a plethora of rock types. Also, rocks of the same scientific rock type displaying different colours and/or variations in physical properties may appear under several commercial classifications. Since there are no universal standards for the classification of dimension stone, commercial names may also vary from country to country or even at different places within a country.

Today, the majority of rocks commonly used for dimension stone tend to fall into six major commercial categories. These are granite, black granite, sandstone, limestone, marble, and slate. Subsets of these major groups include grey granite, quartzite and quartzitic sandstone, and green marble. Other commercial categories include trachyte, bluestone, multicolour, basalt or 'trap rock', flagstone, and greenstone. In addition, there are a number of less-commonly used rock types in the dimension stone industry that fall outside the normal commercial categories. The majority of these are listed together with commercial dimension stone nomenclature and equivalent rock types in Table 1.

Major commercial categories

Granite

This group comprises all quartzofeldspathic, crystalline granitic rocks with interlocking, visible mineral grains. The group includes felsic to intermediate plutonic rocks ranging from granite to syenite and charnockite, coarse-grained extrusive rocks such as rhyolite and dacite, and metamorphic rocks including granite gneiss, granofels, and granulite. Grain texture is generally homogeneous ranging from fine to coarse grained, but may also be megacrystic or gneissic. Primary colours range from white to pink, red and grey, whereas secondary colours include brown, green, and blue. Western Australia has numerous Archean to Neoproterozoic granitic and gneissic rocks potentially suitable for export-grade stone. These rocks display a wide variety of textures from fine-grained equigranular to coarse-grained or megacrystic forms; colours range from pink to red and mid- to dark brown, and also from green to grey.

Black granite

The term 'black granite' is a misnomer as rocks from this group cannot be equated to true granitic rocks. Instead, it is a name adopted by the dimension stone industry to describe black, generally fine grained, intrusive igneous rocks. Principal rock types are dolerite*, gabbro, norite, diorite, and anorthosite, while less-common varieties include hyperite, peridotite, and pyroxenite. Black granites are described by Shadmon (2003a) as possessing an interlocking crystalline texture similar to granites, although they contain little or no quartz or alkali feldspar. Instead, these mafic to ultramafic rocks mostly contain intermediate to calcic plagioclase together with dark-coloured ferromagnesian minerals, especially pyroxene, hornblende, and biotite.

The only exception is anorthosite. Found in Norway, Canada, and the USA, this rock is largely to completely composed of coarse-grained calcic plagioclase (labradorite and bytownite). This mostly dark coloured rock, commonly

* In the USA and in a number of other countries the term 'diabase' is used in preference to 'dolerite' as used in Australia, the United Kingdom, and associated countries.

Table 1. Dimension stone nomenclature and equivalent rock types

Commercial name	*Rock type*	*Commercial name*	*Rock type*	*Commercial name*	*Rock type*
Granite	Granite	**Basalt or trap rock**	Basalt	**Marble**	Marble
	Quartz monzonite		Andesite		Metalimestone
	Granodiorite		Dacite		Dolomitic marble
	Quartz diorite		Diorite[(a)]		Travertine marble
	Tonalite		Dolerite[(a)]		Serpentine marble
	Monzonite		Gabbro[(a)]		Onyx marble
	Diorite		Amphibolite[(a)]		Calc-schist
	Syenite		Peridotite[(a)]		
	Larvikite		Pyroxenite[(a)]	**Green marble**	Serpentinite
	Charnockite				Diopsidic marble
	Rhyolite	**Sandstone**	Sandstone		Peridotite
	Dacite		Quartz arenite		
	Granite gneiss		Feldspathic sandstone	**Greenstone**	Metabasalt
	Granofels		Arkose		Metadolerite
	Granulite		Litharenite		Metagabbro
			Ferruginous sandstone		Serpentinite
Black granite and grey granite	Dolerite		Calcareous sandstone		
	Gabbro		Conglomerate	**Slate**	Slate
	Hyperite				Siltstone and sandstone[(a)]
	Norite	**Quartzite and quartzitic sandstone**	Quartzite		Mica schist[(a)]
	Diorite		Quartzitic sandstone		Phyllite
	Peridotite				Metamudstone
	Anorthosite	**Flagstone**	Sandstone		
	Pyroxenite		Quartzite	**Other dimension stones**	Diatomite
			Siltstone		Tripolite
Trachyte	Trachyte		Slate		Spongolite
			Limestone		Alabaster
Bluestone	Basalt				Pumice
	Andesite	**Limestone**	Limestone		Scoria
	Feldspathic sandstone		Calcitic limestone		Tuff
	Siltstone (blue-grey)		Dolomitic limestone		Ignimbrite
	Bluestone		Calcarenite		Steatite/pyrophyllite
	Brownstone		Dolomite		Jasper
			Travertine		Tiger iron
Multicolour	Orthogneiss		Calcareous tufa		Hornfels
	Paragneiss		Coquinite		Schist
	Granulite		Oolitic limestone		Mylonite
	Migmatite				Lateritic duricrust
					Porcellanite

NOTES: (a) Fine-grained varieties

SOURCE: Oosterhuis (1999); Quick (2002); Dolley (2004) displays an intense, bluish schillerization effect emanating from the tabular plagioclase crystals. This effect has made this rock a much-used dimension stone in the building and monumental industries.

In Australia, it is dolerites, gabbros and norites that are sought after as black granites. In South Australia, deposits of medium-grained black norite are quarried for the construction industry, whereas in Western Australia, attention has been focused on the Paleoproterozoic, jet-black dolerites from the West Kimberley, Ashburton, and Fraser Range regions. These fine-grained black granites take a very high, mirror-like polish, and are much sought after as building panels and by the monumental stone industry. They have been exported to a number of countries, and especially to South East Asia.

Grey granite

As for black granite, the term 'grey granite' is a misnomer as it also cannot be equated to true granitic rocks. Grey granite is a term particularly used in southern Africa as a subset of black granite to describe lighter coloured rock types from this group, usually dolerite, gabbro, norite and syenite, that are commonly dark grey in colour.

Sandstone

Sandstone is an indurated, clastic sedimentary rock defined as being largely composed of sand-sized quartz grains in the range 0.06 – 2.0 mm diameter, with a minimum of 60% free silica, and bonded by a variety of chemical cements (Quick, 2002).

As dimension stone, the term sandstone covers a much broader range of grainsize and mineral content. For example, sandstones containing varying proportions of feldspar grains, and/or rock fragments are covered by the terms feldspathic sandstone, arkose, and litharenite. Depending on cementing materials, which include silica, carbonates such as calcite, iron oxides, and clay minerals, the rocks are often identified by terms such as ferruginous or calcareous sandstone, and quartz arenite. Also, the grain size of some rocks included in the sandstone group may be considerably coarser than the maximum 2.0 mm diameter. In particular, conglomerates contain clasts that may range in size from pebbles to cobbles and large boulders, commonly cemented in a fine-grained sandy or silty matrix.

In Western Australia, the Cretaceous Donnybrook Sandstone has been mined for over 100 years. This is a fine- to medium-grained, feldspathic sandstone that ranges through white to cream, pink, and pale brown in different areas. It is particularly suitable for the carving of intricate patterns and has been used in many historic buildings and is currently exported to Europe.

Quartzite and quartzitic sandstone

This subset of the commercial sandstone group comprises the high-grade quartzitic sandstones and equivalent quartzites th0at contain at least 90% quartz grains plus siliceous cement. These rocks are very strong and consequently have been used in load-bearing situations in building construction.

In the East Kimberley region of Western Australia, the Early Cretaceous Melligo Sandstone is quarried for use in high-quality wall panels and expansive streetscapes. This sandstone varies from light beige to multicoloured forms displaying prominent liesegang banding over a beige-coloured sandy matrix. In the same area, a pale beige stone named Kimberley Quartzite is also quarried. This extremely strong material appears to have acquired its strength through the resilicification of the original sandstone.

Limestone

True limestone is a sedimentary rock composed primarily of calcium carbonate with less than 5% magnesium carbonate. As the magnesium carbonate increases to between 5 and 40% the rock becomes dolomitic limestone, and over 40% the material becomes dolomite. Limestone containing a high proportion of quartz grains is known as calcarenite. Calcitic rocks precipitated around hot and cold calcareous springs are termed calcareous tufa and travertine, and oolitic limestone may be formed in shallow water environments or by inorganic precipitation. Coquinite is a detrital limestone consisting of calcareous fossil debris, such as shells, that has become firmly bonded, commonly by carbonate cement.

Currently, Western Australia has a vibrant calcarenite limestone block industry located in the Carabooda–Nowergup and Moore River areas to the north of Perth. Here, limestone blocks are extracted and processed largely for the domestic building stone industry over much of Australia.

Marble

Commercial marbles are derived from metamorphosed limestone, dolomite, and serpentine rocks. During the metamorphic process, the carbonate minerals, principally calcite and/or dolomite, are recrystallized to a greater or lesser degree, forming an interlocking crystal structure. It is this recrystallization process that enables marbles to take a high polish for decorative or ornamental purposes. This group includes pure marble, dolomitic marble, travertine marble, serpentine marble (also known as *'verde antique'*), and partially metamorphosed marble known as metalimestone.

Other forms of marble include onyx marble, a dense crystalline form deposited by cold water solutions and distinguished by its partial translucency and characteristic layered structure, and calc schist, a metamorphosed clay-rich limestone displaying a schistose structure.

Green marble

Rocks belonging to this subset of the marble group have the characteristic deep green colour of serpentine marble. Serpentinite is an ultramafic rock, composed almost entirely of the serpentine group of minerals. In areas of Italy, high-quality serpentinite is much sought after as a dimension stone. It is very hard and mainly dark green in colour, commonly displaying patches of white, light green, and black. Peridotite is also a dark green ultramafic rock commonly altered to serpentinite. Also, green diopsidic marble may locally form during contact metamorphism of crystalline limestones.

Slate

Slate is a low- to medium-grade, indurated metamorphic rock formed by the recrystallization of sedimentary rocks such as shale, siltstone, and claystone. The rock is very fine grained and composed mainly of mica, chlorite, and clay minerals, with accessory quartz, feldspar, and iron oxides. Slate is characterized by an excellent parallel cleavage allowing it to split easily into relatively thin slabs for use as roofing shingles, floor tiles, and other specialized applications. Colours vary from light or dark brown and green, to grey and black. In Australia, a high-grade commercial slate deposit is quarried at Mintaro in South Australia, and there are several deposits in Queensland. However, most slate is sourced from overseas, mainly from China, India, and Brazil.

Other, less-indurated, fine-grained rocks have also been classified in the slate rock group. These include fine-grained, partially metamorphosed siltstones and sandstones, mica schist, phyllite, and metamudstone. The rocks generally lack the superior parallel cleavage and hardness of slates and, with the exception of some phyllites, are generally unsuitable for use as roofing shingles but may find applications as floor tiles and paving blocks.

Other commercial categories

Trachyte

Trachyte is an intermediate, extrusive igneous rock. The rock has a megacrystic texture with alkali-feldspar phenocrysts set in a fine-grained matrix. Colours vary from white to light grey, brown or greenish. In the past, trachyte has been used as a dimension stone in eastern Australia.

Bluestone

The term bluestone refers to a number of different rock types in various parts of the world. In Victoria in eastern Australia, bluestone refers to the local Cenozoic black basalt used to build major colonial office buildings, churches and bridges, and, up to recent times, extensive streetscapes. Also, in some places the intermediate volcanic rock, andesite, has been included in this category.

In South Australia and other parts of the world including USA, bluestone is used to describe dense, hard, fine-grained, medium to dark or bluish-coloured sedimentary and metasedimentary rocks. These include sandy or dolomitic siltstone and shale, and metasiltstone in South Australia (Olliver, 2003), as well as feldspathic sandstone and the so-called ‘bluestones’ and ‘brownstones’ of northeastern USA. All of these rocks will split readily along planes to form thin, relatively smooth slabs well suited for the outer cladding of buildings.

Multicolour

Multicolour is a South African commercial term used to describe high-grade metamorphic rocks such as orthogneiss, paragneiss, granulite, and migmatite. These rocks feature two or more intermingling textures and/or colours. An example of a multicolour would be a black to dark grey paragneiss with minor white coloured highlights intermixed with an orthogneiss consisting of lighter colours ranging from red to pink, orange, grey-violet, grey, yellow and, less commonly, white. Other multicolours such as migmatites are noted for their highly changeable textures known as ‘movement’ in the dimension stone industry (Oosterhuis, 1999).

Basalt or ‘trap rock’

This group includes basalt and ‘trap rock’ (a term used in North America and Scandinavia to include dark-coloured igneous rocks that are too fine grained to be categorized as black granites). Extrusive igneous rocks include basalt, andesite and dacite, while intrusive igneous rocks include diorite, dolerite, amphibolite, and fine-grained gabbro, peridotite, and pyroxenite (Dolley, 2004).

Flagstone

The term flagstone is applied to indurated sandstones or quartzites having thin, even bedding or parting planes that allow the rocks to be easily split into regular, thin slabs. Other rocks that may be included in this group include indurated siltstones, slates, and limestones. Flagstones are used to pave streetscapes, footpaths and outdoor areas, and are also used in free-standing walls. Western Australia has two excellent flagstones represented by *Karratha Stone* (quartz sandstone), and *Toodyay Stone* (quartzite).

Greenstone

Greenstone is a name applied to any metamorphosed or altered low-silica igneous rocks such as metabasalt, metadolerite, metagabbro, and serpentinite. The term ‘greenstone’ originated from the predominance of greenish minerals such as chlorite, actinolite, epidote, serpentine, and talc. These rocks are typically dense with poorly defined granularity, and range in colour from dark green to black (Quick, 2002). Commercial operations for greenstone as a dimension stone are known in North America.

Other dimension stones

There are numerous other rock types that have been used as dimension stones in many countries around the world. In general, their use has tended to serve as a building stone for the local area or region in which they are found rather than as a mainstream dimension stone like export-grade marble and granite. The majority of these rock types, including diatomite, tripolite, spongolite, alabaster, pumice, scoria, tuff, steatite and pyrophyllite, are relatively soft and usually may be easily extracted by chain or quarry saws.

Of these soft rock types, steatite (also known as soapstone) and pyrophyllite are extensively used in northern Europe for hearths and fireplaces owing to their exceptional refractory properties. These rocks are also cut for laboratory sinks, benchtops and other applications because of their stain-resistant qualities.

In the far south of Western Australia, soft spongolite is easily extracted in blocks by sawing with chain or quarry saws. Known locally as Mount Barker Stone, this lightweight material is an excellent insulator and is used to construct buildings in the local area. Between 1860 and about 1910, in the Gingin area 70 km north of Perth, a soft diatomaceous claystone, known as *Casuarina Stone*, was quarried from local swamp deposits and used for the construction of a number of town buildings.

Harder rocks in this group include ignimbrite, jasper, tiger iron, hornfels, schist, mylonite, lateritic duricrust and porcellanite. In the Pilbara region of Western Australia, tiger iron is mined. This jaspilite rock comprises thin alternating bands of red jasper, black hematite and smaller amounts of the golden-yellow mineral, tiger eye. As a dimension stone this material is used for speciality floor and wall tiles. Also, a number of historic buildings were constructed in the State from blocks of partly sawn lateritic duricrust. This hard, red-brown, material is composed of iron-rich, indurated pisoliths (Fig. 1).

During the establishment of Darwin in the Northern Territory in the late 1800s, porcellanite was cut into blocks for the construction of a number of historic buildings. Porcellanite is a local name for an indurated, silicified, mottled claystone developed in a siliceous zone beneath lateritic duricrust, and is the result of deep weathering of the Cretaceous Darwin Formation. The material is similar to silcrete, but contains substantially less silica (<90%), whereas pure silcretes generally contain in excess of 97% SiO_2. Investigations have shown that the original claystone has been largely replaced by opaline silica ranging from 60 to 86% content. Colours vary from cream to yellow, orange and purple, and concentric banding, colour zonation, speckling, and veining are common (Doyle, 2001).

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Figure 1. Saint John's Lutheran Church in Perth (1936). Built from blocks of indurated, pisolitic duricrust sourced from Darlington, 20 km east of Perth

Physical properties

After quarrying, 'rock' becomes 'stone'. This term is then applied to all dimension stones so obtained for the construction, building, and monumental stone industries. Apart from the size specifications for blocks and slabs used to define a dimension stone, it is the stone's actual physical properties that determine its commercial success in the marketplace.

Visual properties

Combined with contemporary architectural trends, it is the visual properties of any stone, particularly colour, texture and structure, that largely influence customer demand. A number of other visual properties, associated with the technical property known as durability, tend to become more obvious with the passage of time, such as resistance to weathering, discolouration, and attack by salt, acids and other chemicals.

Colour

Dimension stones are available in most colours, commonly ranging from pure white, through cream, yellow, orange, pink, red, green, brown, mauve, grey, to black. Dominant or background colours in a stone are commonly contrasted with secondary colours associated with a wide range of textural and structural features that may be present in a stone's fabric. There are many causes of colour variation in stone. Examples include differences in mineralogy seen in many igneous and metamorphic rocks, especially granites, as contrasting bands, megacrysts, augen, xenoliths, and other structures that may be included in the original rock matrix. In sedimentary rocks, colour changes commonly result from changes in lithology in adjoining beds — as seen in travertine and jaspillite (tiger iron) — and from different coloured rock particles present in coarse-grained rocks such as conglomerates and limestone breccia. Weathering processes also commonly result in colour changes. For example, the passage of groundwater through porous sandstones may result in the rhythmic precipitation of liesegang bands, which consist primarily of hydrous iron oxides that form concentric rings in an attractive range of colours (Fig. 2).

Texture and structure

In the dimension stone industry, the terms 'texture' and 'structure' relating to the features making up the fabric of a stone tend to be applied interchangeably with 'texture'

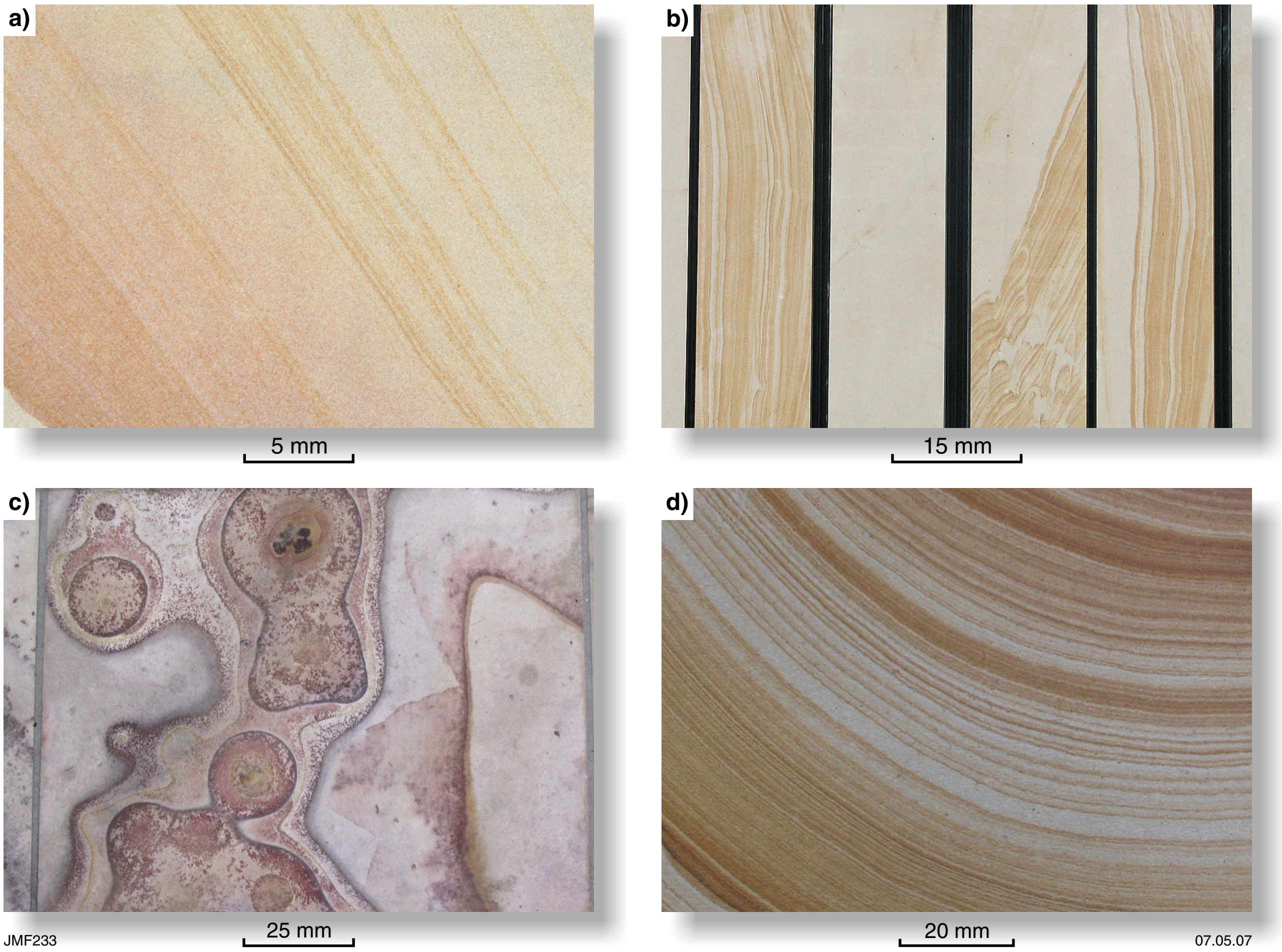

Figure 2. Examples of visually attractive liesegang banding in sandstones: a) banding in pink-beige Beelerup sandstone from Donnybrook; b) pale beige banding in Acrogem sandstone from Donnybrook; c) complex, mauve banding in Kimberley sandstone, Derby region; d) concentric banding in Gosford Sandstone, Mount White, NSW (photo (c) courtesy Meteor Stone)

commonly being used as an all-embracing term to indicate the stone's general physical appearance or character.

In petrological terms, texture indicates the way a stone is organized into its component parts through reference to its smaller, microscopic to megascopic features such as grain size, grain shape, degree of crystallinity and granularity, and contact relationships between the grains. By contrast, structure refers to a stone's megascopic features that indicate the way the stone is made up from component parts, all of which may be observed with the naked eye. Examples of structures include bedding and other sedimentary structures, discontinuities, fossils, concretions, flow structures, banding, orbicules, veins, jointing and fracturing, and visible effects of metamorphism such as schistosity and slaty cleavage.

Technical properties

Behind the more obvious visual properties, it is the technical properties of any dimension stone that will ultimately determine its success in the environment in which it is placed as part of a building, landscape feature, or monument. There are many standardized tests available to determine a stone's viability. The most common set of dimension stone standards used by industry are those devised by the American Society for Testing and Materials (ASTM). These standards are listed in 'C1528–02 Standard guide for selection of dimension stone for exterior use' (ASTM International, 2005). ASTM-referenced documents relating to test methods, specification, and guidelines for dimension stone are listed in Table 2. A summary of the physical properties and ASTM standard specifications for the main dimension stone groups is given in Table 3. Discussion on the various technical properties given below is largely summarized from Quick (2002).

Absorption and bulk density

Absorption is a measure of the quantity of water that can be taken up by the open pores accessible to moisture in any stone (apparent porosity), and is the ratio of the mass of absorbed water to the total saturated mass expressed as a percentage. Absorption is related to bulk density, which is a measure of a stone's mass divided by its volume including the volume of its pore spaces. The bulk density

Table 2. ASTM standard tests, guidelines, and specifications for dimension stone

Reference no.	*Tests, guidelines, and specifications*
C97	Test methods for absorption and bulk specific gravity of dimension stone
C99	Test method for modulus of rupture of dimension stone
C119	Terminology relating to dimension stone
C120	Test methods for flexure testing of slate (modulus of rupture, modulus of elasticity)
C121	Test method for water absorption of slate
C170	Test method for compressive strength of dimension stone
C217	Test method for weather resistance of slate
C241	Test method for abrasion resistance of stone subjected to foot traffic
C295	Guide for petrographic examination of aggregates for concrete
C406	Specification for roofing slate
C503	Specification for marble dimension stone
C568	Specification for limestone dimension stone
C615	Specification for granite dimension stone
C616	Specification for quartz-based dimension stone
C629	Specification for slate dimension stone
C880	Test method for flexural strength of dimension stone
C1201	Test method for structural performance of exterior dimension stone cladding systems by uniform static air pressure difference
C1242	Guide for design, selection, and installation of exterior dimension stone anchors and anchoring systems
C1352	Test method for flexural modulus of elasticity of dimension stone
C1353	Test method for using the Taber abraser for abrasion resistance of dimension stone subjected to foot traffic
C1354	Test method for strength of individual stone anchorages in dimension stone
C1028	Test method for determining the static coefficient of friction of ceramic tile and other like surfaces by the horizontal dynamometer pull-meter method

SOURCE: ASTM International (2005)

of a rock may be measured in grams per cubic centimetre (g/cm^3), but for practical purposes when working in a quarry situation with large rock masses bulk density is generally expressed as t/m^3. ASTM test C97 covers the absorption and bulk density of all rocks except slate, which is covered by test C121 for absorption only.

Strength tests

Engineering structural and safety regulations require that stone slabs and panels are thoroughly tested for their various strength properties before they are destined for use in any construction project. Three principal tests for the majority of stones are; compressive strength, modulus of rupture, and flexural strength (ASTM tests C170, C99, and C880 respectively). Separate procedures apply for flexure testing of slate (ASTM C120). Other tests include modulus of elasticity (ASTM C1352) and structural performance (ASTM1201).

It should be noted that the grain structure of many types of stone is not isotropic, because of preferred grain orientations resulting from bedding, foliation, or other forms of structural deformation. As a result, a stone's structural strength is commonly significantly less in the direction of preferred orientation. Accordingly, it is essential that strength testing be carried out parallel to the direction of grain orientation, as well as in other directions for a complete assessment of the stone's strength properties.

Strength testing is often carried out on a stone both in the wet (saturated) and dry state. This is done because many stones are noticeably weaker when wet owing to a reduction in the inherent strength in the stone's matrix or in various clays that act as binding material. In industry, the higher, dry values for stone strength testing are those more commonly quoted.

Compressive strength

Compressive strength, more accurately known as uniaxial unconfined compressive strength, is a measure of the applied stress (measured in MPa) required to cause failure in any rock. In homogeneous rocks, compressive strength tends to increase as grainsize decreases. Generally, stones with a compressive strength of less than 7 MPa are considered to be fairly weak, whereas those greater than 140 MPa are very strong. These guidelines are important for architects and engineers considering the properties of a stone intended for use in load-bearing structures.

Modulus of rupture

The modulus of rupture test (also known as transverse strength test) causes stone to fail directly under an applied load at a single point and measures a stone's combined shear strength and diagonal strength. This test is invaluable for the assessment of the strength of stone panels at the point of attachment for steel anchoring devices.

Flexural strength

The flexural strength test is used to assess a stone's tensile strength induced by bending. Test results are markedly affected by the condition of the stone's surface under tension. As an example, it has been demonstrated that flexural strength of a thermally exfoliated granite with a

Table 3. Physical properties and ASTM standard specifications for the main dimension stone groups

Stone		*Absorption (weight %)*	*Bulk density (t/m^3)*	*Compressive strength (MPa, dry)*	*Modulus of rupture (MPa dry)*	*Flexural strength (MPa, dry)*	*Mohs hardness*	*Knoop microhardness*	*Abrasion resistance: Taber index (Ha)*	*Linear thermal expansion coeficient (µm/m/°C)*
`	*ASTM test*	*C97 (max.)*	*C97 (min.)*	*C170 (min.)*	*C99 (min.)*	*C880 (min.)*			*C1353 (min.)*	
Granite		0.1 – 3.0	2.6 – 2.7	80–310	9.5 – 18.8	8–18	5–7	400–620	90–160	5–11
	Granite	*0.4*	*2.56*	*131*	*10.34*	*8.27*	–	–	*25*	–
Black granite (dolerite, gabbro and norite)		0.1 – 1.8	2.8 – 2.9	110–300	15–20	15–28	5–6.5	380–560	60–100	4–7
Bluestone (basalt)		0.3 – 4.0	2.7–2.9	50–280	10–90	11–16	4–6.5	360–480	50–90	2–5
(blue–grey metasiltstone)		0.87	2.7	209	19.1	na	na	na	48	10.3
Sandstone (medium density)		2.0 – 25.0	2.0 – 2.6	20–240	5–13	4–16	2–7	na	5–40	2–12
	Sandstone	*8*	*2.00*	*27.6*	*2.4*	–	–	–	*2*	–
Quartzite		0.1 – 1.5	2.6 – 2.7	110–350	10–100	10–25	5–7	450–740	20–70	8–16
	Quartzite	*1*	*2.56*	*137.9*	*13.9*	–	–	–	*8*	–
	Quartzitic sandstone	*3*	*2.40*	*68.9*	*6.9*	–	–	–	*8*	–
Limestone (medium density)		0.3 – 20.0	2.2 – 2.6	20–230	4–11	4–20	2–3	90–230	6–28	2–6
	Low density	*12*	*1.76*	*12*	*2.9*	–	–	–	*10*	–
	Medium density	*7.5*	*2.16*	*28*	*3.4*	–	–	–	*10*	–
	High density	*3*	*2.56*	*55*	*6.9*	–	–	–	–	–
Calcarenite		19.0 – 27.5	1.5	3.5	na	2.5	na	na	na	na
Marble		0.1 – 1.5	2.6 – 2.7	40–190	4–30	7–19	2–4	80–220	8–35	3–7
	Marble	*0.2*		*52*	*7*	*7*	–	–	*10*	–
	Calcitic marble	–	*2.60*	–	–	–	–	–	–	–
	Dolomitic marble	–	*2.80*	–	–	–	–	–	–	–
	Serpentine marble	–	*2.69*	–	–	–	–	–	–	–
	Travertine marble	–	*2.31*	–	–	–	–	–	–	–
Slate		0.1 – 2.5	2.6 – 2.7	50–300	62	35–55	3–5	na	8–20	3–9
	ASTM test	*C121*	–	–	*C120*	–	–	–	*C1353 (min.)*	–
	Slate:exterior	*0.25*	–	–	–	–	–	–	*8*	–
	– across grain	–	–	–	*62.1*	–	–	–	–	–
	– along grain	–	–	–	*49.6*	–	–	–	–	–

NOTES: ASTM standard values in italics
na: not available
µm: micrometres

SOURCES: Quick (2002); Smith (1999)

roughened surface finish may be up to 30% lower than for a granite displaying a polished surface.

Also, when a tensile stress is applied to stones with preferred grain orientations, higher flexural strengths are usually recorded parallel to the grain than for stress applied in other orientations. This is an important consideration in the orientation of cut slabs in order to maximize the flexural strength in the finished product

This test is essential in the design of stone panels for use on building facades in assessing the maximum load a wall panel can withstand when attached by steel wall anchors. The test is also used for determining the stone's resistance to wind loads. In addition, flexural strength is important for testing stone for flooring applications.

Hardness

In the building industry, stone hardness is an important factor in the application and ultimate placement of dimension stone. For example, softer stones such as some types of sandstone, limestone, marble, and slate would not normally be used in areas of high traffic as they would soon become scratched and ultimately worn by particles of grit and sand transported by pedestrian traffic and wind. There are two tests for assessing the hardness of dimension stones. The first of these is the relative scratch hardness of stones determined by the well known Mohs scale. The second test is referred to as Knoop microhardness.

Mohs hardness

Mohs hardness is an empirical scale of relative mineral hardness from one to ten with one being the softest, and ten the hardest. The standard minerals for this test in order of increasing hardness are talc, gypsum, calcite, fluorite, apatite, orthoclase, quartz, topaz, corundum, and diamond. In testing dimension stone by this method, the hardness of a stone is expressed as the number of the mineral immediately preceding that of the first mineral (in increasing order) on the Mohs scale to succeed in scratching the stone. Stones with variable scratch hardness values, often the result of coarse-grained textures and/or differences in mineralogy, are rated with the lowest hardness recorded.

Knoop microhardness

In order to determine an absolute hardness value for stone an instrument known as the Knoop microhardness tester is employed. This machine provides a controlled and accurate method of hardness evaluation through the use of a precisely shaped, flat pyramidal diamond point known as the Knoop indenter. The loaded diamond indenter is used to cut indendation grooves in the surface of a stone under test. The applied load and the length of indentation produced are the principal factors used in the determination of the stone's Knoop hardness number. It has been found that hardness values generally increase with decreasing grainsize of the stone (Quick, 2003). This test has found extensive application in Europe for hardness testing of limestones. A detailed description of the Knoop microhardness tester and hardness calculation methodology is given in Winchell (1945).

Durability

Dimension stones used in buildings, monuments, and other applications are commonly selected, amongst other factors, for their apparent long-lasting ability. In the long term, many of these stones do not live up to their surmised durability having been introduced into environments in which they are not entirely suited. In time, these stones begin to break down under conditions such as freeze and thaw, attack by water, (including rising damp, saltwater incursion, and acid rain), dissolution of deleterious minerals such as pyrite and iron oxides, and also by wind erosion. The style and rate of attack can vary enormously, but in a relatively corrosive urban or industrial environment these weathering processes may be particularly rapid (Oosterhuis, 1999).

Durability is defined in ASTM C199–90 (Terminology related to dimension stone) as: 'the measure of the ability of dimension stone to endure and maintain its essential and distinctive characteristics of strength, resistance to decay, and appearance. Durability is based on the time that a stone can maintain its innate characteristics in use. The time will depend on the environment and the use of the stone in question (for example, outdoor versus indoor use)' (Smith, 1999). This definition simply means that the durability of a stone is assessed by the extent of the stone's weathering over a set period of time.

Durability is linked to a stone's strength, both compressive and flexural, in which both properties are related to the stone's bonding strength between mineral grains. For example, high grain-bonding strength make the stone more resistant to mechanical forces applied to the mineral bonds by the freezing of water, or crystallizing of salts. If the mineral grains' bond strength is exceeded the stone may weather and deteriorate (Mann, 2005).

Another indicator of durability is a stone's water-absorption capacity. Typically, stones having high water-absorptive properties may be subject to the entry of aggressive solutions containing salts or acids. Should the pore spaces be sufficiently permeable (i.e. interlinked), these solutions can physically or chemically affect the structural integrity of the stone, again causing the stone to discolour and deteriorate over time. It should be noted that porous sandstones and limestones commonly absorb more water than other dimension stones (Table 3).

Abrasion resistance

Related to durability in terms of a stone's long-lasting ability, the abrasion resistance test is used to determine surface wear resistance of a dimension stone when used in flooring or paving applications. Surface wear is caused mainly by pedestrian traffic and to a lesser extent by the passage of light-wheeled commercial equipment and the shifting of furniture. Abrasion resistance is a useful test for comparing the wear resistance of different dimension stones. The stone surfaces to be tested should be almost flat, and the stones themselves should ideally be homogeneous in texture. Stone containing beds, bands or lenses of variable lithologies, megacrysts, veins, and inclusions is likely to give highly variable abrasion resistance values due to differential hardness within the stone.

Abrasion resistance is calculated from ASTM test C1353, using a Taber abraser machine that uses standardized abrading wheels to calculate an abrasion resistance value known as the Taber index (Quick, 2002). The Taber index (Ha) is calculated from the loss of weight resulting from abrasion of the stone under controlled conditions, and the bulk density of the stone. Stone with higher Taber index values is more resistant to abrasion and therefore more resistant to surface wear in flooring and paving applications. Accordingly, granites and basalt bluestones are in demand for these applications with their high Taber index values ranging from 50 to 160 Ha. Minimum Taber index values relate to light duty applications in order of: domestic (8 Ha), medium duty, light commercial (12 Ha), and heavy duty (15 Ha).

Another abrasion resistance standard has been developed by the Commonwealth Scientific Industrial Research Organisation (CSIRO) in Australia. This method, known as the CSIRO Capon index, is based on a similar European system and operates by grinding a chord-shaped cut into a stone using abrasive and a steel wheel. The Capon index is then calculated from the abraded weight loss and the bulk density. Values obtained by this method are generally higher than those obtained by the Taber method.

Linear thermal expansion

Linear thermal expansion is expressed as a coefficient relating to the linear dimensional change in a stone subjected to changes in temperature. The linear thermal expansion coefficient is defined as the ratio between the increase in length of the material being tested (corresponding to the increase in temperature, ΔT), and the product of its original length and ΔT. Linear thermal expansion is expressed in units equivalent to micrometres per linear metre per degree centigrade (µm/m/°C). For example, a stone with a linear thermal coefficient of 5 would expand by 100 units per 1 000 000 when subjected to a temperature increase of 20°C, which is the equivalent of 0.1 mm per linear metre of the stone's length (Smith, 1999; Quick, 2002).

Other dimension stone standards

Around the world, many countries have their own standards for the testing of dimension stone. For example, Spain has the UNE standard, Great Britain the BS, Germany the DIN, France the NF, Singapore the IAPMO, and the USA the ASTM. Each standard provides accurate methods of defining stone properties for industries located within individual countries. The problem is that every set of standards defines the physical properties of stone in different ways making it extremely difficult for buyers and sellers in different parts of the world to compare the physical properties of a stone from one country with that from another (Litosonline, 2003). This problem tends to account for the use of ASTM standards as a de facto medium for comparison of stone properties by industry in many parts of the world.

During the 1990s the Committee for European Standardization (CEN) began to develop a set of dimension stone standards (EN) for the European Union. A comprehensive set of more than 30 standards has been under development by Technical Committee TC246 under the broad headings of Terminology and General Standards; Test Methods; and Product Standards. Once the approval process is complete the new EN standards are being progressively released. At the end of 2001, twelve test methods had been published, and by September of 2003 another nine were due to be ratified and three more were under study. Also, six product standards are due for release in the near future. A comprehensive listing of the EN standards is given by Shadmon (2003b).

The implementation of the EN standards means that in the near future any stone bought or sold in Europe will have to conform to these new standards. This means that any Australian stone sold in Europe will have to be tested in accordance with the EN standard test methods to guarantee that their product meets the new European standard specifications (West, 2003).

To date, Standards Australia does not have any standards relating to the use of dimension stone as building stone products. Standards that currently exist are AS4455: Masonry units and segmental pavers (1997); and AS4456: Masonry units and segmental pavers — Methods of test (2003). Currently, AS4455 is undergoing a substantial upgrade principally to provide clearer specifications for materials used in masonry units, segmental pavers and flags, and retaining-wall units. In particular, it is expected that there will be significant changes made to the requirements for segmental pavers and flags in the areas of product definition, and minimum values for thickness, breaking load, abrasion resistance, and slip resistance (West, 2004). A draft version of this part of AS4455, made available for public comment in 2005, is yet to be finalized.

Chapter 3

A brief history of dimension stone

Historical applications

Since the dawn of civilized society, man has accessed numerous rock types for use as dimension stone in many areas around the world. As a general rule, from prehistoric times until the invention of mechanized transport, rock material with suitable physical properties for block manufacture would be sourced from rocks in the local area for use in building projects ranging from simple stone shelters and walls through to large stone bridges and major buildings such as defensive castles. Exceptions to this tended to occur in major civilizations, such as ancient Egypt, Greece and Rome, which had the economic means and the manpower to source large stone blocks with more attractive colours and/or superior physical properties that were situated at great distances from construction sites. This is evident in the variety of stones used in their massive monuments and buildings including gigantic statues, temples, and mausoleums.

Neolithic period

During the Neolithic period (New Stone Age) between 7000 and 4000 years ago, many thousands of stone structures comprising large tombs, long barrows, temples, and massive standing stones were erected throughout Western Europe. Free-standing stones, also known as megaliths or menhirs, were erected either in large stone circles or as avenues of stones at times extending over many kilometres with the largest megaliths weighing up to 350 t. Near the town of Carnac in western France, a linear field of almost 3000 megaliths is arranged in up to eight parallel rows extending over 3 km. The Carnac site has been tentatively dated at 3300 BC (Megalithia, 2002).

The Stonehenge monument on Salisbury Plain in southern England was mostly constructed between 2100 and 1500 BC. The structure consists of several concentric rings of standing stones surrounding an inner horseshoe of five trilithons of sarsen stone (a form of silcrete) with each trilithon consisting of two 45 t pillars supporting a 7 t lintel stone. A circle of 30 sarsen stones, each weighing about 25 t and capped by lintels was then constructed around the central horseshoe. Later, over 80 bluestone blocks, each of about 4 t, were added in circular structures within the outer ring (Dimitrakopoulos, 1999). Geological evidence suggests that many of the massive stones may have been transported to the site from as far as the the Prescelly Mountains in central Wales, a distance of over 380 km (Glover, 2003).

Ancient Egypt

The Pyramids of Giza, located west of Cairo in Egypt, were built about 4500 years ago. The largest of these, the Great Pyramid of Khufu (Cheops), was originally 147 m tall, and covered an area of 5.3 ha. The Great Pyramid contains about 2.3 million blocks of locally sourced, foraminiferal limestone mostly between 2 and 4 t in weight, and the entire structure has an estimated mass of 7 Mt. The smaller second and third pyramids of pharaohs Khafre (Chephren), and Menkaure (Mycerinus), are 136 and 66 m high respectively, and are also constructed of large blocks of the local limestone (Fig. 3). The pyramids were originally cased with large blocks of finely polished, white Turah limestone (now mostly removed), and to a lesser extent, blocks of pink Aswan granite around the lower sides of the Khafre and Menkaure pyramids to a maximum height of about 15 m above their base lines (Tour Egypt!, 2005).

The ancient Egyptians were also extremely skilled at extracting and moving huge blocks of stone over long distances. At Aswan on the Nile River in southern Egypt, a pink quartz monzonite quarry is still in existence that originally supplied large blocks to massive temple complexes such as Karnak and Luxor, over 200 km downstream (Fig. 4). It is thought that the tools for cutting

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Figure 3. Mainly constructed of large limestone blocks, the Pyramids of Giza near Cairo are about 4500 years old

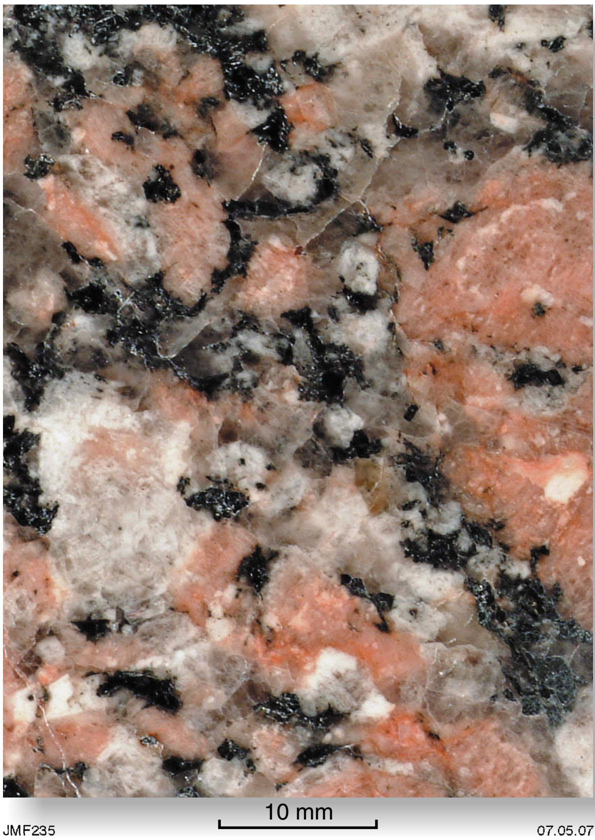

Figure 4. **Quartz monzogranite from the ancient Egyptians' quarry at Aswan in southern Egypt. Polished slab shows large, pink potash feldspar megacrysts**

and shaping such blocks were probably made from rocks, such as chert and dolerite, hard enough to cut and grind away granite. Within the quarry is the Unfinished Obelisk dated 1450 BC (Fig. 5). When erected, this obelisk would have been almost 42 m in height with an estimated weight of about 200 t (Glover, 2003).

During this period, the Egyptians pioneered the use of stone roofing material comprising large stone slabs supported by closely spaced columns, and also became masters in the creation of huge stone-carved monuments such as the sandstone colossi of Rameses II at Abu Simbel in southern Egypt (Fig. 6).

Ancient Greece and the Roman Empire

During the period from about 495 BC to 395AD, the ancient Greeks and Romans sourced vast quantities of limestone, marble, travertine, sandstone, granite, andesite, porphyry, and other rocks for use as various forms of dimension stone. These were located over much of western Europe, including England, and also into Asia Minor. Most of the stone appears to have come from countries around the northern coast of the Mediterranean Sea. In 177 BC, the Romans, searching for new sources of marble located closer to Rome, discovered the great marble field of Luni, about 7 km west of Carrara in Tuscany, Italy. Carrara continues today as one the world's most famous mining districts for fine white marble (Vallardi, 1982; Fig. 7).

Both the Greeks and Romans used dimension stone for the construction of extensive temples and other buildings, roads, ports, monuments, tombs, and sculptures (Fig. 8). The Romans also invented mortar and concrete that enabled them to design extremely strong arches used in the construction of very large stone bridges and aqueducts (Day, 2005).

Ancient Central America

About 150 AD in Mexico, the stone city of Teotihuacan was built by an unknown race of people. Once the size of ancient Rome, the city contains the famous stepped Pyramid of the Sun built of large stone blocks (World-Mysteries.com, 2005). In the nearby city of Cholula is the Great Pyramid that was built over many centuries. With an estimated volume of 4.45 Mm^3, this huge, lower angled, stepped stone structure is estimated to be almost one-third larger than the Great Pyramid Giza in Egypt (Wikipedia, 2005).

Figure 5. **Unfinished, 42 m-tall obelisk (1450 BC) in situ in the Aswan granite stone quarry in southern Egypt. Note the shallow slots cut in the rock (left foreground). It is thought wooden wedges were forced into these slots beneath a newly completed block causing the block to split away from the quarry floor (Glover, 2003)**

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Figure 6. Four, 20 m-high, sandstone colossi of Rameses II (c. 1250 BC), at Abu Simbel in southern Egypt

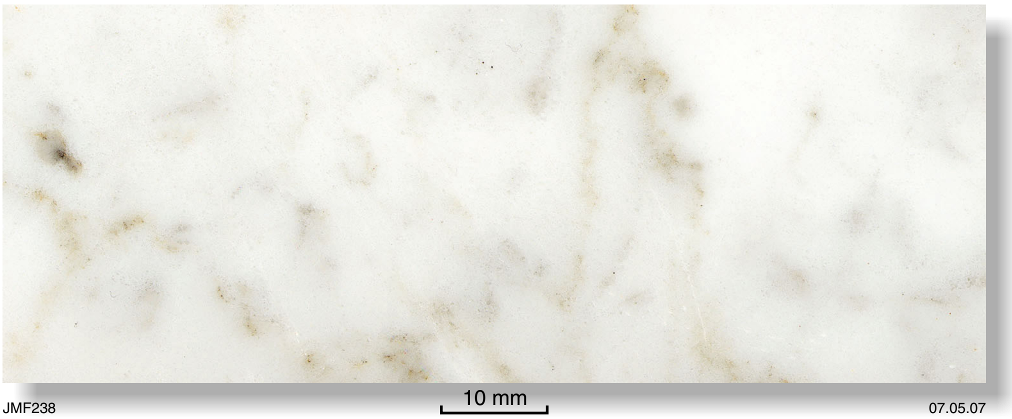

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Figure 7. Fine, white Bianco Carrara Venato marble displaying pale grey highlights

Figure 8. **Applications of Greek and Roman dimension stone: a) the marble temple of Hephaestus built by Pericles in 449 BC is the best preserved Doric temple in Greece; b) the Roman temple of Trajan, in pure white marble, at Pergamon in eastern Turkey is built over an earlier Grecian palace constructed of blocks of brown andesite; c) polished statue of Aphrodite carved in white marble, Ephesus Museum, Turkey; d) Roman street in Ephesus paved with marble slabs dating from the 5th century AD and still in use**

Europe in the Middle Ages

During the Middle Ages from about 1100 AD, it became necessary to fortify cities, towns and castles with strong stone walls. For these and all other stone constructions including roads, bridges, churches, and monuments, huge quantities of dimension stone were used. Each major region in Europe tended to specialize in different stone types. Examples included Italy (marble and travertine), Spain (marble), Finland and Sweden (granite), and France (sandstone; Fig. 9). This specialization of stone types sparked an extensive trade in dimension stone within Europe as well as into Russia (PCPedras, 2002).

South East Asia and South America

About the same time as the Middle Ages in Europe, major civilizations in other parts of the world also built huge stone structures. In South East Asia, the Khmer Empire constructed extensive stone cities and structures, including the magnificent temple of Angkor Wat in Cambodia between 1113 and 1150 AD. Also, in the 15th century in South America, the Incas of Peru built the massive stone fortress of Sacsahuaman. This structure is a masterpiece of construction, being more than 550 m in length and made of closely fitted, mortarless stone blocks up to 11.6 m long, 5.5 m high, and 1.8 m thick.

Europe during the Renaissance

During the Renaissance Period (1400 to 1600 AD), many ornate palaces and cathederals were built throughout Europe. In Italy, the use of white and coloured marbles in these constructions probably reached its zenith (Fig. 10). The extensive use of such materials is illustrated in the famous Duomo of Florence, completed in 1436. The walls and bell tower of this substantial building are completely covered with white marble slabs inlaid with thousands of cut pieces of coloured marble arranged in intricate patterns (Casa Editrice Bonechi, 2004; Fig. 11).

China

In China during the Ming Dynasty, the Great Wall of China was built between 1368 and 1644 AD. This defensive wall postdates three earlier walls and stretches some 6700 km across northern China. The section of the wall at Badaling, north of Beijing, is constructed from blocks of a hard granite forming the defensive walls, while the upper walkway is made of a porous basaltic rock designed to rapidly absorb rainwater to provide maximum mobility for soldiers guarding the wall. The average height of the wall is 10 m and the width 5 m (Travel China Guide, 2005; Fig. 12).

India

In 1653, the Taj Mahal was completed at Agra in India. Shah Jehan's magnificent memorial was built as a mausoleum for his wife, Mumtaz Mahal. Built over 22 years by 20 000 people, the tomb with its dominant central dome rising to 61 m, and four surrounding minarets, are sheathed in inlaid slabs of polished white marble (Fig. 13). Two mosques set on the transverse axis to the main structure are built entirely of red sandstone. Both stones were sourced in Rajasthan, about 300 km west of Agra, with the marble quarried at Makrana, and the sandstone at Fatehpur (India Travel Agents, 2005).

Dimension stone usage from the 18th to the 20th centuries

From the early 18th century, many cities and towns in different parts of the world were built wholly or partially from stone, often sourced locally. An example of this is the splendid Georgian city of Bath in Somerset in southwest England. Largely built between 1725 and 1795, the city was built of blocks of golden brown, oolitic limestone, of Jurassic age, known as 'Bath Stone' that was sourced from 11 quarries at various sites in the nearby Cotswold Hills (Hawkins, 1999).

By the 19th century, dimension stone extraction for civil engineering projects became a well established industry, and many countries, especially in Europe, became large producers. At this time the Italian marble industry, centred on Carrara in Tuscany, began to increase production leading to the export of marble blocks to the rest of Europe and the USA. At the same time, other European countries such as France, Spain, and Greece also commenced production of a number of types of dimension stone to satisfy the growing demand. This trend continued to expand into the 20th century in many countries throughout the developed world until the 1930s, when the industry slipped into decline. This was attributed largely to the invention of artificial building materials such as truck-delivered, bulk-poured concrete for major

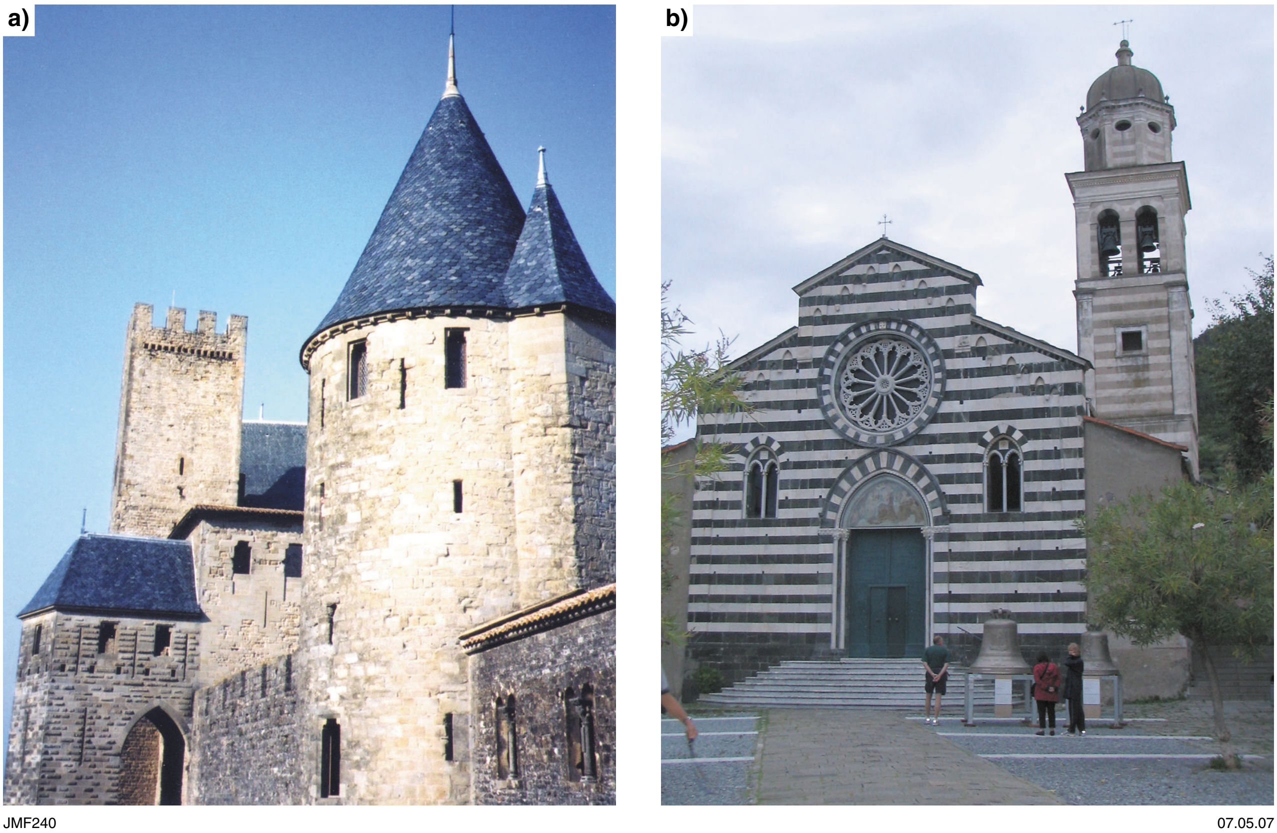

Figure 9. Two examples of medieval architecture using stone block construction: a) the walled city of Carcassonne (1226 AD) in southern France. The defences, including double outer walls and siege towers are built of massive sandstone blocks; b) the church of San Andrea (1230 AD) in Levanto in Liguria, Italy. The façade is constructed of blocks arranged in alternating rows of local dark green serpentinite, and white Carrara marble

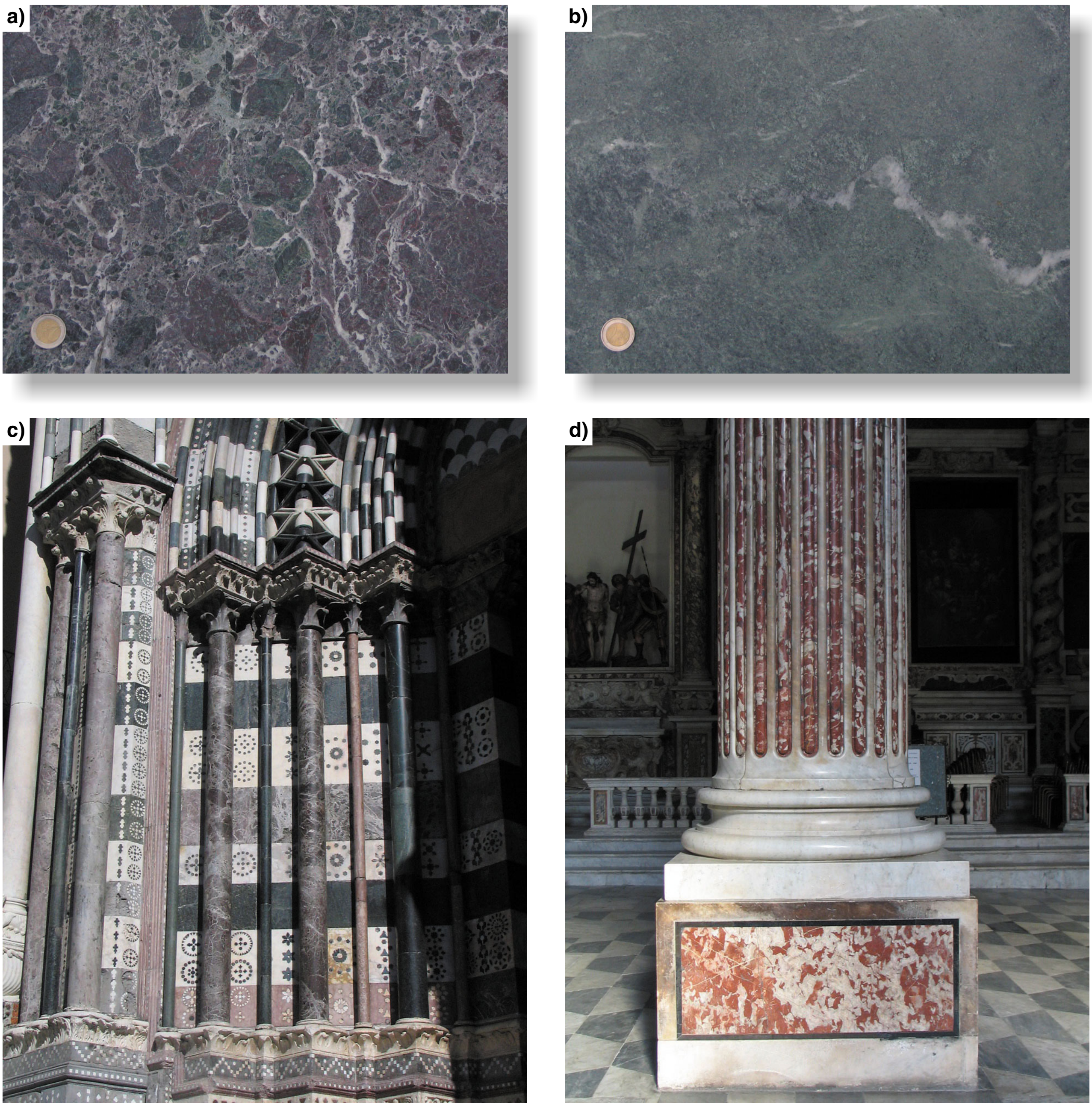

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Figure 10. Examples of Italian coloured marbles used extensively since the Renaissance period: a) deep red *Rosso Levanto* marble from Levanto in Liguria, northwest Italy; b) Green serpentine marble from the La Spezia region, northwest Italy; c) multicoloured, inlaid marble ornamentation forming the entrance to San Lorenzo Cathedral in Genoa (1118–1557 AD); d) column and plinth in red and white marble, Church of Santa Maria delle Vigne, Genoa (13–16th century AD)

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Figure 11. The renaissance-style Duomo of Santa Maria de Fiore (1436) in Florence. Built of white marble inlaid with thousands of pieces of coloured marble ranging from pink to brown, green, and black

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Figure 12. The Great Wall of China (1368–1644) extends 6700 km across northern China

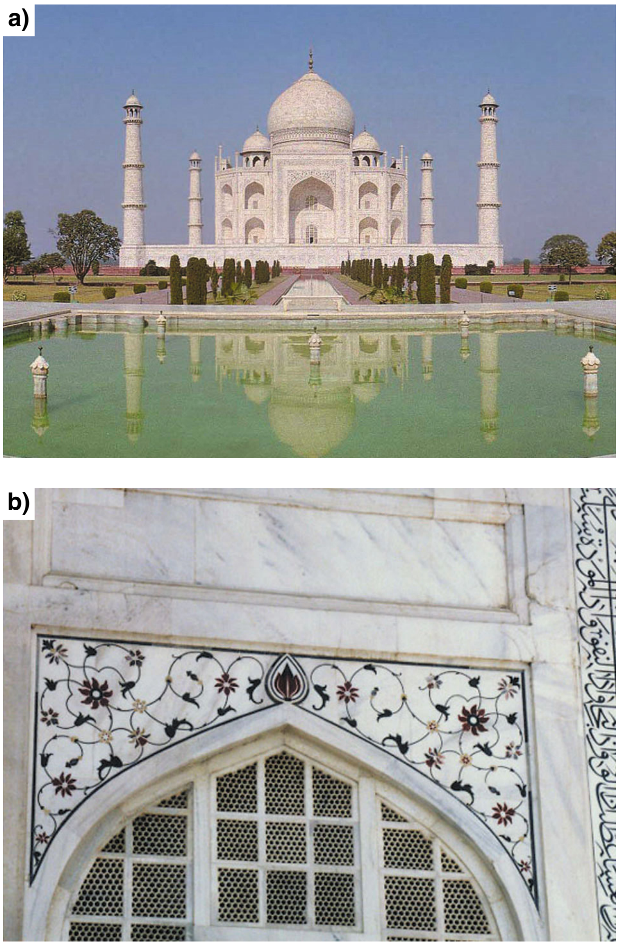

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Figure 13. The Taj Mahal at Agra in India: a) Built of inlaid, polished white marble, Shah Jehan's masterpiece was completed in 1653; b) detail of the exquisite marble inlay (photo (a) courtesy www.taj-mahal.net, © 2005 Armchair Travel Co. Ltd)

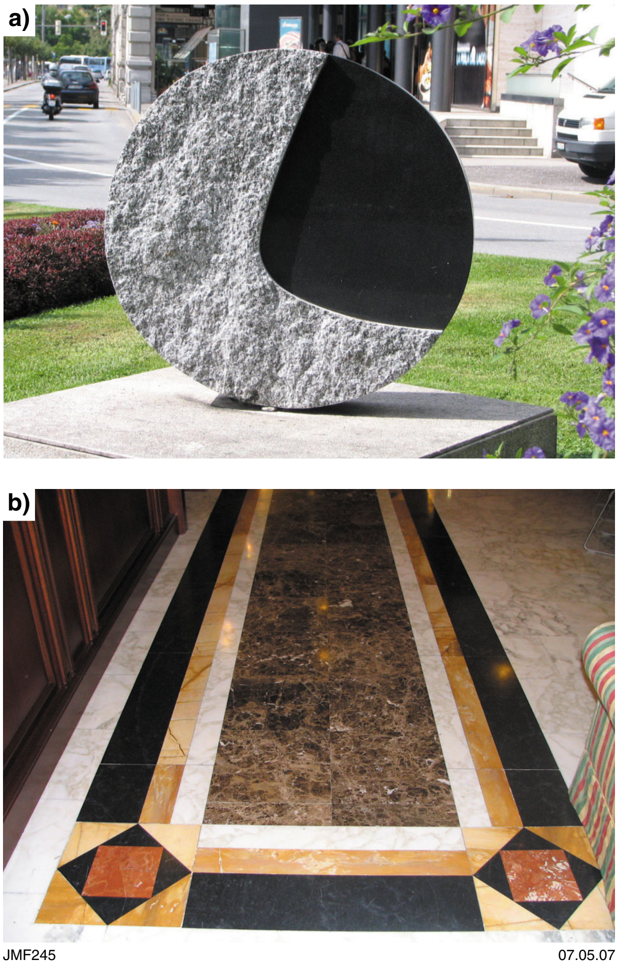

Figure 14. Contemporary examples of dimension stone applications; a) sculpture in grey and black granites, Lugarno, Switzerland; b) hotel lobby featuring multicoloured marble floor tiles, Turin, Italy

project construction such as large city buildings and dams (dee Concrete Accessories, 2005). This innovation was soon followed by the onset of the Second World War.

The decline in the use of dimension stone continued until the 1980s, when architects rediscovered stone as a building material largely for decorative purposes, and began by cladding large buildings both inside and out with pre-cut stone slabs. In recent years, this trend has spread especially relating to the use of marble, granite, black granite, gneiss, limestone, and sandstone, which have found numerous applications in the home and office construction, streetscape, and monumental industries. The demand for other dimension stones such as quartzite, serpentinite, slate and other suitable stones has also expanded, often for special applications (Fig. 14). Stone production methods from quarrying to processing and finishing have been expanded and have become more automated to handle larger volumes of raw material in a cost-effective manner as demand increases.

Chapter 4

Early applications and development of the industry in Australia

Eastern Australia

Australia's capital cities were settled in the late 18th and early 19th centuries. Shortly after initial establishment, suitable stone was sought locally for the construction of substantial, weatherproof buildings such as government buildings, warehouses, churches, banks, and homes for wealthier citizens. Other stone requirements were for the construction of port facilities, bridges and main roads. In general, each city initially used the closest suitable stone in their construction works.

New South Wales

Sydney

Sydney, in New South Wales, was the earliest of Australia's cities, being settled by the First Fleet in 1788. The first recorded stone buildings were built around Sydney Cove and the Rocks in the early 1800s.

Sandstone and granite

In Sydney, the initial stone of choice was the locally available, Triassic, multi-coloured, quartzose Hawkesbury Sandstone (Franklin, 2004). One of Australia's earliest surviving stone buildings is Cadman's Cottage. Built from sandstone on the shore of Sydney Cove in 1815–16, Cadman's Cottage was originally the Coxwain's Barracks attached to Governor Macquarie's dockyard and storehouses (City of Sydney, 2005).

In later years, numerous, outstanding examples of colonial buildings were constructed from blocks of local Hawkesbury Sandstone such as Government House (1845), the Lands Department (1881), General Post Office (1890; Fig. 15), and Sydney Hospital (1894). About this time, other dimension stones came into use in the city's buildings. Paleozoic granites were brought from the interior of the State from quarries located at Bendemeer (*Koala Blue*), Cowra (*Blue Crystal*), Dundee (*Steel Grey*), Eugowra, (*Carmina Grey*), Forbes (*Grandee*), Mudgee (*Mudgee Red*), Sodwalls, west of Lithgow (*Christmas Bush*), Tarana (*Tarana Pink*), and Tocumwal (*Riverina*). Other granite localities included Ariah Park, Grenfell, Moruya, Montague Island, Gunning, and Uralla. Another significant igneous rock was the *Bowral Trachyte* from Mount Gibraltar at Bowral.

Later dimension stone developments

In the 1920s, the sandstone industry commenced extraction of blocks in a variety of colours from the Triassic Hawkesbury Sandstone in the Somersby area near Gosford on the central coast, and later near Bundanoon in the southern tablelands. In later years, the quarrying of white, cream, and grey Silurian marbles commenced at Wombeyan and several other localities in the southern and central tablelands.

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Figure 15. Entrance to the General Post Office in Martin Place, Sydney. Constructed from Hawkesbury Sandstone in 1890, the main entrance features a superbly carved British coat of arms, surmounted by a memorial to Queen Victoria sculpted in white Sicilian marble flanked by polished granite columns

Tasmania

Hobart and Richmond — sandstone heritage

Hobart, the capital city of Tasmania, was settled in 1804 at Sullivan Cove on the Derwent River. However, it was not until after a visit by Governor Lachlan Macquarie in 1811 that plans were drawn up for the central part of the city followed in 1814 by the construction of the Anglesea Barracks. In the following 25 years many fine Georgian-style, sandstone homes and warehouses were constructed in localities such as Battery Point, New Town, and Salamanca Place at Sullivans Cove. Stone blocks for these building were sourced from quartzose and fluvial sandstones of the Phanerozoic Tasmania Basin.

The historic Georgian village of Richmond, 27 km north of Hobart, contains a convict gaol and numerous other well-preserved sandstone buildings of the period 1825–36. Richmond is also the site of Australia's oldest existing stone bridge. Built in 1823 using convict labour, Richmond Bridge comprises six sandstone arches, and is still is in use today by motorized traffic (Fig. 16a). All of the sandstone used in Richmond during this period was sourced from the nearby quarry at Butchers Hill (Our Australia, 2005).

Later dimension stone developments

After the initial settlement period, sandstone continued to dominate the supply of stone blocks to Hobart. North of Hobart, quarries of Triassic quartzose sandstone were located at Cobbs Hill, Pontville, Molesworth, Elderslie, Oatlands, Linden and Buckland, and in the Launceston district, Permian fluvial sandstone quarries were located at Nunamara and Braemar.

Other dimension stone quarried in Tasmania in later years, mainly for use in building construction in Hobart, has included a number of Devonian granites from Trial Harbour (*Anajul*), Diddleum (*Tequila*) and Devonport (*Natone*), and quartz monzonites from Coles Bay (*Nelson Red*), Blessington (*Jaydon*), and Memory Road (*Martich*). Of particular note is the bright red stone from Coles Bay (*Nelson Red*), used extensively in Tasmania and also exported to mainland Australia. Also quarried were deposits of black and brown slate at Bangor and Back Creek (Ordovician) and Tayatea (Proterozoic), used for paving and ornamental walls, and at Miena, black Tertiary basalt blocks (*Royburg Black*) were produced. In addition, the State has potential dimension stone deposits of marble, serpentinite, limestone, and dolomite (Sharples, 1990).

Queensland

Brisbane

Brisbane was initially settled as a penal colony in 1824, on the Brisbane River, as a result of explorer John Oxley's recommendations to the governor of New South Wales, Sir Thomas Brisbane.

Tuff and sandstone

Throughout the Colonial period, the Brisbane Tuff and the Helidon Sandstone were the principal stone types used in the building industry. The Brisbane Tuff is an Early Jurassic, pyroclastic flow deposit filling earlier stream channels. The tuff is a hard rock, that was originally cut into blocks by convict labour at a quarry located across the Brisbane River at Kangaroo Point. The Helidon Sandstone is a Late Triassic to Early Jurassic, fluvial sediment of the Bundamba Group from the Ipswich Basin. The stone was sourced at Helidon, about 105 km west of Brisbane. This visually attractive sandstone is generally massive and medium grained, and ranges in colour from white, to light brown, pinkish mauve, and light grey (Hensel, 2004). Today, it remains one of Queensland's principal sources of high-quality sandstone blocks.

Over the period 1824–80, there were three major building periods in Brisbane. The first period occurred between 1824 and 1839 when the city was a closed penal colony. Brisbane's oldest remaining buildings, the Old Windmill and Commissariat Store (1828–29) date from this period and were constructed from Brisbane Tuff and Helidon Sandstone. Only two buildings survive from the second building period from 1842 to 1859 when Brisbane was opened to free settlement. They are the old Saint Stephen's Church (1850) and the Deanery (1859), both constructed mainly of Brisbane Tuff. The third building period (1860–80) was a boom time when many fine buildings, churches and residences were built from Brisbane Tuff and Helidon Sandstone. Buildings included Old Government House (1862), Parliament House (1868), Victoria Barracks (1874), and Saint Patrick's Church (1880) (Walkabout–Brisbane, 2005).

Saint John's gothic cathedral was commenced in 1901. Over 100 years in construction, the cathedral was built from brick, Brisbane Tuff, and two types of sandstone (Helidon, and sandstone from Pyrmont in Sydney; Fig. 16b). In 1909, construction began on the University of Queensland at Saint Lucia. All of the buildings on the university's Great Court are constructed of Helidon Sandstone, which displays hues of beige to brown with overtones of grey, pink, and mauve.

A number of other sandstones have been used in southeast Queensland. Similar to the Helidon Sandstone, the Murphys Creek Sandstone, located 12 km west of Helidon, is an off-white stone with pale pink to pale brown variants. In the Warwick area, the Warwick Sandstone has been worked from about nine separate quarries and was used in the construction of many local buildings. This yellow-brown to brown coloured rock ranges from very fine grained, hard, banded to soft, coarse-grained material. At Beaudesert, about 60 km south of Brisbane, the greenish brown Beaudesert Sandstone was used to build the Anglican church at Mundoolan in the early part of the 20th century. More recently, a sandstone known as *Beau Grey* has become available in slabs, blocks, and tiles.

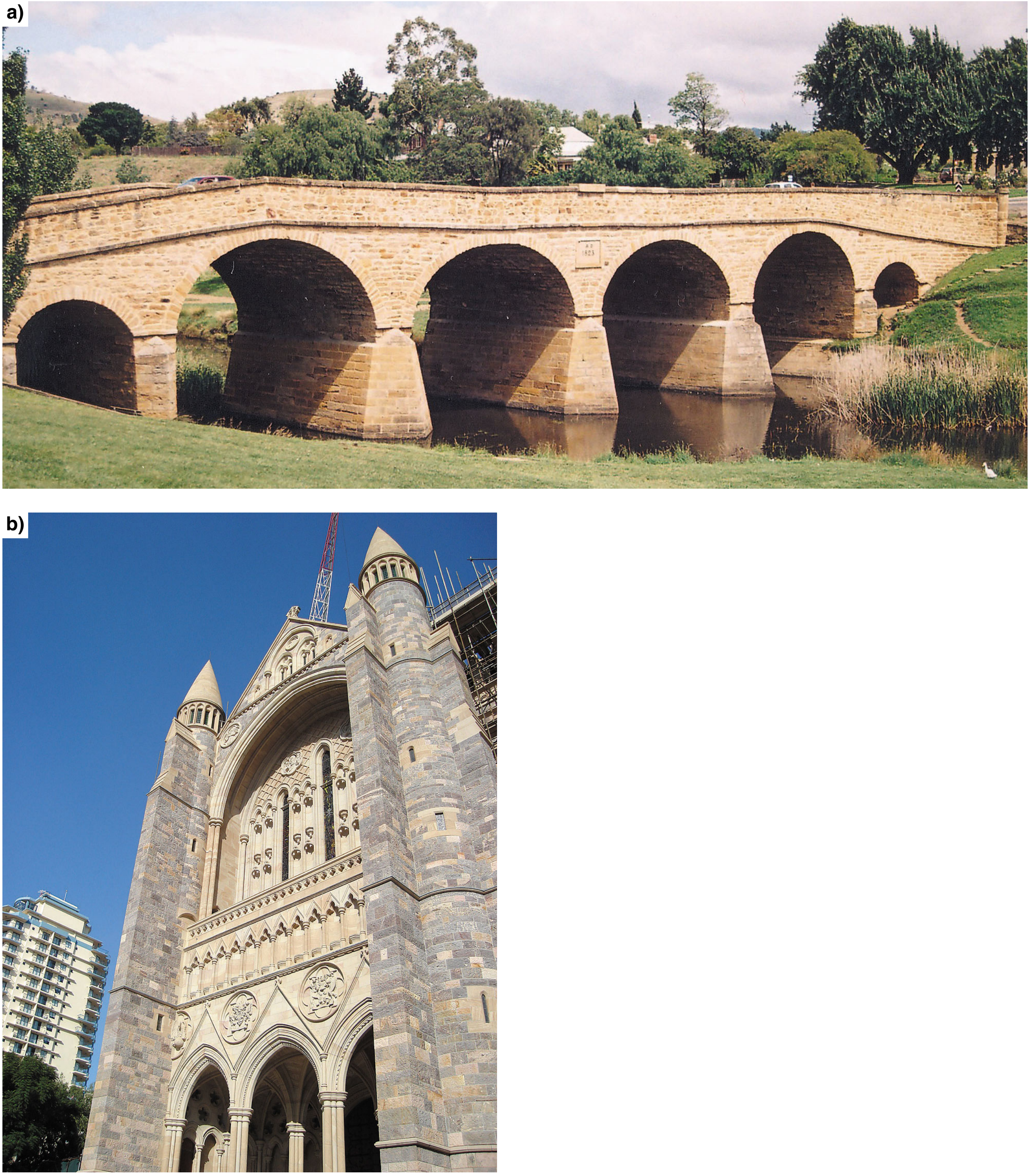

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Figure 16. Original and contemporary building stone applications in colonial architecture: a) Richmond Bridge in Tasmania is Australia's oldest stone bridge. Built of sandstone blocks by convict labour in 1823, it is still in use today; b) Originally commenced in 1901, Saint John's Cathedral in Brisbane is currently being extended. Stone used in the newly constructed western façade comprising side towers of pink and grey Brisbane Tuff, and main entrance, central wall, and spires in pale brown Helidon Sandstone, has been selected to closely match the building's original stone

This pale grey stone with a finely speckled appearance is a lithic quartz arenite.

Other Queensland dimension stones

Other dimension stones that have been produced in Queensland include marble from Chillagoe in the north of the State. In this area, massive, mainly even-textured, multicoloured marbles occur in metamorphosed zones adjacent to local granitic intrusions. The marbles form part of the Silurian to Early Devonian Chillagoe Formation, an extensive north-trending limestone belt extending 165 km. Chillagoe marbles include: *White Pearl*, *Bianca Mist*, *Champagne*, *Dreamtime*, and *Blue Crystal*.

A number of granites have also been quarried for building stone in the State. In southeastern Queensland, Permian to Triassic granites are the source of *Austin Red* at Crows Nest, and *Toowoomba Coral* from the Toowoomba district. Other potential granites in the southeast are located at Warwick, Stanthorpe, Nanango, and Blackbutt. The only other granite quarrying recorded in recent times is the Proterozoic Sybella Granite located near Mount Isa in the northwest of the State (Natural Resources and Mines, 2001).

Small quantities of slate have also been produced from the Palmer River, and Petford–Herberton districts in north Queensland.

Victoria

Dimension stone has been used in Victoria since 1838, initially in Melbourne and subsequently spreading to numerous towns and cities. A full description of dimension stone in Victoria is given in King and Weston (1997).

Melbourne

The city was founded by John Batman in 1835 on the banks of the Yarra River, a few kilometres upstream from Port Phillip Bay.

Bluestone

As early as 1838–39, the first Government 'blue' basalt quarry was established on Merri Creek to the north of the city. Because of its availability and excellent durability, blue basalt, more commonly known as 'bluestone,' became the characteristic stone of Melbourne's colonial and early 20th century buildings. These basalts, belonging to the late Cenozoic, Newer Volcanics Group, range in age from about 5.0 Ma to 0.1 Ma, vary from alkalic to mainly tholeiitic composition, and cover extensive areas of central southern and southwestern Victoria.

The original Merri Creek quarry provided bluestone for the Old Customs House and Government Offices. By the 1850s, numerous bluestone quarries had opened in the Merri Creek area, Williamstown, Newport, and Footscray and supplied blocks for the construction of buildings such as Royal Terrace (1858), Saint Patrick's Cathedral (1858–97), Goldsborough Mort Building (1862), and the portico of the Melbourne Town Hall in 1887. At that time, bluestone pavers and 'pitchers' (a type of cobble) were used extensively to pave inner Melbourne streets.

In the mid-1900s there was a decline in the use of bluestone until the construction of the Arts Centre in 1974, and City Square in 1980. More recently, there has been a resurgence in the use of bluestone in central Melbourne in the cladding of the Southgate building in 1991, and in the extensive use of sawn blocks in the construction of new streetscapes. Currently, two major quarries, at Deer Park to the northwest of the city and at Port Fairy, supply the bulk of the demand for bluestone (King and Weston, 1997).

Sandstone

From 1839, a brown Silurian sandstone was quarried in Fitzroy in central Melbourne and from many other sites in the local area. The use of this stone was short lived as it was found to be subject to rapid and serious decay, in one instance within three years of the construction of a hotel. This material was soon replaced by other dimension stones such as local Cenozoic sandstone and bluestone used in the construction of Saint James Cathedral in 1839.

In following years, other sandstones were sourced for Melbourne buildings with varying degrees of success. These included a brown–yellow Permian sandstone from Bacchus Marsh (Old Treasury Building in 1858, and Parliament House Library in 1861), a white sandstone from Kangaroo Point in Tasmania (Supreme Court in 1884), and brown and green Cretaceous sandstone from the Barrabool Sandstone, west of Geelong (Saint Paul's Cathedral in 1891). Subsequent exploration located the durable, white, Silurian Stawell Sandstone from the Grampian Mountains in the central west of the State. This was used for the construction of the western elevation of Parliament House completed in 1888. Between 1916 and 1942, the Barrabool Sandstone and the Permian Lauriston Sandstone from Kyneton were used in the construction of buildings in the University of Melbourne. The Barrabool Sandstone is still in use for restoration projects on the city's historic buildings.

Granite

In Victoria, over 420 individual Paleozoic granite intrusions have been recorded. However, only 13 have been sourced as granite dimension stone for building construction in Melbourne, and of these only the grey Harcourt Granite from the Castlemaine district, and the greenish brown Dromana Granite, from the Mornington Peninsula were widely used. Applications for granite have mainly been as base cladding, columns, and entrance ways in buildings. Good examples of the use of Harcourt Granite include the former Goode House (1891), Flinders Street Railway Station (1911), Port of Melbourne Authority (1930), and the T&G Building (1938). The Dromana Granite is used in the ANZ and National Australia banks in Collins Street, and the Commonwealth Bank in Bourke Street. In recent years, only two granites were still in production: the grey

Harcourt Granite, and the salmon-grey *Snowy River Pearl* with bluish pearlescent overtones, sourced from Benambra in the northeast of the State.

Other dimension stones

Other dimension stones found in Victoria include a number of deposits of marble (mostly crystalline limestones), limestone, and slate. The Silurian and Lower Devonian 'marbles' from eastern Victoria include the Buchan, Tyers, Cooper Creek, Lilydale, Limestone Creek, Bindi, and Martins Creek deposits. The Buchan marble in the Orbost region in eastern Victoria found considerable popularity from about 1912 to 1940 in buildings such as the State Museum (1913), where it was used mainly in entrances, foyers, and stairways. Named varieties include *Black Buchan*, *Oyster*, and *Golden Vein*. The Oligocene–Miocene Waurn Ponds, and Batesford Limestones, located west of Geelong were quarried at least as early as 1870 and were commonly used as dressings on bluestone or the Barrabool Sandstone on buildings such as Saint Paul's Cathedral (1881; King and Weston, 1997).

Ordovician slate occurs mainly in the Castlemaine area of central Victoria. The first slate quarries commenced operation in 1856, producing cut slate for flagging, kerbing, and lintels. In the 1950s and 1960s, slate from Castlemaine became popular in Melbourne as feature walls, fireplace surrounds, and in landscaping projects. Today, only small quantities of slate are mined.

Regional centres in Victoria

Numerous examples of buildings constructed from locally quarried dimension stone exist in many towns and cities around the State. The City of Geelong has numerous historic colonial buildings constructed from the local Barrabool Sandstone and dating from 1841 (Saint John's Lutheran Church). Other centres that made extensive use of local sandstones in the mid-1800s include Stawell (Stawell Sandstone), Bacchus Marsh, and Bendigo. Local granites were used to construct the Gabo Island Lighthouse in 1862 (Gabo Island Granite), and the Old Court House at Beechworth in 1864 (Beechworth Granite). In Kyneton, near Bendigo, the Bank of New South Wales was constructed in 1856 of locally obtained bluestone.

South Australia

For about 170 years, South Australia has produced a wide range of dimension stones from various areas in the south of the State. These have included, bluestone (indurated siltstone, metasiltstone, and shale), slate, sandstone, limestone, and numerous granites.

Adelaide

Adelaide was first settled in 1836–37 on the Torrens River according to a city plan based on a square grid designed by Colonel William Light.

Bluestone

The early settlers in the city soon discovered that local bluestones were a readily available source material for building stone. The original Adelaide bluestones consisted mainly of dark bluish-coloured, laminated, fine-grained, sandy or dolomitic siltstone and shale. These Neoproterozoic sedimentary rocks from the Adelaide Geosyncline proved to be dense and relatively impervious with excellent splitting properties, making them ideal for building stone. The first bluestone quarry in the Adelaide Hills commenced operation in 1838 and others followed throughout the remainder of the century. The availability of this material soon made bluestone Adelaide's principal dimension stone for domestic housing during the nineteenth century. Excellent examples of bluestone buildings can be seen in Ayers House (1846) and the walls of the Cathedral of Saint Francis Xavier (commenced 1856) from Dry Creek bluestone quarry, and Saint Augustine's Church in Unley, built in 1870 from Tapley Hill bluestone. The base courses of the South Australian Museum (1856) and Art Gallery (1881) are bluestones quarried at Tarlee and Auburn respectively.

From the 1960s onwards, new bluestone quarries opened at Kanmantoo and Wistow in the Mount Lofty Ranges supplying *Kanmantoo,* and *Wistow Bluestone* to the domestic housing market and for the construction of streetscapes. These bluestones are fine-grained, durable, Cambrian metasiltsones from the Kanmantoo Trough (Olliver, 2003).

Slate

Neoproterozoic slate, has been produced from four discrete areas. Quarries in the Tapley Hill Formation at Willunga produced slate since the 1840s *(Willunga Slate).* Until their closure in the 1930s, the Wilunga quarries produced almost 30 million roofing shingles and about 60 000 t of slate for pavers and walls. The *Mintaro Slate* forms part of the Mintaro Shale located near the town of the same name. Opened in 1856, the Mintaro quarries are amongst the oldest continuously worked quarries in Australia. These quarries produce high-quality slate for architectural work, billiard tables, and material for paving, wall panels, and floor tiles (Hough,1999).

More recent slate operations are located at Spalding (*Broughton River Slate*) and the *Parachilna Slate* at Jones Hill in the Flinders Ranges. These operations supply tiles, blocks, and pavers largely to the local market, and roofing shingles for restoration work.

Sandstone

From about 1860 until 1950, large quantities of sandstone were quarried close to Adelaide for residential and public buildings. Sandstones interbedded with the Neoprotozoic Skillogalee Dolomite were quarried to the east of Tea Tree Gully (*Tea Tree Gully Sandstone* and *Glen Ewen Sandstone*). These sandstones were used in the construction of historic buildings such as the Adelaide Town Hall (1863), Supreme Court (1866), and Edmund Wright House (1875). During the 1880s, a quarry in the Neoproterozoic

Aldgate Sandstone near Stirling was opened. Known as the *Mount Lofty Sandstone*, this quarry produced large quantities of cut stone for construction projects, especially during the 1920s and 1930s. From the 1950s onwards, sandstone quarries were opened at Basket Range, Kapunda, Brinkworth, and Manoora. In recent times, the *Basket Range Sandstone*, as well as a sandstone from the Permian Cape Jervis Formation known as *Finnis River Sandstone*, has continued to operate (Hough, 1999).

Limestone and marble

A Pliocene, calcareous sandstone, the Hallett Cove Sandstone, known as *Adelaide Limestone*, was available to the early settlers in the centre of the city on the banks of the Torrens River. In 1840, the Holy Trinity Church was built of this material, followed by the Old Legislative Building in 1857.

As early as 1844, quarrying of the Oligocene–Early Miocene Gambier Limestone commenced in the Mart area, about 10 km west of Mount Gambier in the southeast of the State. This material, known at *Gambier Stone*, is a white to cream to light-brown, lightweight, medium-grained, porous limestone. Peak production during the 1950s yielded over 1 Mt of limestone blocks for use in house construction, both in the Mount Gambier area and suburban Adelaide. Quarries are still operating in the area (Olliver, 2002).

Quarrying of the Miocene Mannum Limestone (*Murray Bridge Freestone*) commenced around Murray Bridge on the Murray River, east of Adelaide, early in the last century and supplied limestone blocks for the construction of part of Saint Peter's Cathederal (1901), the South Australian Museum (1908–15), Bonython Hall (1933), and the Art Gallery of South Australia (1936). More recently, in 1996, the bell tower and spire of the Cathedral of Saint Francis Xavier were also constructed from this limestone (Hough, 2006).

Northeast of Adelaide, there are extensive areas of limestone along the cliffs of the Murray River. The Pliocene *Waikerie* and *Ramco Limestones* were produced from this area, and in the 1930s the *Waikerie Limestone* was used to construct the upper stories of the Savings Bank of South Australia and the Westpac Bank, both in King William Street. *Ramco Limestone* was used in the Westpac Bank's lower floors (Olliver, 2004).

From about 1850 to 1980, Cambrian marble was quarried in the area from Angaston (*Barossa White*) to Kapunda (*Kapunda Marble*), about 100 km north of Adelaide. The Kapunda quarry yielded marble that varies from white to pale grey, some with dark banding, and also a streaky pink variety. In 1889 and again in 1936, *Kapunda Marble* (laid on a granite plinth) was used in the construction of the new Parliament House in Adelaide.

Granite, gneiss, and black granite

South Australia has numerous granites that have been exploited in a spectacular range of colours and textures. Many of these operations are of comparatively recent origin, with some commencing within the last 15 years. The Eyre Peninsula in western South Australia has numerous Mesoproterozoic granites that form part of the regional Hiltaba Granite Suite. The granites that have been mined for building stone, monuments and streetscapes include the spectacular pinkish-red *Calca Granite*, quarried near Streaky Bay in the far west, and *Desert Ruby, Desert Lilac, and Desert Rose* from the Minnipa–Wudinna area.

Forty kilometres southeast of Wudinna, a grey, Archean granite gneiss (*Koongawa Grey*) was recently quarried, and near Cowell on Spencer Gulf, a Paleoproterozoic gneiss (*Royal Mahogany*) has been quarried from 1998. Near Wallaroo on the northern Yorke Peninsula, a gneissic, calcsilicate metasomatite known as *Harlequin* is currently in production. This spectacular stone is of variable colours, notably pink, red, and green.

A suite of younger, Paleoproterozoic granites are located in the southeast of the State in the Kingston SE–Padthaway area, and also in the eastern Mount Lofty Ranges, east of Adelaide. In the southern area, a coarse-grained, blue granite known as *Kingston Blue*, and the greenish grey *Padthaway Granite* (also known as *Balmoral Green and Tatiara Green*) have been recently produced. In the eastern Mount Lofty Ranges near Murray Bridge, the light-grey *Monarto Granite* and the orange–pink *Murray Bridge Granite* were extensively used in Adelaide city buildings from about 1880 to 1940. There has also been intermittent production since 1963 of the pale pink to pale brown *Sienna Brown* granite from near Cambrai (Hough, 1999).

In the same area of the eastern Mount Lofty Ranges, black granite has been quarried for over 40 years at Black Hill, about 30 km northeast of Mannum. The rock forms part of the Middle Ordovician Black Hill Gabbroic Complex. It is a hard, coarse-grained norite capable of taking a very high polish. These characteristics have created a strong market for this material as building stone panels and for monumental work. Currently, three large-scale operations produce at least two grades, known as *Imperial Black* and *Adelaide Black* (Fig. 17).

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Figure 17. Ten tonne block of export-grade black granite (*Imperial Black*) from Black Hill, South Australia

Northern Territory

Darwin

After several failed attempts at settlement in the region, Darwin was laid out by Surveyor General George Goyder in 1869.

Porcellanite

Ten years later in 1879, porcellanite blocks were used in the construction of the Darwin Police Station and Courthouse. Other historic porcellanite buildings followed including the Town Hall (1883), Browns Mart (1885), Victoria Hotel (1890), and the Anglican Church (1902). At this time, porcellanite was obtained from local quarries situated close to the coast at Larrakeyah and Fannie Bay (Doyle, 2001). A description of porcellanite rock is given in **Other dimension stones** in Chapter 2.

Granite

More recently, a quarry was opened at Mount Bundey, 95 km southeast of Darwin, to source the Mesoproterozoic Mount Goyder Syenite for dimension stone blocks (Doyle, 2001). This coarsely crystalline, rich brown syenite, known as *Darwin Brown*, has been used extensively as polished slabs in the new Northern Territory Houses of Parliament, as well as other Darwin city offices and monuments. Blocks of this material have been exported to other states and overseas.

Other areas in the Northern Territory

Other rocks have been sourced as dimension stones in the Territory, including a Proterozoic granite quarried intermittently in the Tennant Creek region. Known as *Dreamtime*, this medium- to coarse-grained granite is coloured brown, with blue and beige overtones. In past years in the Alice Springs region, the orange-red, Paleozoic Mereenie Sandstone (*Ooraminna Sandstone*) has been quarried as a source of flagstones for local building purposes.

Western Australia

Western Australia was first settled at Albany in 1826 by Major Edmund Lockyer who had been dispatched from Sydney to construct a military base. Three years later, in 1829, Captain James Stirling founded the Swan River Colony, which was to become the city of Perth. This was followed by the larger regional centres in the State such as Bunbury (1843), Geraldton (1850), and Kalgoorlie (1895). As was the case in the eastern states, the search was soon underway in each local area to find stone suitable for the building of substantial stone buildings and other structures, and again, deposits of suitable rock were sought as close to possible to the intended development sites.

Perth, Fremantle, and Rottnest Island

For over 100 years from 1831 to 1932, both Perth and Fremantle relied heavily on access to local high-grade dimension stone deposits for the construction of major public buildings for the provision of government services, as well as parliamentary buildings, schools, churches, courts, gaols, and also for a number of houses. During the latter part of the 19th century, smaller quantities of stone with special properties and/or colours such as granite and sandstone were transported from localities up to 200 km distant. A summary of historic buildings in Perth, Fremantle, and Rottnest Island using local building stones is given in Table 4. Additional information relating to building and facing stones used in buildings in Perth and Fremantle, both in historic and relatively recent times, is given in Geological Survey of Western Australia (1984).

Tamala Limestone

The early settlers in the Perth area soon discovered the extensive resource of Pleistocene Tamala Limestone located in places along the coastline, mainly from Scarborough southwards to Coogee. Another large, high-grade Tamala Limestone resource was found on Rottnest Island about 20 km offshore from Fremantle. This coarse- to medium-grained sandy limestone, or calcarenite, originally deposited in sand dune and littoral beach environments, was found to be relatively soft and easily workable. Accordingly, Tamala Limestone became the first stone to be used extensively in early stone buildings of the Colony. Quarries were established at Fremantle, Cottesloe, Mosman Park, Coogee, and Reabold Hill in the City Beach area (Fig. 18).

The Round House, Western Australia's oldest public building, was built at Arthur Head in Fremantle in 1831 and was used as a gaol until 1857 and then as a detention centre until 1900. Building continued in Fremantle using Tamala Limestone in the construction of splendid colonial and early 20th century buildings for the next 100 years. These include the Fremantle Prison and Warders' Quarters (1851–59), the Commissariat Store (1851), the Fremantle Boys' School (1854), Saint John's Anglican Church (1879), the Princess May Girls' School built about 1897 (Fig. 19), and Saint Patrick's Basilica constructed between 1900 and 1916 (*frontispiece*).

In the centre of Perth, Tamala Limestone was also the preferred building stone until 1900. Excellent early examples include the Old Perth Boys' School (1853–1868), the Old Court House and Gaol (1854), the Perth Mint (1899), Fire Brigade No. 1 Station (1900–14), and Old Parliament House (1902–04). In 1932, Winthrop Hall at the University of Western Australia, the last of Perth's grand dimension stone buildings of the era, was completed. This magnificent building was built in the style of an Italian medieval guildhall. The walls and bell tower are of high-grade, cream-coloured, Tamala Limestone blocks quarried from the University's own quarry at Coogee; ornamental stonework and dressings are all of fine-grained Donnybrook Sandstone (Fig. 20).

Table 4. Historic buildings in Perth, Fremantle, and Rottnest Island incorporating local building and facing stones

Dimension stone	*Building*	*Construction date/s*	*Location*	*Address*	*Comments*
Tamala Limestone	Round House	1831	Fremantle	Arthur Head	Western Australia's oldest public building
	Prison Warders' Quarters	1851	Fremantle	7–41 Henderson Street	
	Shipwreck Galleries	1851	Fremantle	Cliff Street	Originally Old Commissariat Store
	Fremantle Prison	1852–59	Fremantle	The Terrace	
	The Perth Film and Television Institute	1854–1910	Fremantle	92 Adelaide Street	Originally Fremantle Boys' School
	St John's Anglican Church	1879	Fremantle	26 Queen Street	Walls: Tamala Limestone. Tower and spire: Donnybrook Sandstone
	Fremantle Museum and Art Gallery	1861–86	Fremantle	1 Finnerty Street	Originally Asylum for the Criminally Insane
	Sampson House	1888–90	Fremantle	61 Ellen Street	
	Wesley Church	1889–1928	Fremantle	Cnr Market and Cantonment Streets	
	Fremantle Education Centre	1897?	Fremantle	Cnr Parry and Cantonment Streets	Originally Princess May Girls' School
	St Patrick's Basilica	1900–16	Fremantle	47 Adelaide Street	Walls: Tamala Limestone. Spires, buttresses, window dressings and entrance are shaped and carved from Donnybrook Sandstone
	Old Perth Boys' School	1853–68	Perth	139 St Georges Terrace	
	Old Court House and Gaol	1854	Perth	Cnr Beaufort and Francis Streets	
	St Mary's Catholic Cathedral	1865–1930	Perth	Victoria Square	
	Swan Barracks	1896–97	Perth	Francis Street	
	Perth Mint	1899	Perth	310 Hay Street	
	Fire Brigade No. 1 Station	1900–14	Perth	25 Murray Street	
	Old Parliament House	1902–04	Perth	Harvest Terrace	Ground floor: Tamala Limestone. 1st floor: Donnybrook Sandstone
	Edith Cowan University, Claremont Campus	1902	Claremont	Bay Road	Originally Claremont Teachers' College
	Redemptorist Monastery and Church	1903–	North Perth	190 Vincent Street	Commenced 1903 and completed in stages over many years
	Winthrop Hall	1932	Perth	University of Western Australia, Mounts Bay Road	Walls: Tamala Limestone. Columns, upper walkways, window dressings, friezes, and balcony are cut or carved from Donnybrook Sandstone
	Thomson Bay Settlement	1840–49	Rottnest Island	Thomson Bay	Includes military barracks, boat house, cottage, superintendent's house, and a sea wall
	Main Lighthouse	1896	Rottnest Island	Wadjemup Hill	
Donnybrook Sandstone	Perth Court of Petty Sessions	1905	Perth	Cnr Beaufort and Roe Streets	
	Perth Government Stores	1911	Perth	70–74 Murray Street	
	Public Health Department	1912	Perth	57 Murray Street	
	General Post Office	1914–23	Perth	Forrest Place	Upper floors: Donnybrook Sandstone. Ground floor: Mahogany Creek Granite
	Commonwealth Bank	1930–33	Perth	Cnr Forrest Place and Murray Street	Originally CBC Bank. Ground floor: Mahogany Creek Granite
	First Church of Christ Scientist	1939	Perth	264 St Georges Terrace	
	Parliament House (new)	1964	Perth	Entrance from Malcolm Street	Outside porch: Mulroy Green Granite, Front steps: Mundaring Granite
	Scottish House	1898	Fremantle	10–12 Phillimore Street	Sandstone rests on a granite basal plinth
	Railway Station	1907	Fremantle	Phillimore Street	
	Customs House	1908	Fremantle	4–8 Phillimore Street	
Mundaring Granite	Perth Town Hall	1868	Perth	Cnr Hay and Barrack Streets	Plinth and some upper facing
	Palace Hotel	1896	Perth	Cnr St Georges Terrace and William Street	Plinth facing blocks
	State War Memorial Cenotaph	1929	Perth	Fraser Avenue, Kings Park	
	Parliament House (new)	1964	Perth	Entrance from Malcolm Street	Front steps
	Scottish House	1898	Fremantle	10–12 Phillimore Street	Plinth and lower facing
	ANZ Bank	1935	Fremantle	84 High Street	Plinth and front steps

Table 4. (continued)

Dimension stone	*Building*	*Construction date/s*	*Location*	*Address*	*Comments*
Greenmount Granite	Old Museum and Art Gallery	1902–08	Perth	James Street	Ashlar blocks up to ground-floor level James Street frontage
Meckering Granite	Old Museum and Art Gallery	1902–08	Perth	Beaufort Street	Ashlar blocks up to ground-floor level Beaufort Street frontage
	Old Parliament House	1902–04	Perth	Harvest Terrace	Base course
	Supreme Court	1903	Perth		Foundations and base course
Kellerberrin Granite	Old State Reference Library	Early 1900s	Perth	James Street	Base course
Mahogany Creek Granite	General Post Office	1914–23	Perth	Forrest Place	Ground floor and basement
	Commonwealth Bank	1930–33	Perth	Cnr Forrest Place and Murray Street	Originally CBC Bank. Ground floor and entrance arch
Lateritic duricrust	St John's Lutheran Church	1936	Perth	16 Aberdeen Street	Cut and dressed blocks
	New Church	1940	Perth	176 Adelaide Terrace	Cut and dres

Figure 18. Rehabilitated Tamala Limestone block quarry at Reabold Hill, City Beach area, Perth

Quarrying commenced on Rottnest Island soon after the arrival of the arrival of Henry Vincent, the island's superintendent in 1839. Quarries were established in deposits of high-grade Tamala Limestone adjacent to the Thomson Bay settlement, where stone was removed using blasting powder and then sawn into blocks using pit saws. Completed blocks were then moved on wooden carts to nearby construction sites. By 1849, Vincent had completed various limestone block buildings including a barracks for the military guard, a boathouse, a cottage, and a house for the superintendent, as well as a sea wall along Thomson Bay (O'Connor, 1977; Rottnest Island Management Planning Group, 1985).

The Main Lighthouse on Wadjemup Hill in the centre of the island was completed in 1896. The building, which is almost 39 m high, was built to replace a smaller lighthouse constructed in 1849 using convict labour. The limestone blocks for both structures were quarried at Nancy Cove on the island's southern shoreline about 1 km south of Wadjemup Hill (Fig. 21).

About the beginning of the 20th century other quarries were established on the island. It is likely that substantial material was quarried from an area close to the Army Jetty at the southern end of Thomson Bay. This is probably the source of Rottnest limestone blocks used in the construction of the Perth Mint, in the ground floor of Old Parliament House in West Perth, and sections of the Old Museum and Art Gallery in James Street in the city.

Donnybrook Sandstone

The Early Cretaceous Donnybrook Sandstone is located near the town of Donnybrook, about 200 km south of Perth and about 40 km south-southeast of the Port of Bunbury. The massive, fine-grained sandstone's value as a building material was first recognized about 1895 for its natural hardness that made it an excellent material for high-precision-cut blocks and intricate, high-quality carving, as well as for its consistency of colour within localized discrete beds. However, it should be noted that there is considerable colour variation in the sandstone at different sites and stratigraphic levels ranging from white to off-white, pale pink, mid-brown, mottled yellow, pink and golden brown.

As the sandstone's properties became more widely known, small-scale quarrying commenced with the removal of select areas of stone for use in the construction of buildings in Perth, either in whole or in part. The first of these was Scottish House in Fremantle, completed in 1898. In Perth, Old Parliament House was completed in 1904, followed by buildings including the Perth Court of Petty Sessions (1905), Government Stores (1911), Public Health Department (1912) and the General Post Office (1923; Fig. 22). In the early 1930s, Winthrop Hall at the University of Western Australia (Fig. 23) and the CBC Bank (now Commonwealth Bank) in Forrest Place were built. At this time, up to eight quarries were operating at Donnybrook. In the years following the Great Depression and leading up to the Second World War, most quarries

Figure 19. Historic Tamala Limestone buildings in Fremantle: a) the Round House is Western Australia's oldest public building (1831); b) the Commissariat Store was commenced in 1851 (now the Shipwreck Galleries); c) Fremantle Prison warders' quarters were built in 1851; d) The Fremantle Boys' School (1854) is now the Film and Television Institute

closed down and remained that way until 1981. One of the few large stone buildings constructed during this time was the new Parliament House in 1964, when Donnybrook Sandstone was used for the front wall and main entrance. A more complete description of the Donnybrook Sandstone and its use as a dimension stone is given in Fetherston (2005).

Granite

A total of five Archean granites from the Yilgarn Craton have been quarried and used in major buildings in the Perth area since the 1860s. Three of these, the Greenmount, Mundaring, and Mahogany Creek Granites are located between 20 and 45 km east of Perth in the Darling Range adjacent to the Great Eastern Highway. The Meckering and the Kellerberrin Granites are located beside the Trans Australia Railway about 115 and 180 km east of Perth respectively.

All these light-medium grey and medium-grained granites are typical of the period in which they were used until the 1930s. These stones were commonly used as base courses and foundation plinths of buildings upon which another feature stone would be used for the upper floors (Table 4). The first application for granite as a building stone was in the construction of the Perth Town Hall in 1868 where Mundaring Granite was used in the building's plinth and some upper level facing. Probably the most impressive use of granitic building stones in Perth is the Mahogany Creek Granite used in the ground floors of the General Post Office (Fig. 22) and adjacent CBC Bank in Forrest Place in 1923 and 1933 respectively. In 1929, the State War Memorial Cenotaph was completed at a site overlooking the Swan River from Kings Park. This spectacular monument is constructed of Mundaring Granite (Fig. 24).

Lateritic duricrust

Cut and dressed lateritic duricrust blocks in various shapes have been obtained from deep weathering profiles overlying mainly Archean granites in the Darling Range, 20 km east of Perth. The hard, red-brown lateritic duricrust, composed of iron-rich, indurated pisoliths, has been used in the construction of two historic churches on

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Figure 20. Historic Perth buildings constructed from Tamala Limestone and Donnybrook Sandstone: a) Completed in 1899, the Perth Mint was constructed from Tamala Limestone blocks quarried on Rottnest Island; b) Fire Brigade No. 1 Station (1900–1914) in Tamala Limestone; c) Old Parliament House (1902) in Harvest Terrace, West Perth. The ground floor is built of Tamala Limestone blocks, and the upper level is of pale brown Donnybrook Sandstone; d) Winthrop Hall at the University of Western Australia. Constructed in 1932, the walls and bell tower are constructed of Tamala Limestone. The upper level walkways with colonnaded windows, archways, window dressings, friezes, and tower balconnette are all of Donnybrook Sandstone

the perimeter of the City of Perth. Saint John's Lutheran Church in Aberdeen Street was built in 1936 (Fig. 1), and the New Church in Adelaide Terrace dates from 1940 (Geological Survey of Western Australia, 1984).

Early regional development

Albany

In Albany, on the State's southern coast, a Mesoproterozoic, grey, megacrystic granitoid (*Albany Granite*) was quarried at Mount Melville immediately west of the town. This visually attractive stone provided blocks for the construction of a number of historic buildings such as Old Albany Gaol (1873), Saint John's Anglican Church (1875), the Town Hall (1888), and the Courthouse (1897). Also, local Pleistocene coastal limestone (calcarenite), the equivalent of the Tamala Limestone on the west coast, was quarried close to the coast as a source of lightweight building material.

Bunbury and Geraldton

In the towns of Bunbury and Geraldton on the west coast, many early buildings were constructed from local stone, including the cell block of the Bunbury Court House (1856) and, in Geraldton, the Old Railway Station (1878).

In both areas, deposits of high-grade Pleistocene Tamala Limestone were quarried close to the coast and used in the construction of a number of buildings, including the Old Post Office in Bunbury in 1860 and, in Geraldton, the Residency in 1861 and the Post Office in 1878.

Other local stones available to these communities included the columnar, black, Bunbury Basalt of Cretaceous age that was used in the Bunbury area as slabs in entrance ways of early buildings, and also as cobbles in road construction (Fig. 25). In the Geraldton region, a partially weathered, coarse- to medium-grained,

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Figure 21. The Main Lighthouse on Wadjemup Hill, Rottnest Island. Completed in 1896, it is constructed of Tamala Limestone blocks quarried at nearby Nancy Cove

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Figure 22. The General Post Office in Forrest Place, Perth. Built in 1923, the ground floor is constructed of light grey Mahogany Creek granite. The upper walls, window dressings, and Ionic columns are of pale brown Donnybrook Sandstone

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Figure 23. The 'Juliet-style' balconette on the bell tower of Winthrop Hall at the University of Western Australia. Built in 1932, it is a fine example of carving in fine-grained Donnybrook Sandstone by master stonemasons

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Figure 24. State War Memorial Cenotaph, Kings Park, Perth. Completed in 1929, the monument is built of blocks of pale grey Mundaring granite

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Figure 25. Rough-cut blocks of Bunbury Basalt surrounding an ornamental pool in central Bunbury

bedded sandstone was quarried from the Lower Jurassic Greenough Sandstone at several sites including White Peak quarry (Fig. 26), and Chapman Valley Road quarry, both 13 km to the north and northeast of Geraldton respectively (Playford, P. E., 2005, written communication). This mottled, slightly ferruginous sandstone was used extensively as a building stone in Geraldton in the construction of buildings such as Saint Francis Xavier Cathedral (1916–38; Fig. 27) and Saint John's Uniting Church (1894; Playford et al., 1970; Langford, 2001).

Kalgoorlie–Boulder and Coolgardie

In the Eastern Goldfields, the discovery of gold in Coolgardie in 1892 and in Kalgoorlie the following year, caused a gold rush that brought many thousands of people to the area. In 1895, the Municipality of Kalgoorlie was proclaimed and a demand was created in the adjoining towns of Kalgoorlie–Boulder, and in the town of Coolgardie about 40 km southwest, for building stone to construct major government and commercial buildings. Suitable material was subsequently located about 2 km west of Bullabulling on the Great Eastern Highway some 30 km west of Coolgardie.

In this area the Ashlar* Stone quarry was developed to cut blocks from the weathered and comparatively soft regolith zone comprising bedded felsic volcanic and volcanogenic rocks including arkose, grit, and reworked equivalents from the Archean Black Flag Beds. Stone from this quarry was of three distinct varieties: a white quartz, gritty, bedded material; a pinkish brown variety of the former; and a rusty-coloured variety containing goethite nodules and inclusions. Of these, the pinkish brown variety, known as *'Ashlar Pink Stone'* or *'Local Pink Stone'*, appears to have been the most commonly used building stone in the region between 1894 and the early 1900s.

In Kalgoorlie, the *Ashlar Pink Stone* was used in the construction of many buildings including the Kalgoorlie Railway Station (1896), Post Office (1899), and the front facade of the Town Hall (1908). In Coolgardie, situated much closer to the Bullabulling quarry, it appears that most substantial colonial buildings were built from this material. Most impressive of these is the Wardens Court completed in 1898 (Fig. 28). Other buildings include the Post Office (1894), Warden Finnerty's house (1895), and many other houses and hotels of the period. Today, it appears that the Bullabulling quarry has been largely depleted (Fagan, R. K., 2005, written communication).

Other areas

There are many other towns and settlements throughout the State where historic buildings were constructed from local stone. From about 1860 until 1930, it was a common practice to construct public buildings from local stone, especially in towns throughout the wheat belt between Geraldton and Esperance, and later in the Eastern Goldfields and settlements in the north of the State.

* Ashlar: square or rectangular dressed stone building blocks commonly less than 38 cm square and having squared sides and corners. External faces are generally smooth or polished and may be decorated with a variety of surface treatments.

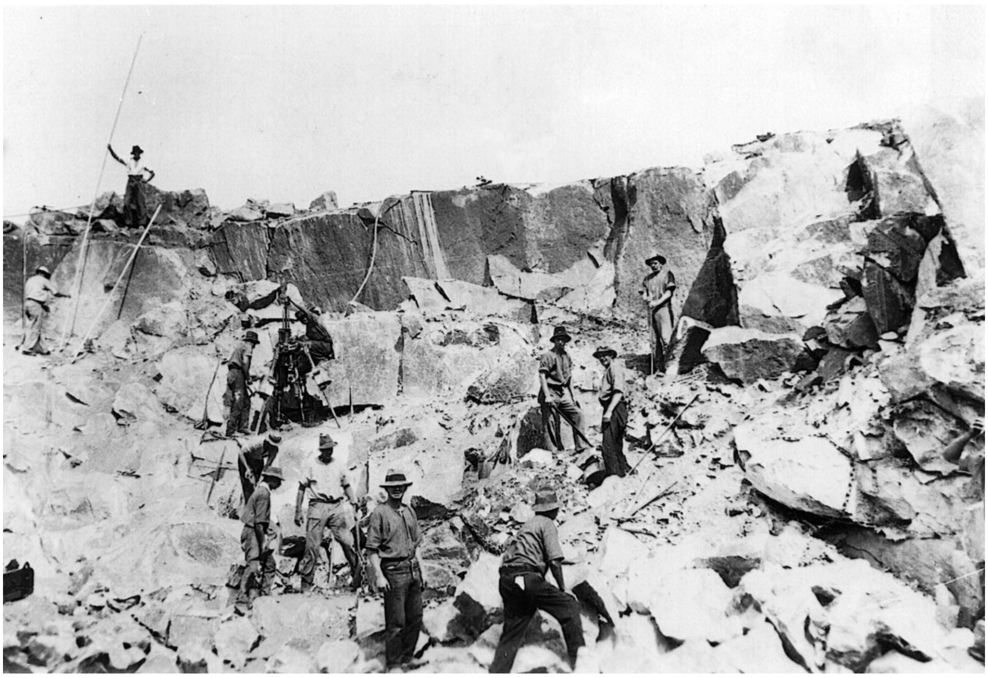

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Figure 26. Quarrymen working at the White Peak quarry in 1926. At this site the Greenough Sandstone was quarried for building blocks destined for construction projects in Geraldton (photo A. C. Burns)

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Figure 27. Saint Francis Xavier Cathedral in Geraldton constructed between 1916 and 1938. The walls are built from blocks of mottled Lower Jurassic Greenough Sandstone

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Figure 28. The Coolgardie Wardens Court completed in 1898. The building is constructed of *Ashlar Pink Stone* quarried at Bullabulling

Two examples of the use of local stone may be seen in Northampton, about 50 km north of Geraldton, and in the farming towns of Gingin and Dandaragan, 70 and 140 km north of Perth respectively.

Northampton

The historic mining town of Northampton has a number of attractive stone buildings, both public and residential, constructed from 1870 to about 1930 of blocks of Silurian Tumblagooda Sandstone from the Southern Carnarvon Basin. This slightly friable sandstone, which varies from pink to white, cream and buff, was quarried from a mineral claim about 14 km north-northwest of the town. Connolly (1959) states that in the area of the mineral claim there is a large quantity of sandstone that is of only slightly lesser quality than the well-known Donnybrook Sandstone. A fuller description of the Tumblagooda Sandstone present at this site is given in Chapter 10.

Gingin and Dandaragan

In the town of Gingin there are a number of historic buildings constructed from an unusual building stone locally known as *Casuarina Stone*, a grey to beige and pale yellow coloured material of Holocene age ranging from a clayey diatomite to diatomaceous clay (Hocking et al., 1975). In the Gingin area it was quarried from a number of sites along Gingin Brook between 1 and 7 km to the west and northwest of the town. The material is comparatively soft when quarried but hardens considerably on exposure to air.

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Figure 29. Philbey's cottage in Gingin was constructed in 1903 from local *Casuarina Stone*

From 1860, a number of buildings were constructed in Gingin from *Casuarina Stone* including Saint Luke's Anglican Church (1861) and Rectory (1898), and a number of houses such as Philbey's cottage in Brockman Street (1903; Fig. 29). In 1855, the old Bedamanup Homestead located about 7 km northwest of Gingin was built of *Casuarina Stone* resilicified with opaline silica (Udell, 1979). Farther north, in the town of Dandaragan, the local schoolhouse is also recorded as being constructed from *Casuarina Stone* probably sourced from sites adjacent to local diatomaceous swamps about 13 km southwest of the town.

Chapter 5

Stone selection, resource estimation, and quarry design

In any successful dimension stone operation it is vital to first select a site accessible for quarrying within an economic distance of a port or processing plant. The potential site must contain stone with the right properties and sufficient resources to satisfy customer requirements on a consistent basis. Surface expressions of potential deposits may appear to be far more extensive than the sub-surface stone resource that ultimately turns out to be suitable for quarrying. In practice, it is often difficult to locate large resources of durable material with uniform grade for the production of 10–25 t blocks on a commercial basis.

Selection criteria

Holmes et al. (1982) list six key characteristics that any potential dimension stone resource must possess before quarrying is contemplated:

- The stone in question must have aesthetic appeal and factors such as colour, pattern, texture and finish are important characteristics that must match current demand. It must be remembered that the popularity of various dimension stones remains very much at the whim of the architectural profession. Accordingly, it is vital that new dimension stones entering the market must match or stimulate current architectural tastes. It should also be remembered that decorative stones in vogue today may not have the same degree of popularity in a few years time.
- The stone resource must be relatively free from joints, fractures, and other imperfections which would preclude the extraction of large blocks. Closely spaced joint sets may severely limit maximum block size, while imperfections, such as xenoliths and veins, may otherwise spoil the visual appearance of a block (Fig. 30).
- The stone must be sound and durable.
- It must be uniform in colour and texture.
- Stones required for polishing must have the property of taking and retaining a polish. This generally applies to relatively hard rocks such as granite, black granite, granite gneiss, and metamorphic rocks including highly crystalline marble and serpentine marble. This property is essential for polished stone destined for outdoor applications and exposure to the weather.
- The stone resource must be available in sufficiently large quantities to satisfy demand for uniform material to supply large orders both in the short and long term. Sufficient material should also be available to meet future demand for stone maintenance and restoration projects.

With these characteristics in mind, the following processes summarize the main stages involved in the delineation of a dimension stone resource in Australia. A detailed description of these stages and other methods of investigation is given in Smith (1999).

Exploration and assessment

Once a potential dimension stone has been identified (usually as a result of random sampling) that appears to satisfy most of the foregoing criteria, there are a number of field assessment stages necessary to prove up what may ultimately become a commercial quarry operation.

Field mapping

Once a search of previous geological exploration and/or mining data relating to the local area, mineral tenements, and other necessary local administrative matters has been carried out, the most important stage of the exploration program is the investigation of the prospect by a close-spaced ground survey. Gathering field data to prepare a detailed geological map (that generally ranges from 1:1000 to 1:10 000 in scale depending on the area of the prospect)

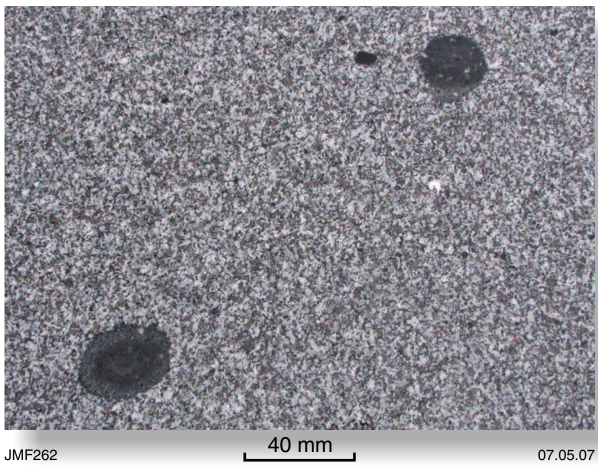

Figure 30. Xenoliths in polished granite

is a vital tool in the determination of whether to proceed to the next phase of the exploration process.

The field mapping process should include a detailed examination of surface outcrop ranging from relatively level surfaces to moderate to steeply dipping rock faces in road cuttings, old quarries, and watercourses. Geological data collection should include all the usual rock attributes including detailed lithological descriptions, geological boundaries, and structural data such as strike and dip of strata, folding, faulting and jointing, as well as foliation and lineation features in igneous and metamorphic rocks. The geological interpretation process is generally backed up by the use of aerial photos or other remotely sensed data such as orthophotos, satellite imagery, and digital elevation models (DEM).

Dimension stone quality evaluation

In addition to the geological mapping tools listed above, the field mapping survey must also address the criteria relevant to the overall evaluation of the quality of the particular stone under investigation. Of particular importance is the degree of variation in the stone over the area of interest. In this assessment, uniformity of colour and texture are vital characteristics as is the degree of weathering, which may have profound effects on the strength and durability of the rock.

Criteria that limit stone usage include the presence of deleterious minerals such as pyrite, iron oxides, and vanadium minerals that may cause severe staining, planar micas that may cause stone delamination, and minerals such as swelling clays and sulfates that may cause dimensional instability such as warping. Other limiting criteria may include the degree of deformation and/or metamorphism, and natural splitting directions within the stone.

Joint survey

A detailed joint survey is of particular importance over the area of interest. As previously noted, in order to obtain blocks of a minimum saleable size, it is vital that the stone resource must be relatively free from joints. In reality, this means that the minimum spacing of natural rock joints in three dimensions must exceed the required block size to be extracted from the quarry wall. Accordingly, during the field survey both horizontal and vertical rock surfaces should be carefully examined for the presence of various joint sets in different orientations. Joints in a set are usually parallel to each other and have more or less equal spacing that may vary from tens of centimetres to hundreds of metres apart. Horizontal and vertical joint sets should be carefully mapped to record their orientation and spacing.

Jointing is common in brittle rocks such as sandstone, quartzite, and granite, particularly where the rock has been subjected to a number of tectonic events. Such rocks may contain up to four or more sets of joints in different orientations. Horizontal joints are particularly common in intrusive igneous rocks such as granites. Also known as unloading joints, these joints tend to form parallel to the ground surface as erosion removes the overlying rock and normal stresses contained within the rock are released. Close to the surface, unloading joints may be spaced as little as 50 cm apart, but spacing tends to increase with depth to between 1 and 3 m within the average quarry.

Surface sampling and testing

During the field reconnaissance and mapping program, it is vital to collect representative rock samples from each locality visited during the survey. Provided rock outcrop is sufficiently extensive and relatively unweathered, sampling should be carried out over a regular grid pattern, initially at about 50–100 m intervals, and reducing the sampling grid to 10–25 m intervals once the area of interest has been identified. This operation is necessary to establish the overall degree of uniformity of a stone's colour, texture, strength, and durability. The Schmidt hammer is a useful portable tool for assessing the relative strengths of bed rock in situ, stone blocks, and core samples. Samples collected should be large enough to prepare test polished or ground slabs, and for a range of required ASTM physical tests outlined in Chapter 2.

In areas where overburden is too thick for surface sampling, other survey methods are normally employed, such as cutting trenches or costeans to a maximum depth of 3–4 m using a bulldozer or hydraulic excavator to expose the bedrock at a number of points over the survey area. Not only do these exposures provide fresh rock for sampling, they usually permit a much better visual examination of the bedrock itself and are often useful in the determination of joint spacing and orientation. If overburden thickness remains a problem, then a diamond drilling program may be required to obtain representative site samples.

It is important to assign geographical location coordinates to each sample locality. Currently, hand-held geographic positioning system (GPS) instruments are capable of giving readings in latitude and longitude, or Map Grid of Australia (MGA) coordinate values in metres as eastings and northings, with a horizontal accuracy of ±10 m. Improved accuracy can be obtained using more precise surveying techniques.

During the survey, samples collected should be tagged with the locality number prior to dispatch for petrographic analysis and physical testing so that they may be readily identified and matched with structural field mapping data from the same point.

Exploratory drilling

Exploratory drilling is a relatively expensive method of obtaining new or additional data on a dimension stone prospect. Drilling is necessary when the overburden is too thick for any of the previously listed survey methods to be of value in the assessment of the deposit. Also drilling may be required if results from initial surface surveys indicate a definite area of interest that is worth following up to delineate resources and facilitate ultimate quarry design.

Two drilling methods may be employed. The first of these is non-core drilling, commonly employing rotary airblast (RAB) or reverse circulation (RC) techniques that are useful for determining depth to bedrock, and thickness and discontinuities in the subsurface dimension stone target. Although this is a less expensive form of drilling, results obtained in the form of rock chips do not provide worthwhile data relating to the actual physical quality of the stone, particularly colour, texture, strength, durability, and uniformity. Diamond drilling is the method that is used to collect this information. This method is capable of collecting continuous rock core samples of sufficiently large diameter (commonly 40–60 mm) for the required physical laboratory tests matched against ASTM standards. Diamond drilling from both vertical and inclined holes also provides invaluable data on joint spacing and orientation. Data from drill core or rock chips should then be carefully logged onto scaled drill log charts for further evaluation.

Geophysical surveys

Of the many shallow, ground geophysical techniques available to the explorer, only a few are employed in dimension stone exploration.

Ground seismic

The most commonly used technique is ground seismic reflection or refraction where a seismic wave, induced by ground vibration or near-surface explosion, is reflected from or refracted along the boundary of two subsurface layers having different seismic velocities. The time taken for the seismic wave to return to a surface detector can be measured and the depth to the reflecting/refracting layer calculated. These techniques may be used to detect subsurface horizons commonly interpreted as marker beds, and discontinuities such as faults.

A comparatively inexpensive and easily transportable method employing seismic refraction is known as hammer seismic. This process may be of use in the calculation of overburden thickness at different sites over a potential body of stone. In this operation a line of geophones (seismic detection devices) is laid out over about 30–40 m. At the far end of the array an operator strikes a steel plate with a sledge hammer. The resultant seismic wave travels downwards into the ground and is refracted along the upper boundary of the first-encountered layer of denser material. The shallow, lower velocity layer normally comprises soil or weathered material, while the deeper, higher velocity layer represents the upper surface of the bedrock. A portable seismograph records the time taken for the refracted wave to arrive at the surface and calculates the depth to bedrock in the immediate area.

Downhole logging

Downhole logging techniques may be used to gain a better idea of the properties of the bedrock, particularly in a non-cored drillhole where only rock chips have been logged. A number of these are given in Smith (1999). These techniques involve the recording of data received from a variety of geophysical probes lowered down a drillhole at a predetermined rate so the exact depth of the probe from the surface is always known.

Drillhole cameras and calipers

Drillhole cameras are used to provide a contiuous view of the inside of the drillhole. Their use in conjunction with inclinometers and magnetometers will determine the orientation of the drillhole. Once the spatial position of the drillhole is known, calculation of the orientation of strata, faults and joints can be carried out from the camera image logs.

Calipers are used for the continuous monitoring of the drillhole diameter. Rapid increases in diameter may indicate the presence of intercalations of weaker strata between the harder target rocks.

Sonic

Sonic logging probes are used to produce continuous 360° acoustic image profiles of the inside of the drillhole. The resulting sonic logs often show discontinuities in strata that can be used to determine their angle of inclination. These logs may also be used to provide an indication of the overall porosity of a rock.

Resistivity

Boundaries between different rocks may sometimes be detected using a resistivity probe that senses differences in electrical resistivity between various rock types.

Gamma ray

This technique is used in sedimentary rocks such as sandstone and limestone where a gamma ray probe can locate discontinuities between strata by detecting zones of potassium-rich clay minerals contained in softer argillaceous material such as shales and claystones interbedded between target sandstones or limestones. Accordingly, this technique can provide an indication of the thickness of the potential dimension stone in the drillhole.

Also, scattering and loss of energy by gamma rays is proportional to the electrons emitted from potassium-rich minerals encountered in host rocks and the resultant ‘electron density’ of a body of rock can be calculated, thereby allowing an estimate of bulk density to be made. Gamma ray logs used in conjunction with sonic logs may provide an indication of rock strength.

Neutron

Neutron logs are used to detect the presence of water- or air-filled voids in strata and can provide an estimate of porosity and permeability.

Sample analysis

At the conclusion of both surface and drillhole sampling, representative stone samples must be prepared for petrographic analysis, slab polishing or grinding and surface finishing, and a variety of physical tests of correctly sized material under conditions specified by the ASTM (ASTM International, 2005).

Petrographic analysis

Petrographic analysis is an important method of dimension stone assessment. In this process a thin section of stone, mounted on a glass slide, is examined under a polarizing microscope. This procedure identifies component minerals and their relative percentages within the rock, enabling the petrologist to provide an accurate petrographic name and description of the potential dimension stone.

Petrographic analysis is also useful in identifying characteristics such as porosity and state of weathering in a rock as well as the presence of undesirable minerals. Results of this examination may provide information on the most appropriate physical tests to be undertaken and assist with interpretation of test results. This technique is also used to provide information on the durability and long-term performance of dimension stone destined for exposure in different climatic conditions.

Quick (2003) identified the scope of information that may be provided by petrographic analysis of potential dimension stone as well as the performance of stone already in service. A summary of this information is given below:

- *Petrographic classification*: Based on mineralogy, texture, provenance, and classification standards.
- *Primary mineralogy, grain size, and texture*: Identifies mineral characteristics, mineral alteration, and potential problems that may affect future durability and strength such as high mica or quartz contents in granites, and undesirable anisotropic properties in schists and gneisses.
- *Knoop indentation microhardness*: A test to determine absolute hardness values for minerals and stone as described in Chapter 2.
- *Nature of cement or binder in sedimentary rocks*: Determination of the composition, percentage, structure, and hardness of cements or binders in sedimentary and weathered rocks. Includes siliceous, calcareous, and ferruginous cements, and clay binders.
- *Weathering/mineral alteration*: Extent of weathering and decay due to mineral alteration,
- *Deleterious minerals*: Swelling clays, zeolites, volcanic glass, sulfates and sulfides may cause dimensional instability such as shrinking and swelling, expansion, warping, and zones of weakness. Pyrite, iron oxides, and vanadium minerals may cause severe staining, and micas aligned along bedding or cleavage planes may cause delamination in sandstones (but may prove useful in the cleavage of slates).
- *Porosity, microcracking*: The extent of pores, voids, microcavities, and microcracks present in rocks, particularly sandstones and porous limestones, may be subject to freeze and thaw, salt attack, and capillary water movement, especially those carrying harmful salts into the interior of a stone.
- *Thermal variation*: Some minerals and textures vulnerable to thermal variation may cause physical disruption to the stone.
- *Origin of stone*: Used in stone conservation projects to determine the original quarry site for stone matching or replacement.

Laboratory testing

The most commonly specified physical tests used to promote dimension stone are:

- Water absorbtion by weight (%).
- Bulk density (t/m^3).
- Compressive strength (wet and/or dry; MPa).
- Modulus of rupture (wet and/or dry; MPa).
- Flexural strength (wet and/or dry; MPa)

Other physical properties such as durability, abrasion resistance, hardness, microhardness, and linear thermal expansion are normally carried out in accordance with specific client requirements. An outline of all of the above physical tests is given in Chapter 2 and average values and ASTM specifications for dimension stone are listed in Table 3.

Data analysis, resource estimation, and quarry design

Data analysis and resource estimation involves the collation of all data collected during the exploration and assessment phase. Although the entire process may be achieved by manually plotting field data to create maps, cross sections, and three-dimensional diagrams, computer assisted design has largely become the modern medium for data analysis, resource estimation and quarry design. In this instance, data from field samples, joint surveys, drill logs, geophysical surveys, petrographic and physical testing are tabulated and stored in a database in a readily retrievable format, and spatial data are plotted in a detailed large-scale, digital site map.

In the following stage, computer-assisted design may be used to incorporate spatial data such as topography, drainage, surface contours, sample localities, and location and inclination of drillholes with the above datasets to construct a three-dimensional block diagram of the proposed quarry site. Within the block, different data layers could be switched on individually or in a combined format to maximize data interpretation. Accordingly, data from ground surveys, geophysics, drillhole logs, and joint surveys could be combined in different ways to show three-dimensional views of overburden thickness, target stone horizon, and joint-set spacing and orientation.

Providing sufficient data have been collected, estimates could be made in situ of potential stone block size and volume. Assuming stone block size is within acceptable limits, a dimension stone resource estimation exercise could be carried out based on the proposed quarry design. This design would need to consider problems and costs of overburden removal, and the correct orientation of the quarry parallel to major structural elements, especially major joint sets, to maximize extractable block size. At the same time, the design would need to address safety issues related to slope stability of quarry walls to prevent plane, wedge, and toppling failures. Another important item to be considered for an economically viable operation is an appraisal of the ease of mining on the chosen site with the object of reducing operating costs while achieving maximum productivity.

Project feasibility study

Assuming all of the above factors have been satisfied during the field exploration, physical testing, data analysis and resource estimation stages, and the site is accessible for the development of a new dimension stone quarry, it is necessary to carry out a feasibility study to assess the economic viability of the project. The following factors need to be considered.

Markets

Before commencing any new dimension stone quarrying operation, it is vital for the viability of the project that there is a more or less guaranteed market for the stone it is to produce. As previously mentioned, the stone must have aesthetic appeal and factors such as colour, pattern, texture and finish are important characteristics that must match current trends largely controlled by the architectural profession. In some cases a successful marketing niche may be created if the new stone has an unusual colour or texture not available elsewhere.

Once established, it is important to be able to maintain markets by being able to satisfy customer requirements in terms of quality control and consistency of supply on a long-term basis.

Quarry extraction costs and operating efficiency

In any quarry operation, extraction costs and operating efficiency are paramount to the success of the venture.

Extraction costs

Important cost factors to be considered are:

- Cost of capital equipment such as quarry tools, machinery, and vehicles.
- Fixed operating costs in terms of labour, repairs and maintenance, power, overheads, and depreciation.
- Variable operating costs including materials, fuel, explosives, overburden removal, plant hire, and royalties (if applicable).
- Cost of transporting blocks to a port or processing plant (quarry must be within economic haulage distance of these facilities).

Operating efficiency

Operating efficiency in the quarry is an important tool used to reduce costs. There are usually a number of ways to improve operating efficiency on site and some of these are listed below.

Ease of mining and recovery rate

- In the planning phase, the proposed quarry should be designed in such a way that its major alignment is parallel to major vertical joint sets to maximize extractable block size and increase operating efficiency.
- Ideally, the quarry should be designed on a series of benches above ground level to permit operation at several sites simultaneously. If possible, the quarry should be self-draining so that pools of water do not restrict access to the stone resource.
- The quarry design should include a plan for the progressive removal of overburden. Ideally, the quarry should be sited where overburden is at a minimum thickness. Thicker overburden profiles will radically increase operating costs, and will often restrict access to parts of the stone resource below.

Reduction of wastage

Stone wastage is one the most critical factors in determining whether the operation is a success. Minimizing wastage can be achieved through correct quarry design to maximize extractable block size, limiting or abandoning the use of explosives in favour of other methods used to free blocks from the quarry wall, using appropriate methods to minimize damage to the block when toppled away from the quarry face, and exercising care when preparing saleable blocks.

In Australia, a typical stone quarry has a wastage rate of 40% or higher, although in some countries this factor can be much higher where wastage rates can be factored against operating costs and/or value of the material recovered. For example, wastage rates in major producing countries such as Finland are as high as 85%, and in South Africa, 90% (Trezise, 1990).

Byproducts

Assuming the new operation is located within economic haulage distance of potential consumers, a useful way of reducing wastage is by the development of markets for byproducts produced from some or all of the waste material. Examples include hard, equigranular rocks such as granite and basalt that can be crushed and sized for railway ballast, and aggregate for road surfacing or concrete manufacture. Large boulders of the same material may also prove useful as armourstone used in the construction of breakwaters and dams (Fig. 31). An example using soft calcarenite limestone is in the manufacture of reconstituted limestone blocks for the housing and landscaping industries.

Available water supply

Access to on-site water supplied from streams, dams or bores is vital for a number of quarry processes, especially diamond wire or diamond blade rock sawing, and also for on-site dust control. The requirement to cart water from

Figure 31. A stockpile of durable granite–gneiss boulders (mostly 2–3 m in diameter) possibly suitable for use as armourstone in breakwater or dam construction. Woodlands granitic gneiss

an external source will almost certainly result in increased costs.

Routine maintenance

A routine maintenance program for all mining equipment should be in place. Unexpected breakdowns may radically affect production, resulting in increased costs.

Project financial assessment

The final stage in the assessment of the likelihood of success of any new dimension stone project requires a thorough financial evaluation by persons specializing in this field. Having access to all of the data collected in the field, laboratory studies and completed feasibility study, the specialist will analyse critical financial aspects of the project and prepare a report on the probability of financial success or otherwise of the proposed project.

In the financial assessment a number of items need to be considered. These include the estimated cash flow for the project's first year and discounted cash flow (DCF) for future years. This is used to calculate the net present value (NPV) of the project for periods of up to 20 or 30 years into the future. Other factors considered are the internal rate of return (IRR), where the estimated project rate of return may be compared against interest rates on other forms of investment, and the payback period (PBP), in which the time required to pay back the initial cost of capital equipment is calculated.

In the final stages, a sensitivity analysis is run to assess the risks involved with investment in the proposed project. The sensitivity analysis is used to predict changes in NPV, IRR, and PBP associated with substantial falls in items such as stone price, quarry production, and market share, and increases in the cost of capital equipment (Smith, 1999).

Chapter 6

Quarry development and operation

Licences

Once all of the necessary resource estimation, quarry design, marketing, feasibility studies and financial assessment have been finalized and found to be favourable for the dimension stone project to proceed, it is necessary to progress to the project approvals stage. This involves working with government, local government, and landholders to progress the project to an operational level.

In Western Australia, dimension stone is classified as a mineral under the term 'building stone' if located on Crown Land. Consequently, all activities are governed by the Mining Act (1978), including exploration under an exploration or prospecting licence, and for quarrying under a mining lease. Accordingly, it is usually necessary for operators to apply for the issue of the appropriate licence or lease from the Western Australian Government.

In some states, including Western Australia, dimension stone is interpreted as 'rock' if located on privately owned land. In this case, an extractive industry quarry licence covering basic raw materials may be obtained from the local government shire or municipality administering the land, assuming an agreement has been reached with the landowner of the property.

It should be noted that in Western Australia, applications for the issue of a mining lease or an extractive industry quarry licence must be accompanied with a 'Mining Proposal' (formerly known as a 'Notice of Intent') to government or local council as appropriate. The mining proposal sets out all aspects of the proposed quarrying operation, and addresses a range of environmental issues including noise abatement, water management, local flora and fauna, quarry buffer zones, and rehabilitation plans.

Overburden removal

On-site operations may commence when all of the required licences and approvals have been granted. If the site has not been used for quarrying in the past, then the overburden overlying the stone deposit will usually need to be removed. The removal process is carried out by bulldozers, scrapers or other earthmoving machinery. The topsoil is removed first and stored separately. Semi-indurated and indurated overburden such as ferricrete and silicrete, and fresh rock overlying the target material, may need to be removed by ripping and/or drilling and blasting. The overburden is commonly stored in graded stockpiles away from present and future areas of the quarry for use in progressive rehabilitation work as required.

Quarry development

Four basic quarry types

Quarry design is usually based on the local topography together with the size, structural elements, and physical properties of the stone resource to be recovered. In general, there are four basic quarry types from which arise numerous variations. In addition, at a later stage in the life of a quarry when initial resources are depleted, the quarry design may change in order to maintain production at that site. The four basic quarry types are illustrated in Figure 32.

The first of these types is a quarry cut into the side of a comparatively steep hill, usually consisting of resistant rocks such as gneissic granite, black granite, quartzite, basalt, marble, and indurated limestone. In this design, horizontal benches for block removal are cut in a near-vertical quarry wall every 3–6 m above the bench below. The quarry face and benches may simply consist of a single straight line on one face or may follow around the outside of the hill either in a convex or concave pattern.

The second quarry type is where the local topography forms a moderate- to low-sloping hill, formed by rocks such as granite and indurated sandstone. In granitic terrains, benches may form naturally on near-horizontal unloading joints in the granite. It is these joints that tend to define the height of the blocks, commonly between 1 and 3 m.

The first and second quarry types have a distinct advantage over other designs in that they are naturally self-draining and rainwater is channeled into settling ponds or a watercourse. With runoff contained, there is usually little problem with access to the stone resource anywhere in the quarry.

The third type of quarry is sited where a large resource is located virtually at ground level (apart from overburden considerations) and may extend laterally over a considerable area. In this situation there may be a considerable variety of rock types ranging from very hard black granite to very soft limestone and sandstone. Quarries of this type often have problems with rainwater ponding around operational areas and require intermittent pumping to provide access to the site.

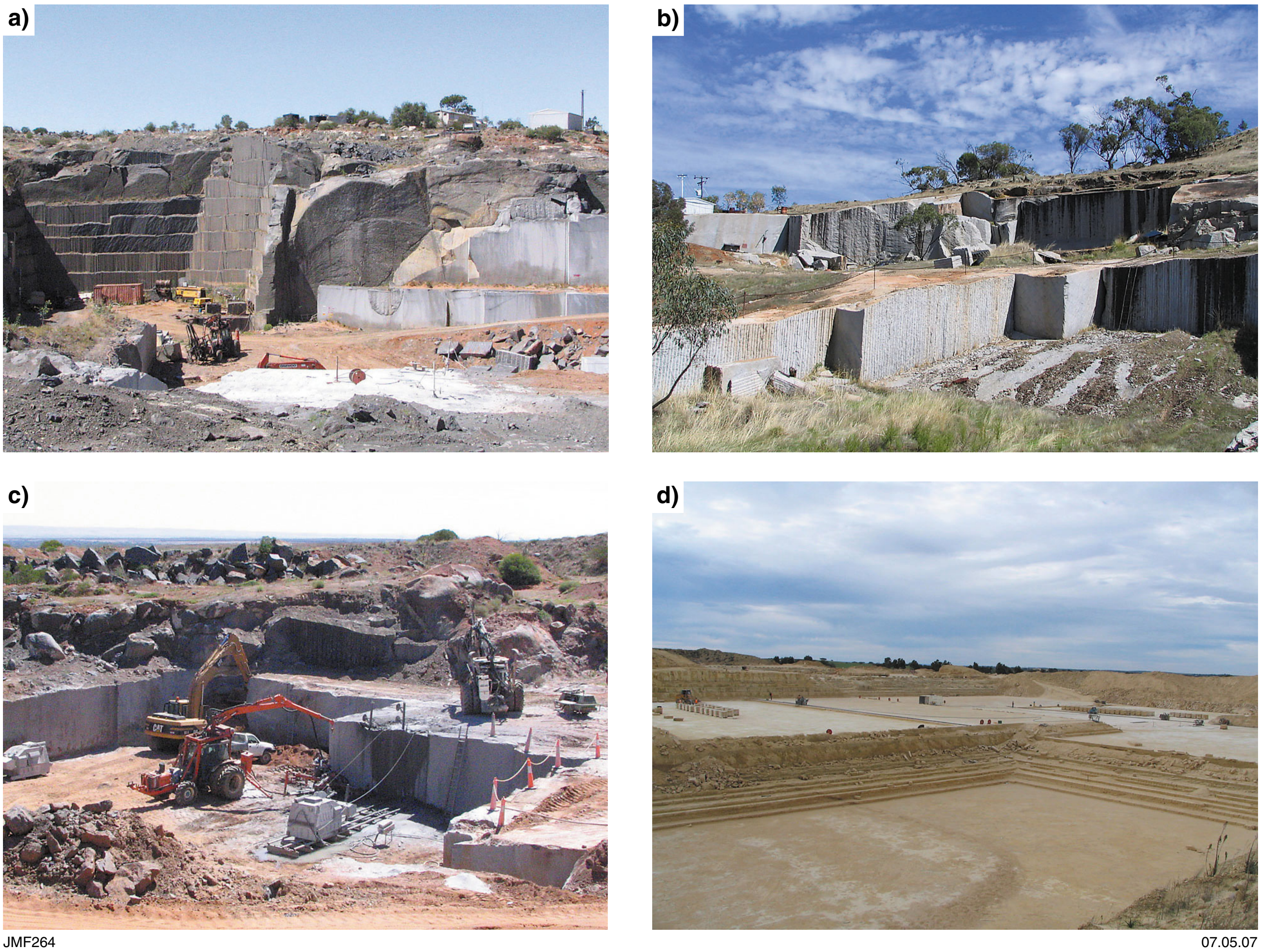

Figure 32. Four basic quarry types: a) near-vertical, quarry cut into the side of a steep hill (Black Hill norite, South Australia); b) benched quarry situated on a moderately sloping hillside (*York granite*, Western Australia); c) quarry situated close to ground level (Black Hill norite, South Australia); d) below ground level quarry (calcarenite, Moore River, Western Australia)

The fourth quarry type often tends to be utilized after other types have become exhausted or where no other design is appropriate in a particular topographic situation. In this design the quarry is sited below ground level, sometimes extending to considerable depth dependent on the value of the stone recovered. In places in North America and Europe, large, deep, near-vertical quarries have been constructed to extract stones such as special granites and marbles. These quarries are a natural reservoir for rainwater and often require continuous pumping to keep them dry and operating on a regular basis.

In Western Australia the quarrying of calcarenite limestone blocks is commonly carried out in this type of subsurface quarry, albeit on a smaller scale than that mentioned above. In this situation, continuous extraction of calcarenite building blocks may be carried out over an area of many hectares. Once the upper level has been exhausted, quarrying operations move to a lower level within the original quarry until a final level of about 10–20 m below ground level is reached. In this environment, water ponding in the pit is not an issue because of the highly porous nature of the calcarenite and comparatively low rainfall of the area.

Opening a new hard rock quarry

One of the most important initial operations in a new hard rock quarry is to determine the rock's principal splitting directions in both the horizontal and vertical planes. Splitting direction is controlled not only by joints, but also by what is known in quarry parlance as the 'grain of the rock' (Koirala, 2002). This property is the result of discrete mineral zones in various proportions, textures, spacings, and preferred mineral orientations such as mica zones in some indurated sandstones and gneissic rocks. The grain of the rock is often related to cleavage, bedding, and other planes of weakness. Zones of weakness that split easily in the horizontal or near-horizontal plane are known as the 'rift' or 'freeway' and may correspond to bedding planes in sedimentary rocks. Quarrymen with many years experience are usually well qualified to recognize the grain of the rock, although some trials may be required involving explosives in test blocks in situ to establish block splitting directions and finalize the quarry orientation.

In a new quarry where the stone is buried below ground or is otherwise inaccessible, after overburden removal it is necessary to create a 'keyhole' cut to release the first block. In this situation, close-spaced percussion drillholes are first inserted around the perimeter of a suitable block. A hole is then drilled down the block at its centre and an explosive charge is loaded in this hole and fired. The explosion frees the block which is subsequently removed and in this way access is provided for normal block extraction to commence.

Development of a quarry with near-vertical faces commonly requires the excavation of a trench to establish the initial working bench. This is achieved through the use of explosives or other methods or by the removal of keyhole blocks to provide access to fresh rock in the quarry face and at the same time to relieve inherent strain in the rock (Trezise, 1990).

Quarry operation

In contemporary dimension stone quarries there are essentially two methods of stone extraction. The first of these is applied to rocks ranging from very hard granite, gneiss and quartzite, through basalt and indurated sandstone, to moderately hard types including marble and limestone. This method involves extraction of large primary blocks, commonly 400–900 t, as feedstock for the production of transportable 10–25 t quarry blocks. While the overall modus operandi in most quarries is essentially the same, extractive techniques vary according to hardness and degree of difficulty of block removal.

The second extractive method applies to soft rocks such as calcarenite and semi-indurated sandstone. In this process, quite different methods are used to acquire a variety of generally smaller sized quarry blocks.

Different categories of rock types and the techniques employed for their extraction are listed in Table 5.

Hard rock quarrying

The Finnish method

During the 1970s, the Finnish method of quarrying was developed in Finland as a result of the introduction of mechanized quarry drilling equipment and plastic pipe explosive cartridges. Improvements such as the advent of hydraulics to rock drilling equipment soon followed, resulting in substantial savings in labour and operating costs (Smith, 1987). As a result, the Finnish method rapidly became a more efficient method of stone extraction in the country's many granite quarries. Today, numerous variations based on the Finnish method are used in hard rock dimension stone quarries throughout most of the developed world.

The Finnish quarrying method is a highly mechanized system of block extraction relying on explosives and the use of special machinery for each stage in the process. This method has been proved to be very efficient as it can be used for year-round production in most climates on rocks ranging

Table 5 Extractive quarrying techniques

Rock type		*Extractive techniques*
Very hard rocks	*(massive to moderately well jointed)*	
Granite		• drilling
Black granite		• explosives
Gneiss		• diamond wire
Quartzite		• water-jet cutting
		• thermal lance (flame jet cutting)
		• plug and feathers
		• expandable powders
Hard rocks	*(massive to very well jointed)*	
		• drilling
Basalt		• explosives
Trachyte		• diamond wire
Indurated sandstone		• plug and feathers
Indurated siltstone		• expandable powders
Slate		• quarry chain saw
		• wedges
Moderately hard rocks	*(moderately well jointed to massive)*	
Marble		• drilling
Limestone		• quarry chain saw
Dolomite		• diamond wire
Travertine		• plug and feathers
Sandstone		• wedges
Soft rocks	*(jointing commonly absent)*	
Semi-indurated sandstone		• tungsten carbide saws
Calcarenite		• tungsten carbide cutting wheels

SOURCE: Smith (1999)

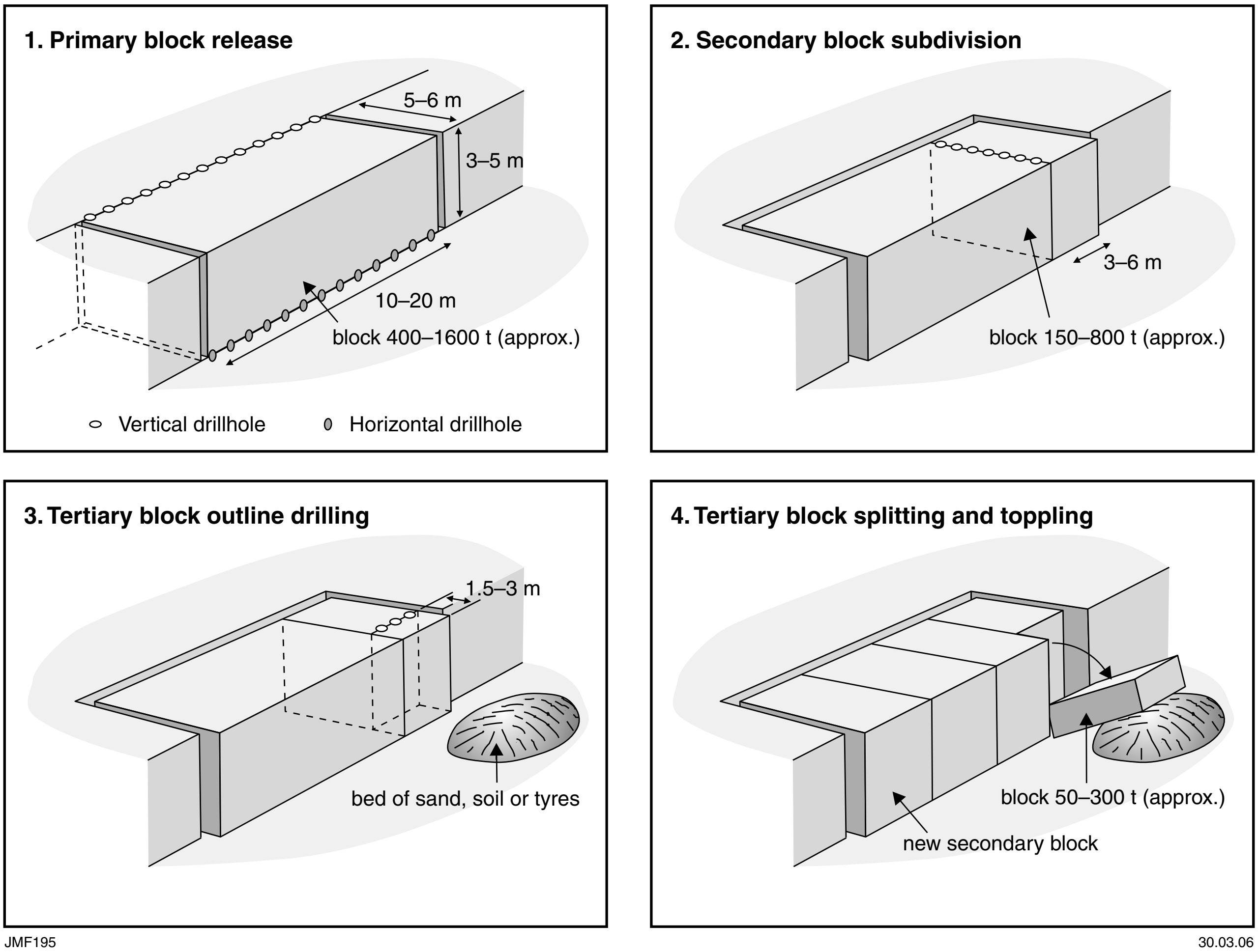

Figure 33. The four-stage Finnish method of quarrying (modified from Finska, 2006)

from granite to marble. At the same time it is invaluable for maintaining quality control in terms of block size, colour and texture to meet customer specifications. There are four stages in the original Finnish quarrying method as illustrated in Figure 33 (Finska, 2006).

Primary block release

The first stage involves the release of the primary (or stope) block from the quarry rock wall. In Australia, primary blocks are usually in the order of 400–900 t but may range up to a mass of about 1600 t. In some overseas countries, especially in Finland where the method was developed, it has been shown that it is possible to produce primary granite blocks many times this size. In the original method, the release of the primary block involved close-spaced vertical drilling along the back of the block and by horizontal drilling underneath, and the release of each end of the primary block was also achieved by close-spaced vertical drilling. The drillholes were then packed with light-charge K-pipe explosive in plastic pipe cartridges and detonated in a simultaneous, controlled explosion freeing the undamaged block. More recently, the release technique for each end of the primary block was modified to allow the use of thermal lance (flame-jet cutting), diamond wire sawing, or water-jet cutting processes (Fig. 34).

It is worth noting that in the most favourable situations, quarry benches are aligned parallel to major vertical joints or other vertical discontinuities, known as the ‘back’, together with horizontal joint or bedding planes (Smith, 1999). It is these discontinuities, along which the rock will break naturally, that are used to enhance the effectiveness of the Finnish method.

Secondary block subdivision

In the second stage of the Finnish method the primary block, depending on its size, is subdivided into a number of secondary blocks each of about 150–800 t. This is achieved by vertical close-spaced drilling of one sidewall (Fig. 34) and K-pipe explosive blasting or by employing diamond wire sawing, thermal lance, or water-jet cutting techniques.

Tertiary block removal

The third and most critical stage of this method involves the removal of a much smaller tertiary block of about 50–300 t. The process originally used close-spaced vertical drilling across the back of the block followed by light-charge K-pipe explosive blasting to release it from the secondary block (Fig. 34). Today, this technique has been

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Figure 34. An 800 t primary block of *Desert Brown* granite from Esperance in the far south of Western Australia. The primary block, previously separated by close-spaced drilling and diamond wire sawing, is being subdivided into secondary blocks by in-line drilling (centre right). At centre left, an in-line block drill is cutting a smaller, tertiary block into saleable-sized blocks (photo courtesy Melocco Stone)

largely replaced by other methods such as diamond wire sawing, thermal lance, expanding chemical compounds, plug and feathers, wedges, and water-jet cutting.

Once the upright tertiary block has been freed, it must be moved out from the back wall to facilitate the toppling process. This is achieved by inserting a number of 'hydro-bags' or 'pneumatic wedges' (air bladders) into the comparatively narrow space between the block and the back wall. These expansive devices are then filled with water or compressed air under high pressure. Providing that sufficient bags are employed to match the size of the block, the considerable lateral force exerted by the expansion of these devices is sufficient to move the block forward up to 150 mm (Doyle, 2001). The process is repeated by lowering the bags further down inside the gap and the pressure re-applied until the required tilt is achieved to allow the block to topple onto a pile of soft sand, soil or rubber tyres to cushion the impact and minimize damage to the block (Fig. 35).

Alternative methods used in the toppling process include the application of specially designed hydraulic jacks that are fitted into slots cut behind the tertiary block. Pressure is progressively applied by hydraulic cylinders in the manner described above, ultimately causing the block to topple. Hydraulic jacks are also used in combination with water bags or air bladders used to make the initial block separation before the jacks are inserted to effect the toppling process.

Another common method for toppling smaller blocks is achieved by wedging the bucket teeth of a large hydraulic excavator into holes behind the block. When the bucket is rotated the applied force is generally sufficient to cause the block to topple.

Final block preparation

The toppled tertiary block is then surmounted by an in-line block drill that is used to subdivide the block into saleable-sized quarry blocks ranging from 10 to 25 t according to transportation methods and customer requirements. Once again, the block drill cuts a line of close-spaced holes and at this stage in the process, methods such as plug and feathers or expanding chemical compounds are used to minimize block damage during final splitting. In some situations diamond wire sawing is also used to produce finished blocks. These are examined for defects such as mafic inclusions usually in the form of xenoliths (Fig. 30), veins, cracks, open joints, and cavities. Quality blocks are graded and numbered and then transferred to the block storage area while faulty material is rejected as waste.

Application of the Finnish method in Australia

In Australia, the traditional three-stage Finnish method is seldom followed completely. While the principles of the method are adhered to, the steps involved have been adapted to suit the rock type, quarry style, and the availability of different types of extraction equipment as determined by the quarry manager.

Commonly in Australian quarries, the block removal process has been simplified by involving a primary and tertiary stage, or a tertiary stage only. In the first instance, the primary block, commonly about 800–900 t, is close-spaced drilled or diamond sawn. In the case of drilling,

Figure 35. Tertiary block wedging and toppling: a) wedging completed with a block of black granite about to topple; b) black granite slab toppling onto a pile of soft earth; c) Block of red granite (at centre) toppled onto a pile of rubber tyres; d) pneumatic air bladder in position for wedging process (photos (a) and (b) courtesy Granites of Australia, photo (c) courtesy PIRSA)

the block is normally separated from the quarry wall using light-charge K-pipe explosives, or thermal lance techniques. This block may be sufficiently small to be toppled in its own right. The release of the much smaller tertiary blocks are accomplished by further diamond sawing, or drilling followed by the application of expanding chemical compounds or plug and feathers. This two-stage process is illustrated in Figure 34.

In some quarries where access often precludes the release of a primary block, tertiary blocks are drilled or diamond wire sawn straight from the quarry wall. Often, in this situation, long and relatively thin blocks are removed which measure up to 12 m in length and only about 1.5 m in thickness. Large slabs of this thickness have the advantage that usually they would require only two cuts to achieve final block size (Fig. 35b).

Hard rock quarrying techniques

Drilling

Several drilling methods are employed in the block removal process. The in-line (or line) drilling method is practised in numerous Australian quarries. Other drilling methods include drilling and broaching, and stitch drilling.

In-line drilling

In this procedure, hydraulically operated drilling equipment is commonly rail-mounted on an extendable hydraulic boom arm at the front of an all-terrain heavy-duty tractor. Percussion drilling equipment is set up on the front rail for the purpose of drilling single or simultaneous multiple holes to depths ranging from 4.5 to 8.0 m. In hard rocks such as granite, holes are usually spaced about 130 mm apart. Boom arms can usually be rotated by 90° to drill straight lines of both vertical and horizontal holes around and underneath blocks (Fig. 36; Trezise, 1990).

Disposable tungsten carbide drill bits are used for in-line drilling holes ranging from 22 to 40 mm in diameter. Button bits are often used for drilling hard rocks and employed on rigs drilling multiple overlapping holes to achieve a 120 to 200 mm spacing. This is an efficient method of rapidly achieving a line of holes along a block as each pair of simultaneously drilled 4–5 m holes takes no more than one or two minutes to complete (Fig. 37).

Drilling and broaching

This long-used technique for cutting most types of stone is similar to in-line drilling in that the drilling and broaching equipment is also rail-mounted on a hydraulic boom arm. The rig is designed to drill closely spaced or overlapping holes. Once a line of holes is completed, a spade-shaped, hydraulically actuated broaching bar is employed to remove the rock remaining between drillholes. This process assists in the removal of the block, often without recourse to other methods.

Stitch drilling

Also known as close-spaced drilling, the stitch drilling method involves drilling a line of close-spaced holes


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Figure 36. Tractor-mounted hydraulic boom arm supporting a rail-guided twin percussion drill rig at *Austral Waterfall* quarry near Bruce Rock

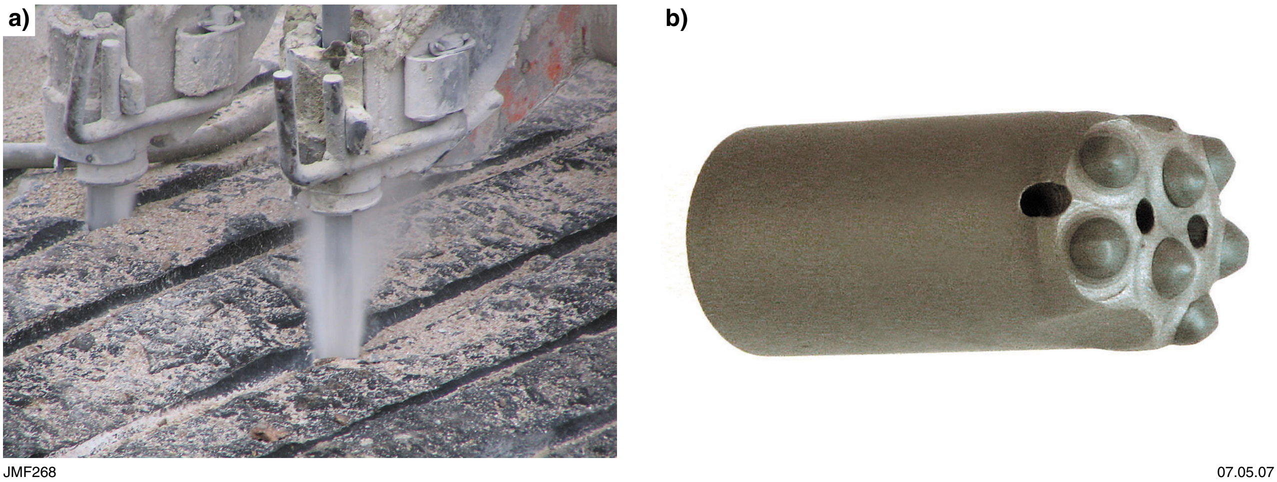

Figure 37. In-line block drilling: a) simultaneous drilling of two holes spaced about 260 mm apart. The next pair of holes drilled will overlap resulting in an in-line spacing of 130 mm; b) a 30 mm-diameter tungsten carbide-tipped button bit capable of rapid drilling in hard rock

only a few centimetres apart. Assisted by the use of other methods such as plug and feathers, hydraulic splitters, expanding chemical compounds, or explosives, it is possible to achieve a relatively clean break along block sides (Trezise, 1999).

Diamond wire sawing

Modern wire sawing of stone was introduced in the late 1970s with the introduction of the diamond wire saw. The saw comprises a continuous loop of multi-strand, stainless steel wire rope about 5 mm in diameter and between 20 and 80 m in length. Onto the wire are threaded small metal cutting beads 10–12 mm in diameter. The beads are impregnated with a coating of sintered cobalt–bronze alloy containing approximately 4% by weight industrial diamonds of about 0.35 mm diameter. Different wires are used for rocks of different hardnesses. For hard rocks such as granite and gneiss, the wire contains between 35 and 40 beads per metre separated by plastic spacers. For softer rocks, including marble and travertine, generally fewer beads are required at around 28–35 per metre and are usually separated by spring spacers (Smith, 1999; Fisa, 2003). An example of a contemporary diamond cutting wire is shown in Figure 38.

The wire sawing machine is powered by a rail-mounted, electric-drive unit attached to the diamond wire loop by a large-diameter drive wheel. To set up a sawing operation, two pilot holes are drilled, one vertically and the other horizontally, specially orientated to intersect at the lowermost point at the rear of the block to be cut out (Fig. 39). The diamond wire is threaded through these holes and the loop attached to the drive unit. In operation, the diamond wire, lubricated by water from overhead jets, travels at speeds of between 20 and 40 m/s. Tension on the wire is maintained by the automatically controlled progression of the drive unit away from the cutting face (Fig. 40). Wire cutting rates vary according to the hardness of the rock with 1.5 – 3.5 m^2/h for granite and hard sandstone, 4–6 m^2/h for marble, 2.5 – 7.2 m^2/h for medium to soft sandstone, and 6–8 m^2/h for slate (Castle Tools, 2006).

Diamond sawing is usually carried out on the quarry bench in front of the face where blocks are to be removed. Where access permits, wire saws may also be sited in situations where it is possible to cut the whole length of the back of the block. A completely wire-sawn tertiary block in the process of toppling is illustrated in Figure 35b.

Despite the added costs of using diamond wire, Smith (1999) highlights some of the following advantages of using diamond saws to enhance quarry operations:

- Blocks can be cut independently of joints or cleavage planes.
- Finished blocks have smooth, fracture-free faces on most sides and can be sized more easily to customer specifications.
- Narrow cuts contribute to a marked reduction in block wastage.
- Quarry operating noise is markedly reduced compared with other methods of extraction.
- In many cases increases in productivity can be achieved quickly and efficiently.

Explosives

Today, in most modern dimension stone operations, the use of explosives for block extraction has significantly declined largely due to the acceptance that blasting may introduce fractures into blocks that were previously devoid of cracks. Explosive usage may have the effect of increasing block rejection rates resulting in increased wastage and operating costs. Also, explosive-induced microfracturing may only become apparent sometime afterwards, and possibly may contribute to accelerated weathering of blocks in service. Other reasons for the reduction in explosive usage include noise pollution and fly rock and seismic vibration damage in areas close to urban development, and increased worker safety concerns.

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Figure 38. An example of a contemporary, plastic-coated, diamond cutting wire. Note the industrial diamonds impregnated in the metal cutting beads (photo courtesy Castle Tools Tyrolit)

Original explosives used were mostly of the low-power type producing large volumes of expanding gases to minimize block fragmentation such as black powder (gunpowder). Later, detonating cord containing a core of the explosive PETN (pentaerythritol tetranitrate) was brought into service, being much easier to use than black powder. Since PETN was a high-velocity explosive, it was necessary to carefully determine optimum blasthole spacing, and amount of explosive and filling used to control the explosion to minimize fracturing (Trezise, 1990).

With the advent of the Finnish method of quarry operation, K-pipecharge (or K-pipe) explosive was introduced. This is in the form of a light charge of nitroglycerine (NG) explosive packed in plastic pipe cartridges. The cartridges are designed to be packed into drillholes and detonated in a simultaneous, controlled explosion freeing the undamaged block. One of the most common uses for K-pipe explosive appears to be for freeing (or 'popping') of the underside of large blocks.

Thermal lance

The thermal lance method of block cutting is also known as 'flame-jet cutting' or 'jet piercing' and has been a common method applied to the cutting of quartz-rich granites and some other hard igneous and metamorphic rocks. The procedure is carried out using a long hand-held

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Figure 39. Vertically drilled, 30 mm pilot hole at top into which the diamond wire is threaded. Note the smooth, vertical faces resulting from the diamond wire cutting process. Orange Grove black granite, Bridgetown

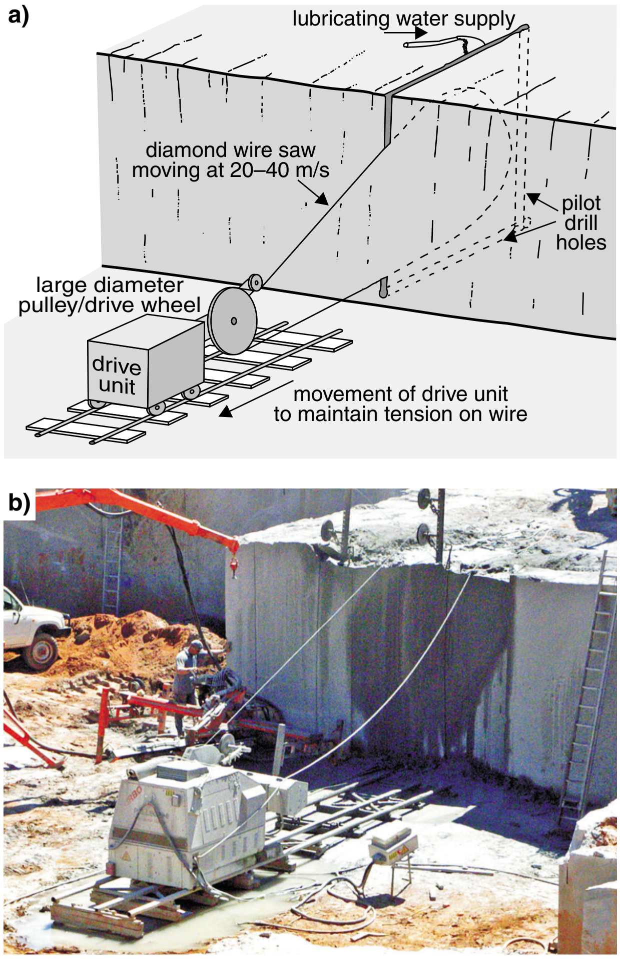

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Figure 40. Diamond wire sawing operations: a) schematic diagram showing the operation of a diamond wire saw (modified from Smith, 1999); b) diamond wire saw cutting blocks of black granite

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Figure 41. Blackened quarry walls at upper right previously subjected to thermal lance cutting

tube, or lance, fed by a mixture of compressed air and fuel oil (diesel) to produce a jet flame at about 2000°C. The flame is moved backwards and forwards along the perimeter of the block gradually cutting a vertical channel between 70 and 150 mm wide to a maximum depth of 4 m. The high-temperature flame induces differential expansion, partial fusion, and thermal shock causing flaking and spalling in the rock, thereby reducing the granite crystals to a coarse sand. Each pass of the flame cuts about 5–7 mm into the developing channelway (Trezise, 1990; Mayer, 1996). Quarry walls subjected to thermal lance cutting are shown in Figure 41. Thermal lances may also be used to accelerate block cutting along lines of drillholes. In this instance, the remaining rock between drillholes is subjected to the thermal treatment described above.

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Figure 42. A high-pressure water jet cutting a vertical slot (76 mm wide) in granite (photo courtesy North Carolina Geological Survey)

This form of cutting cannot be used on rocks such as marble and limestone as the high temperatures in the process would cause calcination of the rock. Also, it is comparatively expensive and slow (about 0.5 – 1.0 m^2/h) to operate, and is very noisy and therefore cannot be used in areas close to urban development (Smith, 1999).

Water-jet drilling

Also called hydraulic piercing, water-jet drilling is more commonly used in countries such as the USA for drilling and cutting granitic rocks. Often used in combination with diamond wire sawing, the process can quickly provide additional, smooth-cut quarry faces throughout the area of operations.

This process utilizes a high-pressure water jet to cut 76 mm-wide vertical slots to depths exceeding 6 m. As the jet arm moves up and down, while progressing along a horizontal guide rail mounted on a boom, it directs water through jet nozzles onto the rock face at a pressure of 2.8 t/cm^2 (Fig. 42). The applied pressure is capable of cleanly cutting through the rock, resulting in a smooth block face. Often jet drilling is used to create pilot holes used for threading diamond wire loops prior to blocksawing. The combined process is capable of providing improvements in quarry efficiency (North Carolina Geological Survey, 2000).

Plug and feathers

Plug and feathers are simple tools commonly used in the final splitting of commercial-sized blocks. The ‘plug’ is a thin tapered steel wedge, 500 mm in length, and the ‘feathers’ is a pair of tapered rods about 450 mm in length. Feathers are flat on the inside, but have an outside semicircular profile that increases in diameter towards the bottom end. Feathers also have ‘ears’ at the top in the form of right angled bends designed to prevent them from

Figure 43. A set of plug and feathers used for final block splitting

falling into drillholes. A set of plug and feathers is shown in Figure 43.

This technique is used to split blocks ranging from very hard rocks such as granite and gneiss to hard and moderately hard rocks, including indurated sandstones and some limestones. The procedure involves placing pairs of feathers in drillholes spaced a predetermined distance apart in a line of drillholes, and a plug is inserted between each pair. The spacing between pairs and the depth of drillholes varies according to physical properties related to strength and brittleness of the individual rock, usually determined by trial and error. Once a line of plug and feathers is in place, a hydraulic hammer is used to very tightly wedge each plug between the feathers in each drillhole (Fig. 44).

The plug and feathers are usually left in place overnight and during that time the stress induced in the rock by these wedging devices is sufficient to cause the block to crack cleanly along the line of holes, separating it from the tertiary rock mass. Plug and feathers are still commonly used in preference to more mechanized block cutting methods, since they are inexpensive to use, and in the hands of a skilled quarryman can produce perfectly shaped, quality blocks for customers.

Expanding chemical compounds

A variety of proprietary, non-explosive, expanding chemical compounds are also used in the final splitting of commercial-sized blocks without inflicting additional damage. Originally developed for splitting concrete in demolition projects, these silicate-based compounds, similar to cement, are mixed into a slurry containing about 30% water. The slurry is poured down a line of drillholes, between 30 and 40 mm in diameter, and spaced at varying distances (commonly 250–500 mm) according to the splitting properties of the rock (Smith, 1999). Over a period of one to two days, the ensuing hydration reaction causes the slurry in the drillholes to expand and harden, exerting a pressure in the order of many thousands of tonnes per square metre and causing the rock to crack cleanly along the line of holes (Sumitomo Osaka Cement, 2006; Fig. 45).

Quarry chain and diamond belt saws

These electric, rail-mounted saws have proved to be invaluable tools for cutting rocks such as marble, indurated sandstone, and slate. Machines are fitted with a vertical cutting arm that can be rotated to cut at virtually any angle into rock to a depth of 1.9 – 4.0 m. Water cooled, quarry

Figure 44. A quarryman inserting sets of plug and feathers in a line of drillholes

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Figure 45. An expanding compound used to effect a clean break along a line of drillholes in black granite. Note the dried expanding material placed in alternate drillholes 250 mm apart

saws are capable of operating at high speeds and rates of 30 m/h have been reached cutting sandstone to a depth of 2.5 m. Saws are designed to operate on relatively flat ground (Trezise, 1990).

The original cutting system employed a linked chain fitted with tungsten carbide cutting teeth that rotated on a track around the outside of the cutting arm. More recently, machines have become available where the chain cutter has been replaced by a plastic belt fitted with sintered metal segments containing industrial diamonds (Fig. 46). Today, there are machines capable of cutting in either the vertical or horizontal planes, and some belts have been designed for dry cutting in marble (Benetti Macchine, 2005).

Although both types of saw are still used in different quarry situations, it has been found that the diamond impregnated belts are capable of operating in harder rocks, at increased cutting speeds, and generally with less wear.

Wedges

In some quarries, wide, tapered, steel wedges are hammered into natural or artificial lines of weakness in the block such as previously cut split lines (either underneath or along the back), natural joints, or bedding planes. This process is designed to complete the block splitting process, or to move the block to facilitate other handling processes. Block damage may be minimized by inserting the wedge between two flat, steel plates before hydraulic hammering commences. Today, wedging has largely been replaced by hydraulic cylinders and other methods used for manoeuvring blocks prior to toppling (Smith,1999).

Block storage and transportation

In the final stage of the hard rock quarrying process, saleable blocks normally between 10 and 25 t are produced. These are graded mainly according to colour and texture, and numbered and catalogued. Large hydraulic excavators then transfer finished blocks to a storage and display area. It is this site that clients such as architects often visit to make their initial stone selection (Fig. 47).

Purchased blocks are loaded onto a low loader, either as two 10 t blocks or one larger block per consignment. In Western Australia, these are transported by road either to the nearest port for export by container shipping, or to

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Figure 46. Electric-powered quarry saw fitted with a diamond impregnated cutting belt. The blade is approximately 2 m in length (photo courtesy Electrolux Construction Products Australia)

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Figure 47. Storage area for granite gneiss blocks at Bruce Rock quarry

Perth and the eastern states (mainly Adelaide, Melbourne, and the Sydney region) for further processing mainly for domestic use by the construction and monumental industries (Fig. 48).

Soft rock quarrying

Rocks in this group are mainly sandstones ranging from moderately hard to soft, semi-indurated varieties, and soft limestone, commonly calcarenite. Because of their more fragile properties, their comparatively simple and less vigourous mode of extraction differs markedly from the hard rock extractive methods described above.

Before quarrying can commence, overburden consisting of soil and upper, weathered saprolite rock must be removed. This is usually achieved using bulldozers or other heavy earthmoving machinery to establish a smooth and level site immediately over extractable stone. As with hard rock mining on a level site, it is then necessary to carry out a vertical cut or 'key run' to provide an opening face so that the first blocks can be released.

Sandstone

Softer sandstone blocks were originally removed by a chanelling operation in which a large-diameter cutting wheel was used to make parallel cuts to outline rows of blocks spaced approximately 1.0 m apart and 2.0 m deep in the quarry floor (Fig. 49). Large, rectangular sandstone blocks up to 9.0 m in length and weighing about 35 t were then detached from the quarry floor using plug and feathers to split the stone along bedding planes. These stone prisms were then subdivided, again using plug and feathers, into blocks of manageable size up to 3–4 m in length.

In recent years, this mode of operation has been largely superseded in sandstone quarries of this type, although large-diameter cutting wheels are still sometimes used to make long parallel cuts in relatively soft sandstone. In today's quarries containing sandstone of this type, cutting wheels have been largely replaced by 3.5 m-diameter saws with cutting teeth faced with small tungsten carbide blocks. These saws are mounted on excavator arms that make them highly versatile cutting devices that can effect a rapid cut from a variety of angles that is both precise and narrow (Fig. 50).

Not only does this technology help reduce quarry wastage through narrow cutting, but a trained operator can take advantage of the much cleaner conditions on the quarry floor to select material suitable for a particular end-use, such as ashlar stone cut perpendicular to bedding planes, or pavers cut parallel to bedding (Hargreaves, 2004a).

Softer sandstone blocks tend to be somewhat smaller than blocks produced from harder stone types, with block sizes in the order of 1 m in both thickness and depth; lengths generally vary from 0.9 to 2.1 m in line with customer requirements.

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Figure 48. Low loader transporting a 10 tonne block of Esperance granite (photo courtesy Melocco Stone)

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Figure 49. A 3 m-diameter cutting wheel fitted with tungsten carbide cutting picks for cutting relatively soft sandstone

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Figure 50. Sandstone block sawing operations. A 3.5 m-diameter rock saw, mounted on the arm of an excavator, deftly cuts out sandstone blocks

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Figure 51. Extractive process for limestone (calcarenite) building blocks: a) The level limestone floor is cut with a series of parallel saw cuts to produce blocks in a variety of standard sizes; b) rail-mounted, multi-blade quarry saw cutting standard size blocks; c) quarry saw blade fitted with tungsten carbide cutting teeth; d) quarry-cut blocks packed on site for dispatch to clients (photo (d) courtesy Meteor Stone)

Calcarenite limestone

Soft calcarenite limestones also require special quarrying techniques for their extraction. In Western Australia, deposits of Tamala Limestone, a fine to coarse-grained eolian calcarenite, are quarried for the building industry from Geraldton in the north, almost to Bunbury in the south. Despite its wide distribution, selected areas of high-grade stone north of Perth from Carabooda–Nowergup, north to Moore River, are the only localities in the State where natural limestone blocks are currently quarried.

In other operating calcarenite quarries throughout the southwest coastal area, the stone is generally too soft to be quarried in block form. In these areas the $CaCO_3$ content ranges from 48 to 78%, all below the preferred 85% cutoff grade for high-grade stone for block-cutting. Instead, this lower-grade material is crushed and manufactured as ‘reconstituted limestone’ blocks either on site or at a processing plant some distance away. The reconstituted block process is discussed under **Byproducts** in Chapter 7, and **Substitutes** in Chapter 8.

Before operations commence, calcarenite block quarries also require a smooth and level site to be prepared over extractable stone as described above under **Soft rock quarrying**. The calcarenite block extraction process is divided into two parts. The first of these is the quarry-cut block extraction process where rough-sawn building bricks and blocks are cut to final size and packed for sale on site in the quarry. The second operation is the diamond cut block process where quarry blocks are transported to a plant for further processing, using diamond saws and other machinery to produce a vast array of bricks, blocks, wall cladding, pavers, and shaped stone profiles. This added-value processing is discussed under **Specialist processing** in Chapter 7.

In the first stage of the quarry-cut block process, large areas of the quarry floor are sawn with parallel cuts, spaced to produce a block commonly 350 mm in height and with a variety of widths. In the second stage, block cutting is completed using a rail-mounted, electric-powered sawing machine fitted with a number of tungsten-tipped saws designed for making simultaneous vertical and horizontal cuts. In this process, the cutting machine travels at right angles to the original quarry-floor cut lines. During these passes, the machine is adjusted to cutting different lengths and widths to produce quarry-cut blocks in a variety of standard sizes.

Quarry-cut blocks, ranging in size from 1000 × 350 × 350 mm to 500 × 159 × 100 mm, are removed from the cutting operation in an excavator bucket and stacked onto pallets on the quarry floor. Figure 51 illustrates the extraction process for quarry-cut blocks. Once packing is complete, the blocks are ready for dispatch to clients. The finished blocks have a slightly roughened, quarry-cut texture reminiscent of early colonial cut stone. They are produced specifically for use as housing bricks, and blocks for landscaping and retaining walls.

Chapter 7

Added-value processing and product application

In today's competitive market, dimension stone processing plants tend to be centralized, usually located close to a city with a ready market close at hand. Processing companies not only commonly access a variety of stones from their own quarries, but also from privately owned operations, often in widely separated locations across Australia, and even imported stone. Exceptions to this are specialist suppliers of a single type of stone. In this situation, the processing plant is normally located close to quarries producing specialist products such as high-quality sandstone or calcarenite limestone blocks, slabs and bricks for the construction and landscaping industries.

One reason for the centralization of processing facilities is the high cost of capital equipment required to carry out a full range of stone processing, including a variety of sophisticated surface preparation and stone-profiling techniques in final processing stages. Also, many quarries are operated on a campaign basis; they are mined according to demand to acquire sufficient stone for a particular contract, or to produce material destined for stockpiling. This process avoids the necessity for continuous quarrying operations, particularly in poor weather conditions, and may assist in reducing labour costs. Lastly, with centralized processing facilities, clients are able to view a much wider range of processed material at the same site, and the company is able more efficiently to organize the transportation of finished products both within Australia and overseas.

This chapter is a summary of the principal stages of dimension stone processing and applications for a number of the products fabricated. In most processing plants there are up to four main stages in the production process: block trimming and primary sawing, surface finishing (such as polishing and a variety of other surface textures), secondary sawing, and stone profiling (optional). Also discussed are secondary stone processing industries operated by monumental masons and artisans, who produce a variety of memorials and carved artworks for public and private display.

Processing operations

Centralized processing

Centralized dimension stone processing works tend to be located in or close to a major Australian city, principally Sydney, Melbourne, and Adelaide. In these locations a number of processing works are owned by long-established companies equipped with an extensive range of machinery in their production lines, and with considerable experience to service customer requirements.

Apart from actual processing equipment used in the production of stone products, the plant must also be equipped with efficient lifting or rolling equipment to manipulate the stone between processing stages. On arrival at the plant, raw quarry blocks weighing between 10 and 25 t are usually unloaded and moved using a heavy-duty forklift machine, but once inside the plant area, heavy-duty lifting is more often accomplished by an overhead gantry crane (Fig. 52). Smaller blocks and slabs are moved by trolleys, roller tracks, or hoists fitted with vacuum cup devices designed to lift and move polished or finely sawn, impervious slabs between processing stages (Fig. 53).

It is important to note that contemporary stone processing machinery is in large part computer controlled. This is particularly important in various sawing processes, where slab width and depth, angle of cut, and predetermined shapes are precisely controlled by computer programming. Computer control is also vital in the block profiling process where detailed designs are cut into blocks to form intricately shaped finished products.

Block trimming and primary sawing

Once a block is required for processing, it is removed from the plant's holding stockpile and set up in the primary sawing area. The block may first be trimmed to a standard size before slab sawing commences, or more often, it may be left in its rough state and the coarse edges removed by secondary sawing after surface finishing has been completed. There are four methods of primary sawing used, according to block size and hardness of the stone: gangsawing, blocksawing, multi-disk sawing, and diamond wire sawing.

Gangsawing

Also known as frame saws, gangsaws have been in use for over 100 years. The saws consist of a horizontal reciprocating frame fitted with as many as 100 parallel, steel blades designed mostly for cutting blocks of hard stone such as granite, but also softer materials such as sandstone or marble. Gangsaws are capable of cutting large blocks up to 3.4 m in length and 1.8 m high (Fig. 54a). As a rule, increased stone hardness causes a reduction in the gangsawing rate. Gangsawing is the most common method of cutting worldwide, and some large plants have more than 30 gangsaws in operation at a single location.

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Figure 52. An overhead gantry crane lifts a cut slab onto a polishing line (photo courtesy Tillett Natural Stone Industries)

Lubricated by a water spray, the blades travel rapidly forwards and backwards across the block, gradually forming vertical cuts from 8 to 20 mm wide by abrading away the stone. Depending on the hardness of the stone, abrasive cutting media such as sand, chert, cast iron, silicon carbide, and steel shot are introduced with the water into the slots occupied by the moving steel blades to increase the cutting rate. Cutting speeds may range from 10 to 400 mm per hour; however, higher speeds often result in rougher surfaces that may require further finishing (Trezise, 1990). Modern gangsaws for cutting marble, basalt, and sandstone are fitted with diamond-tipped blades that can produce a high-quality surface finish. By contrast, steel-shot-sawn sandstone often results in a coarser, natural-textured finish providing cut stone for visually attractive pavers and capping materials designed for landscaping projects (Hargreaves, 2004b).

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Figure 53. A vacuum cup hoist in operation transporting polished basalt slabs

Blocksawing

Large-diameter blocksaws with a single circular blade are very common in processing works because of their flexibility of operation. Although these saws can make only a single cut at any time, they are usually programmed to make repeated passes, rapidly cutting large blocks into numerous, accurately sized slabs of almost any thickness on a continuous operational basis. Most saws are mounted on an overhead steel bridge spanning the cutting area. As the blade passes over the block, it is incrementally lowered. After a designated number of passes the blade is raised and is automatically positioned to allow the next cut to provide a slab of predetermined thickness (Fig. 54b).

Primary saw blades vary in diameter from about 1.5 m to a maximum of 5.0 m. The most commonly used 3.0 m blade is capable of making cuts to 1.1 m in depth. Cutting teeth are retippable, diamond-impregnated segments designed for cutting very hard stone such as granite and gneiss through to moderately hard material such as marble, bluestone, and sandstone. In operation, blades are often laser guided and are capable of producing an accurately cut slab honed to an almost smooth finish (Trezise,1990).

Multi-disk sawing

These saws comprise numerous vertical cutting disks at preset but adjustable spacings. They can vary from a small number of disks for cutting thicker slabs (or billets as they are referred to in this process) to 100 disks for cutting 11 mm slabs . Nearly all 10 mm-thick marble and granite tiles produced worldwide are produced by this method. Blades range from 900 to 600 mm in diameter and are capable of the rapid cutting of blocks to a maximum depth of about 650 mm (Fig. 55). As is the case with blocksaws, the cutting teeth on each blade are usually retippable diamond-impregnated segments designed for cutting specific types of stone.

Once the vertical cutting has been completed to the correct level, these saws usually incorporate a single or double horizontal blade for cutting the billets from the original block. Advanced models also employ automatic unloaders to remove billets and stack them for the next operation.

Although multi-disk block cutters cannot produce large slabs, it has been demonstrated that for smaller products savings of up to 60% may be obtained over gangsaw cutting costs for a similar job (Litosonline, 1998).

Diamond wire sawing

Diamond wire sawing employs an endless carrier wire that rotates around two large-diameter vertical wheels (guidewheels). This wire incorporates diamond-impregnated beads at regular intervals that are used to subdivide large blocks into slabs of required thickness for further processing. In these machines, the cutting wire is positioned over a stone block aligned with its longest axis parallel to the direction of the rapidly rotating wire. The machine slowly descends bringing the cutting wire into contact with the top of the block, and the downward pressure of the water-lubricated wire creates a clean cut through the block (Fig. 56).

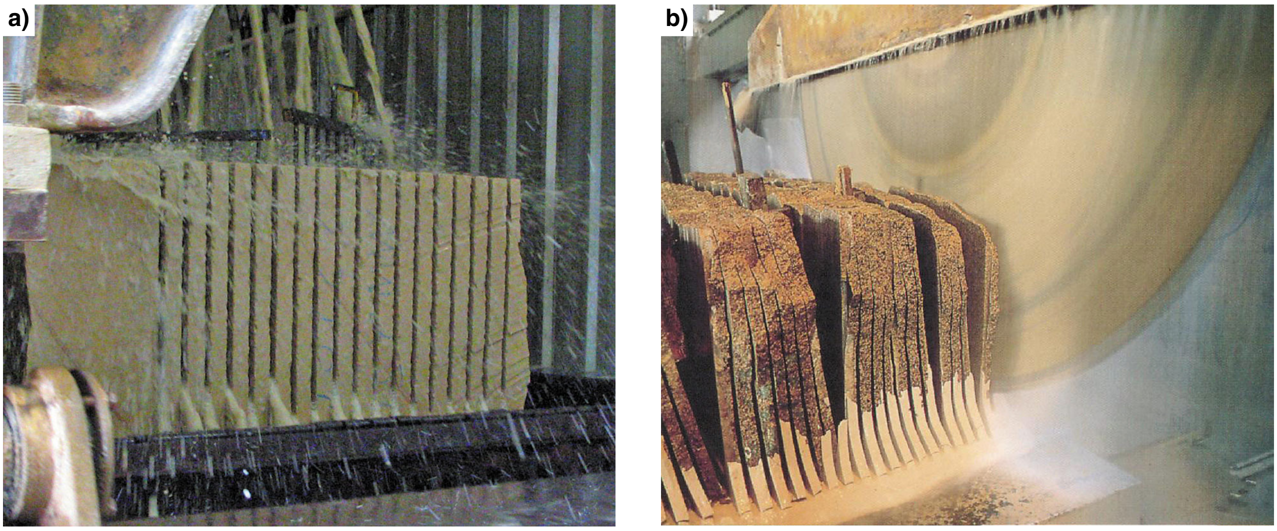

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Figure 54. Primary sawing operations — gangsawing and blocksawing: a) a gangsaw cutting sandstone slabs from a block approximately 1.0 m high; b) a 3 m blocksaw cutting slabs to a depth of about 1.0 m (photo (b) courtesy Melocco Stone)

Diamond wire saws are produced in several varieties. With the 'stationary' model, the block is loaded on a moving table that progresses underneath the wire so that adjacent cuts can be made, whereas the 'travelling' wire saw moves along a runway over a stationary block to make successive cuts. Stationary wire saws are the most common machines employed to trim blocks for initial processing.

Because of the flexible nature of the cutting wire, these saws can also be programmed using computer numeric control (CNC) to carve out intricate two-dimensional shapes. The most sophisticated machines are also fitted with independently controlled guidewheels that permit the shaping of three-dimensional stone objects. Over the last 10–15 years, the use of diamond wire saws has increased markedly at the expense of gangsaws and blocksaws owing to comparatively lower capital and installation costs. Moreover, their environmental impact is lower compared with that of gangsaws.

More recently, multiwire saws have come into use. These machines have developed from models using several wires into machines employing up to 50 parallel diamond wires to simultaneously cut multiple slabs from large blocks ranging from hard granite to comparatively softer marble, basalt, and sandstone (Fig. 56). Minimum slab thickness is 10 mm but is more commonly 20 mm. Multiwire saws have proved to be particularly efficient and flexible for cutting slabs and have become a real alternative to gangsaws (Pellegrini Group, 2006).

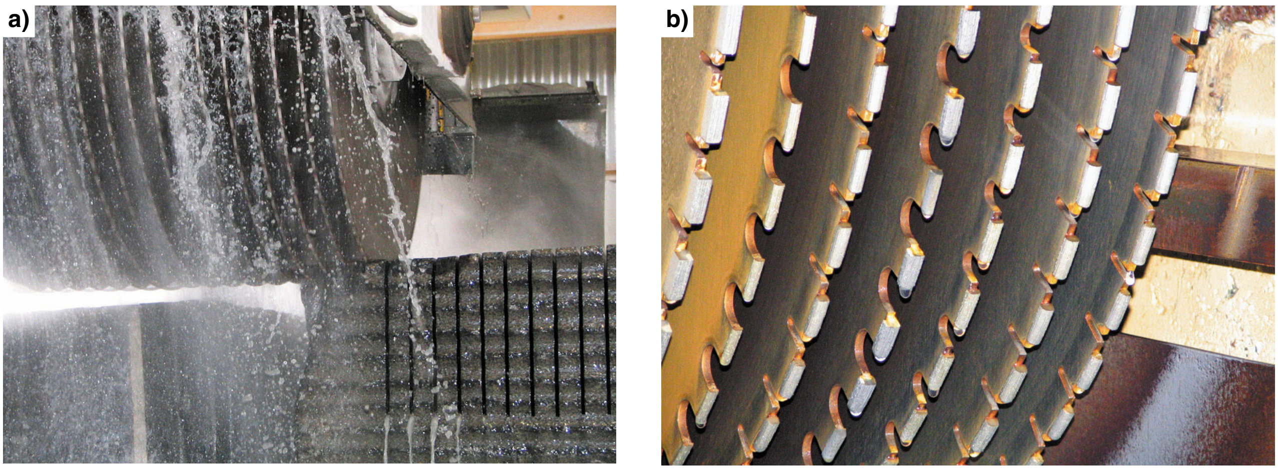

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Figure 55. Primary sawing operations — multi-disk sawing: a) a large multi-disk saw dividing a large basalt block into slabs for paver manufacture; b) detail of multi-disk saw blades with diamond impregnated saw teeth, set for cutting 50 mm-thick slabs

a)

b)

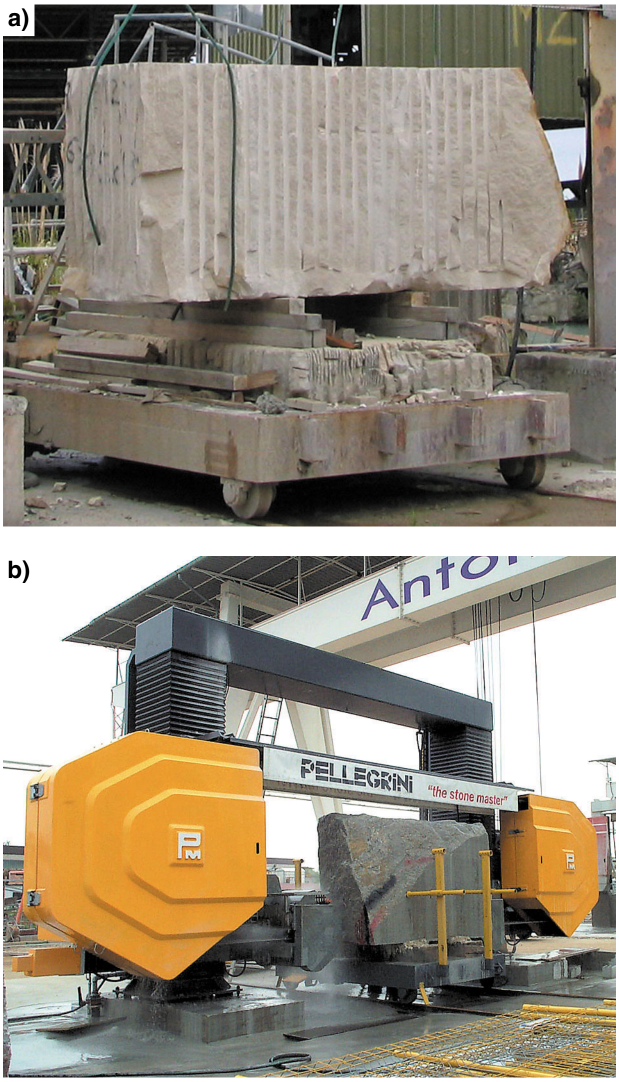

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Figure 56. Primary sawing operations — diamond wire sawing: a) a 10 t block of Donnybrook Sandstone ready for diamond wire sawing using a single-strand diamond wire; b) a multiwire diamond saw cutting slabs from a large block of hard rock (photo (b) courtesy Electrolux Construction Products Australia)

Surface finishing

Surface finishing is carried out after primary sawing is completed and comprises a variety of treatments designed to visually enhance the attractive qualities of the stone. Apart from aesthetic considerations, the type of surface finish selected for a stone is dependent on its technical properties such as strength, hardness, and resistance to wear (Table 3). It is these and other properties that determine the purpose (and environment) for which a stone with a particular finish is suitable. For example, it is necessary to carefully assess the non-slip performance of selected stones and potential finishes under different weather conditions before a final choice of stone type and finish is made.

It is also worth noting that finished blocks or slabs of the same stone, may exhibit very different shades of their natural colour depending on the type of surface finish that has been applied. For example, a green stone that is polished may appear dark green to black to the naked eye, while the same material with a roughened surface finish, such as exfoliated, or bush hammered, may appear pale grey-green.

Different styles of surface finishing have been divided by SlabUSA (2004) into three groups depending on the treatment required:

- *Mechanical finishing*: Includes polished, honed, sawn, rubbed, striated, and chiselled-margin finishes.
- *Impact finishing*: Includes bush-hammered, exfoliated, etched, antiqued, and waterstormed finishes.
- *Chemical finishing*: Includes acid-wash finish.

A summary of common surface finishes is given in Table 6 and a discussion of the most popular contemporary finishes is given below.

Polished

In this process, an extremely high gloss finish is created on a near-flat surface of hard to moderately hard rocks such as granite, black granite, gneiss and multicolour metamorphic rocks, basalt, trachyte, and marble. In general, softer rocks such as sandstone, limestone, slate, diatomite, and spongolite are not suitable for polishing. It is recognized that the finish achieved with softer materials will not be a full gloss and will often appear somewhat patchy although such finishes are occasionally specified.

The quality of a stone's polish may be assessed using two factors: reflectivity, which can be calculated by the angle of an incident light beam to the normal known as the 'gloss value'; and the 'roughness value', which can be calculated by averaging the height or depth of irregularities across the surface profile. Whereas unpolished sawn slabs may indicate roughness values between 15 and 20 µm and gloss values below 10%, the high-gloss finish of polished slabs may give roughness values lower than 0.5 µm and gloss values in excess of 90%. It should be noted that with coarsely grained rocks such as some granites, surface grain boundaries may show significant roughness values even on highly polished surfaces. Consequently, with these rocks care should be exercised in the interpretation of gloss and roughness values (Smith, 1999).

Slab polishing is achieved using one of three machines. One of the oldest types still in use by monumental masons is the 'Jenny Lind' polisher. This is a manually operated machine with a single polishing disk, either arm-mounted or supported by an overhead bridge. The second machine is known as a bridge polisher. This machine also has a single polishing head but is completely automated and travels over the slab in a prescribed pattern evenly covering the slab's entire exposed face. Single-head polishing machines must be stopped to change the polishing disk each time an incrementally finer grade of polishing abrasive is required, although automatic head changing machines have now made this a continuous operation. The single-

Table 6. Common surface finishes applied to dimension stone

Surface finish	*Alternative name or similar finish*	*Physical appearance*	*Applications*
Polished		An extremely smooth, near-flat surface polished to a brilliant, mirror-like finish	Slabs and blocks for cladding in building construction, monumental masonry, and artisanal applications
Honed	Fine honed Emery finish	A partially polished surface ranging from matte to semi-gloss, displaying stone textures and slightly reduced colour tones	Exterior stone panels, and interior paving in high-traffic areas requiring higher slip resistance than for polished stone
Sawn	Diamond sawn Gangsawn	Rustic, slightly irregular sawn surface remaining after blocks are initially sawn into slabs. Saw-induced grooves to 1.0 mm deep are common. Sandstone and limestone are commonly used	Natural-textured building blocks and bricks for outdoor buildings, and pavers and blocks for landscaping
Rubbed	Coarse rubbed Diamond rubbed	A sawn finish treated with an abrasive block or power sanding to remove saw marks. All stone types can be treated	Ashlar blocks, cladding, and slip-resistant pavers
Bush hammered	Dolly pointed Pecked Fine axed Scabbled Pitched	A rough-textured surface, ranging from fine to coarse pits, irregular lines, and sunken dots 1–3 mm wide and deep either randomly or regularly spaced	External masonry, and slip-resistant pavers, kerbs, steps, risers and plinth courses
Exfoliated	Flamed Flame textured Flame scorched	Heat treatment of granite and granite gneiss to remove the hardest surface minerals (mainly quartz) by thermal shock. This produces a rough-textured, often vitreous surface resembling natural weathered stone. Colour is generally faded and textures masked	Slabs mainly for outdoor cladding, and slip-resistant pavers and tiles
Etched	Bead blasted Grit blasted Shot blasted Sand blasted	A smooth, lightly textured surface with a matte gloss finish. Restores both colour and original texture to the sawn slab	Commonly applied to granites used in outdoor situations, slip-resistant floor tiles, and etched pattens and lettering on polished surfaces
Striated	Chiselled Combed Sclype Benched Tooled Boasted Denteled	Fine to deep parallel grooves or striations set at different spacings. Groove profiles range from square to U-shaped, V-shaped, and irregular. Grooved sets are combined with a variety of other surface finishes	Used where maximum slip resistance is required in staircases, kerbstones, pavers and doorsteps. Also used as contrasting bands when combined with other finishes
Chiselled margin		A striated (or combed) margin chiselled around the perimeter of a rough-faced block in a different finish	Commonly used in historic sandstone, limestone, and bluestone (basalt) buildings
Antiqued	Brushed	Stone surface is mechanically treated by abrasives or brushes to produce an aged appearance caused by wear and tear	Decorative stonework
Waterstormed	Water finished	High-pressure water jet used to produce the opposite effect to exfoliation by removing the softest parts of the stone to produce a rough surface finish mainly in granite and marble. Colour and texture are unaffected	Slabs and slip-resistant pavers and tiles
Acid wash		Acid etching used to simulate a variety of finishes such as waterstormed and antiqued	Slip-resistant, and decorative stonework

SOURCES: Trezise (1990)
Melocco Stone (2003a)
SlabUSA (2004)
Pierre Bleue Belge (2005)

head polishing system has proved to be very successful in the polishing of marble (Fig. 57a).

The third polishing machine is the automatic polishing line containing 12 or more in-line grinding and polishing heads, each with its own polishing disk. In this operation, 2–3 m-long slabs with widths of up to 2.0 m, are transported on a rubber belt below the polishing bridge. The bridge moves from side to side of the slab while the polishing heads rotate and the abrasive disks on the head grind and polish the slab. Abrasive disks are graded along the length of the polisher from very coarse at the start to grind the slab flat, to very fine at the end to polish out any remaining scratches. Mediums used for abrasive disks vary from metal-bond diamonds for grinding, to varying grades of silicon carbide for grinding and progressive finishing to a final polish. Resin-bonded diamonds are also becoming popular and can be used from the start to the finish of the process. This process is particularly effective in the polishing of granite slabs (Fig. 57b).

In the automated polishing line, polishing rates may vary between 15 and 40 m^2/h. Slabs passing through the machine are normally in the untrimmed state, with rough edges, since little can be done to prevent edge damage at this stage (Smith, 1999; Fig. 57c). Once this process is completed, the polished slab may be sawn to exact dimensions or supplied to dimension stone retailers where trimming is carried out to match client specifications (Fig. 58a).

Honed

This is a partially polished finish that may be applied to virtually any natural stone but is particularly popular in granite, especially black granite. The honed finish ranges from no gloss at all under normal light, known as 'eggshell finish', to a semi-gloss finish. The degree of honing or partial polishing is controlled by the fineness of the final polishing grit (Melocco Stone, 2003a).

The resultant non-reflective finish has a smooth, fine surface in which the original colour and texture of the stone are only slightly reduced (Fig. 58b). Honed floor tiles are commonly used for interior, and less commonly for exterior, paving because of their increased slip resistance over fully polished stone. Also, external walls are commonly clad with visually attractive honed panels.

Sawn and rubbed

Sawn finishes are the result of primary sawing either by gangsaw or any type of diamond-impregnated saw. Gangsaw cut granite slabs are the result of cutting using steel blades and shot. This produces relatively irregular textured surfaces that have become popular due to their natural, rustic appearance. Gangsawing is also used for cutting sandstone and basalt slabs and the degree of texture achieved will depend on whether the process employed steel blades and steel shot, or diamond gangsaw blades. Diamond-impregnated saws are used to achieve a much finer sawn surface compared to a steel shot gangsaw cut, although saw marks may still be visible on the smoother surfaces. Diamond sawing has the added advantage in that it can be carried out on virtually any natural stone (Fig. 59).

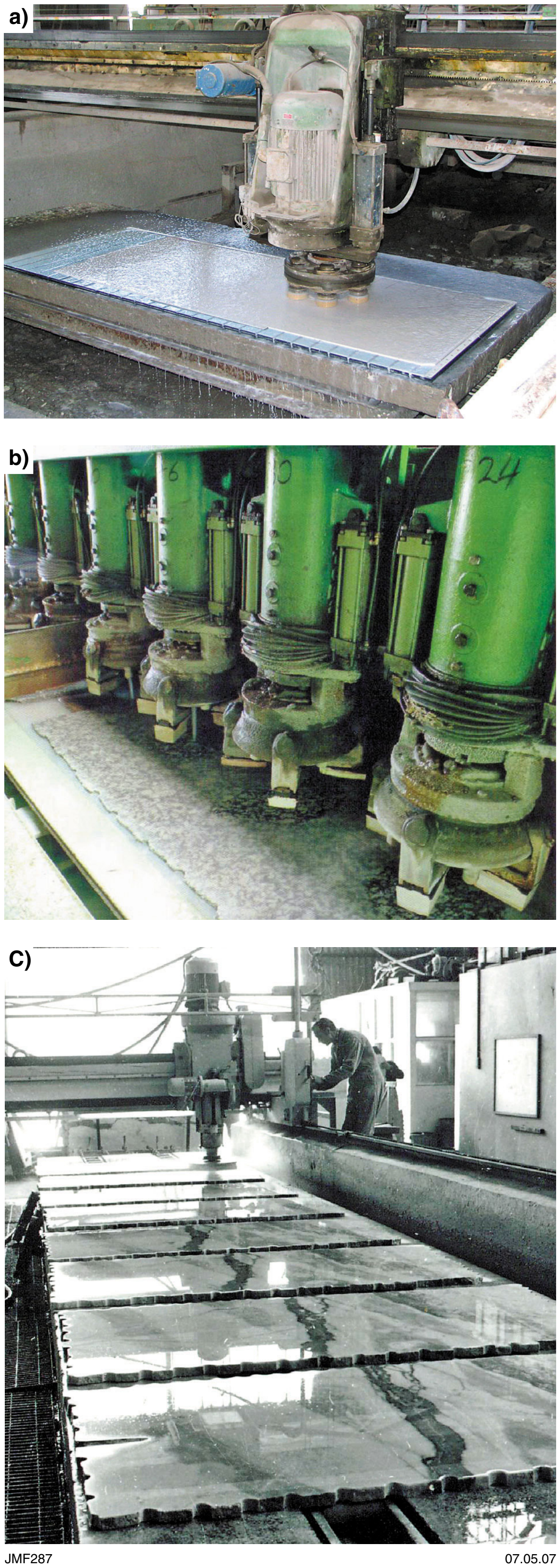

Figure 57. Slab polishing operations: a) an automated single-head bridge polisher in operation over a fixed slab; b) a large granite slab moving through an automatic polishing machine containing about 12 in-line, grinding and polishing discs: c) highly polished marble slabs rolling off the production line of an automated single-head bridge polisher (photos (b) and (c) courtesy Melocco Stone)

a)

b)

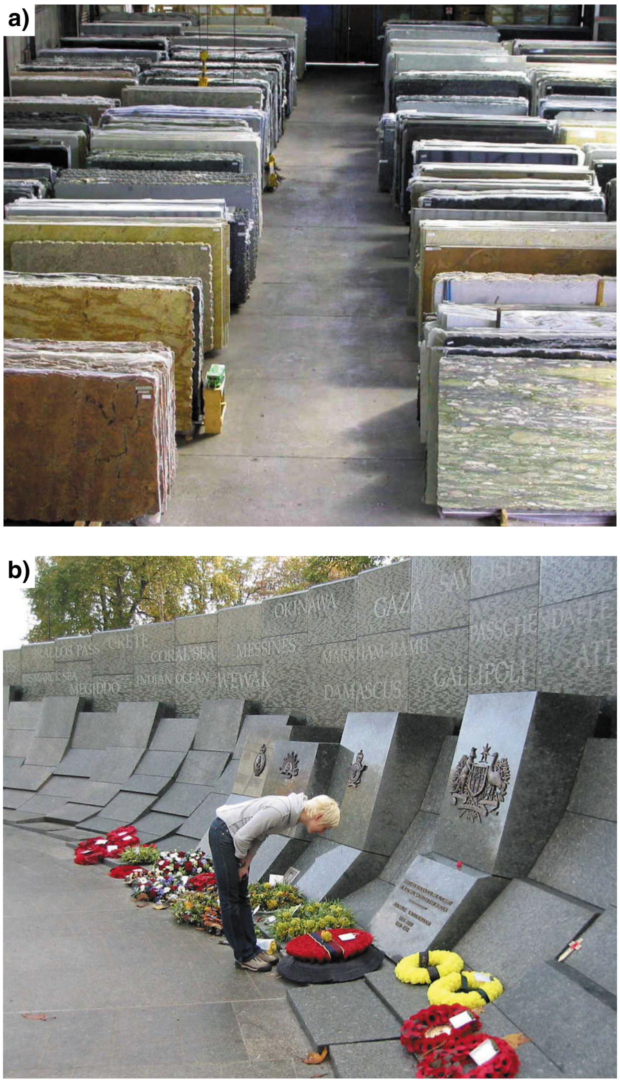

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Figure 58. Polished and honed stone panels and blocks: a) showroom display of untrimmed, polished stone panels; b) Australian War Memorial, Hyde Park Corner, London featuring polished and honed stone panels and blocks of *Laguna Green* granite from Jerramungup in southwest Western Australia (photo (a) courtesy S & N Bros Pty Ltd, photo (b) courtesy Neil Mackenzie, Tonkin Zulaikha Pty Ltd)

Sawn stone has a matte surface and colours tend to be comparatively light. This material is commonly used in the production of natural-textured building blocks and bricks for mainly outdoor applications in building, paving and landscaping applications. In the Perth region, the coastal Tamala Limestone is commonly processed in this way.

Rubbed finishes are the result of further treatment to sawn blocks to remove saw marks and achieve a finer finish. This finish can be achieved by using either power sanding to retain the relatively coarse finish, or by diamond-impregnated abrasive blocks for a finer result. Ashlar building blocks, wall cladding, and slip-resistant pavers are in demand in this finish.

Exfoliated

Generally used for the treatment of granite, granite gneiss, and coarser grained black granite, the exfoliation process involves passing slabs and panels through extremely hot gas flame jets at about 1100°C. Under this condition, surface minerals, especially quartz, undergo thermal shock causing them to flake off resulting in a rough-textured and often vitreous surface resembling natural weathered stone with somewhat faded colours and masked textures (Fig. 60). Because of their different crystalline structure this process is not effective on marble, basalt, and sandstone (Melocco Stone, 2003a).

This process has advantages over other methods in that it is comparatively rapid and operates at reduced noise levels. Exfoliated finishes have proved to be extremely successful as slip-resistant pavers and tiles and have been used extensively in large outdoor plazas and other public areas. They have also found use as an external cladding medium.

Bush hammered

One of the oldest methods of creating surface finishes, the bush-hammering process includes a range of impact-produced finishes achieved either manually or mechanically with a variety of hammers, picks, chisels, and routing tools. This technique provided the original slip resistance in stone pavements, kerbs and steps (Fig. 61). It also remains popular as a surface finish in some types of external masonry. Today, bush-hammered finishes have been substantially replaced by much faster and less noisy finishing processes such as exfoliation and waterstorming (Table 6).

Striated

Striated or chiselled surface finishes are applied to a stone in the form of parallel grooves varying in depth from fine to deep and which may be set at different spacings. These grooves are designed to provide maximum slip resistance

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Figure 59. Large sandstone blocks rubbed to remove saw marks (block length about 1.0 m)

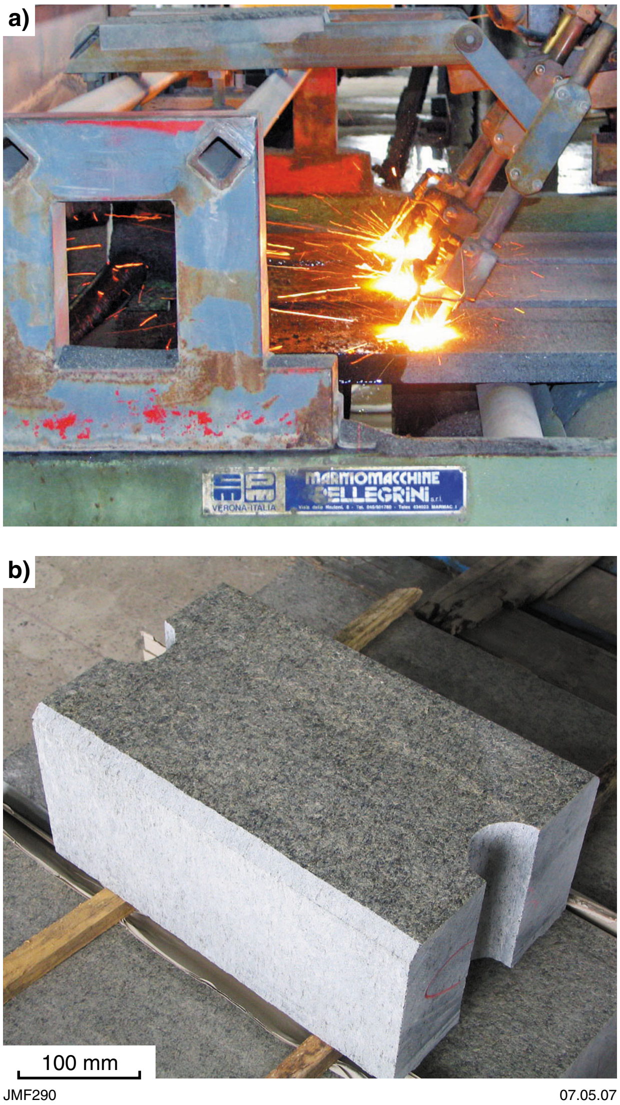

Figure 60. The exfoliation process: a) Granite slabs passing through extremely hot flame jets at 1100°C causing thermal shock to surface minerals and forming a rough-textured, exfoliated surface; b) a kerbing block of *Verde Austral* granitic gneiss from Fraser Range in southern Western Australia. The block's top surface is an excellent example of an exfoliated finish

required in situations such as staircases, kerbstones, pavers and doorsteps. Groove profiles range from square to U-shaped, V-shaped and irregular, and may be combined with other surface finishes. Examples of non-slip, striated pavements are shown in Figure 62. Chiselled finishes may also be used as decorative, contrasting bands when combined with other finishes on blocks and panels.

Etched

Etched or bead-blasted finish is accomplished by the use of a high-pressure jet to blast variously finished stone surfaces with high-velocity particles including steel shot, silicon carbide grit, carborundum particles, slag, fine glass beads and, formerly, silica sand. Different particles are used to create a range of textures on most types of natural stone. When applied to granite, it produces a lightly textured surface with a matte gloss finish in which the original colour and texture are preserved.

Stone etching is used by monumental masons and artisans who create designs, borders, and lettering by masking stone panels with a prepared template prior to the blasting process. In this way, durable and sharply contrasting patterns and lettering can be created on slabs, panels, and memorials.

Secondary sawing

In this process, smaller, diamond-tipped sawblades, usually 600–900 mm in diameter, are used to longitudinally subdivide large primary slabs into stone panels. Secondary sawing may also be employed at various stages during processing for crosscutting, trimming, and detailing panels and small blocks to specified shapes and dimensions. Commonly known as bridge or dimension saws, these machines are fitted to an overhead fixed or, more

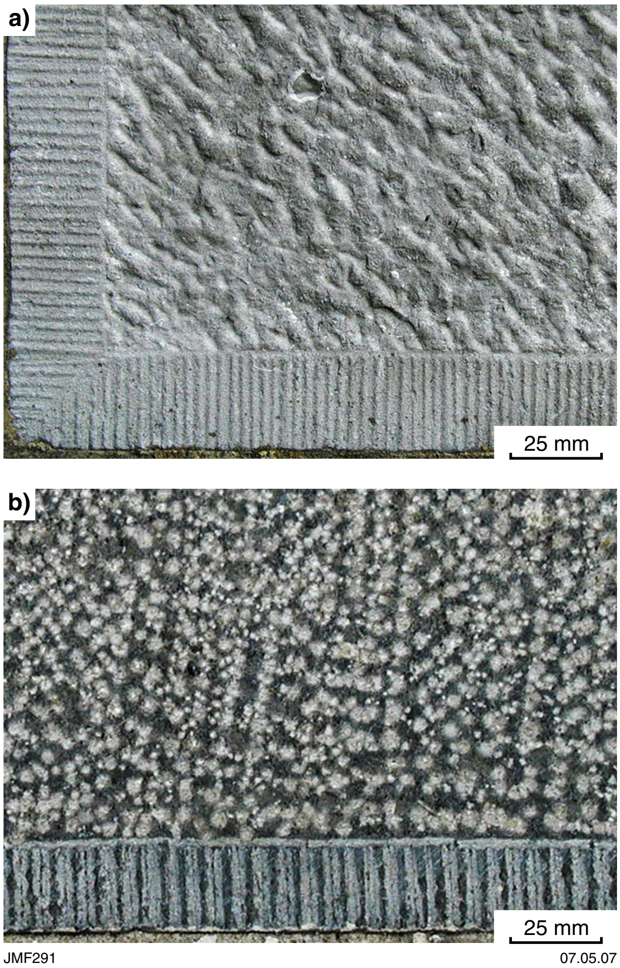

Figure 61. Black marble blocks showing two styles of bush hammering. Surrounded by chiselled margins, both styles are designed for use as kerbstones with non-slip surfaces: a) medium- to coarse-textured pits; b) regularly spaced, sunken dots

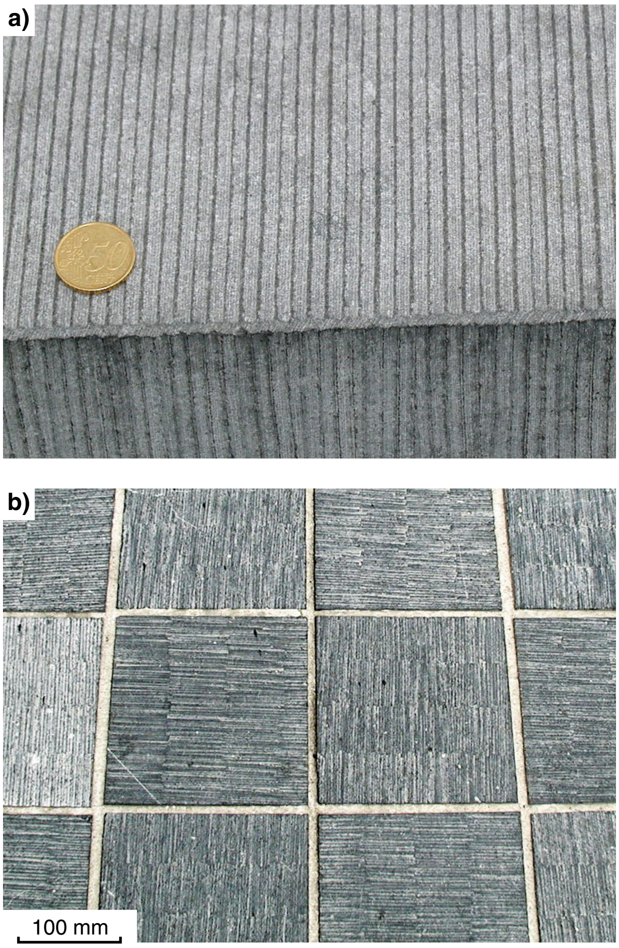

Figure 62. Non-slip, striated pavements in black marble: a) parallel grooved kerbstone; b) pavers showing a complex grooved or 'boasted' finish

commonly, moveable bridge over the work area (Trezise, 1990).

The slab to be sawn is mounted on wooden slats fixed to the cutting table beneath the bridge saw. This table may be raised, lowered and/or rotated according to the cutting process being undertaken. Once operational, the saw moves over the slab cutting out panels in accordance with pre-programmed instructions (Fig. 63). More recent innovations include the use of multiple-bladed bridge saws designed to speed up the automated cutting process, and the use of roller tables to quickly move newly cut panels onto the next processing stage. This type of sawing is capable of producing panels accurate to within small tolerances and, as such, has been partially responsible for the success of stone paneling as a cladding material in major construction projects (Smith, 1999; Fig. 58b).

Another type of secondary sawing utilizes fixed crosscutting machines mounted level with the processing table. Machines are mounted singly or in banks of up to eight, each fitted with a cutting disk up to 350 mm diameter. The single saw configuration is used to crop stone strips to a standard length to a maximum of 750 mm, whereas the multi-bank machines are used for tile cutting (Socomac, 2006). Marble is the preferred stone for this process, although granites up to 40 mm in thicknesses may be handled.

Stone profiling and shaping

Stone profiling is an optional production process, as a large proportion of surface-finished stone is sawn to customer specifications in the form of building panels, blocks, pavers, bricks and tiles and dispached straight to clients without the need for further processing. The remaining material may be used in the stone profiling process to create two- and three-dimensional stone shapes according to architectural specifications. A number of different processes are used to achieve a variety of special profiles and standardized shapes through the use of automated profiling saws, and various stone-working tools including milling machines, stone lathes, routers, and calibrating (levelling and planing) devices.

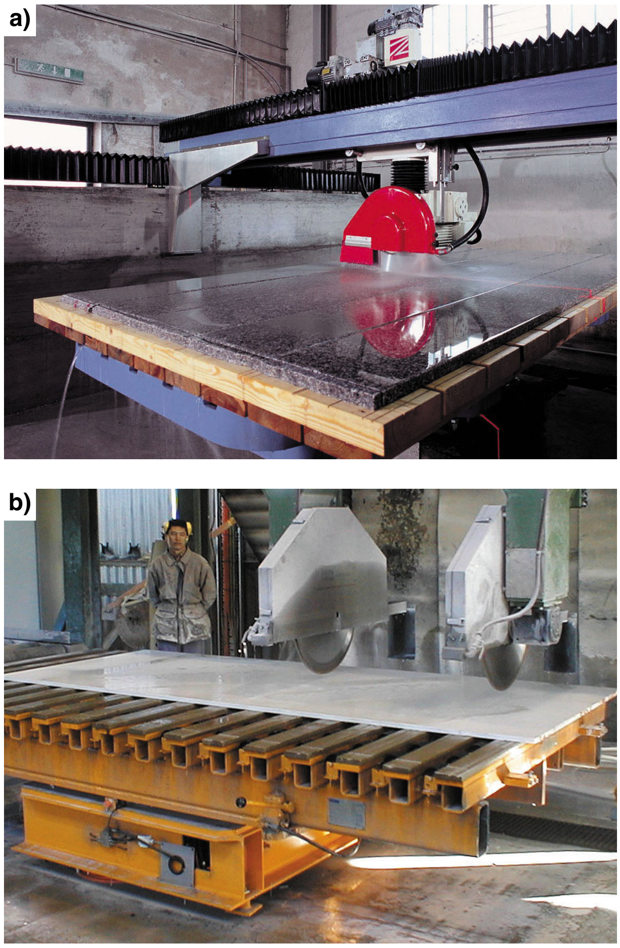

Figure 63. Bridge saws in operation: a) automated bridge saw cutting granite panels; b) a multi-bladed bridge saw operating in an automated sawing plant (photo (a) courtesy Castle Tools Tyrolit, photo (b) courtesy Melocco Stone)

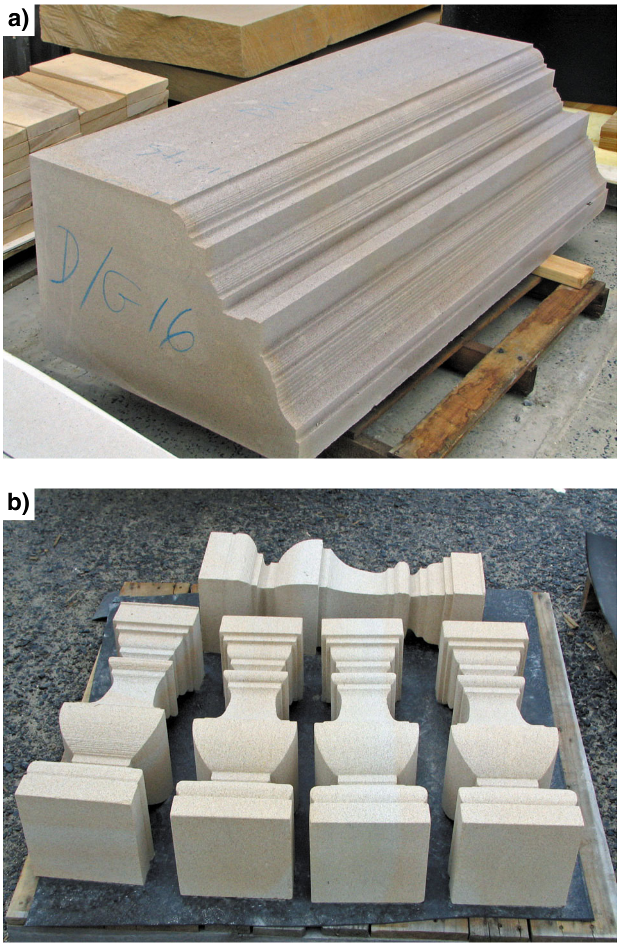

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Figure 64. Automated profiling of blocks and slabs: a) a series of finely spaced, parallel cuts outlines an intricate pattern in a sandstone block; b) sandstone banisters cut by a computer-controlled profiling saw

Automated profiling

In this process, bridge saws fitted with computer numeric control (CNC) are programmed to carry out detailed profiling exercises whereby blocks are shaped in accordance with architectural specifications, often in the most intricate, two-dimensional designs. To form the profile of an object, these machines are capable of creating a series of cuts, some with less than a millimetre separation, to form curves, chamfers (bevelled edges), steps, slots, and rebates (Fig. 64).

In recent years, automated profiling has also been performed using diamond wire on machines fitted with CNC to produce two-dimensional objects. Advanced wire sawing machines are now available for the production of three-dimensional objects, a feat previously not possible with bridge saws.

Milling

Stone milling is an important process where visible edges require processing. Edge profiles are commonly convexly curved (bullnose) or partially curved (half bullnose), or even double curved (s-shaped). Other profiles include square, rounded edge (pencil round), chamfered, and shark's nose.

These profile shapes are achieved using diamond-faced, profiling or grinding wheels with specially shaped cutting faces. To achieve the required profile, a wheel shaped with the same profile is attached to a milling machine. As the slab passes through the machine, the spinning wheel grinds the edge to the required shape.

Profiling machines are also used to manufacture curved arch sections, curved risers for stone staircases, and for the cutting of rebates and apertures in slabs (Smith,1999).

Other profiling and shaping processes

Other profiling and shaping processes more fully described in Smith (1999) and Pedrini (1997) include:

Lathe profiling

This technique is used where a circular piece of stone such as column sections or rounded banisters are required. In this process, a roughly sawn hexagonal or octagonal block is fitted to a lathe, with the long axis mounted horizontally if the diameter is small, or vertically if large. The attached block is spun against a cutting tool to produce a circular finished product in either standard or variable diameters.

Routing

Routing is carried out on the table of a stone-working machine fitted with a diamond-coated, cylindrical, conical, or ball-shaped cutting tool. Rotating at high speed, the cutting tool can move over the stone surface in any direction and is used to cut out complex shapes, patterns, or lettering as required. Previously, shape cutting was carried out by a skilled operator following a pre-formed three-dimensional template, or by using tracing simply placed over the stone. More recently, computerized CAD systems that communicate directly with cutting machines fitted with CNC have automated the process to the extent that complex patterns and shapes can be cut into a stone slab without human intervention.

Calibration (levelling and planing)

Calibration machines are used to grind slabs and blocks to the correct thickness and specified degree of levelness. Modern machinery employs grinding rollers set either at right angles or obliquely to the direction of the stone conveyor belt. Diamond-tipped cutters in the form of spiral metal coils welded around the outside of the roller traverse its width. Grinding rollers vary in width from 395 to 1220 mm and can be operated either singly or in groups of up to four.

The calibration process originally grew out of the need to produce tiles of a consistent thickness to speed up their rate of installation. This process is generally carried out prior to slab polishing or honing operations but more recently has found application in the calibration of slabs intended for use as bench tops. This process reduces the time required for grinding benchtop slabs to a consistent thickness as well as making the edge lamination process much easier.

Benchtop and larger scale profiling equipment

In recent years, much effort has gone into the design of equipment that specifically addresses automated benchtop manufacture of profiled stone in an extensive variety of shapes, and at the same time combines many forms of profiling into one machine. This is largely due to high volume demand for stone products that may be produced by benchtop profiling.

In this process, most equipment uses highly advanced CNC equipment with interchangeable diamond tools that allows the one piece of equipment to cut polished slabs, size and mill edges to shape, and finally to apply a polish. These machines can also carry out routing operations and can even machine stone sinks from solid blocks. Similar machines, with significantly larger ranges of operation than benchtop machines, have been developed for use in major commercial operations. These machines are capable of producing large, intricate shapes such as fluted columns or sculptured pieces directly from stone blocks.

Most of the contemporary profiling equipment listed above is based around bridges that are able to precisely position a tool (or a number of tools) to automatically shape a block or slab held on the table beneath the bridge. More recently, a new automated robotic machine with the same profiling capability has been developed that carries the profiling tools at the end of an articulated arm.

Setts and other rough-cut blocks

In this process, hydraulic splitting machines are used for splitting hard to moderately hard homogeneous rocks, mainly granite, black granite, basalt and, less commonly, marble and sandstone into rough-faced cubes, rectangular bricks and small blocks known as ‘setts’. Generally, setts are individually cut using a hydraulically actuated guillotine with a splitting capacity of about 25 t to form cube-shaped blocks with faces approximately 100 mm square. Larger sized bricks and blocks, with thicknesses between 100 and 300 mm, are produced using more powerful splitting machines up to 60 t capacity. A newly manufactured batch of black granite setts is shown in Figure 65.

Specialist processing

This form of processing is normally carried out by specialist processors of a single stone type obtained from one or more quarries in a local area. The quarried stone is transported only short distances to a centralized processing plant. Cut stones falling into this category are typically softer varieties of sandstone, limestone, and spongolite for use by local building construction, paving and landscaping industries. A number of cities in eastern Australia are serviced by local specialist industries producing natural stone blocks, bricks, wall cladding, pavers and shaped-stone profiles. In Western Australia, it is the calcarenite limestone block industry in the Perth region that requires specialist processing, and is discussed below.

Tamala limestone block industry

As previously discussed in Chapter 6 under **Soft rock quarrying**, Western Australia’s coastal Tamala Limestone (calcarenite) is quarried for natural building blocks in the area from Carabooda–Nowergup to Moore River, between 35 and 80 km north of Perth. The first stage of the block cutting process occurs in the quarry in which natural-textured quarry-cut blocks are produced partly for direct sale to clients. At the same time, a substantial proportion of these quarry blocks are transported to nearby brick-cutting plants for further added-value processing using diamond saws and other machinery.

Quarry-cut blocks

Quarry-cut calcarenite limestone blocks are cut mostly in the quarry by tungsten carbide-tipped saws that produce a rustic textured finish on the surface of the blocks, often with saw marks in evidence. Quarry-cut stone from Moore River quarries, near Guilderton 80 km north of Perth, has a distinctive biscuit-coloured, earthy tone, whereas stone

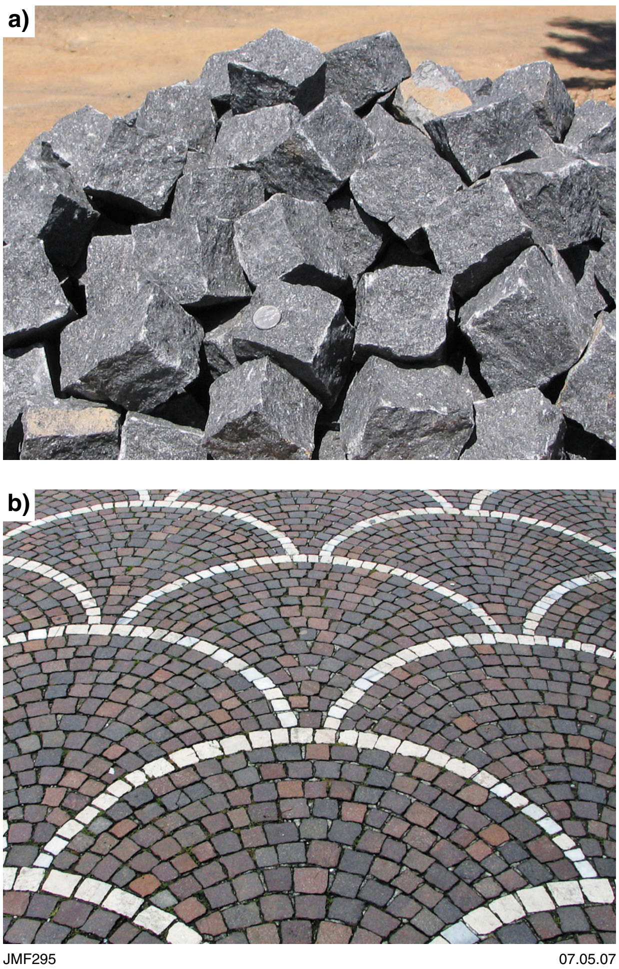

Figure 65. Setts and their application: a) a newly processed batch of black granite setts with 100 mm-square faces, produced on an hydraulic splitting machine; b) a complex pavement design using red-brown felsic volcanic rock setts framed with setts in white marble

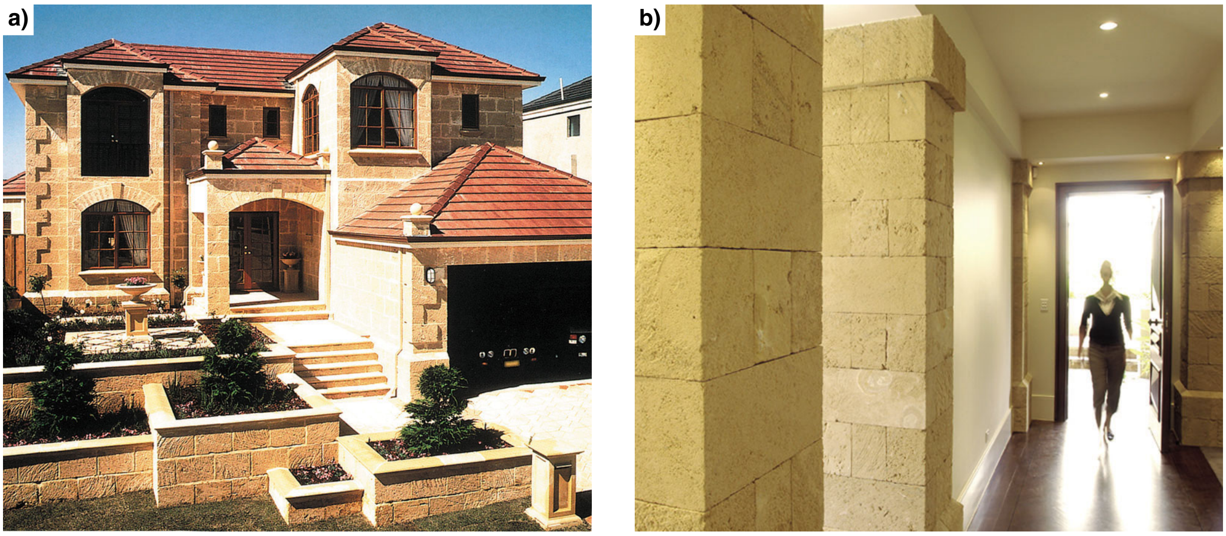

Figure 66. Applications of quarry-cut Tamala Limestone blocks: a) house and garden walls constructed from rough-textured, biscuit-coloured quarry blocks from Moore River; b) quarry-cut housing blocks from Moore River used as column cladding in a contemporary villa (photos (a)–(b) courtesy Limestone Resources Australia, photo (b) © Discovering Stone, 2006)

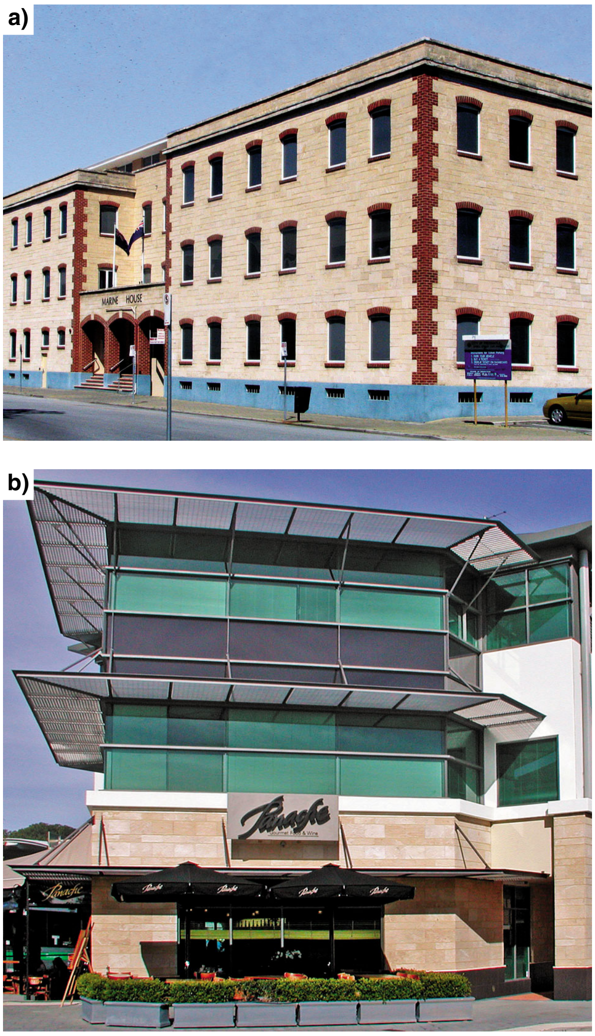

Figure 67. Diamond-cut limestone bricks, blocks and cladding used in building construction: a) Marine House, a contemporary office building in Fremantle, constructed of cream, diamond-cut bricks and blocks; b) diamond-cut, cream-coloured slabs from the Carabooda–Nowergup area used to clad a modern office building in Perth; (photo (b) courtesy Meteor Stone)

from the Carabooda–Nowergup area, some 35–40 km north of Perth, has a cream-coloured appearance.

Currently, quarry-cut blocks and bricks are in demand for the construction of homes, retaining walls and landscaping features by clients requiring a more natural-textured surface (Fig. 66). Quarry blocks are produced in two lengths of 500 and 1000 mm, and in a variety of heights and thicknesses ranging from 105 to 350 mm.

Diamond-cut products

Bricks

According to customer requirements, quarry-cut blocks delivered to the cutting plant are progressively reduced in size by cutting on diamond-tipped saws to produce more highly finished blocks and bricks with much smoother surfaces and increased dimensional accuracy. In the plant, quarry blocks are diamond sawn in the first instance to produce quarry-face housing bricks in which the visible face and perps (vertical ends) are left in their natural state. The bricks may then have their quarry-cut faces smooth sawn with perps remaining and, finally, may be diamond-cut on all surfaces.

All blocks and bricks produced with quarry-cut faces and/or perps are a standard 500 mm in length with heights

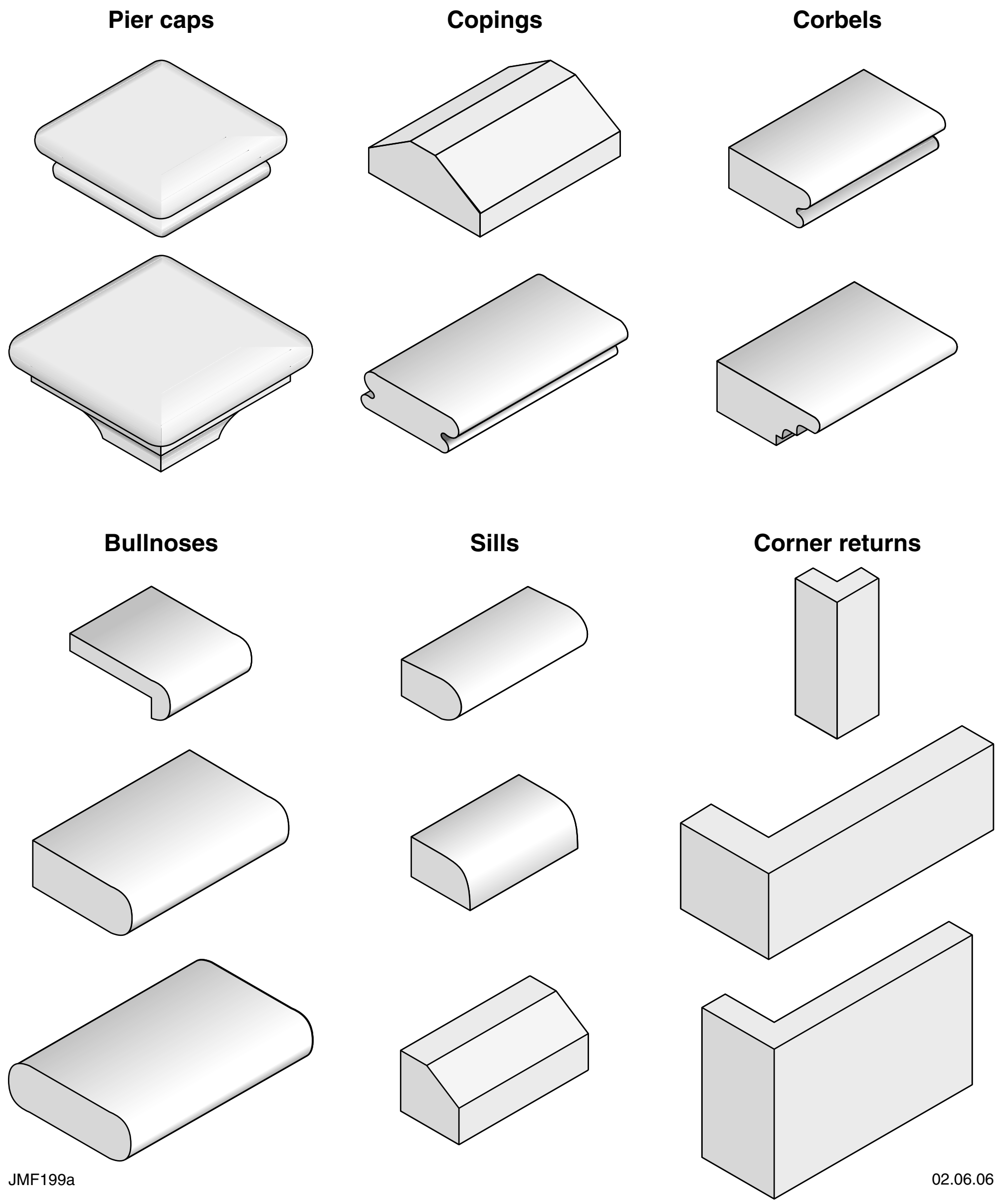

Figure 68. Examples of special-profile limestone blocks (data courtesy Meteor Stone, and Limestone Resources Australia)

varying from 76 to 332 mm, and thicknesses from 100 to 165 mm. Bricks diamond cut on all surfaces are smaller, being a standard 100 mm in thickness, 330–475 mm in length, and with variable heights between 117 and 332 mm. An example of a contemporary commercial building constructed from diamond-cut bricks is shown in Figure 67.

Cladding, pavers, and pier blocks

Other mass-produced limestone products only requiring diamond sawing include cladding, pavers, and pier blocks. Although most styles are diamond cut on all sides for improved visual appearance and dimensional accuracy, a few designs retain quarry-cut edges and perps. Cladding slabs are 30 to 35 mm in thickness and are produced mainly as rectangular panels with longest sides between 300 and 500 mm.

Paver blocks have a standard thickness of 60 mm and are square or rectangular in outline with longest sides between 300 and 500 mm. Pier blocks are cut as rectangular prisms in about six sizes to a maximum size with a face measuring 400 × 332 mm and a thickness of 195 mm.

Special profile products

A number of special profile products are produced for the building and landscaping industries. All these products require special diamond cutting and many require special curved profiles to be added to complete the design. Curved profiles are accomplished using a milling machine fitted with a variety of diamond-faced grinding or specially shaped profiling wheels designed to cut the required curvature in stone edges. Examples of these products are shown in Figure 68.

Special products include pier caps for fixing to the top of limestone piers, ornamental copings for fitting to the tops of walls, corbels for wall ornamentation, and bullnoses and sills for fitting around doors, windows, and other ornamental features. Many designs require a combination of diamond cuts and curved profiles to complete, whereas others only require additional cutting. Most products are produced in lengths or square sides ranging from 300 to 500 mm. Some sills have lengths up to 1000 mm.

Corner returns are right-angled blocks designed to wrap around wall ends for a more complete finish. These special blocks only require multiple diamond cuts to complete and range from 150 to 490 mm on the longest side.

A number of other limestone products also require added-value processing for completion including diamond sawing, profiling, and other processes. These include ornamental pedestals and plinths between 420 and 1030 mm in height, table legs, and garden edging, as well as ornate fireplace surrounds (mantelpieces and hearths).

Byproducts

In a number of Tamala Limestone block quarries, minor zones of weathering have developed in areas of groundwater movement where some or all of the calcium carbonate binder within the limestone has been dissolved and removed from the rock. This weathering process generally renders the limestone too soft for block cutting, resulting in its removal as waste material. Rather than dumping the limestone waste into landfill areas, it is retained and combined with other waste products such as large quantities of limestone grit generated during the cutting of quarry blocks, limestone offcuts from diamond sawing operations, and other reject material.

These waste materials form the basis of a byproduct industry known as reconstituted limestone, which is carried out as a secondary industry by many of the limestone block producers in the Carabooda–Nowergup area. Producers in this area estimate that about 40% of total limestone production goes into the manufacture of reconstituted limestone blocks. In areas where weathering is more extensive, this estimate may be higher, possibly reaching 60% in a few places.

In the reconstituted limestone process, waste limestone is first crushed to a coarse powder. It is then mixed with water and cement in a predetermined ratio. Coloured oxides for tinting may also be added. The mixture is added to a batching machine that applies considerable pressure to compress the material into block-sized moulds. The newly formed blocks, produced in various sizes and profiles, are deposited in batches as the machine progresses across a concrete pad on the quarry floor forming lines of finished product (Fig. 69). The reconstituted limestone industry is discussed further under **Substitutes** in Chapter 8.

Secondary processing industries

Secondary dimension stone processing industries include monumental masons who specialize in the construction of stone memorials, plaques and inscriptions, and artisans who use stone as a medium to create carved artworks in a vast assortment of shapes and styles.

Granite and marble are the preferred stones for monumental and artisanal works because of the stones' ability to take a high polish as well as their high resistance to weathering processes in most climates. This is illustrated by examples of granite obelisks carved in ancient Egypt about 3500 years ago. To this day, many of these monuments retain their smooth surfaces, and their carved hieroglyphs show little evidence of weathering. However, in very cold climates weathering of hard rocks such as granite may be accelerated by frost wedging, and in areas of significant atmospheric pollution, acid rain may have a detrimental effect on marbles and limestones.

Monumental masons

Monumental masons operate in every city and large town providing stone memorials especially for the mortuary industry, ranging from simple grave markers, to inscribed tombstones, vaults, and mausoleums. The industry also produces public monuments, notably war memorials, as well as stone lettering and inscriptions for placement on offices, public buildings and in landscaped areas.

Until comparatively recently, monumental masons began their stone processing operations with large stone blocks, usually of granite, marble or sandstone, obtained from their own quarry or purchased from an Australian or international supplier. These blocks were slabbed and polished by the masons to provide stock for their monumental works. Because of the current economic situation in the stone industry in Australia and other developed countries, an increasing number of monumental masons are no longer involved in this process and are purchasing stocks of pre-cut and polished slabs from both local and overseas producers.

Monumental masons still using the complete stone manufacturing method undertake many of the processes conducted by much larger dimension stone plants. These include the use of blocksaws to cut slabs from large primary blocks, slab polishing using single or multiple head polishers, and slab division using bridge saws for cutting component parts for monuments under construction. These processes are illustrated in Figure 70, and are more fully described earlier in this chapter under **Centralized processing**.

Once the polished stone component parts for the monument have been completed, it is the job of skilled engravers to cut lettering and designs into stone panels and headstones. Two methods of stone engraving are shown in Figure 71. The first of these methods is by the

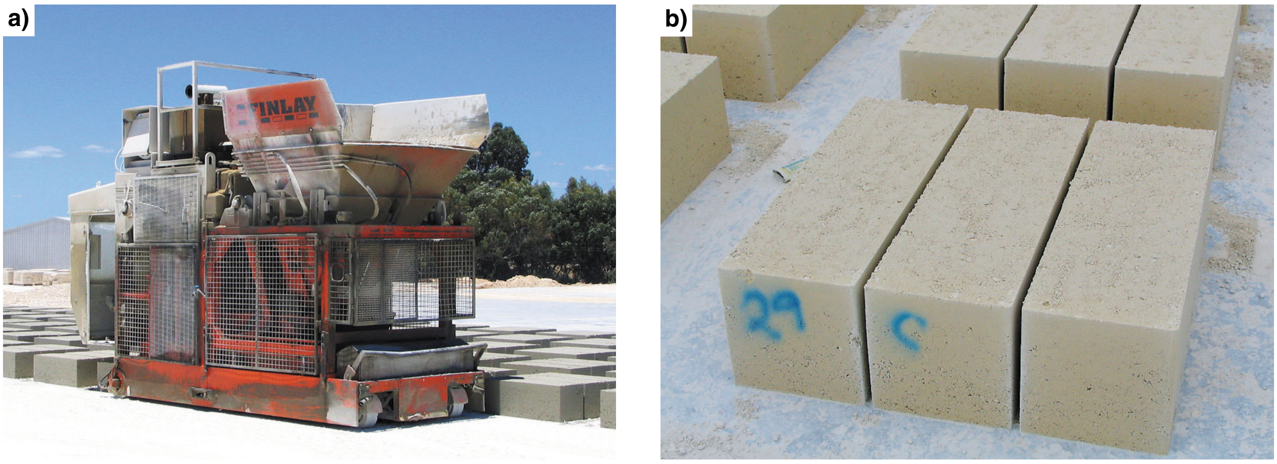

Figure 69. Batch making reconstituted limestone blocks: a) a mobile batching machine in operation; b) a newly formed set of reconstituted blocks, 1.0 m in length

Figure 70. Operations in a stonemason's yard: a) block of red granite sawn into thick slabs by a blocksaw; b) stonemason wielding a hand chisel to shape red granite blocks; c) granite slab after polishing by a single-head bridge polisher; d) bridge saw cutting component parts for a monument from a granite slab

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Figure 71. The stone engraving process: a) lettering template and floral design applied to a granite slab; b) engraver using a power chisel to cut stone lettering using an overlying template; c) operator using a pantograph machine to inscribe lettering onto a marble slab; d) detail of the engraving head cutting lettering into the marble surface

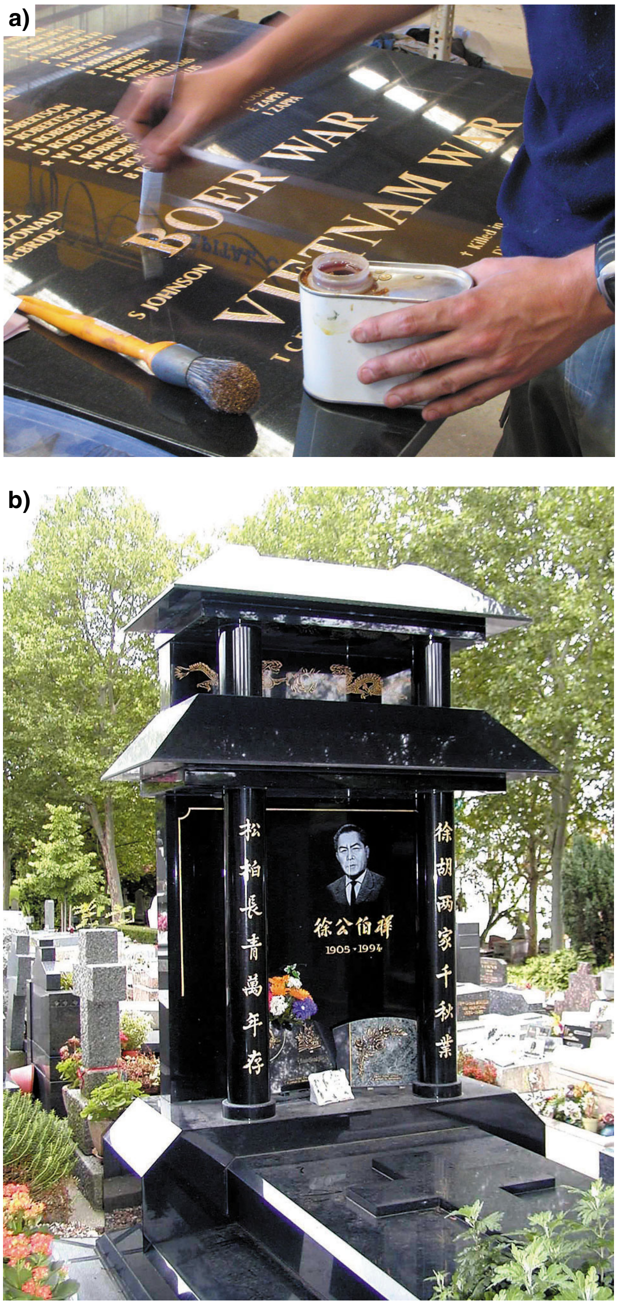

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Figure 72. Monument completion and display: a) gold leaf applied to the engraved lettering on a black granite slab is firmly attached with fixative; b) a funerary monument with ornate headstone in highly polished black stone engraved with gold characters

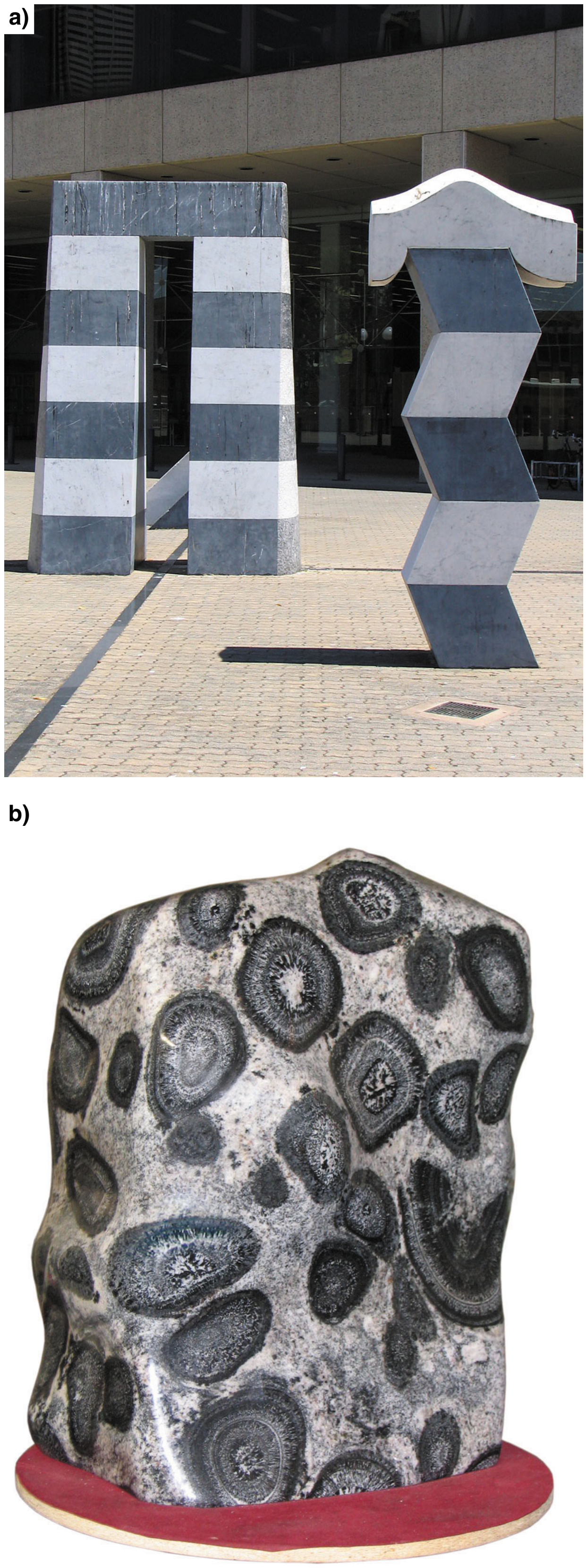

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Figure 73. Artworks in stone: a) contemporary artforms in black and white marble, Alexander Library, Perth; b) a beautifully shaped and polished ornamental block of Western Australian Boogardie orbicular granite carved by a Perth artisan

use of a power chisel, where the engraver uses a number of differently shaped chisel blades to cut lettering and designs in the stone by skillfully following a template that has been applied over the surface of the slab. The second method illustrated, is a machine working on the pantograph principle, where the operator follows a separate template and the machine cuts lettering in appropriate font styles and sizes into the surface of the stone.

Once this process is complete, it is necessary to highlight the inscribed lettering and designs using either coloured pigments or gold leaf. Over a long period it has been demonstrated that gold leaf does not tarnish or corrode and is particularly long lasting in most situations. In the application process, gold leaf is applied by pressing down over the lettering. The surplus gold leaf is then carefully brushed away leaving the gold adhering to the walls of engraved cuts. A fixative is applied, firmly attaching the gold leaf to the stone. After cleaning, the completed panel is ready for attachment to the monument (Fig. 72).

Artisanal applications

Carved stone artworks have been produced since the dawn of civilized society. Since the Neolithic period between 7000 and 4000 years ago, right up until the present day in some societies, many carved stone statues and other stone artworks appear to have been made for ritualistic or religious purposes.

Today in Western society, while some carved stone works of art are produced for religious purposes or to commemorate a person or historical event, many others are produced for their artistic appreciation alone. These are commonly erected in public places such as city and town squares, parks, universities, and art galleries. An increasing number are also created for display in private homes.

Contemporary stone artworks appear in an extraordinary range of styles and sizes from the very large to the very small. Bas-reliefs appearing as images or scenes carved into stone walls have also been popular. Examples of two different styles of contemporary stone artwork are shown in Figure 73. Other stone artworks, ranging from ancient to modern, appear in Figures 6, 8, and 14.

Chapter 8

Production, prices, market trends, and substitutes

World dimension stone production and prices

World production

In 2004, world production of dimension stone by 25 countries was estimated at 89.5 Mt by Internazionale Marmi e Macchine Carrara SpA (2005). In addition, another six producing countries with as yet unrecorded production for 2004 are estimated to have produced a total of about 2.5 Mt. This, added to the official figure of 89.5 Mt, provides a world production estimate for 31 countries of approximately 92 Mt for 2004.

China remains the world's largest dimension stone producer by a considerable margin. In 2004, China's production reached 20.6 Mt, followed by India, Italy, and Iran (11.2, 10.6, and 10.4 Mt respectively). Production figures for the ten countries producing over 2.0 Mtpa, which also include Turkey, Spain, Brazil, Portugal, Egypt and Greece, are given in Figure 74. Other large producers in 2004 with outputs between 0.5 and 2.0 Mtpa include USA (1.3 Mt), France (1.2 Mt), Saudi Arabia (1.2 Mt estimated), Mexico (1.1 Mt), Poland (1.1 Mt), Syria (0.8 Mt), Finland (0.6 Mt), and South Africa (0.5 Mt). Australia's stated production of 0.04 Mt is well below Australian national estimates for 2003–04 of approximately 0.41 Mt. These estimates are discussed below under **Australian dimension stone production**.

It is estimated that the world produces more than 5000 varieties and colours of dimension stone (Matthews, 2001). A list in excess of 2600 named varieties of dimension stone produced throughout the world is given by FindStone.com (2006). Although this list of named varieties is incomplete, it provides an insight into the size and diversity of output by some of the larger producing countries. The list includes granite, marble, limestone, travertine, sandstone, slate, and conglomerate as principal stone types. In this index, India is listed as producing 225 named varieties of granite followed by China and Brazil producing 98 and 84 granite varieties respectively. In the marble industry, Italy dominates with 308 named marble varieties followed by Greece (108), and Turkey (75). Italy also has the largest number of named limestones and travertines while Germany and India dominate with named varieties of sandstone, India with slate, and the USA with conglomerate.

Prices

Dimension stone prices quoted on world markets show substantial variation not only between stone types but also within the same stone due to differences in quarrying and processing costs in different countries, as well as quality variations of colour, texture and structure, and overall finish. Differences in these physical properties appear to play a significant role in the price and marketability of every variety of stone.

An internet search, together with data from Dolley (2004), produced numerous quotations for a wide variety of dimension stone in recent years. Prices for blocks and slabs on world markets are normally quoted in US dollars,

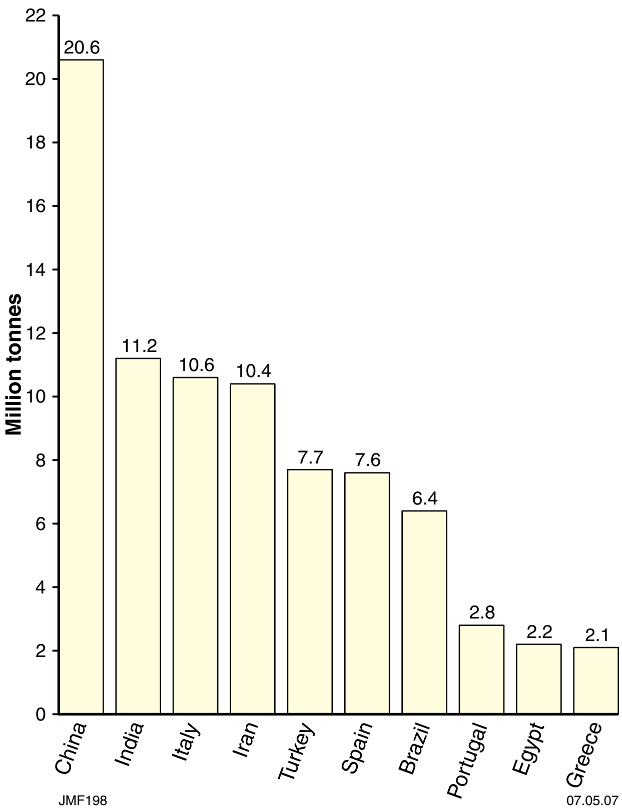

Figure 74. Ten top countries producing dimension stone in 2004 (modified after Internazionale Marmi e Macchine Carrara SpA, 2005)

Table 7. Examples of current averaged prices for dimension stone blocks and slabs on world markets

Stone	*Country*	*Average price (US$/tonne)*	*Average price (US$/m³)*
Granite	South Africa	(a)387	1 025
	Ukraine	(a)300	795
	USA (i)	(a)283	750
	USA (ii)	251	(b)665
	Brazil	(a)249	660
	India	(a)230	610
	Egypt	(a)164	435
Black granite	Zimbabwe	(a)430	1 140
	South Africa	(a)404	1 070
	Brazil	(a)302	800
	India	(a)292	775
Marble	Pakistan	(a)474	1 255
	Brazil	(a)340	900
	Italy	325	(b)861
	Egypt	183	(b)485
	USA	163	(b)432
	Turkey	152	(b)403
Limestone	USA	168	(b)370
	Turkey	132	(b)290
	Egypt	81	(b)178
Travertine	Turkey	122	(b)281
	Iran	51	(b)117
Sandstone	Australia	(a)295	650
	China	(a)211	465
	USA	118	(b)260

NOTES: (a) Mass equivalent of prices quoted in cubic metres
(b) Volumetric equivalent of prices quoted in tons/tonnes

SOURCES: Current prices quoted on the internet; Dolley (2004)

either as US$ per tonne or US$ per cubic metre. A survey of prices mainly from large-scale producers in 13 countries indicated an average world price for dimension stone of around US$244/t. Average prices per tonne for different types of stone varied from US$357 for black granite, to US$272 for marble, US$266 for granite, US$208 for sandstone, US$127 for limestone, and US$87 for travertine. Examples of averaged prices for different stones from a variety of countries are given in Table 7.

World market trends

Today, international applications for dimension stone are dominated by stone flooring products at 38%, followed by interior and exterior building cladding totalling 20%, and material supplied to the mortuary industry of 15% (Keating, 2005). It is expected that this trend should continue at least in the short term. A chart indicating the total spread of product applications is shown in Figure 75.

According to Buyers Guide (2005), the stone industry has expanded rapidly since the early 1990s with world production growing by 7.3% and trade increasing by 8.7% to 2005. Notwithstanding this substantial growth, average prices on main markets over this period were somewhat depressed. This was in part attributed to the ready availability of substitute materials such as ceramics and stoneware. However, future forecasts indicate a rapid growth in stone production and trade from 2006 until 2025, at which time gross world stone production should exceed 450 Mt*, and the total quantity of stone traded internationally should reach 60% compared with 54.3% in 2005. During this period an increasingly important role is predicted for countries such as China, India, Turkey and Brazil, whose production and distribution capacity is expected to increase substantially.

Other countries such as Spain, Portugal, Finland, and Taiwan are also predicted to expand production. At the same time it is expected that production from Italy, USA, Canada, and Japan may tend to slow down, while some traditionally important producers such as Belgium, Sweden, Germany, and the United Kingdom may continue to lose market share due to exhaustion of reserves and restrictions on development (Smith, 1999). Stone sales in the USA for 2004 were expected to remain flat in the near term for major project construction but with some growth predicted for new home construction, prestige home improvement, and home renovation industries Dolley (2004).

Australian dimension stone production

Estimation of annual dimension stone production in Australia is a complex issue. Firstly, published records of dimension stone production within a number of Australian state government departments may not be inclusive of all

* Gross production includes quarry offcuts and processing waste

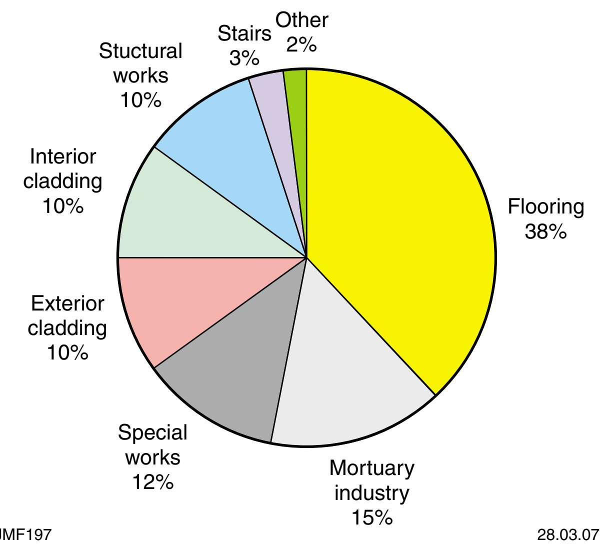

Figure 75. International applications for dimension stone (modified after Keating, 2005)

stone types. For example, in Western Australia, production from the cut limestone block industry is not recorded as dimension stone. Instead, it is included in figures for total limestone production. Secondly, in some states including Western Australia, dimension stone is classed as a basic raw material and as such falls outside the State Mining Act when quarried on freehold land. Freehold land quarrying is commonly controlled by local government authorities under extractive quarry licences (or equivalent). As such, production from these operations may not be recorded by government, and production data must be individually obtained from the operating companies.

This situation may tend to explain the low figure quoted for Australian dimension stone production by international sources such as Internazionale Marmi e Macchine Carrara SpA (2005), who estimated Australian production for 2004 at 40 000 t.

Accordingly, total production figures for dimension stone in Australia should be regarded as estimates. Production figures for 2003–04 were obtained from all Australian state and territory governments responsible for the mining industry and from as many dimension stone companies as possible. As a result, total production for 2003–04 is estimated at almost 408 000 t. This figure may tend to be somewhat conservative as there may be areas of stone production from freehold land outside Western Australia that have not been included in the figures. Australian production estimates for 2003–04 are given in Table 8.

Australian Bureau of Statistics figures reveal that over a three-year period Australian dimension stone exports experienced a 20% increase in monetary returns from A$12.21 million in 2001 to A$14.64 million in 2003. Over this period, there were increases in returns for limestone (53%), and granite (45%) while sandstone decreased by 26%, and marble declined slightly. Total returns for the three-year period was A$37.68 million. These trends are shown in Figure 76.

According to Keating (2005), Australia's main overseas markets in 2004 for quarry blocks, and cut stone blocks and slabs were as follows:

- *Limestone*: New Zealand (95%), and Fiji/French Polynesia (5%).
- *Granite*: Quarry blocks — Italy (71%), Taiwan (12%), Indonesia (6%), and New Zealand (3%); Cut blocks and slabs — New Zealand (41%), China (35%), Indonesia (9.8%), South Korea (5%), and Japan (4.8%).
- *Sandstone*: Quarry blocks — China (94%), Malaysia (3%), and South Korea (2%); Cut blocks and slabs — China (59%), Indonesia (15%), USA, (7.8%), Germany (7.4%), and Singapore (6.4%).
- *Marble*: Taiwan (43%), Switzerland (23%), Saudi Arabia (19%), and Italy (10%).

Market opportunities

In 2004, Austrade identified niche market opportunities for Australian dimension stone mainly in the Indo-pacific region (Keating, 2005). It appears that opportunities may exist in the rapidly growing economies of South Korea, Taiwan, Hong Kong, Macau and Thailand, usually at the high end of the construction industry for luxury buildings, apartments, holiday resorts, and entertainment complexes where the supply of high-quality stone blocks is paramount. In particular, Taiwan has been in need of high-quality pavers as well as blocks, and Thailand has a requirement for light brown and cream, high-quality marble and granite for use in the construction of tourist centres. Also, China has recently been reported to have been seeking supplies of Australian sandstone as well as light-coloured marbles, and brown and red granites.

Other potential niche markets exist in New Zealand where Australia may have a competitive advantage in their steadily growing building industry owing to our close proximity and hence lower transportation costs. Dubai, situated on the Persian Gulf in the Middle East is another possible market for high-quality stone. This country is currently experiencing a building boom with 80 hotels either under construction or in the planning phase in addition to the reported construction of the world's tallest building and largest shopping mall, as well as other city and marina projects. It is also possible that top-end niche markets may be developed in the USA with the opening

Table 8. Estimated dimension stone production in Australia 2003–04

	Limestone and dolomite	*Granite*	*Sandstone and quartzite*	*Marble*	*Basalt*	*Slate*	*Other*	*Total*
	(t)							
Western Australia	233 942	8 342	5 385	397	–	–	22	**248 088**
Queensland	–	192	34 603	13 722	–	20	–	**48 537**
South Australia	14 056	12 528	5 748	113	–	7 427	–	**39 872**
Victoria	–	1 600	150	–	30 000	548	–	**32 298**
New South Wales	–	1 445	27 606	–	–	–	–	**29 051**
Northern Territory	–	5 302	–	–	–	–	–	**5 302**
Tasmania	–	–	1 872	–	–	–	2 747	**4 619**
Total	**247 998**	**29 409**	**75 364**	**14 232**	**30 000**	**7 995**	**2 769**	**407 767**

SOURCES: Western Australian Department of Industry and Resources, mineral statistics 2003–04
Australian State and Territory Government Geological Surveys, mineral statistics 2003–04
Australian dimension stone producers, 2003–04 production

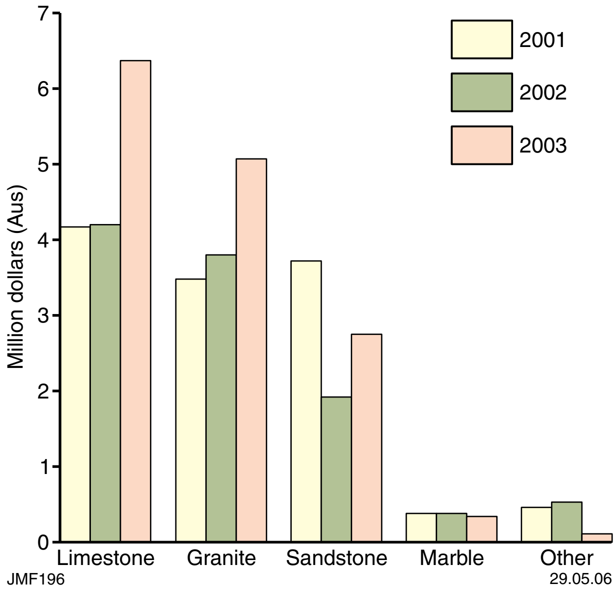

Figure 76. Australian dimension stone exports 2001–03 (source: Australian Bureau of Statistics)

of the free-trade agreement. Currently, Australian stone is not well known in the USA, and to succeed in their stone markets, Australian material must demonstrate a competitive advantage with distinctive colours, textures, and overall quality to compete with stone from countries such as Mexico.

Dimension stone production in Western Australia

An extensive search of Departmental statistical returns, together with discussions with producers of dimension stone from both mining leases and extractive quarries on freehold land, has revealed the degree to which annual production of cut stone blocks is understated in Western Australia. Estimates for 2003–04 given in Table 8 show that the State is the largest producer of cut limestone blocks in Australia at almost 234 000 t, valued at approximately A$4.57 million. Also, production figures for granite and sandstone (8342 and 5385 t respectively) have been substantially increased since, for the most part, they are obtained from extractive quarries for which official records are not usually maintained. These estimates show that for 2003–04, Western Australia was Australia's largest dimension stone producer at over 248 000 t valued at approximately A$7.81 million.

In line with increasing production trends in many overseas countries since the early part of the 21st century, Departmental figures indicate that Western Australia also experienced a substantial increase in both production and value of dimension stone averaging about 66% per annum over the three years between 2001–02 and 2004–05, albeit not in the same order of magnitude as the major international producers.

Currently, cut-stone production is centred on the limestone block production areas of the Swan Coastal Plain in the Carabooda–Nowergup, and Moore River areas to the north of Perth. Granites and granitic gneisses are quarried in the central and southern wheatbelt areas from Bruce Rock, Esperance, Jerramungup and Watheroo, and farther east at Fraser Range. Sandstones are sourced from Donnybrook near Bunbury in the southeast, Mount Jowlaenga near Derby in the west Kimberley region, and also from Karratha in the west Pilbara. Quartzite is quarried near Toodyay to the east of Perth, and marbles are sourced from Maroonah and Nanutarra in the Ashburton region of the central west. Minor production of jaspilite rock is recorded from the Ord Ranges east of Port Hedland in the Pilbara, and spongolite building blocks are quarried near Mount Barker in the south of the State. Locations of these quarries and other significant dimension stone deposits are shown in Figure 77, and a detailed summary of these sites and products is given in Fetherston (2004).

Substitutes

In today's competitive international markets for the building and paving industries, a number of materials have been developed as substitutes for dimension stone in certain applications. Dolley (2006) lists a number of these including brick, ceramic tile, concrete, glass, plastics, resin-agglomerated stone, aluminium, and steel. In Western Australia, the reconstituted limestone industry has developed not only as a by-product as discussed in Chapter 7, but also as a substitute product in direct competition with natural limestone blocks. Some of these materials are discussed below.

Reconstituted limestone

In a number of areas of the Swan Coastal Plain, especially around Yanchep, north of Perth, the Hope Valley – Postans area near Kwinana, the Narngulu area, southeast of Geraldton, and areas north of Bunbury at Myalup and Kooallup, the Tamala Limestone is quarried as a weathered, friable calcarenite. This material is crushed and processed for the manufacture of reconstituted limestone building blocks and pavers.

There are two methods employed in the manufacture of reconstituted limestone products. Firstly, blocks are manufactured in a variety of shapes and sizes by deploying a batching machine that presses out blocks onto a moulding pad already described in **Byproducts** in Chapter 7. In the second method, pavers are manufactured in rubber moulds by wet casting. In this process, a wet mixture of crushed limestone and cement is poured into rubber moulds. Other additives to the mixture may include aggregate for added strength, coloured oxides for standardized tinting, and a moisture dispersant to reduce the effects of efflorescence. The moulds are designed to produce pavers in various standard sizes and surface textures. On drying, the pavers are turned out of the moulds and stockpiled for curing. In a third stage, special orders may be hand finished with profiling treatments such as bullnosing. Some of these processes are illustrated in Figure 78.

Figure 77. Location of operating quarries and significant dimension stone deposits in Western Australia

In this industry, reconstituted limestone products are produced to simulate most blocks, pavers, and special application items such as pier caps, copings, and bullnoses produced by the natural limestone block industry. Reconstituted limestone products have several advantages over natural limestone. In the first instance they are inherently stronger owing to their vastly increased density (up to 60%) caused by a substantial reduction of pore space. Also, body strength is increased by the addition of aggregate to the mixture. This material may also be tinted by natural oxides to produce about 10 different standardized colours. It seems the main disadvantage of reconstituted limestone is that it is extremely difficult to reproduce the appearance and feel of surface textures present in natural limestone.

The estimated production figures for reconstituted limestone products in Western Australia for 2003–04 was in the order of 237 000 t valued at approximately A$3.08 million. This figure, when combined with the almost equivalent estimate for natural limestone block production of almost 234 000 t, yields a total production for the limestone building block industry in excess of 471 000 t with an estimated total value of production in the order of A$7.65 million for that year.

Ceramic and glass tiles

The use of wall and floor tiles is almost as old as that of dimension stone itself in the same application. The use of

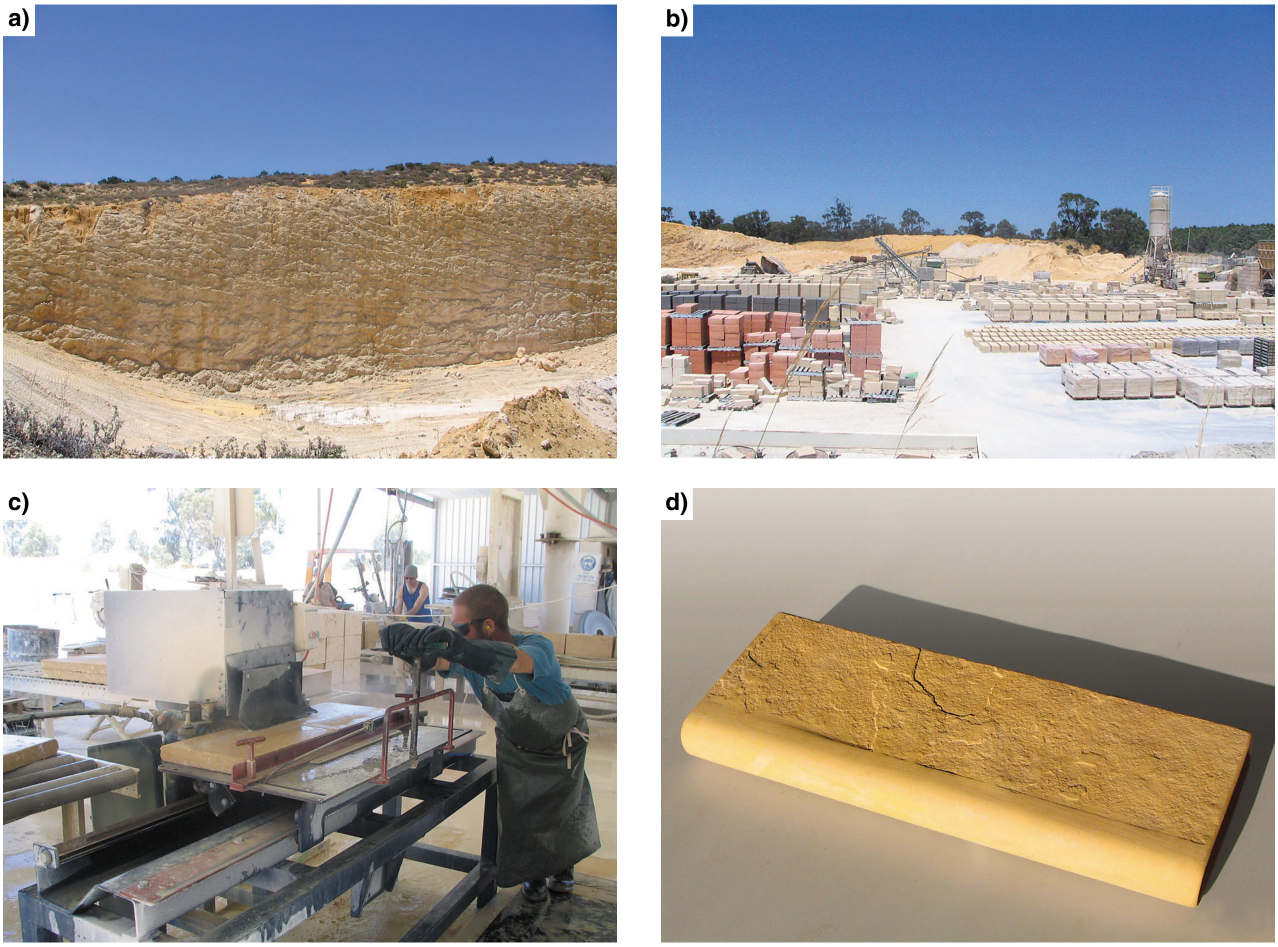

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Figure 78. Reconstituted limestone block and paver processing: a) Tamala Limestone quarry at Yanchep consisting of friable, weathered calcarenite; b) operations yard showing finished product stockpile (foreground), block moulding pad (centre), and crusher unit (background); operator controlling a profiling wheel cutting a bullnose edge; d) an example of finished product: a colour-tinted, bullnosed paver, 40 cm in length (courtesy Archistone)

tiles has been recorded in ancient Egypt around 6000 years ago, and it is known that by the 10th century AD their use was well established in Persia, Syria, and Turkey. By the end of the 12th century the manufacture and use of ceramic tiles, mainly for use in floors of churches and cathederals, had spread across Europe from Italy and Spain (Johnson Tiles, 2006).

Ceramic tiles are mainly high-grade clays (kaolin and ball clay), quartz, and feldspar with incidental additives such as talc, calcium carbonate, and wollastonite that have been fired to a vitrified state between 800 and 1100°C. Many varieties of tiles are glazed in a second firing to acquire a sealed gloss, semi-gloss, or matte finish.

Glass tiles, a much later invention based on silicate ceramics, are manufactured mainly from microfined minerals comprising mainly quartz with which clay, feldspar and other additives as described above are mixed prior to firing. The glazing process ultimately yields a product with a smooth and attractive surface similar to that of ceramic tiles.

Today, interior wall and floor tiles, as well as exterior paving tiles in certain applications, are used extensively throughout the world in direct competition with dimension stone interior wall cladding and floor tiles, and with some types of exterior stone pavers.

Resin-agglomerated stone

Currently, there are a number of types of artificial stone panels and slabs on the market designed for use in a variety of interior and exterior applications and, as such, are in direct competition with natural dimension stone panels and slabs used in the same situation.

Resin-agglomerated slabs

Today, there are a number brands of resin-agglomerated slabs available for use in the building industry. These artificial stone products are made from aggregated quartz particles that are thoroughly mixed with pigments and new-age polyester resins to ensure an even distribution of all particles. A high-tech vacuum and vibration process is then employed to mould and compact the mixture at a pressure of about 15.5 t/cm^2. The pre-formed slabs are then heated at 88ºC in a curing kiln for 30 minutes. Hardened slabs are then placed on a calibration and polishing line where they are machined to correct thickness and highly polished prior to stockpiling for sale (CaesarStone, 2005).

Slabs are generally manufactured with an average area of 3.04×1.4 m^2 and thicknesses of 12, 20 and 30 mm. The finished product is very hard and stain resistant, and finds application in interior situations such as kitchens and bathrooms, where it is machined to form benchtops, fireplace surrounds, floor tiles, and wall cladding.

Reconstituted stone wall cladding

Exterior, ventilated wall panels are currently manufactured from granulated, natural marble and granite thoroughly mixed with a specially formulated thermosetting resin. This material is pressed, sintered and resin-aggregated at a temperature of over 200ºC. The panels are then given surface treatments ranging from light to medium sandblasted textures through to highly polished finishes. Completed lightweight panels, typically 650 mm square, may then be attached to slabs of insulating material cladded to the exterior façade of buildings, leaving a ventilated air cushion of 30–100 mm between the reconstituted stone panel and the insulating material (Methodo, 2006).

Ventilated façade technology has been adopted extensively in Europe and more recently in Australia and is used with both natural stone panels and reconstituted wall cladding. Ventilated stone façades have the advantage of being able to use the internal aircushion to greatly reduce building heat absorption in the warmer months of the year and, in cooler climates, warranting the fitting of internal insulating slabs as described above to efficiently prevent up to 50% loss of building heat through external walls.

Chapter 9

Stone weathering and decay processes, and maintenance and restoration techniques

Weathering and decay processes

In relation to these processes, it is important to note that once any stone has been removed from its rock mass in a quarry, it is in a state of disequilibrium as part of a stone structure in a new environment (Smith, 1999). As the stone re-attempts to reach a state of equilibrium it may be subject to a wide range of weathering processes including natural processes present in the new environment as well as biological attack and man-made environmental hazards, both of which may tend to accelerate weathering rates. These processes may affect the durability of a stone, resulting in reduced strength, cohesion, and bulk density as well as increased volume, surface area and permeability, and may form new minerals and solutions (Dragovich, 2000). The effects of this weathering may cause micro-pitting or surface roughening, scaling or flaking, honeycombing, blistering, case-hardening, staining, spalling, cracking and splitting prior to complete physical breakdown or dissolution of the rock.

Physical and chemical processes

There are many physical and chemical processes that are often interrelated and commonly dependent on the effects of weather. Chief among these are thermal cycling, freeze–thaw process, rain and water weathering, salt crystallization and, to a lesser extent, the effects of wind damage. The effects of environmental pollution such as atmospheric pollutants and acid rain may also play significant roles.

Thermal cycling

Dimension stones subject to the greatest variation in temperature extremes have been demonstrated to undergo more deterioration than stones in environments with comparatively small ranges of temperature. An example of an extreme range of temperatures is Minneapolis in Minnesota, USA, where the extreme annual average maximum temperature is 36.1°C, and the extreme annual average minimum is -30°C, representing an annual average temperature range of about 66°C (Scheffler and Normandin, 2004). By comparison, in southern Australia extreme temperature ranges are usually much smaller, often at around half this figure.

In moist climates it appears that some types of marble are most susceptible to thermal cycling, where differences in expansion between inner and outer surfaces may cause bowing or dishing of the panels. This is attributed to the anisotropic expansion and contraction of calcite crystals within the marble matrix. This deformation process is known as marble hysteresis where panels, once deformed, do not normally return to their original shape. In addition, thin stone panels are much more at risk of deformation owing to their large surface to volume ratio that tends to respond more quickly to changes in temperature. If left in situ, the effects of repeated thermal cycling will ultimately cause susceptible marble panels to disintegrate.

It is also possible for thermal cycling to occur on a daily basis in warm to hot climates where dark-coloured stones used as cladding on the north face of a building are exposed to the direct rays of the summer sun. In this situation, it is estimated that these stones could attain maximum surface temperatures up to 77ºC. At night, these stones could cool to below 20ºC representing a substantial diurnal range of thermal cycling. However, it has been demonstrated that hard rocks with relatively more even expansion properties, such as granites, are not normally affected by thermal cycling (Smith, 1999; Scheffler and Normandin, 2004)

Freeze–thaw process

This process is most evident where stones having considerable porosity, especially some types of sandstone and limestone, become fully or partially saturated with water and are then subjected to freezing conditions such as those induced by heavy frost. As the pore water freezes, it expands its volume by about 9% (Smith, 1999). Accordingly, the hydraulic pressure exerted by the growth of trapped ice and unfrozen water is considerable, causing progressive microfracturing or loss of cohesion along grain boundaries, resulting in progressive loss of strength in the rock. Other factors related to this process are relative humidity and the possible presence of salts (Ondrasina et al., 2002).

Freeze–thaw damage may include deep cracking, surface scaling and exfoliation, and may even cause large pieces of stone to break away from the structure. In buildings, the main areas of damage caused by this process, are exposed areas where water collects such as copings, cornices, and window surrounds or around blocked gutters and rainwater pipes.

Rocks with low porosity, such as granite, schist and gneiss, are typically unaffected by this process. Likewise, it should be noted that some highly porous and permeable rocks with rapid drainage properties, or containing sufficient pore space to accommodate the expansion of ice crystals, may be resistant to damage caused by the freeze–thaw process. In general, areas having the highest number of freeze–thaw periods have the highest incidence of stone damage caused by this process.

Rain and water weathering

This process is most effective in areas of high rainfall and humidity where it is known that these factors increase the rate of deterioration of many types of stone compared with much slower weathering rates for the same stone in drier climates. The related process of wet and dry cycling of stone is also known to contribute to stone weathering (Scheffler and Normandin, 2004).

One of the most common effects of rain and water weathering is the dissolution of calcium carbonate present in limestone and marble and other calcareous rocks such as calcarenite, dolomite, and travertine. In this process, repeated water incursions both over the surface and along previously formed grooves and channelways cause the dissolution and recession of the stone, ultimately creating a ragged, karstified surface (Fig. 79a).

Sandstones may be radically affected by water incursion into their pore spaces. This often results in the hydration and oxidation of contained iron-rich minerals including hematite. This process may cause these minerals to expand, inducing sufficient internal stresses that may lead to ultimate disintegration of the rock. Also, the release of iron may cause the deposition of a ferric oxide coating over quartz grains as well as forming red and yellow staining on outer surfaces of the stone.

Also present in some sandstones are absorbent clays such as mixed-layer, and smectite clays. Upon wetting, clay lattices contained in these minerals expand by the adsorption of water molecules. This action induces pressures that may weaken the bond between the clay matrix and quartz grains causing dislodgement of material from the surface of the stone. At the same time, there may be chemical and physical disruption inside the clay matrices as they expand and contract on wetting and drying of the stone (Dragovich, 2000).

Weathering effects associated with the wetting and drying of sandstones include scaling that results from clay-sized particles blocking the surface pores of smooth-cut sandstone. This results in a reduction of surface permeability causing water to be trapped just below the surface of the stone. This forms a zone of weakness that may be subject to eventual detachment from the rock body. At the same time, a case-hardened layer rich in iron oxides may form on the surface of the stone (Fig. 79b).

Honeycomb weathering in sandstone commonly occurs at many sites over the surface of the stone, usually trending along bedding planes or other structural lineaments (Fig. 79c). This process is normally initiated by the breaching of the outer, case-hardened layer. The honeycomb pits become progressively deeper and extend laterally until they coalesce. Eventually, the entire case-hardened area and pit boundaries weather away to the depth of the pits (Fig. 80a).

One of the most common forms of weathering in sandstones is micro-pitting or surface roughening. This is a form of surface disintegration where quartz grains, protruding above the surface of the stone binding matrix, become dislodged along with matrix material forming a roughened, micro-pitted surface (Fig. 80b). This tends to be a self-perpetuating form of weathering where the loosened surface material is regularly removed by rainwater or wind (Dragovich, 2000).

Salt weathering

Salt weathering, considered to be one of the most damaging weathering processes in stone, is present throughout the world from the most inhospitable deserts to Antarctica. It is a complex and much-researched topic with many commentaries focusing on unique case studies that may not be applicable at other sites. The two major difficulties encountered in salt weathering research are the multiple variables involved, together with physico-chemical reactions vital to this process, that take place in thin films only nanometres thick within porous solids (Doehne, 2002). Doehne (2002) also provides a detailed listing of variables in the form of substrate, solution, salt type, and environmental properties with interactions governed by thermodynamic and kinetic factors to produce a range of salt behaviours.

Although not all salt incursions result in actual stone deterioration, major salt damage in many instances includes scaling, deep cracking and spalling, uniform expansion, micro-cracking, granular disintegration, and delamination. The process commences when salt-laden solutions are absorbed into stone cavities — mainly pores, joints, and fissures. Once the stone begins to dry out and the contained water evaporates, salt is deposited within these cavities. Initially, evidence of salt may be indicated by a salty growth (known as efflorescence) on outer surfaces of the stone. Although the appearance of efflorescence may be unsightly, often in the form of white, fluffy masses, it is usually not damaging to the rock fabric.

Repeated wetting cycles within the stone cause hydration reactions in which anhydrous salts are converted into their hydrated phase. This phase change involves an increase in salt crystal volume resulting in a buildup of pressure within pores and fissures. Apart from crystallization pressure, other salt weathering mechanisms that may also operate are hydration pressure and thermal expansion. Once the combined strength of these applied forces exceeds the tensile strength of the stone, failure occurs and the decay process commences. If left unchecked, the process usually continues to the ultimate disintegration of the stone (Smith, 1999; Dragovich, 2000).

A number of salts are known to damage various types of dimension stone. In Australia, the most common salt incursions into stone are from sodium chloride (halite) and calcium sulfate (gypsum). Sodium chloride is mostly sourced in coastal areas from seawater that is transported

Figure 79. Rain and water weathering effects in limestone and sandstone: a) karstified surface of Tamala Limestone blocks, (Fremantle, c. 1851); b) case-hardened headstone breached by water weathering allowing softer, sandstone matrix to partially collapse; c) honeycomb weathering in sandstone headstone (images (b) and (c) Pioneers Cemetery, East Perth)

and deposited as fine droplets in windblown aerosols or rain. It has been estimated that the amount of marine salt deposited annually in the Sydney region ranges from 70 t/km^2 along the coast to 20 t/km^2 about 30 km inland (Heiman and Riley, 2000).

Saline groundwater is also a source of salt pollution whereby both halite and gypsum may enter buildings as rising damp. Gypsum salt may also be derived from clay bricks, mortar, and wall plaster used in the same structure as the affected stone. Other salts known to cause damage include sodium and potassium sulfates, carbonates, and nitrates as well as magnesium sulfate and potassium chloride.

Salt weathering is probably the greatest cause of damage to dimension stone blocks in Australia. In particular, some types of porous sandstone are very susceptible to salt damage linked to their water absorption capacity that controls the amount of salt entering the stone

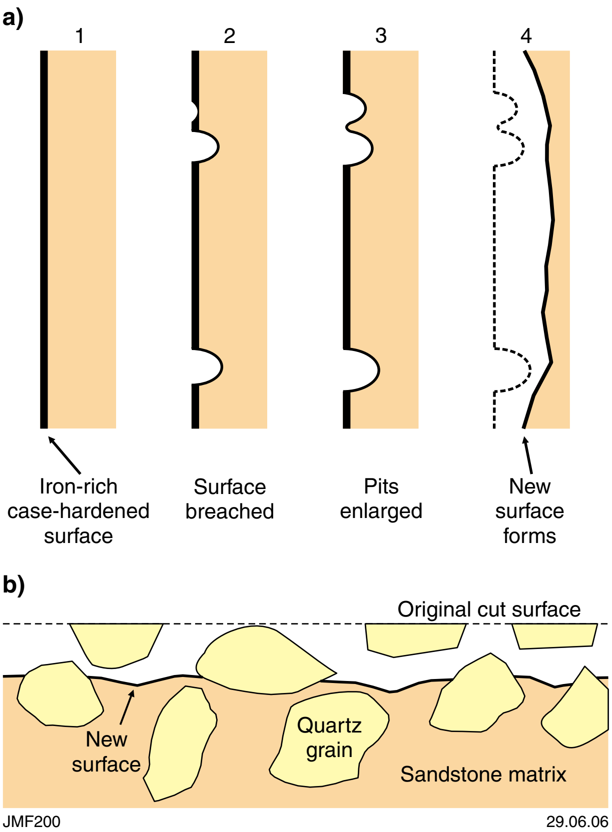

Figure 80. Two weathering processes in sandstone: a) stages of development of honeycomb weathering; b) development of micro-pitting in sandstone surface (modified after Dragovich, 2000)

(Dragovich, 2000). Other susceptible rocks include porous limestones, and given sufficient time even hard rocks such as some types of granite may be affected if situated in an environment prone to salt water incursion (Fig. 81).

Wind damage

In the past it was thought that strong winds were responsible for the erosion of softer building stones such as sandstones and limestones. Today, it is generally accepted that wind erosion itself is not responsible for the external weathering of blocks (except for minor surface abrasions) over an historic timescale.

The main damage from wind is in the form of frequent, hard, wind-driven rain showers on stone buildings and other structures causing thorough stone wetting. During this process, wind-borne salts may be transferred to the stone and, on cessation of the rain, persistent wind may rapidly dry out blocks creating ideal conditions for salt crystallization damage (Smith, 1999).

Dry deposition by atmospheric pollutants

The dry deposition process is important as a source of building stone weathering in polluted industrial areas. The key to its effectiveness lies in short-range transportation of pollutant gases and particulate matter, including aerosols, directly to the stone surface in the absence of rainwater.

Gases tend to be the principal dry deposition pollutants with sulfur dioxide, derived mainly from the burning of fossil fuels and to a lesser extent from ore smelting and natural sources, by far the greatest pollutant. Other pollutant gases include oxides of nitrogen (NO and N_2O) and ozone, which react under the right conditions to form corrosive nitric acid vapour. Pollutant sulfate and nitrate aerosols may also be present in this environment. Dry deposition of gases and particulate matter is largely controlled by concentration of pollutants as well as the type of stone, its surface texture, porosity, chemical affinity to various pollutants, and surface moisture content, all of which determine the stone's reactivity to attack (Charola and Ware, 2002).

Sulfur dioxide is the main contributor to stone deterioration, resulting in the formation of calcium sulfate (gypsum) as black, surficial crusts particularly on

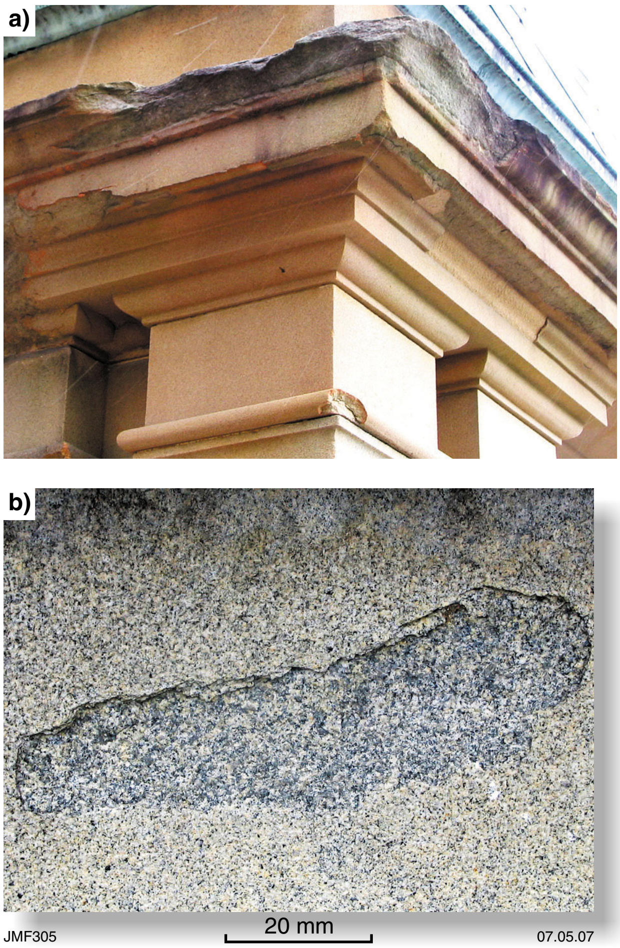

Figure 81. Stone damage caused by salt weathering: a) spalling of *Pyrmont Yellow* sandstone, Sydney Hospital stone restoration project; b) exfoliation and partial staining of Mundaring granite basal plinth of a 100 year old building in Fremantle

calcareous rocks such as limestone and marble. Crusts may also form on other stones such as calcareous sandstones, and even on granites and other igneous rocks. Key factors relating to deterioration appear to be surface texture and porosity of the stone, where subsequent dissolution of the gypsum crust and penetration into subsurface pore spaces are critical. This process may result in the buildup of platy gypsum crystals within void spaces of susceptible stones leading to pressure buildup and subsequent disaggregation of the surrounding stone as already described under **Salt weathering**.

Wet deposition by acid rain

Contrary to common belief, wet deposition caused by acid rain plays a lesser role than dry deposition and occurs mainly in rural areas with low pollution and high rainfall. In these areas, acid rain is formed by cloud droplets incorporating pollutants, particularly sulfur dioxide, often carried long distances from their source in urban and industrial centres. Minor sulfur pollutants are also derived from seawater sulfate.

Acid rain deterioration is difficult to evaluate. Damage is determined by stone type and the presence of moisture. It is recognized that calcareous building stones, such as limestone, dolomite, and marble, are more susceptible to damage from acidified rainwater than are siliceous stones. Stone damage includes loss of mass, changes in porosity, and discolouration of outer surfaces (Charola and Ware, 2002; Smith, 1999).

Biochemical weathering

Biochemical weathering of stone is caused by a wide variety of organisms, mainly botanical and bacteriological agents, and to a lesser extent by insects and birds. Such weathering has been demonstrated to cause damage to many rock types from some forms of limestone to more resistant stones such as slate and granite.

Botanical agents such as lichens (symbiotic colonies of algae and fungi), ferns, and some higher plants are capable of invading stone surfaces with hyphae or roots, which cause physical damage and introduce organic acids and chelating agents that form organic complexes capable of dissolving otherwise insoluble minerals such as feldspar, mica, and quartz. In addition, it has been demonstrated that cyanobacteria also play a role in stone surface weathering. These processes may lead to stone disaggregation whereby gaseous and particulate air pollutants, especially sulfur dioxide, may penetrate the stone leading to the crystallization of gypsum and other salts, causing further stone damage as already discussed (Schiavon, 2002).

It has also been demonstrated that bacteria are capable of converting pyrite and other iron-rich sulfide minerals into ferric ions and sulfuric acid in pyritic slates. The worst weathering occurs in situations where calcium carbonate is available in the form of calcite, causing a reaction with the sulfuric acid and forming gypsum. This ultimately results in spalling, flaking and delamination of the stone (Smith, 1999).

Maintenance, conservation, and replacement of weathered and decaying stone

Stone maintenance, conservation and replacement techniques are the subject of a vast amount of literature and continuing research. Accordingly, a detailed description of this topic is beyond the scope of this publication and a summary is provided here. Detailed accounts of the subject are given by Smith (1999) and Winkler (1994). Maintenance guidelines are provided in Melocco Stone (2003b).

For a variety of reasons, even with the most modern techniques, it is virtually impossible to completely restore partially weathered or decaying stone. Accordingly, stone restoration is the process of treating stone so it appears similar to stone in its original state while preserving its aesthetic qualities and enhancing its future integrity. With today's modern stone buildings as well as those older stone structures in good repair, it makes economic sense to embark on a program of simple maintenance and periodic cleaning rather than allowing stone to deteriorate to the point where major restoration becomes necessary to preserve the structure (Wenger, 2003).

Stone maintenance

In modern cities and urban areas where varying degrees of atmospheric pollution are present, it has become necessary to develop a regular cleaning program for stone buildings and monuments not only for aesthetic reasons but also to prolong the life of the structure's stonework. Layers of dirt that have accumulated on stone tend to extend over the surface as a persistent layer of more or less equal thickness (Monserrat and Baltuille Martin, 2003). These layers may be divided into three categories:

- *Smoke and dust*: particles of ash, solids, and oils.
- *Crusts*: and remnants of previous surface treatments.
- *Spots*: areas of efflorescence, colour loss, and stains resulting from metal corrosion, sprays and paints, and biological stains from plants, lichen, and microfauna.

General cleaning methods

There are many techniques available for the cleaning of stone using a variety of chemicals. However, in the past these have often been applied without first testing the material to be cleaned to detect any reaction between the cleaning chemical and the stone itself. As a result, there have been many cases of excessive use of corrosive chemicals causing accelerated scaling and discoloration in the stone surface. In particular, calcareous rocks such as limestone and marble are badly affected by the misuse of acid-based cleaners.

Before any cleaning commences, the stone should be tested for its current state of weathering (i.e. its current state of durability) and the presence of salt contamination within the stone matrix. If the state of weathering is advanced or salt contamination is present then other methods of restoration or conservation may have to be applied.

Water washing

This technique is the normal recommended method for stone cleaning on a regular maintenance program. In this process, warm water with a mild detergent is used to remove accumulated dust and dirt from the stone. This method has been found to be particularly effective with heavily polluted sandstone and limestone surfaces, including the preservation of outer, case-hardened layers of the stone (Wenger, 2004). The use of hot water may be useful in the removal of gypsum deposits, grease, and paint.

Other forms of water washing include pulse washing, and pressure washing. Pulse washing is an electronically controlled application in which atomized sprays of water are sprayed onto the stonework through fine nozzles. This is an effective method where water application times can be controlled in accordance with the amount of scrubbing required, and water wastage is also minimized. Pressure washing with medium to high-pressure jets is used for a quick and relatively cost-effective result and may be useful for the removal of stubborn areas of dirt. However, the abrasive nature of the water jets preclude its use on sandstone and limestone as this may result in limestone dissolution in areas of soft water, damage to pore structures, and erosion of finely crafted features (Winkler, 1994).

Steam cleaning

This is an effective method of low-pressure application of steam jets against polluted masonry, particularly limestone, and on carved features. It is particularly useful for the removal of soot and bonded carbon as well as deposits of grease, tar, wax, and gum.

Abrasive cleaning

Abrasive cleaning includes hand cleaning methods of dry brushing using metal brushes, sandpaper, pumice stone, or carborundum blocks, and also hand-held electric tools fitted with rotating abrasive discs.

More commonly, abrasive cleaning involves the use of compressed air abrasives applied either wet or dry through nozzles, usually at low to moderate pressures to minimize damage to the stone. Abrasive particles include steel shot, glass beads, blasting grit, non-siliceous grits (copper and iron slag, carborundum, and aluminium oxide powders), olivine, dolomite, and crushed egg or nut shells (Smith, 1999). The use of quartz sand as an abrasive has largely fallen into disuse due to health issues involving silicosis.

Dry abrasive cleaning techniques are very effective at removing thick, resistant incrustations, black crusts, and thin surface crusts on stone, and also can overcome problems of stone saturation caused by inappropriate wet cleaning methods. This technique requires skilled operators trained to minimize stone damage during the application of the abrasives, particularly in the preservation of smooth surfaces to prevent trapping of pollutants such as soot and dust (Winkler, 1994; Monserrat and Baltuille Martin, 2003).

Chemical cleaning

Stone chemical cleaners fall into three categories: acidic, alkaline, and organic. It is important that this technique is carried out by skilled operators to produce excellent results. The use of inappropriate chemicals may produce substandard results, cause more staining, or even cause disastrous results through the use of acids on limestone, marble, and calcareous or iron-rich sandstones. The use of hydrofluoric acid to clean silicate rocks is extremely hazardous and must be carried out only by specially trained operators.

Acidic cleaners range from the extremely harsh hydrofluoric acid, to phosphoric, hydrochloric, sulfuric, and acetic acids, and ammonium bifluoride. Hydrofluoric acid is used to clean quartz sandstones and is often mixed with phosphoric acid to prevent iron staining. Ammonium bifluoride may be used as a substitute for hydrofluoric acid as it is less dangerous and less corrosive on quartz and other minerals (Smith, 1999). Hydrochloric acid is used for removing excess cement, limewash, and paint as well as for cleaning granite floors and sandstone pavers.

Alkaline cleaners include sodium, potassium, and ammonium hydroxides, as well as sodium carbonate and bicarbonate. Once again, care must be exercised when using alkaline chemicals. Sodium and ammonium hydroxides are most commonly used to remove surface stains, but care must be taken to prevent mobilization of iron and silica that may form rusty blotches or grey coatings. Limestones should only be cleaned with sodium hydroxide as a last resort when other methods have proved unsuccessful. Ammonium hydroxide has proved to be useful as a degreasing agent and for dissolving gypsum incrustations on calcareous stones (Winkler, 1994; Smith, 1999).

Organic cleaners are solvents, including aromatic and chlorinated hydrocarbons, that may be used for the removal of oil, grease, and bituminous materials. In certain circumstances their use may be restricted because of flammability and toxicity issues (Winkler,1994).

Laser cleaning

This technique is the most recent stone cleaning tool. It is still under development but shows a great deal of promise for the industry. The laser used in this process is an Nd: YAG (neodymium-doped yttrium aluminium garnet) type that emits short duration light pulses of 20 microseconds designed to minimize photomechanical and heat damage to the stone.

Tests have shown that laser cleaning is very accurate, being capable of removing thin layers a few microns thick for each laser pulse. It has been demonstrated to be excellent at pulverizing black crusts, and can successfully treat very weak, highly weathered stone surfaces. Also, it is capable of cleaning surfaces previously treated with chemicals such as fluosilicates and for which no other subsequent cleaning treatment is available (Pini et al., 2003).

Stain removal

Stains are a common problem in various dimension stones in different environments, especially in home and office situations. Consequently, a specialized area of stone maintenance has developed to manage stain removal. Key factors relating to a stone's resistance to staining are its water absorption capacity (porosity and permeability) and chemical composition. Accordingly, stones with low porosity such as granite, quartzite, and slate are much more resistant to staining than porous limestones and sandstones. Also, stones containing acid sensitive minerals, particularly limestone, calcitic marble, and calcareous sandstones, are subject to acid attack and etching from acidic and other domestic chemicals and foodstuffs that often result in moderate to severe staining (Mann, 2006).

Stain removal is the process of reversing the absorption of stain-producing agents from the pores of a stone. The principal stain-removing technique is known as 'poulticing'. Poultices are made from absorbent materials such as clays (kaolin, attapulgite, bentonite (fuller's earth), and sepiolite), diatomaceous earth, talc, chalk, and methyl cellulose. In general, poultices made from clay or diatomaceous earth are the most effective.

In forming the poultice, the selected absorbent material is wetted and mixed into a stiff paste. This may be incorporated in wetted binding agents such as paper towels, cotton balls, or gauze pads. The mixture is applied over the stain, covered with plastic and taped down to keep it moist. The poultice is left between 24 and 48 hours to dry out slowly, in which time the stain should be drawn from the stone and incorporated in the absorbent agent within the poultice. Once dry, the poultice is carefully removed. If stain removal is incomplete it may require poultice re-applications (up to five times for difficult stains).

Because many stains are deeply embedded in the stone, it may require the addition of various chemical solutions to the poultice to assist with the stain withdrawal. In this process, both the poultice absorbent agent and the chemical are first drawn into the stone and the chemical reacts with the stain and subsequently is re-absorbed into the poultice's absorbent agent prior to withdrawal from the stone (Melocco Stone, 2003b).

Most stains can be classified into five groups. These are shown below together with examples of common sources of staining:

- *Oil-based stains*: oil, grease, wax, tar, bitumen, and oily food.
- *Organic stains*: coffee, tea, wine, fruit, vegetables, tobacco, cosmetics.
- *Metallic stains*: iron (rust), copper, bronze.
- *Biological stains*: algae, mildew, timber, bird fouling.
- *Chemical and pigment stains*: domestic chemicals and cleaning agents, ink, paint.

Stain removal techniques are detailed in Melocco Stone (2003b) together with an extensive list of chemicals commonly used in the process.

Stone conservation

That excess water in the pores of building stones will ultimately cause damage is a well-known problem, particularly in humid climates where air containing excess moisture may enter various types of stone via pore structures. Ideally, conservation strategies should be enforced to protect susceptible stones, especially after cleaning operations.

Two methods of conservation are available. The first is through the application of surface sealants to create a strong, water repellent surface that strictly limits the ingress of water into the pore structure of the stone. The second method is through the use of consolidants that penetrate the body of the stone and adhere to grains as a form of cement designed to replace natural stone matrix cements lost due to weathering processes.

Sealants

Sealants have been applied to stone for many centuries. Originally, linseed oil and paraffin were used but were found to break down under solar radiation (UV) causing brittleness and yellowing. Later, chemicals such as acrylates, urethane, styrene, and silicones were tested. Of these, only silicones were found to be very effective and long-lasting as they were not affected by UV radiation. More recently, advanced proprietary sealants have become available that are not only UV-resistant but also allow the transmission of moisture vapour to and from the pores of building stones.

Correct application of sealants can assist in the prevention of efflorescence, and flaking caused by trapped water. Other preventable stone damage is from spalling resulting from pressures exerted by the internal growth of salt crystals, particularly gypsum, as well as freezing and thawing of excess pore water.

In general, suitable stones for treatment by this process include granite, slate, marble, and other calcareous rocks such as limestone and dolomite. Surface sealing of many sandstones is not recommended because their high porosity and permeability permit water to easily penetrate the stone from any direction and, as a result, surface sealing may result in severe scaling and other problems (Winkler, 1994).

Consolidants

The use of consolidants is also not new, having been practised since Roman times. Consolidants are used to prevent further stone decay by increasing the cohesion of the near-surface grains thereby increasing the stone's mechanical resistance to further weathering. In general, consolidation processes are non-reversible and as such are commonly used as a last option in stone conservation before block replacement becomes the only alternative. An extensive discussion of stone consolidation is given in Rodrigues (2001).

There are many chemical consolidants in use today for different applications. They all have varying degrees of penetration inside porous stone and many may ultimately cause some degree of discolouration. Consolidants are divided into inorganic and organic types (Winkler, 1994). In general, water-based, inorganic consolidants appear to perform better in harsh weather owing to their effective reduction of the porosity of the stone. Alternatively, organic consolidants effect greater stone permeability, mechanical resistance to weathering, and water repellent properties.

Inorganic consolidants

- *Limewater*: The oldest recorded use of a consolidant. Limewater was used to restore calcareous stone; however, the rate of calcification was extremely slow.

- *Fluates*: The process of replacing surface carbonate minerals in limestone, dolomite and marble by colourless calcium fluorite that is virtually insoluble in rainwater. However, a grey surface coating may ultimately develop.

- *Barite*: Soluble carbonate minerals are replaced by insoluble barite (barium carbonate) in the presence of urea, which acts as a catalyst. This process is limited by its slow reaction rate and grey colouration of surfaces.

- *Waterglass*: Also known as silica gel, comprising aqueous solutions of sodium or potassium silicates. On contact with minerals in the affected stone, these chemicals rapidly bond to their surfaces ultimately forming hard to very hard amorphous silica coatings. These consolidants appear to be most effective in substantially improving the strength of well-weathered quartz sandstones but are less effective in the treatment of decaying calcareous stones such as marble. Disadvantages of this treatment may include the formation of some white efflorescence and hard white crusts.

Organic consolidants and water repellents

In recent years, the use of organic consolidants and water repellents has become increasingly popular. Of the many types available, the three most important groups in use are: ethyl silicates (silicic acid esters), organic resins, and water-repelling siloxanes, silanes and siliconates.

- *Ethyl silicates*: These chemicals form the most widely used stone consolidant group, especially for sandstones. Following a reaction lasting several weeks, good penetration of the stone's weathered surfaces is achieved in which layers of amorphous silica are deposited within the pore structures. The amorphous silica exhibits good compatibility with quartz grains and other silicate minerals in the stone. Although, ethyl silicates are used as consolidants for carbonate minerals, the bonding effect is not as compatible as for silicate minerals. Recent tests on carbonate rocks confirm ethyl silicates capacity for very high migration within stones together with a slight reduction in water vapour permeability. However, only small increases in strength result (Rodrigues, 2001).

- *Organic resins*: These comprise a large number of resin groups including acrylic, epoxy, and polyurethane resins. Examples of applications of these chemicals include a mixture of ethyl and methyl methacrylate mixed with a silicone-based water repellent that demonstrated that acrylic consolidants tend to act like hardening adhesive agents in stones such as dense, fractured limestone. Alternatively, tests on an epoxy resin have shown an excellent impregnating capacity in both fractured granite and porous limestone where penetration and consolidation was up to 7.0 cm depth in granites and greater than 2.0 cm in limestones (Rodrigues, 2001). Polyurethane resins are elastic polymers which are good waterproofing agents but unsatisfactory as consolidants.

- *Silanes, siloxanes, and siliconates*: These silicon-based chemical groups find application principally as water repellents for building stone: silanes are used as clear, water-repellent coatings. They are used in relatively high concentrations, together with an alkaline catalyst to speed reaction time, to bond with silica- or alumina-rich minerals to form water-repellent surfaces. Because of their small molecular structure, silanes exhibit good penetration of stones with relatively dense substrates. Siloxanes (silicone group) are clear-coloured polymers also possessing good penetration, water-repellent, and silica/alumina mineral bonding properties. Siloxanes have the advantage that they may also be applied to damp surfaces. Siliconates, principally methyl siliconate, are slow-reacting, alkaline solutions forming water-repellant surfaces that have been used to lcombat rising damp (Brick industry Association, 2002).

Stone replacement techniques

In cases where stone blocks have decayed to the point where conservation methods are no longer able to preserve existing stonework, whole or partial replacement of blocks becomes the only viable restoration option.

One of the greatest challenges facing the project architect and geologist specializing in building stones is the location of suitable stone to closely match the original stone used in the building or monument under repair. This task usually involves sourcing stone from the original quarry and sometimes from the same bedding horizon within the quarry. This of course assumes that the original quarry can be located and the quarry walls are still accessible for block removal. Even in Australia, where historic buildings are only 75–185 years old, this task may not be possible. In overseas countries, particularly in Europe, historic stone buildings currently in use, such as churches, may date back almost 1000 years. Over such periods of time, the original quarry sites may well have been lost or overtaken by urbanization spread of most cities, a common event in modern society. This problem highlights the need to conserve old quarries as a source of stone for future restoration work on historic buildings.

Block replacement

Assuming a matching stone can be located as a possible replacement for the decayed stone, there are a number of stone characteristics that must be met before final stone selection can be made. Apart from a lithological match (same rock type), the colouring, weathered surface textures, surface finish, and durability are all important factors in completing the match with the weathered characteristics of the existing building stone when both wet and dry. Another factor that must also be considered is that over long periods of exposure to the atmosphere stones may change colour (Smith, 1999). For example, over time, white or pale cream limestone may weather to a mid-grey, and off-white sandstone may change colour from orange through to mid-brown.

Consequently, obtaining a near-perfect stone match is not possible in many cases and compromises may have to be made. For example, colour matching may have to be made on the basis that in a comparatively short time (possibly 5–10 years) the replacement stone will weather to a colour approximating that of the original.

Once a selection has been made the stone must carefully be cut to the size and profile of the blocks to be replaced. Specially shaped blocks may have to be cut by programmable profiling saws, and detailed pieces and decorations to be carved by banker masons (see cover photograph), or by state-of-the-art computerized profiling machines.

Prior to fitting the new stone, decayed blocks to be replaced are carefully sawn with a masonry saw or diamond cutting disc to facilitate removal without damage to adjoining blocks. Tungsten-tipped chisels are then used for final removal of the decayed material (Fig. 82). Mortar is then spread over a pre-wetted area and the new stone, also with wetted faces to prevent mortar dewatering, is carefully inserted into the space and laid on the mortar bed. Vertical joints adjoining older blocks are then mortar pointed (Smith, 1999).

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Figure 82. Replacement of weathered sandstone corbel blocks. Sydney Hospital stone restoration project

Partial stone replacement

This technique, known as ‘stone grafting’ or ‘piece-in’ replacement is the replacement of a small decayed section of a much larger stone. Once again, a durable, matching piece of stone with the required physical characteristics (detailed above) must be obtained to make the repair as inconspicuous as possible. The key factor in grafting is the way in which the borders or edges are blended into the host stone.

Grafted pieces are usually cut square or rectangular to match the void space cleanly cut out using diamond cutters or chisels. Circular holes may also be cut to allow the insertation of circular, diamond-cut core pieces as grafts. The graft is then affixed in the cut-out using epoxy resin, cement, or other adhesive. If resurfacing of the entire stone is required, the graft should be positioned standing slightly above the surface of the surrounding stone. The entire surface is then carefully ground flat to ensure the edges of the graft are not damaged. The glue joint around the graft is then flattened and patched to render it less conspicuous, and the graft itself may require some ‘artificial ageing’ to create an exact match with the host stone (Wenger, 2005).

Chapter 10

Dimension stones of the Perth Region

This chapter is a detailed account of the dimension stone resources of the southwest of the State centred on the Perth region in terms of existing quarries (both operating, and in care and maintenance), prospects, and historic sites. This area includes high-grade limestone and sandstone resources from the Phanerozoic Perth, and Southern Carnarvon Basins. In the Perth Basin these resources are located mainly on the Swan Coastal Plain, extending southwards from Geraldton in the north, through the economically significant outer Perth metropolitan area, to the Bunbury–Donnybrook area in the south. Also included are the high-quality granitic, mafic, and metamorphic dimension stones from the South West Terrane of the Archean Yilgarn Craton, and Proterozoic Leeuwin Complex within a radius of 300 km from Perth. Petrographic descriptions are after thin section reports by Pontifex (2005, 2006).

Sites for accessible, historic quarries of significance are briefly mentioned because of the need to conserve old quarries as a source of matching stone for future restoration work on heritage buildings in Western Australia. A much fuller discussion of the source and application of historical dimension stones in the State is contained in Chapter 4 under **Western Australia**. This information may assist in the preservation of all or part of these quarries, and may provide future access to matching stone supplies when these sites may be under threat by urban spread commonly experienced in many of our cities and towns.

This chapter contains grid reference values (MGA values) for all quarries, prospects, and historic sites within this area. These locations are also displayed on the regional map (Plate 1, in the pocket of this publication). It should be noted that all MGA values for the Perth region fall within Australia, Zone 50.

Appendix 2 is a summary list of existing and potential dimension stones for the region, together with project operational status, locations, and owner and lease information where known.

A photo image gallery of representative, polished or finely sawn dimension stones from many sites in the Perth region is provided in Appendix 3.

Yilgarn Craton – South West Terrane

Granite and gneiss

Bruce Rock

Three dimension stone quarries are situated about 20 km south-southeast of the town of Bruce Rock in the central wheatbelt. The site is leased by Melocco Stone and operated by Adelaide-based company, AustralAsian Granite Pty Ltd. AustralAsian Granite is currently producing dimension stone from the *Austral Juperana* and *Austral Waterfall* quarries and has been conducting tests on material from the *Austral Coffee* quarry. These sites are covered by extractive quarry licences surrounded by an exploration licence application to allow for future exploration to prove up other suitable sites.

The quarries are situated in an area of Archean granitic gneisses of variable composition and texture (Fig. 83). Close to the area of operations, granitic gneisses are commonly veined by a stockwork of fine- and medium-grained, leucocratic quartz monzonite, and some varieties may exhibit pronounced compositional and textural banding. Although some gneissic rocks are distinctively foliated and banded, there also appears to be a partial gradation both in texture and colour to granuloblastic granofels displaying little or no foliation.

In their first year of commercial production in 2002–03, the Bruce Rock quarries produced over 500 m^3 of high quality stone, mostly of the *Austral Juperana* variety. AustralAsian Granite markets the material overseas and Melocco Stone markets it domestically. While much of the stone has been exported, the stone has found favour with local architects who have employed it in commercial buildings and private homes, particularly as highly polished, interior wall cladding, and attractive kitchen benchtops. A large Australian project using *Austral Juperana* involved the cladding and paving of the atrium of the Canterbury Rugby League Club in Sydney. Recently, the stone has been specified for use in the prestigious Bovis Lend Lease development in Phillip Street, Sydney. This project was designed by renowned international

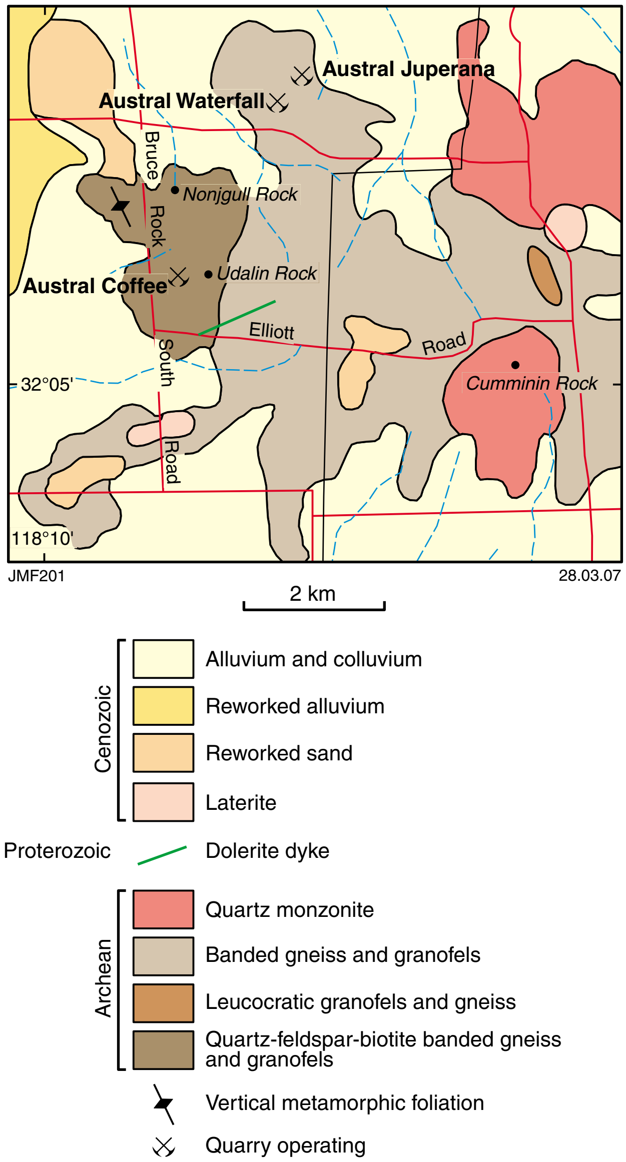

Figure 83. Geology around the Bruce Rock dimension stone quarries (modified after Muhling and Thom, 1985a)

architect, Sir Norman Foster, and the Hassell Group. Some applications of *Austral Juperana* cut slabs are shown in Figure 84.

Austral Juperana quarry (MGA 613719E 6454019N)

This is a hard, medium-grained rock that takes a very high polish. The material varies in places from granitic gneiss with bands or veins about 1–30 mm in thickness to leucocratic quartz syenite granofels with a granuloblastic texture displaying little or no foliation. This spectacular stone typically has a pinkish beige to yellow gold, crystalline matrix with occasional greenish-yellow overtones (Appendix 3.1). Veining ranges from red-brown to dark grey in colour and forms visually attractive swirling patterns distributed throughout the rock (Fig. 85). The dominant mineral is perthitic K-feldspar, with lesser amounts of plagioclase and quartz.

At the *Austral Juperana* quarry there is a paucity of vertical joints that allows for the removal of large primary blocks up to 800 t from benches about 18 m wide and up to 4 m high depending on the vertical spacing of subhorizontal unloading joints visible in Figure 86. The large blocks are then cut into smaller, saleable-sized blocks between 10 and 25 t. These are removed to a holding yard for block matching and for on-site customer selection (Fig. 47).

Typical physical properties for *Austral Juperana* given by Discovering Stone (2004) conform well with ASTM standard values for granite (Table 3) and are given below:

- Absorption (weight %) 0.2
- Bulk density (t/m^3) 2.62
- Compressive strength (MPa, dry) 210.2
- Flexural strength (MPa, dry) 13.5
- Abrasion resistance (Ha) 65

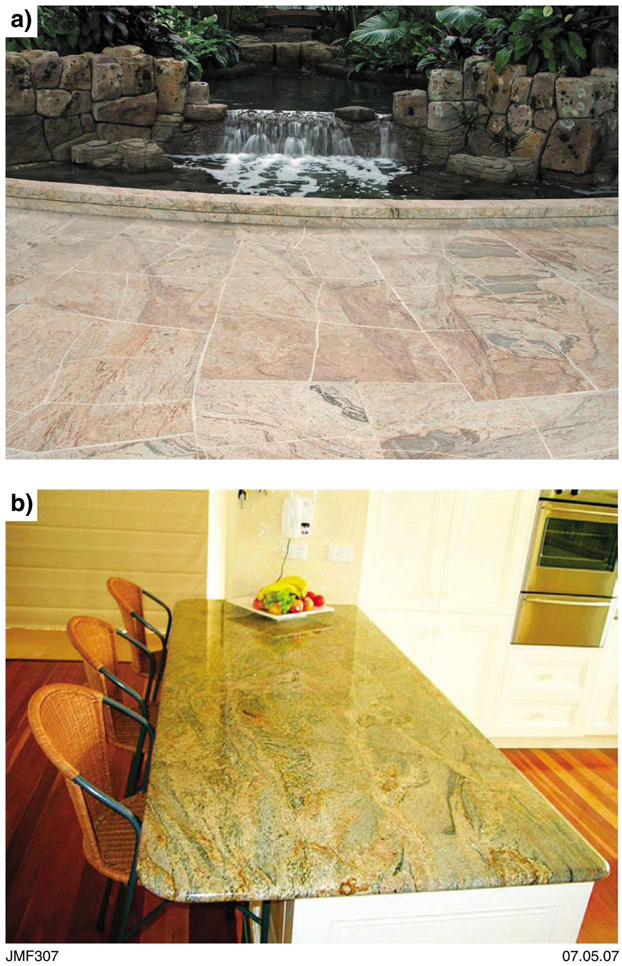

Figure 84. Applications of *Austral Juperana* granite gneiss: a) exfoliated paving slabs used in an atrium floor, Canterbury Rugby League Club, Sydney; b) an attractive polished kitchen benchtop in a contemporary home (courtesy Melocco Stone, © Discovering Stone)

Figure 85. Diamond wire-cut face of an *Austral Juperana* block illustrating the visually attractive swirling texture present throughout the stone

Petrographic description

The sample is composed of leucocratic quartz-syenite granofels, with minor biotite, muscovite and opaque oxide. Weak sericite–clay–limonite alteration is evident, with oxidized opaque oxide and leucoxene. K-feldspar is dominant in this comparatively quartz-poor, leucocratic rock. The distribution of feldspar types is heterogeneous with two plagioclase-rich areas and a larger K-feldspar-rich zone, suggesting incomplete mixing in the final melt.

The visually estimated primary mineralogy includes around 17% quartz, 60% K-feldspar (strongly perthitic microcline), 22% plagioclase, 1% biotite, and <1% muscovite and accessory opaque oxide, indicating quartz-syenite composition. The texture is granuloblastic and inequigranular, with grains from 0.2 to 5 mm in diameter. There is no foliation and the rock is therefore categorized as a granofels. The plagioclase has a weak dusting of sericite and larger flakes of muscovite occur within and between feldspar grains. Clouding by clays and possible limonite can be seen in the K-feldspar, and some biotite is altered to clay(–prehnite).

Austral Waterfall quarry (MGA 613378E 6453655N)

The *Austral Waterfall* quarry is situated 500 m southeast of the *Austral Juperana* quarry on the opposite side of a north-trending ridge (Fig. 83). *Austral Waterfall* is texturally similar to *Austral Juperana* with its swirling,

Figure 86. *Austral Juperana* granite gneiss quarry showing clean-cut, diamond-sawn block removal. Note primary block thickness (1.5 – 4.0 m) determined by subhorizontal unloading joint spacing

light to dark grey veins unevenly distributed throughout the reddish matrix. Despite the textural similarity, *Austral Waterfall* is somewhat mineralogically different with a higher ratio of plagioclase to K-feldspar and therefore is classified as a leucocratic quartz-monzonite granofels (Appendix 3.2).

Mining operations are similar to those at the *Austral Juperana* quarry, where large primary blocks are extracted with a combination of diamond wire sawing, thermal lance, and close-spaced drilling. Final sized blocks up to 25 t are prepared using close-spaced block drilling, and plug and feather splitting to facilitate accurate block sizing. *Austral Waterfall* quarry operations are shown in Figure 36.

Petrographic description

This rock is a leucocratic quartz-monzonite granofels with minor biotite, orthopyroxene, opaque oxide and monazite. This sample is leucocratic but not particularly quartz-rich and has a diffuse compositional layering with some layers rich in K-feldspar and other layers rich in plagioclase. The visually estimated primary mineralogy is 16% quartz, 32% K-feldspar (perthitic orthoclase), 48% plagioclase, 2% biotite, 1% orthopyroxene, 1% opaque oxide and accessory mineral, probably monazite, indicating leucocratic quartz monzonite.

The texture is granuloblastic with grains mostly 0.4 to 4 mm long, but also some smaller grains, especially quartz, opaque oxide and pyroxene. The biotite is partly granular and partly fibrous, suggesting some secondary biotite partially rimming opaque oxide. The biotite is not foliated and the rock is best classified as granofels rather than gneiss. Most of the minerals are fresh, but most of the orthopyroxene has been replaced by clay, possibly nontronite, with cores of orthopyroxene rimmed by carbonate in some altered grains. Sparse, very fine muscovite occurs within plagioclase. The monazite is mostly less than 0.2 mm in diameter and is not uncommon.

Austral Coffee quarry (MGA 612039E 6451251N)

The *Austral Coffee* quarry is located about 3 km south-southwest of the *Austral Waterfall* quarry (Fig. 83). Quarrying commenced in 2004 as a trial site for the extraction of a third type of granofelsic dimension stone. At this site test blocks were removed by diamond wire saw (Fig. 87). Subsequent mineralogical examination revealed that the *Austral Coffee* site is situated at the contact between granodiorite granofels and an interfingering monzogranite pegmatite (Appendix 3.3).

Petrographic description

There is a sharp contact between fine-grained granodiorite and more potassic pegmatite in this sample. The thin section has large areas of pegmatite (80%) with less granodiorite (20%) and is probably not representative. However, the visually estimated primary mineralogy for the granodiorite includes about 20% quartz, 60% plagioclase, 18% mesoperthite, 3% biotite, and minor opaque oxide.

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Figure 87. Diamond sawing test blocks at the *Austral Coffee* quarry

By comparison, the pegmatite has about 28% quartz, 33% perthitic orthoclase, 32% plagioclase, 5% biotite and 2% opaque oxide (monzogranite). Trace possible monazite (or ?zircon) is also present.

The granodiorite texture is granuloblastic with interstitial lobate quartz grains to 8 mm long as well as smaller grains of plagioclase and mesoperthite. Biotite, to 3 mm grain size, has been partially altered to chlorite and is unorientated, indicating the absence of foliation. Uncommon opaque oxide is interstitial and anhedral. Patches of alteration occur in plagioclase-rich aggregate, with sericite and clay-altered biotite as well as minor albitization, but with most feldspar remaining fresh.

The pegmatite contains scattered grains of anhedral quartz to 15 mm and K-feldspar to 20 mm with smaller grains of plagioclase. Oxides are present commonly as lobate interstitial grains and aggregates to 3 mm in diameter, and biotite is up to 7 mm grain size. Fan-like biotite aggregates enclose some of the opaque oxide and seem to be of secondary origin. Some K-feldspar is clouded while some biotite has been altered to chlorite(–quartz), with patches of dense sericite, apparently replacing plagioclase adjacent to opaque oxides.

Both lithologies contain thread-like microfractures filled with carbonate.

Carnamah

Winchester monzogranite quarry (MGA 394656E 6712457N)

Located 3 km southeast of the town of Carnamah in the northern wheat belt, the Winchester quarry owned by Winchester Industries is an extensive granite-aggregate quarry operation covering many hectares (Fig. 88). The quarry currently produces in the order of 100 000 tpa of crushed aggregate for road metal in 7, 10 and 14 mm diameter grades as well as larger -40 mm diameter railway ballast grade.

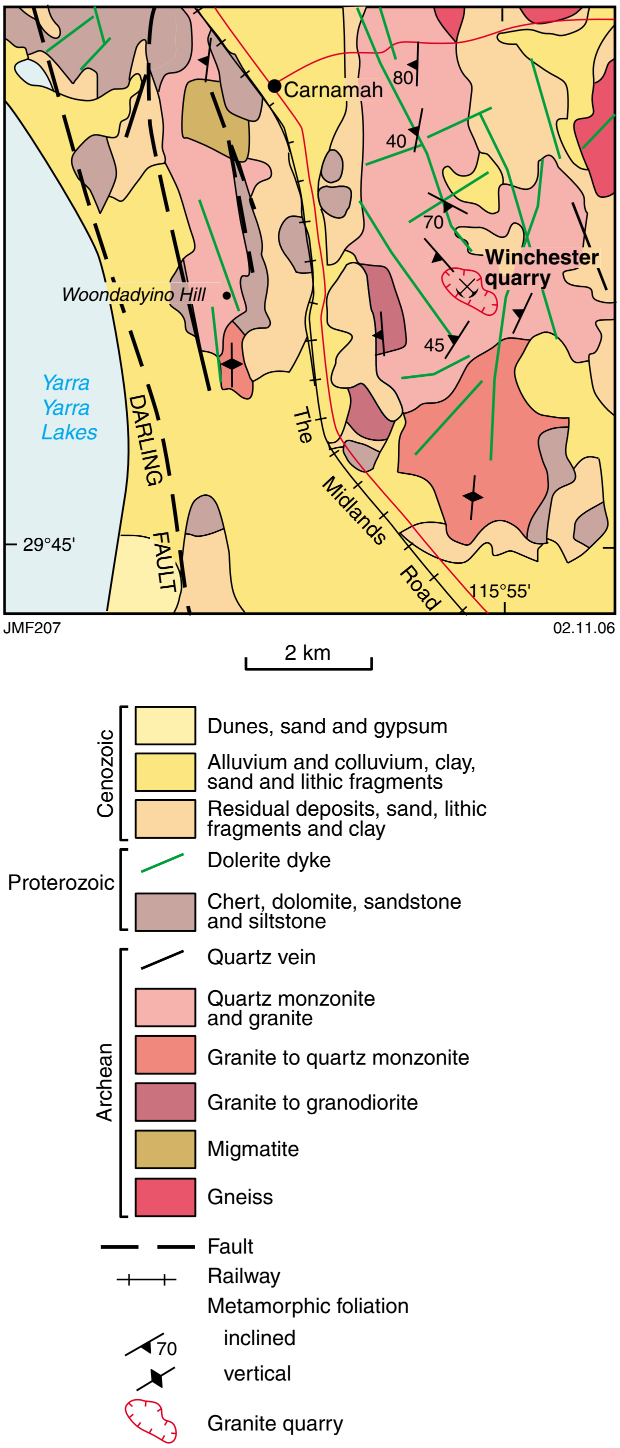

Figure 88. Geology around Carnamah (modified after Baxter and Lipple, 1983)

The grey Archean granite, described as leucocratic, biotite monzogranite, is medium grained with visible medium- to coarse-grained, pale pink K-feldspar phenocrysts. When polished, the stone takes on a visually attractive, mottled appearance due to the relatively uniform distribution of coarse-grained, pale pink microcline and olive green plagioclase feldspar crystals (Appendix 3.4). The uniform granite is well exposed in the quarry walls (averaging 8 m high) with comparatively little overburden

Figure 89. Grey, leucocratic biotite monzogranite in the Carnamah quarry

(Fig. 89). The stone is generally massive with horizontal jointing at between 0.5 and 1.5 m spacing. A second joint set, dipping at about 45° with 1.0 – 1.5 m spacing, may have been enhanced by quarry blasting.

This attractive monzogranite appears to be widespread in the local area, indicating the possibility of adequate resources for a separate dimension stone operation if zones of wider joint spacing are located to facilitate the quarrying of larger blocks.

Petrographic description

This mostly grey granite has roughly equal amounts of K-felspar and plagioclase with less abundant quartz. The visually estimated primary mineralogy includes 35% microcline, 35% plagioclase, 25% quartz, 3% biotite, 1% titanite with magnetite and minor altered allanite as well as opaque oxide and apatite, indicating monzogranite. Uncommon zircon is 0.15 mm in grain size. The quartz and feldspars are anhedral or subhedral and 0.4 to 6 mm long, with smaller biotite, titanite, and allanite grains. Irregular saussuritic alteration has affected the plagioclase, with most of the titanite altered to leucoxene, and most of the biotite to chlorite and microcrystalline titanite. Clay alteration is less common.

Carrido Spring (MGA 371591E 6773794N)

The quarry at Carrido Spring is located about 23 km east of the town of Mingenew in the northern wheatbelt and 2 km northeast of Beere Hill adjacent to the Mingenew–Morrawa Road (Fig. 90). This is a disused quarry that formerly provided crushed rock for road metal. The rock is an Archean, foliated, fine-grained granitic gneiss, more accurately described as a gneissic tonalite. Its potential as a dimension stone is the visually attractive black and white gneissic banding (Appendix 3.5).

At the quarry, the gneiss interfingers with thick bands of black, near-vertically foliated, inequigranular amphibolite (Fig. 91). The gneiss is also highly jointed with at least three sets of joints that tend to form pyramidal

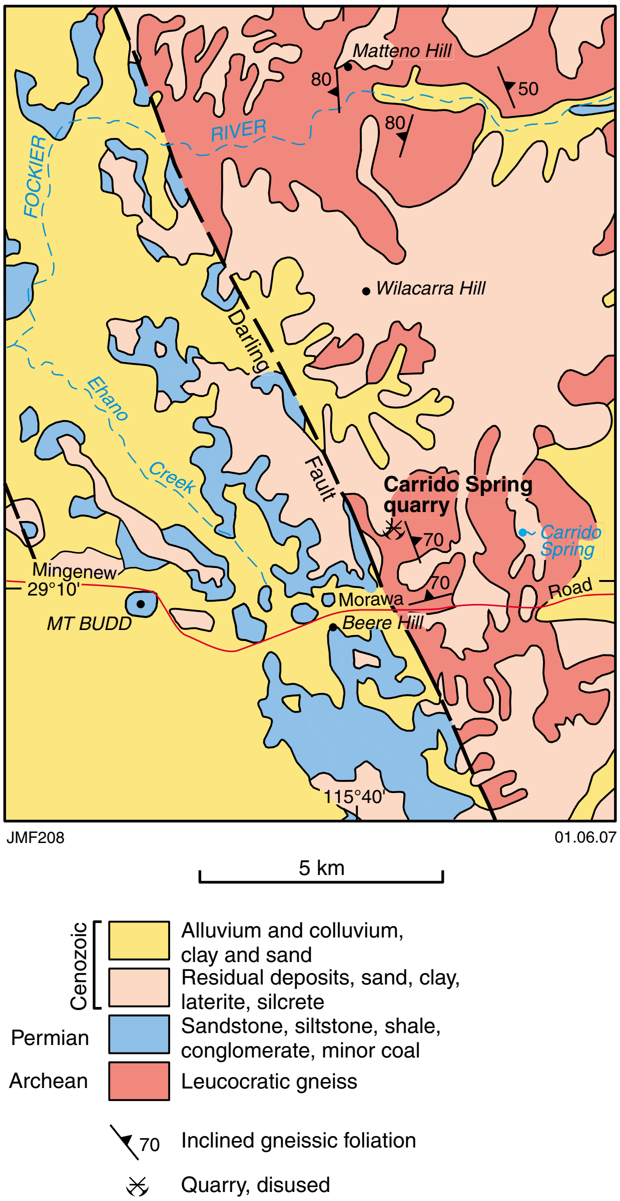

Figure 90. Geology of the Carrido Spring area (modified after Baxter and Lipple, 1983)

blocks with a maximum length on any face of less than 1 m. It is possible that post-Cretaceous tectonic events in the Darling Fault zone, located only 1 km to the west of the quarry, may have been partially responsible for the development of the extensive jointing network present at the quarry.

Local microfracturing, most likely resulting from previous blasting operations, is also evident in the quarry area. Although the stone is very hard and takes a high polish, material from this site is likely to be unsuitable as dimension stone owing to the possibility of microfractures and limited block size. Accordingly, future exploration in this area for potentially less-jointed sites of gneissic dimension stone should probably be directed within the extensive leucocratic gneiss unit, shown in Figure 90, at a substantially greater distance from the fault zone.

Petrographic description

This rock is a foliated, fine-grained, gneissic tonalite or trondhjemite with sericitized plagioclase, clay–chlorite-altered biotite(–prehnite) and altered allanite rimmed by epidote.

The estimated primary mineralogy includes 5% K-feldspar, 50% plagioclase, 40% quartz, 5% biotite, and <1% altered allanite and uncommon apatite. Some quartz grains reach 4 mm in diameter but the feldspars, comprising sericite-clouded plagioclase and clear microcline, are less than 1.5 mm. Biotite, up to 2 mm in grain size, has been altered to clay (?vermiculite) or more uncommonly to chlorite and contains a small number of prehnite lenses parallel to the cleavage. Very minor apatite is disseminated and accessory allanite is altered and rimmed by epidote. A narrow vein contains quartz and clear albite.

Greenmount – Mahogany Creek – Mundaring

Three very similar Archean monzogranite deposits, are situated in the Darling Ranges between 20 and 45 km east of Perth, adjacent to the Great Eastern Highway. These rocks were quarried mainly between 1860 and the 1933 for use as dimension stone blocks in some of Perth's major historic buildings (see Chapter 4). The granites are typically light–medium grey and generally fine to medium grained with megacrysts of K-feldspar being common in some areas. All granites are intruded by Proterozoic dolerite dykes to a greater or lesser extent.

Figure 91. Near-vertically foliated, black amphibolite bands interfingering with leucocratic, gneissic tonalite at the Carrido Spring quarry

Greenmount quarry (MGA 411321E 6468607N)

Also known as Mountain quarry, the Greenmount quarry is situated at the top of the Darling Range escarpment at Boya, 20 km east of Perth (Fig. 92). Originally quarried for granite dimension stone blocks as far back as the 1860s, the quarry was used in more recent times as a source of crushed aggregate, and ultimately reached a maximum diameter of approximately 125 m. Today, the abandoned quarry is situated close to a builtup area and has been partially rehabilitated.

The Greenmount granite is described as an inequigranular, weakly deformed monzogranite with minor biotite, opaque oxide and apatite (Appendix 3.6). In the quarry, the granite has been intruded by large vertical dolerite dykes 10–20 m thick.

Petrographic description

This inequigranular granitoid has a visually estimated primary mineralogy of 40% microcline, 28% plagioclase, 28% quartz, 4% biotite, <1% opaque oxide, accessory apatite and trace zircon, indicating a monzogranite. Some of the microcline occurs as megacrysts (≤15 mm) with other microcline, plagioclase and quartz to 8 mm grain size. There are subhedral plagioclase grains, but most of the rock is composed of anhedral grains. Some biotite seems to have been recrystallized, with undulose extinction. Quartz also shows some weak recrystallization. Microcline has secondary inclusions of plagioclase and sparse, coarse-grained muscovite. Saussurite is irregularly developed in plagioclase, with some areas of coarser muscovite and/or epidote. Chlorite, epidote and titanite occur in and adjacent to the biotite with some separate granular epidote; secondary titanite also occurs as rims on opaque oxide.

Mahogany Creek quarry (MGA 419464E 6468388N)

The abandoned Mahogany Creek granite quarry is located inside State Forest about 2 km south-southeast of the township of Mahogany Creek on the Great Eastern Highway (Fig. 92). The quarry is sited on top of a 4 m-high, oval-shaped granite mound approximately 150 m long by 50 m wide (Fig. 93).

The Mahogany Creek stone is described as an even-grained monzogranite with minor biotite (Appendix 3.7). Several sets of joints are present with vertical joints spaced about 2–10 m apart, and upper, horizontal, unloading joints spaced between 0.5 and 1.0 m apart with spacing increasing downwards. An illustration of the original application of Mahogany Creek granite blocks is shown in Figure 94.

Petrographic description

The visually estimated primary mineralogy for this sample is 34% microcline, 32% plagioclase, 30% quartz, 4% biotite and local apatite, indicating monzogranite. There are a few larger quartz grains up to 7 mm in diameter but most of the feldspar is less than 4 or 5 mm in grain size, and the biotite is less than 1 mm. Very minor myrmekite is noted between plagioclase and microcline. The texture is allotriomorphic granular, but some of the quartz seems to be in irregular narrow veins, cutting primary quartz and feldspar grains but avoiding biotite aggregates. Inclusions of quartz, plagioclase and biotite occur variously within microcline. Saussuritic alteration is variably developed in plagioclase, mostly with microcrystalline epidote and sericite, and also with coarser muscovite and/or epidote in some areas. Minor chloritization has affected the biotite, with epidote and titanite present in various proportions in and adjacent to

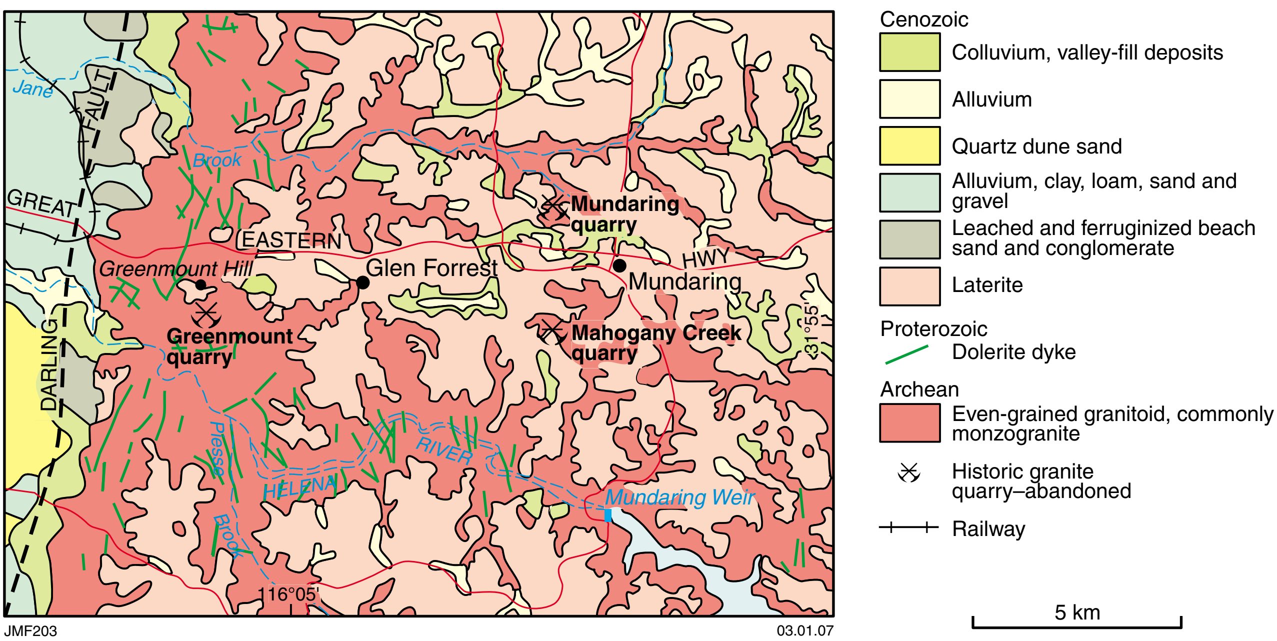

Figure 92. Geology of the area from Greenmount to Mundaring (modified after Low et al., 1978)

Figure 93. The Mahogany Creek monzogranite quarry

biotite. Very narrow carbonate-filled microfissures are seen, mostly in quartz.

Mundaring quarry (MGA 419915E 6471207N)

The historic Mundaring granite quarry, currently under care and maintenance, is situated on private property approximately 1.5 km northwest of the town of Mundaring on the Great Eastern Highway (Fig. 92). This rock is an inequigranular monzogranite with microcline and minor partially recrystallized biotite (Appendix 3.8).

While the last quarrying for dimension stone took place in the 1970s, the extensive stockpiles of large granite boulders (1–2 m^3) have been used in more recent times as a source of armourstone, for example as anchor footings for the Hillarys marina near Perth. As previously mentioned, this granite was used in many of Perth's historic buildings mainly as basal plinths, walls, and stairways. It was also used extensively for monumental work. An excellent example of this application may be seen in the State War Memorial Cenotaph in Kings Park in Perth (Fig. 24).

It is understood that the Mundaring quarry has been listed for rehabilitation owing to its proximity to recent urban development. As a result of this proposal, it is recommended that an area of quality stone within this extensive quarry be preserved to provide access to matching stone supplies for restoration work that will almost certainly be required for some of Perth's historic buildings in the future (Fig. 95).

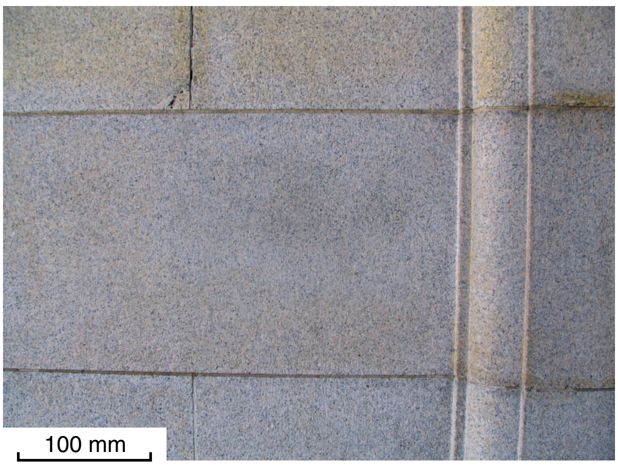

Figure 94. Mahogany Creek monzogranite blocks used in the ground floor construction of the Commonwealth Bank, Forrest Place, Perth

Petrographic description

The visually estimated primary mineralogy includes about 40% microcline, 26% plagioclase, 30% quartz, 4% biotite, and <1% opaque oxide and trace apatite, indicating monzogranite. The texture is inequigranular with mostly anhedral or subhedral feldspar plus anhedral quartz and small aggregates of anhedral biotite. Some of the microcline is present as elongate megacrysts (≤25 mm), but some is finer grained to granular, as is most of the plagioclase. Small inclusions of plagioclase are contained in the larger microcline grains. A few larger plagioclase laths are as long as 8 mm. The quartz, which reaches 6 mm in grain size, shows weak subgrain development and sparse areas of recrystallization. The biotite includes primary crystals up to 1.5 mm long and recrystallized aggregates. There is minor opaque oxide and accessory apatite; zircon is uncommon and very fine grained. The plagioclase has very unevenly developed saussuritic (albite–sericite–epidote) alteration, with secondary quartz in a few grains, and biotite shows weak alteration to chlorite and/or epidote, with microcrystalline titanite in altered grains. Secondary titanite also rims opaque oxide and sparse granular epidote is disseminated.

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Figure 95. Original granite working face still present in the Mundaring quarry. Note the old plug and feather holes used to cleanly split block faces

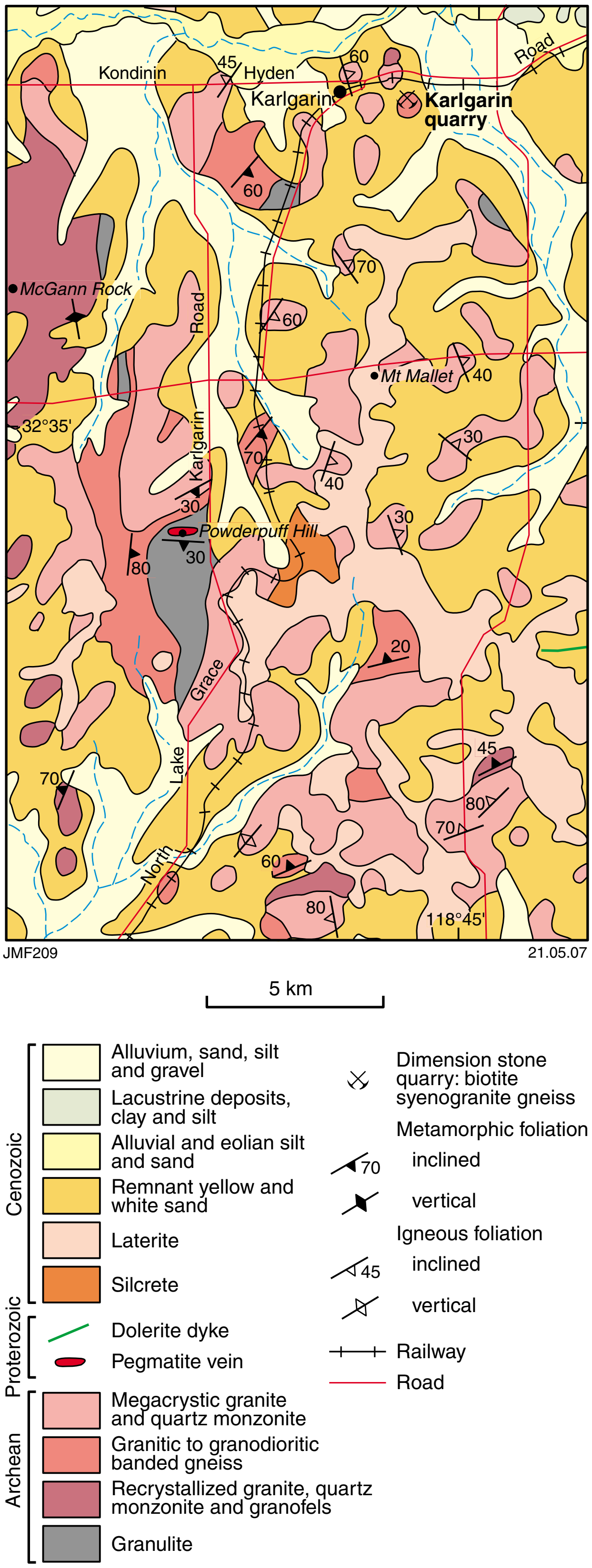

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Figure 96. Geology of the area around Karlgarin (modified after Chin et al., 1984)

Karlgarin (MGA 662357E 6402698N)

The Karlgarin granite gneiss quarry is located in a Government Reserve, 2 km east southeast of the town of Karlgarin in the central wheatbelt (Fig. 96). At this location, a small quarry was last operated in 1994–95. Before this time, the quarry had produced blocks that were slabbed and polished as stone panels fitted to the street frontage of the now demolished Boans Store in Murray Street, Perth.

The Karlgarin area is situated in an extensive area of Archean granitic and gneissic rocks. Previous dimension stone exploration has focused on these rocks to the south of the town (Fig. 96). The rock from the Karlgarin quarry is described as a biotite syenogranite gneiss. The gneiss has a prominent north-northwesterly trending foliation indicated by K-feldspar megacrysts (average length 1–2 cm) and somewhat ragged biotite. The visually attractive polished stone is very hard with a rich-brown background interspersed with linear-trending black biotite crystals (Appendix 3.9).

In the quarry, horizontal unloading joints ranging from 0.3 to 1.5 m vertical spacing, are prominent. In former mining operations these joints were used as vertical thicknesses for blocks extracted from the rock mass.

Figure 97. Smaller blocks of granite gneiss previously extracted from the Karlgarin quarry

Examples of thinner blocks are seen in Figure 97. More recent exploration for this rock type has tended to focus on areas of granitic gneiss 5–10 km south-southwest of Karlgarin.

Petrographic description

There is an irregular gneissic foliation in this sample, although biotite is recrystallized, discontinuous and only weakly aligned. The foliation is largely defined by lenses and lamellae of quartz separated by microcline, with lenses of recrystallized material (plagioclase, microcline and myrmekite(–biotite) commonly between microcline and quartz. The visually estimated primary mineralogy indicates 55% microcline, 35% quartz, 4% plagioclase, 3% myrmekite and 3% biotite, indicating syenogranite gneiss. Minor opaque oxide is also present, as well as rare small grains of zircon.

Microcline grains (≤12 mm) are mostly parallel to the foliation, with patches of myrmekite, but quartz, to 6 mm in grain size, is not so clearly oriented. The microcline is unusual in having a very heterogeneous distribution of exsolution lamellae, with patches rich in very fine lamellae, areas with sparse, coarse lamellae, and areas free of exsolution. Clouding is common in the K-feldspar. Biotite occurs as partly ragged flakes to 4 mm long, some of which are altered to chlorite, clays, and leucoxene. The recrystallized material is mostly 0.1 – 1.5 mm in grain size with some irregular grain boundaries. Some sericite alteration is evident. Fine lamellar biotite–quartz aggregates appears to be secondary and probably related to recrystallization.

Kellerberrin

Doodlakine quarry (MGA 580996E 6502065N)

Over the years many railway ballast quarries were developed to supply the adjacent Trans-Australian Railway, particularly east of the town of Kellerberrin towards Merredin in the central wheatbelt. In the early part of the 20th century, granite blocks from Kellerberrin were used in some of Perth's historic city buildings. Today, the Doodlakine quarry is the only local quarry still in operation for railway ballast, and is located about 14 km east-northeast of Kellerberrin and 2 km east of the Doodlakine township (Fig. 98).

The Kellerberrin–Doodlakine region lies within an area of relatively uniform Archean granite that outcrops extensively to the north of these towns (Fig. 98). At the Doodlakine quarry, the granitic rock present is described as hornblende–biotite monzogranite (Appendix 3.10). This quarry is extensive with walls up to 10 m high. The uniform granite in the walls is fairly massive, light grey, and medium grained. Horizontal, unloading joints are spaced 0.5 – 2.0 m apart, and vertical joint spacing appears to be greater than 2.0 m, indicating the potential for sizable dimension stone blocks as evidenced by a number of very large natural blocks on the quarry floor approximately 2.0 m long and 2.0 m wide (Fig. 99). The granite contains local thin veins of coarse-grained, pale pink K-feldspar with minor biotite.

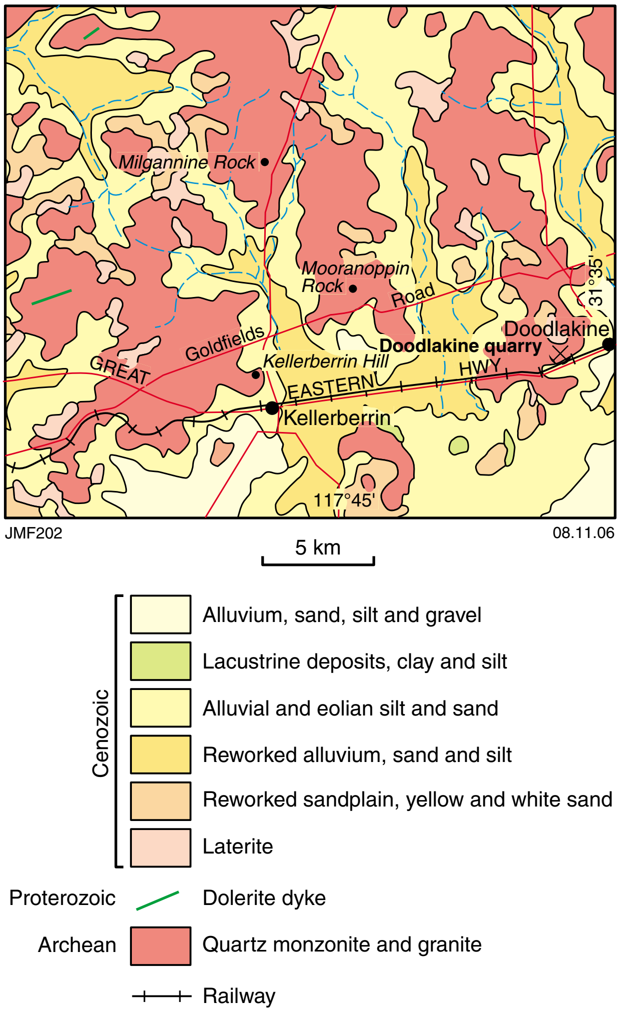

Figure 98. Geology of the Kellerberrin–Doodlakine area (modified after Muhling and Thom, 1985b)

Figure 99. Massive blocks of Kellerberrin granite in the quarry at Doodlakine

Petrographic description

This is a massive monzogranite with an estimated 22% quartz, 37% K-feldspar, 30% plagioclase, 6% biotite, 3% hornblende, 1% opaque oxide, and 1% titanite and altered allanite. This indicates an oxidized, I-type monzogranite. The plagioclase is subhedral, with anhedral K-feldspar, both to 6 mm in grain size, possibly with some larger K-feldspar grains in the hand specimen. Quartz is lobate and appears to have been partly resorbed, suggesting a shallow emplacement level. Biotite to 2 mm grain size is dark brown and possibly iron-rich, with less abundant granular, dark brownish-green hornblende passing into actinolite(–carbonate). Accessory oxides, titanite and altered allanite (partly rimmed by epidote) exist to 2 mm grain size and are accompanied by trace apatite and zoned zircon to 0.15 mm grain size. Minor myrmekite is present.

Sparse sericite is evident in irregular patches in plagioclase and actinolite(–carbonate) rims in some of the hornblende. The allanite appears to be metamict but the zircon is fresh. Thread-like microfractures contain carbonate.

Meckering (MGA 497731E 6499741N)

This is a large quarry, situated on a Railway Reserve, located about 3.0 km west-southwest of the town of Meckering (Fig. 100). Over many years this quarry has been a major supplier of granite ballast for the adjacent Trans Australia Railway. Around 1900, Meckering grey granite was sourced from this area for use as basal plinths and other stone applications in some of Perth's historic buildings.

Two types of Archean granite are present at the Meckering quarry. The principal granite occupying the main body of the quarry is a fine-grained, grey, uniform, biotite–quartz monzodiorite (Appendix 3.11). The base course and stairway constructed from blocks of this granite, may be seen on the western side of Parliament House in Harvest Terrace, Perth (Fig. 101a). The second granitic rock, a biotite granodiorite, is located in the southwest wall of the quarry. It is a distinctive, brown, inequigranular rock containing closely packed assemblages of very large, foliated K-feldspar crystals (Fig. 101b).

Petrographic description

Biotite–quartz monzodiorite

This sample is fine grained and has relatively minor quartz and K-feldspar. The visually estimated primary mineralogy indicates 59% plagioclase, and 18% each of K-feldspar and quartz, as well as 4% biotite, 1% opaque oxide and <1% titanite, indicating an oxidized, I-type biotite-only quartz monzodiorite. The plagioclase laths are well oriented and appear to define flow or a foliation of magmatic origin with laths and subhedral to anhedral

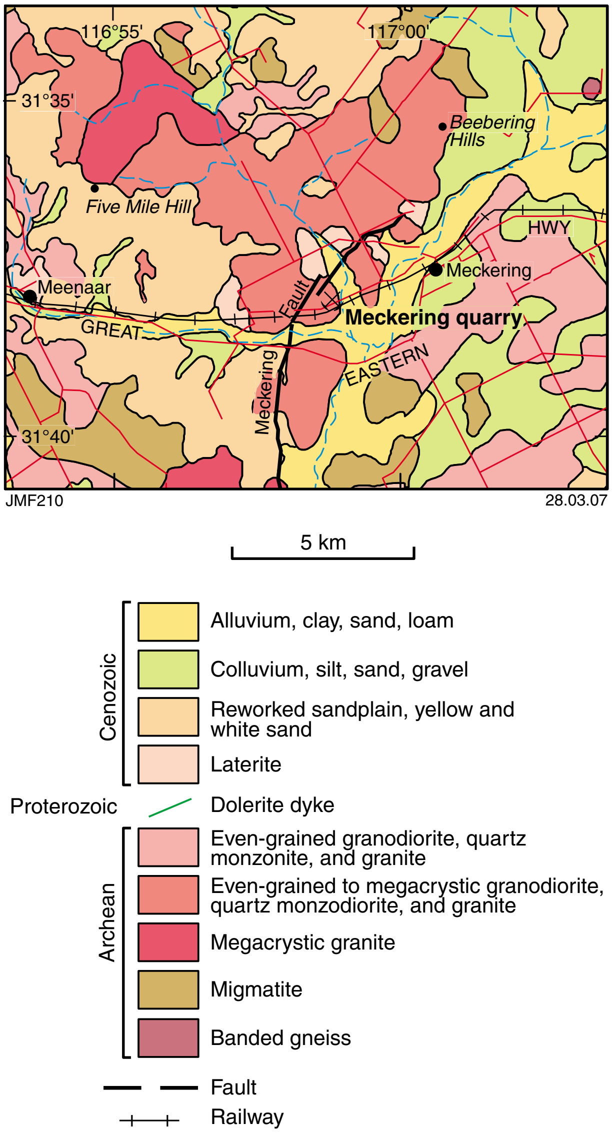

Figure 100. Geology of the area around Meckering (modified after Muhling and Thom, 1985b; Low et al., 1978)

a)

b)

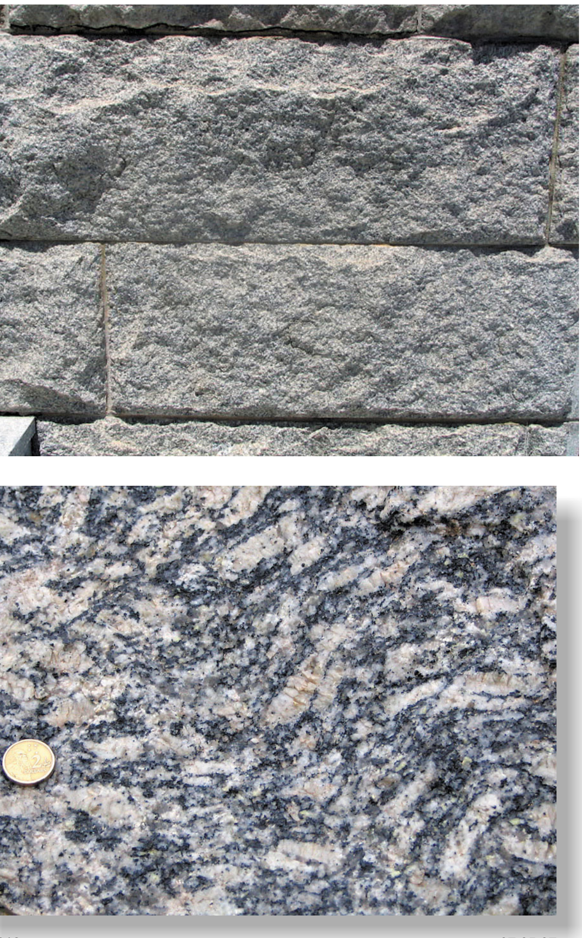

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Figure 101. Granites from the Meckering quarry: a) blocks of fine-grained, grey, uniform, biotite–quartz monzodiorite used in Parliament House, Perth; b) a brown, inequigranular, biotite granodiorite containing closely packed assemblages of very large, foliated K-feldspar crystals

grains up to 4 mm long. The K-feldspar is microcline and is of similar grain size. Biotite flakes to 1.5 mm seem to be less strongly aligned than the plagioclase but also suggest a magmatic foliation. Accessory granular opaque oxide is disseminated as is titanite, some of which occurs as rims on opaque oxide. Apatite is common, and local zircon grains are mostly attached to opaque oxide grains. Irregular small alteration patches contain sericite and epidote in saussuritized plagioclase and chlorite in biotite. Sparse muscovite is scattered and small patches of leucoxene occur within titanite, possibly replacing oxide inclusions.

Biotite granodiorite

There are irregular lenses and sparse larger crystals of K-feldspar in this inequigranular rock. Also, it has a magmatic foliation, similar to the monzodiorite at the same site. The visually estimated primary mineralogy includes about 58% plagioclase, 22% quartz, 13% K-feldspar, 5% biotite, 1% opaque oxide, and 0.5% each of titanite and apatite, indicating granodiorite.

The largest K-feldspar grains (microcline) are at least 15–20 mm long and 6 mm wide, but are partially interstitial to plagioclase and quartz, and therefore not properly phenocrysts that represent early crystallizing minerals. However, these are largely parallel and seem to define a magmatic foliation. Plagioclase grains (≤8 mm) are less well oriented than the microcline, and irregular interstitial quartz grains reach 10 mm in diameter. Myrmekite is uncommon.

Biotite-rich aggregates occur as anastomosing chains of crystals that are roughly parallel to foliation, although some individual biotite flakes (≤2 mm) are poorly oriented. These mafic aggregates also contain opaque oxide, titanite and apatite and accessory zircon to 0.2 mm in grain size. Occasional pyrite is also evident in this sample. There is sparse sericite in the plagioclase, very weak clay clouding in the K-feldspar, and very minor chlorite after biotite.

Merredin

Rifle Range quarry (MGA 624995E 6516386N)

The Rifle Range quarry is located 4 km east of the town of Merredin in the central wheatbelt. This extensive granite quarry with walls reaching 15 m high is sited on the southeastern side of a northeasterly trending granite hill approximately 2.4 km in length (Fig. 102).

The quarry was investigated by Gordon (1966) as another source of ballast for the Trans Australia Railway. The quarry stone is described as a medium-grained, Archean granite containing zones of coarse-grained, megacrystic granite, pegmatite veins, and mafic xenoliths. The colour of this granite probably falls between light pink and grey. The lack of inclined or vertical joint sets implies a massive granite. This was confirmed by a five-hole diamond drilling program which revealed that the only joints present were horizontal unloading joints with an average spacing of about 1.0 m.

Assuming this granite has sufficient visually attractive features, it may have application as a dimension stone. It would appear from the exploration results that the granite is relatively massive and therefore quite large dimension stone blocks may easily be quarried.

Roelands (MGA 393264E 6316295N)

The Roelands quarry is situated in a Government Reserve in the Darling Ranges, overlooking the small town of Roelands on the South Western Highway, 20 km east-northeast of Bunbury (Fig. 103). It was first mined around 1900 to supply large, durable armourstone boulders for the construction of the Bunbury breakwater. The quarry is very large, being cut in two levels into the upper slopes of a mountain with a total depth of around 50 m. It is currently in care and maintenance.

The quarry is situated in an area of Archean, quartz–feldspar–biotite gneiss that extends over large areas of the Darling Ranges. At the quarry the granitic gneiss is vertically foliated and interleaved by large, vertical dolerite dykes (Fig. 104). In this area the host rock is grey and white, medium-grained, layered biotite monzogranite

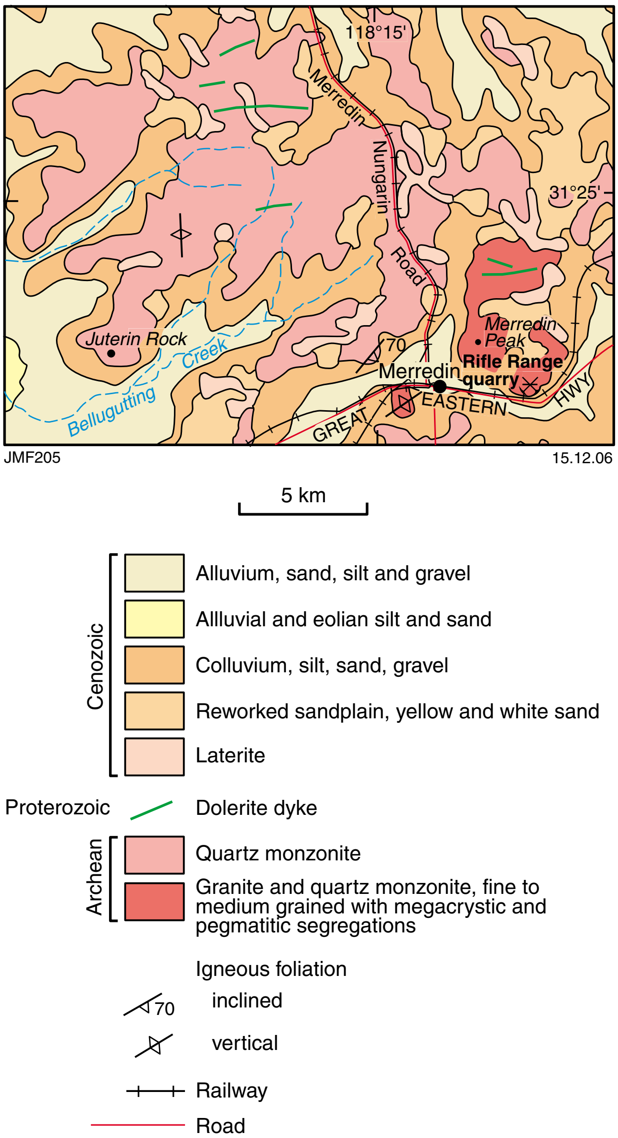

Figure 102. Geology of the area around Merredin (modified after Muhling and Thom, 1985b)

gneiss (Fig. 105; Appendix 3.12). At least two other variants to the host gneiss are also common in the quarry area. These spectacular monzogranite gneisses contain variously coloured, recrystallized lenses or megacrysts of K-feldspar and discrete zones or bands of quartz, plagioclase, and biotite (Appendix 3.13, 3.14).

The visually attractive appearance of the these stones as polished slabs, in addition to the large size of durable boulders (approximately 1.5 × 1.0 × 1.0 m) on the quarry floor, indicates the potential for dimension stone that could be produced from this area.

Petrographic description

Layered biotite monzogranite gneiss

This sample displays gneissic layering with bands rich in relatively fine grained K-feldspar in contact with K-feldspar-poor bands richer in quartz, plagioclase, and biotite. The K-feldspar-rich band has about

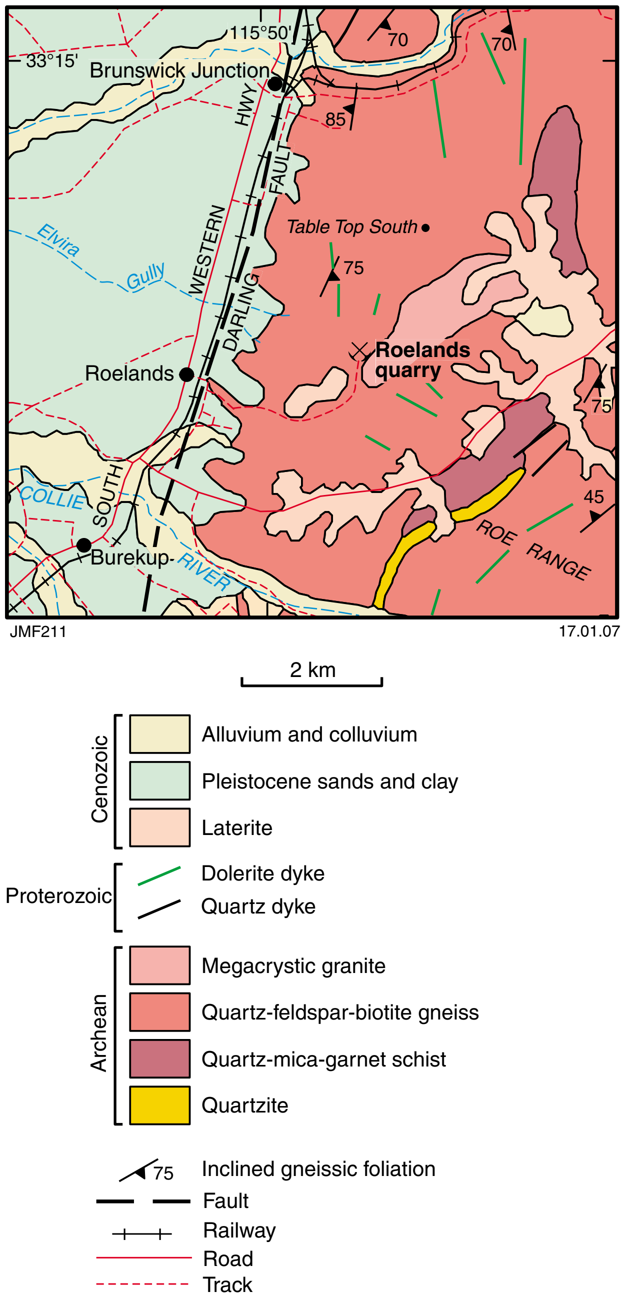

Figure 103. Geology of the area around Roelands (modified after Lowry et al., 1983)

80% microcline, 12% quartz, 5% plagioclase and 3% biotite as well as occasional myrmekite and zircon. Microcline to 4 mm in grain size and biotite to 2 mm are accompanied by mostly fine grained, partly sericitized plagioclase and fine-grained quartz (Appendix 3.12).

The K-feldspar-poor band has 45% plagioclase, 28% quartz, 22% microcline, 5% biotite, accessory apatite and minor zircon. Most grains are less than 2 mm in diameter, with biotite less than 1 mm, but lenses of very fine grained recrystallized material, especially biotite lamellae, are common. The plagioclase has weak sericite, and uncommon chlorite occurs in biotite as well as secondary titanite.

Figure 104. Vertically foliated biotite monzogranite gneiss and dolerite dykes in the Roelands quarry

If the K-feldspar-rich bands make up a quarter of the rock, the bulk mineralogy would include 36.5% K-feldspar, 35% plagioclase, 24% quartz and 4.5% biotite, indicating monzogranite gneiss.

Lenticular layered biotite monzogranite gneiss

This sample has a lenticular gneissic layering with pink feldspar-rich lenses to 15 mm wide and quartz-rich, mostly biotite-rich lamellae with a layer-parallel foliation. Its visually estimated primary mineralogy includes 38% K-feldspar, 20% plagioclase, 35% quartz, 6% biotite, 1% schistose muscovite, plus uncommon altered grains of possibly epidote or allanite, and trace apatite and zircon. The mineralogy indicates monzogranite gneiss (Appendix 3.13).

Two zones in thin section are composed largely of microcline to 6 mm in grain size, but other lenses are rich in granular plagioclase to 4 mm, with quartz or minor microcline. Most of the quartz seems to have been recrystallized, with grains less than 1 mm in diameter, but includes some earlier, strained grains up to 3 mm long. The biotite also includes earlier, irregular quartz grains to 3 mm as well as lamellae of recrystallized new grains, some of which pass into lenses of schistose, very fine grained muscovite. The biotite contains webs of rutile and microcrystalline aggregates of possible rutile or titanite, indicating adjustment to lower temperatures. Saussuritic alteration is seen in the plagioclase and minor epidote is present adjacent to biotite, but chloritized biotite is uncommon. Apatite and zircon are uncommon, but both up to 0.05 mm in grain size.

Figure 105. Detail of layered biotite monzogranite gneiss present at Roelands quarry

Heterogeneous biotite monzogranite gneiss

Samples of this rock appear to contain zones displaying different textures and mineralogy. One piece, elongate at a low angle to the foliation, has megacrysts of K-feldspar to 35 × 20 × 8 mm, elongate parallel to the foliation, in a matrix rich in quartz, plagioclase, and biotite. Another sample, cut at a high angle to the foliation, has recrystallized K-feldspar-rich lenses containing local strained old grains. These lenses, 15–25 mm wide, are fully represented on one side of the hand specimen (from which the thin section was cut) but are narrow or absent from the other side. The overall composition of this rock suggests monzogranite gneiss (Appendix 3.14).

Within the area of the thin section, the microcline-rich bands have one or more strained earlier grains (≤7 mm) as well as a largely granoblastic aggregate of K-feldspar to 1.5 mm grain size. Minor plagioclase and quartz occur in these bands, as well as very fine grained biotite. Most of the biotite is in bands rich in quartz(–plagioclase), together with earlier, strained quartz grains (≤6 mm) as well as small recrystallized new grains. Most of the plagioclase is relatively fine grained and granular, with some biotite to 1 mm as well as very fine grained recrystallized grains in lamellae defining the foliation. In less microcline-rich bands, small areas of microcline contain interstitial aggregates of very fine grained recrystallized microcline, suggesting late deformation, possibly coeval with the very fine grained biotite. Uncommon apatite and zircon are disseminated. Chlorite and epidote occur in the biotite, as well as microcrystalline titanite indicating readjustment to lower temperatures. Weak saussuritic alteration is seen in the plagioclase.

Watheroo–Namban

The Watheroo–Namban area is situated on the Midlands Road between 30 and 40 km north of the town of Moora in the northern wheatbelt. In this district the Archean Namban Granite is present over a wide area (Fig. 106). The Namban Granite comprises a suite of coarse-grained, pink and green, mainly megacrystic granites ranging in composition from monzogranite to quartz monzonite, and quartz syenite at different sites.

Colour differentiation in these visually attractive granites is determined by the relative size and distribution of feldspar megacrysts with varying shades of pink and

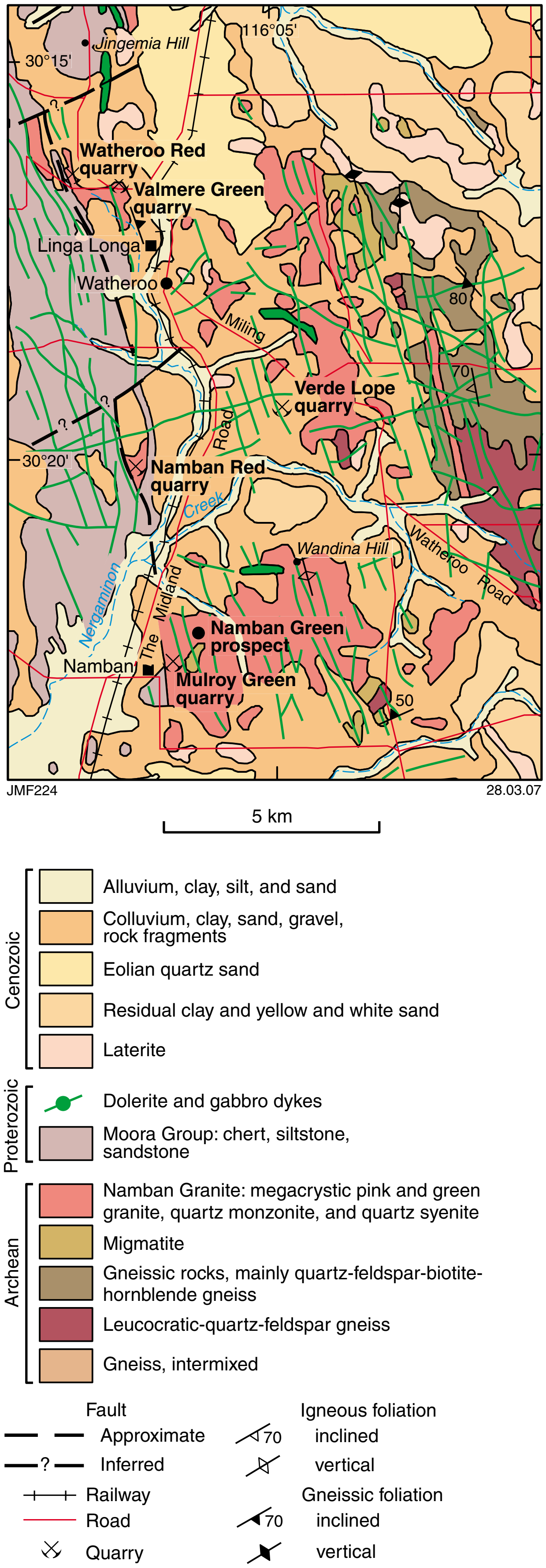

Figure 106. Geology of the Watheroo–Namban area (modified after Low et al., 1982)

red due to hematite staining in K-feldspar (microcline), and pale to mid-green caused by inclusions of chlorite and epidote in plagioclase. In general, quarries along the western margin of the Namban Granite are notably pink to red where K-feldspar usually predominates, whereas quarries distributed throughout the central region of this granite, tend to be green in areas where plagioclase is abundant (Carter and Lipple, 1982).

In the Watheroo–Namban area there are five dimension stone quarries and one prospect that were quarried at different times from about 1960 until a few years ago. All quarries are currently in care and maintenance and are well preserved to the extent that renewed mining activities could recommence without delay. In the north, quarries distributed around the town of Watheroo include the large *Valmere Green* quarry, and smaller quarries known as *Verde Lope*, and *Watheroo Red*. Around Namban in the south, a large quarry known as *Mulroy Green* is located at Namban Homestead. About 1000 m to the north-northeast is the associated *Namban Green* prospect, and the spectacular *Namban Red* quarry is located 5 km to the north-northwest (Fig. 106).

Valmere Green quarry (MGA 408475E 6649865N)

The *Valmere Green* quarry is situated on the Valmere property adjacent to the Midlands Road about 2 km north-northwest of Watheroo. It is a large quarry with a total depth of about 6 m in two floors (Fig. 107). The last quarrying operation appears to have taken place in 1994–95 by Min Holdings Pty Ltd, who carried out extensive exploratory work using close-spaced drilling to obtain test blocks for the preparation of polished slabs for use in an Australian and overseas marketing exercise. No other information is available regarding this venture.

The *Valmere Green* granite, formerly known as *Jade Green*, is described as a coarse-grained, heterogeneous quartz monzonite (Appendix 3.15). In hand specimen the stone has an overall mid-green hue, interspersed with very coarse, pale pink K-feldspar megacrysts (Fig. 108).

An extensive stockpile of quarry blocks in excess of 10 t remains on site.

Petrographic description

This heterogeneous granitic rock is very coarse grained with large grains of K-feldspar (≤25 mm in diameter) as well as grains and aggregates of plagioclase, mostly interstitial quartz, and altered biotite. The distribution of K-feldspar and plagioclase is not uniform, with plagioclase more abundant on one side of the hand specimen (from which the thin section was made) than on the other, suggesting that the thin section is not representative of the rock as a whole. The thin section has plagioclase more abundant than microcline, but the hand specimen suggests that K-feldspar is more abundant than plagioclase. The thin section has only about 16% quartz, 7% former biotite, 1.5% former titanite, 1% opaque oxide and 0.5% apatite, whereas the hand specimen suggests about 44% microcline and 32% plagioclase, indicating quartz monzonite.

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Figure 107. The extensive *Valmere Green* quarry near Watheroo

JMF322 07.05.07

Figure 108. The coarse-grained *Valmere Green* quartz monzonite in hand specimen

JMF323 07.05.07

Figure 109. Coarse-grained, megacrystic, hornblende–biotite *Verde Lope* monzogranite

In the thin section, the plagioclase is partly in aggregates to 15 mm in diameter, composed of grains to 6 mm in diameter, but a single larger grain, at least 10 mm long, is also present. Biotite and titanite crystals are accompanied by opaque oxide and abundant apatite. Zircon to 0.15 mm is partially enclosed in magnetite. The plagioclase shows extensive sericite clouding, with or without minor clinozoisite. The biotite has been altered to chlorite and leucoxene(–epidote) and most of the titanite has been altered to leucoxene.

Verde Lope quarry (MGA 412106E 6644732N)

This is a comparatively small quarry that has probably not been mined for some years. It is located on Watheroo Park property about 4 km southeast of Watheroo townsite. Block extraction appears to have been accomplished by close-spaced drilling and blasting. A few large blocks remain on site. *Verde Lope* is described as a coarse-grained, megacrystic, hornblende–biotite monzogranite. An example of this pale green stone from the quarry site is shown in Figure 109 and in polished form in Appendix 3.16.

Leased by Granites of Australia since 2000, the *Verde Lope* quarry has been a source of stone in recent years, probably from older stockpiles, for the manufacture of large polished slabs, and smaller panels and tiles of the visually attractive, pale green, megacrystic granite.

Petrographic description

This is a very coarse grained granitic rock with larger K-feldspar grains 40 mm or more in length. The small number of quartz and feldspar grains within the area of the thin section would tend to suggest that the mineralogy may not be representative, but the visually estimated primary mineralogy includes 36% microcline, 28% plagioclase, 26% quartz, 4% biotite, 3% hornblende, 2% titanite, 1% magnetite, and <1% apatite and accessory zircon, indicating monzogranite.

As indicated, some of the microcline is possibly 40 mm long and 20 mm wide with inclusions of plagioclase. Separate plagioclase (≤6 mm), is mostly anhedral, with anhedral quartz to 6 mm. Biotite and subhedral titanite reach 4 mm in grain size with hornblende and magnetite to 3 mm. Most of the apatite is enclosed in biotite, hornblende, titanite or magnetite, with zircon adjacent to the mafic aggregates. The plagioclase shows weak saussuritic alteration, with chlorite and clays as lamellae in altered biotite and chlorite partially replacing hornblende.

Watheroo Red quarry (MGA 406804E 6650086N)

The coarse-grained *Watheroo Red* granite is located in a small quarry on Linga Longa property, about 4 km northwest of Watheroo. This site also was explored in 1994–95 by Min Holdings Pty Ltd during their evaluation of the *Valmere Green* quarry.

Watheroo Red, formerly known as *Moora Red*, was also quarried and cut into polished test slabs for trial marketing (Fig. 110). This granite is a coarse-grained

Figure 110. The *Watheroo Red* test quarry

biotite monzogranite with a striking red-mauve hue (Appendix 3.17). At this site, the red K-feldspar grains are notably smaller than those in the nearby *Valmere Green* quartz monzonite quarry.

Petrographic description

This is also a coarse-grained granitic rock but has smaller K-feldspar grains (≤15 mm) and more abundant quartz than the sample from the nearby *Valmere Green* quarry. The visually estimated primary mineralogy includes 30% K-feldspar, 34% plagioclase, 30% quartz, 3% former biotite, 2.5% former titanite. 0.5% magnetite, minor apatite and zircon(–monazite) to 0.4 mm in grain size. This indicates biotite monzogranite.

In addition to coarse-grained microcline, the granitic rock has plagioclase and quartz to 8 mm in grain size and aggregates of altered titanite (≤8 mm) composed of smaller, largely euhedral crystals. Biotite up to 4 mm in grain size is accompanied by magnetite and minor apatite, with uncommonly coarse grained zircon(–monazite). Irregular sericite alteration has affected the plagioclase (without clinozoisite) and the biotite has been altered to chlorite(–carbonate). Leucoxene has replaced most of the titanite, but some fresh kernels remain.

Mulroy Green quarry (MGA 409679E 6638521N)

Mulroy Green monzogranite, also known as *Namban Green*, outcrops 10 km south of Watheroo and 1 km east of the Namban railway siding on Namban property. In the period 1993 to 1994 the site was evaluated with ten diamond drillholes, sampling and dimension stone resource estimation. This was followed in 1994–95 by a mining operation in which a single-level quarry was cut into the eastern face of a low hill (Fig. 111). During this period many 10 t blocks were extracted using close-spaced drilling and explosives (Perth Granite Holdings, 1996). Today, the well-maintained quarry is in care and maintenance and remaining granite resources appear to be extensive. Also, a number of mostly irregular-shaped blocks remain in the stockpile area.

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Figure 111. The well-maintained *Mulroy Green* quarry at Namban

In hand specimen, *Mulroy Green* has an overall mid- to dark green hue — because of the abundant, coarse, green plagioclase grains present in the stone — despite the presence of numerous, deep pink K-feldspar megacrysts (Fig. 112). Cut slabs of *Mulroy Green* have been used in the floor of the external porch at the main entrance to Parliament House in Perth (Appendix 3.18).

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Figure 112. The very coarse grained *Mulroy Green* monzogranite containing large green masses of plagioclase grains interspersed between deep pink K-feldspar megacrysts

Physical properties for *Mulroy Green* determined by Perth Granite Holdings (1996) conform well with ASTM standard values for granite (Table 3) and are given below:

- Absorption (weight %) 0.11
- Bulk density (t/m^3) 2.66
- Compressive strength (MPa, dry) 236.3
- Modulus of rupture (MPa, dry) 12.8
- Flexural strength (MPa, dry) 11.1

Petrographic description

This coarse-grained monzogranite has few grains within the area of the thin section, suggesting that the mineralogy may not be representative. The visually estimated primary mineralogy for the thin section includes 30% microcline (deep pink in hand specimen), 34% plagioclase, 33% quartz and 1% each of former biotite, former titanite, and opaque oxide. Apatite and zircon are less abundant than the previous Watheroo–Namban granites and mostly smaller. The microcline is commonly 15 × 20 mm with quartz as complex interlocking grains (≤10 mm) and plagioclase 15–20 mm in length.

Aggregates formerly composed of biotite, titanite, opaque oxide, apatite and sporadic zircon are disseminated. The plagioclase has dense sericite clouding and seems to be partly albitized, with minor quartz–epidote lenses. The biotite has been altered to chlorite and lamellar leucoxene(–epidote–quartz) with leucoxene replacing titanite. The microcline has irregular clay clouding. Narrow stylolite-like veins contain epidote and chlorite.

Namban Green prospect (MGA 410149E 6639487N)

The *Namban Green* prospect is located approximately 1 km north-northeast of the *Mulroy Green* quarry. In 1960, the prospect (part of former Mineral Claim 720H) was inspected by Connolly (1961a). At that time, a trial pit measuring about 5 × 4 × 1.5 m deep was being opened to investigate the quarry's dimension stone potential. At this site, Connolly (1961a) described the rock as 'a porphyritic granite with flesh coloured feldspar phenocrysts up to 1½ inches [about 38 mm] maximum dimensions, pale green subhedral crystals of feldspar up to 3/8 inch [about 9.5 mm] maximum dimension, quartz and biotite in descending order of abundance in the rock… When cut and polished to a plane surface the rock presents an attractive mottled pale green/pale pink colour of sufficiently subdued hue to be used in large areas.'

Connolly (1961a) also observed that there were large areas where this granite was exposed, together with some thin soil-covered areas, on the mineral claim. Thin section examination revealed that the *Namban Green* specimen contained 'microcline and microperthite in slight excess over oligoclase, with quartz, chlorite (after biotite) and accessory minerals magnetite–ilmenite, sphene (leucoxinized in part), fluorite, zircon and apatite.'

This description of the *Namban Green* granite indicates that it is almost identical to the nearby coarse-grained *Mulroy Green* biotite monzogranite. To date, no further exploration or quarrying appears to have been undertaken on former Mineral Claim 720H.

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Figure 113. The *Namban Red* quarry situated on former Mineral Claim 719H

Namban Red quarry (MGA 408759E 6643604N)

The *Namban Red* quarry is located on freehold land about 5.0 km south-southwest of Watheroo in a small granite enclave enclosed by Proterozoic Moora Group sedimentary rocks. The small quarry is sited in an open area on the flattened crest of a low hilly area, previously investigated by Connolly (1961b) as part of former Mining Claim 719H (Fig. 113). This visually striking granitic rock is described as a quartz syenite with flow-oriented, large, deep red microcline crystals. A quarry specimen of *Namban Red* is shown in Figure 114. In the quarry area, this coarse-grained quartz syenite is interspersed in places by a finer grained deep red syenite rock of similar mineralogy with the exception that quartz content is only 3% compared with 15% in the quartz syenite.

In the shallow quarry of only 2–3 m depth, horizontal unloading joints attain 1.0 – 1.75 m spacing at the lowest point, whereas two vertical joint sets almost at right angles, appear to have been used as planes for separating quarry blocks. It is evident that these blocks were extracted using close-spaced drilling and an expanding chemical compound to achieve final splitting.

In polished slab form this stone presents a visually striking appearance with its coarse-grained, deep red K-feldspar crystals. It is evident that its use as a dimension stone would most likely be in specialized applications requiring bright colours (Appendix 3.19).

Petrographic description

Flow-oriented large, deep red K-feldspar laths are abundant in this hand specimen, suggesting quartz syenite. The visually estimated primary mineralogy includes 70% K-feldspar (microcline), 10% plagioclase, 15% quartz, 3% altered mafic grains, 1% altered titanite, 1% altered, small clay prisms, uncommon apatite and trace zircon. The microcline is up to 25 mm in grain size in hand specimen but less than 12 mm in the thin section, with inclusions of plagioclase, and is largely stained with earthy hematite. Separate plagioclase is anhedral, partially polygonized and intergrown with very fine grained quartz or with very small clay-altered prisms with no remaining fresh material.

The largest quartz grain is mostly interstitial, more than 25 mm long, and contains inclusions of plagioclase. Patches of chlorite may have partly replaced biotite or hornblende and are in aggregates with leucoxene derived from titanite. Other patches of decussate chlorite seem to be interstitial and may be in miarolitic cavities. The plagioclase in this sample is uncommon and could be partly secondary. Narrow quartz veins are also evident.

York–Beverley

In this area an Archean megacrystic granitic rock extends, in a broad band of outcrops, southward from the town of York for approximately 40 km (Fig. 115). Sampling of this rock at different localities has indicated a hornblende–biotite quartz monzodiorite composition.

At different times, two dimension stone operations quarried this granitic rock known as *York Granite*. The oldest and major quarry at Gwambygine, is located adjacent to the Great Southern Highway about 9 km south-southeast of York, and the smaller Waterhatch Road quarry

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Figure 114. Quarry specimen of *Namban Red* quartz syenite displaying large, deep red, flow-oriented, K-feldspar crystals

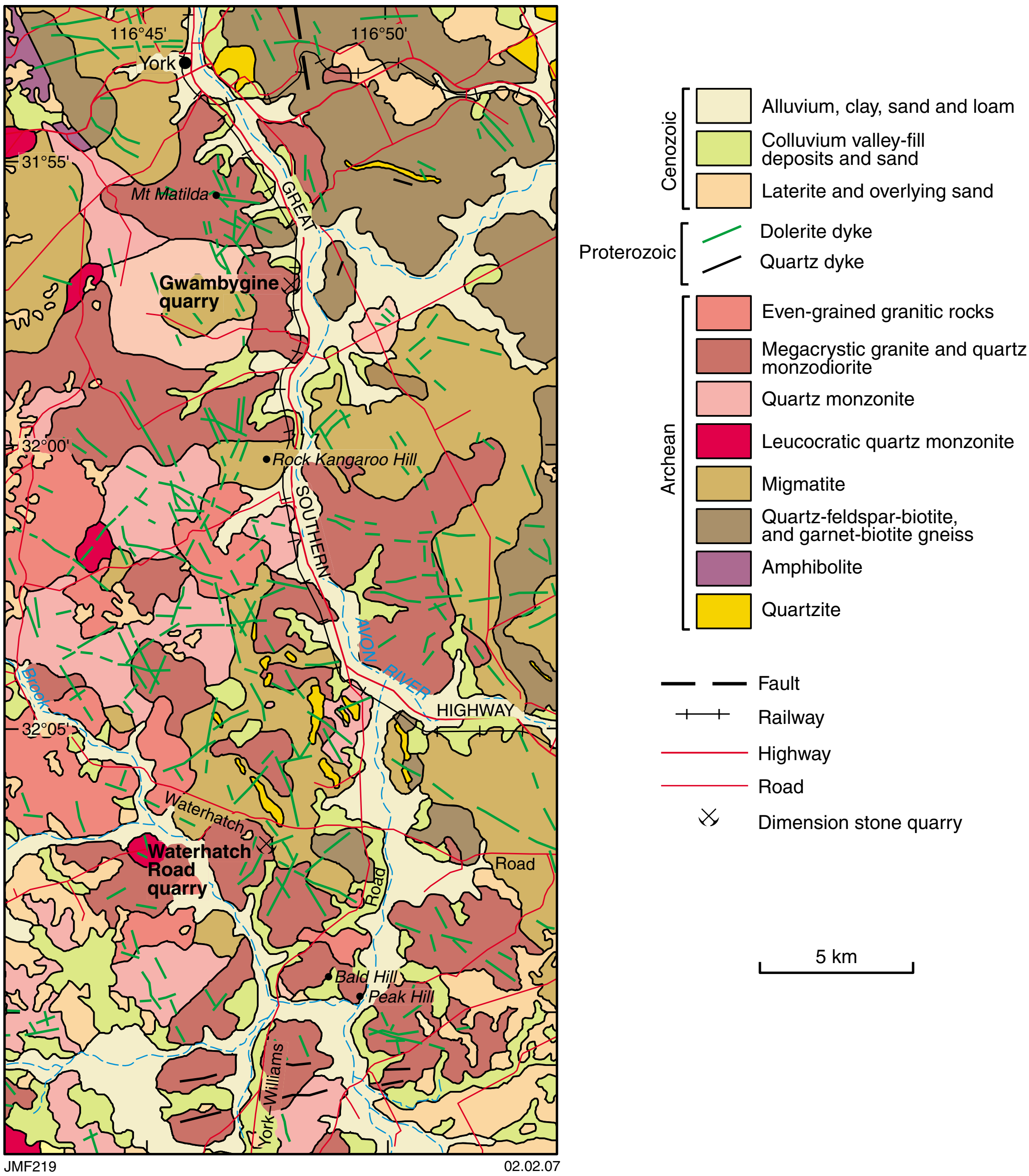

Figure. 115. Geology of the region south of York (modified after Low et al., 1978, 1980)

is approximately 13 km west of the town of Beverley. Today, both quarries are in care and maintenance, although in comparatively recent years they supplied a substantial quantity of granite blocks, largely to the Perth market, for cladding, floor tiles, and numerous monumental applications. Owing to the common occurrence of this megacrystic granitic rock in the region, it is likely that many new sites for *York Granite* could be established locally in the future.

Gwambygine quarry (MGA 481491E 6464373N)

The Gwambygine quarry operated on this site for about 40 years from the 1960s as a replacement dimension stone for the grey Mundaring and Mahogany Creek Granites formerly used in Perth for building construction and for monumental work. Last operated by Wales Quarries from 1989 to 1996, the Gwambygine quarry is a well-designed, self-draining quarry developed on two levels into the lower slopes of a granite hill (Fig. 32b). At this site the quartz monzodiorite rock appears massive with little evidence of vertical joints. This property has facilitated the removal of large primary blocks that were separated from the wallrock by close-spaced drilling and gas-powered thermal lance (Fig. 116). The height of the primary blocks was 3 to 5 m, determined by the distance separating horizontal unloading joints that also determined the height between levels.

In the quarry, the megacrystic nature of the quartz monzodiorite is evident on stone surfaces (Fig. 117).

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Figure 116. Large, primary blocks of quartz monzodiorite present in the Gwambygine quarry. Here, a thermal lance has been used to detach blocks from the quarry wall

Also present in the rock are scattered, black xenoliths composed of mafic biotite amphibolite, rich in apatite, and also containing epidote, tremolite–actinolite, titanite, and opaque oxide. The xenoliths are mostly quite small and do not interfere with the overall appearance of the polished stone but a few range up to oval-shaped masses 30 × 25 mm in size.

In polished slab form, the visually attractive appearance of the *York Granite* can be appreciated with its subtle grey, medium-grained groundmass interspersed with pale pink K-feldspar megacrysts up to 20 mm in length (Appendix 3.20).

Despite the fact that the quarry appears to have a large resource of accessible, high-grade dimension stone, it is understood that operations at this quarry were discontinued in 1996 largely because of the spread of urbanization around York. A large stockpile of cut blocks of up to 10 t each remains on site.

Petrographic description

Megacrysts of K-feldspar to 16 × 8 mm are set in quartz and plagioclase with less abundant disseminated hornblende. The thin section indicates only 15% quartz with 52% plagioclase, 25% microcline, 6% hornblende, 1% biotite, 1% opaque oxide plus titanite, and <1% apatite. Accessories include altered allanite and sporadic zircon. The bulk mineralogy is close to the quartz monzodiorite – quartz monzonite divide. The microcline seems to have formed as phenocrysts and has inclusions of plagioclase and quartz. Some of the quartz, as grains and aggregates to 6 mm in diameter, may formerly have been phenocrysts but later resorbed, and some have lenses of feldspar and hornblende in what may have been resorption channels. The plagioclase is mostly subhedral and less than 4 mm in grain size, with inclusions of K-feldspar.

The hornblende is granular to prismatic with inclusions of quartz, feldspar, apatite and opaque oxide, but some of the amphibole is actinolite and is accompanied by epidote(–chlorite). Biotite, mostly olive-brown in colour, is also partially altered to chlorite. Minor, disseminated, opaque oxide is partly rimmed by titanite, but separate crystals of titanite are disseminated, as well as apatite, altered possible allanite, and zircon. Sericite, epidote and carbonate occur sparsely in plagioclase and there are aggregates of epidote with pale yellow possible zeolite.

Waterhatch Road quarry (MGA 480132E 6446558N)

York Granite was quarried from the Waterhatch Quarry from the early 1970s to about 1986. The quarry covers a relatively small area, some 30 m wide, containing two benches, each 2 m high, and is situated on the side of a gentle hill (Fig. 118). The stone appears to have been removed using close-spaced drilling, blasting, and thermal lance. Remaining resources at this site may be limited.

At this site the stone is almost identical to that at the Gwambygine quarry and is likewise classified as a hornblende–quartz monzodiorite. A polished slab is shown in Appendix 3.21.

Petrographic description

Megacrysts of microcline in this sample reach 12 × 8 mm and occur with large grains and aggregates

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Figure 117. K-feldspar megacrysts protruding from the surface of the *York Granite* at Gwambygine

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Figure 118. The Waterhatch Road quartz monzodiorite quarry

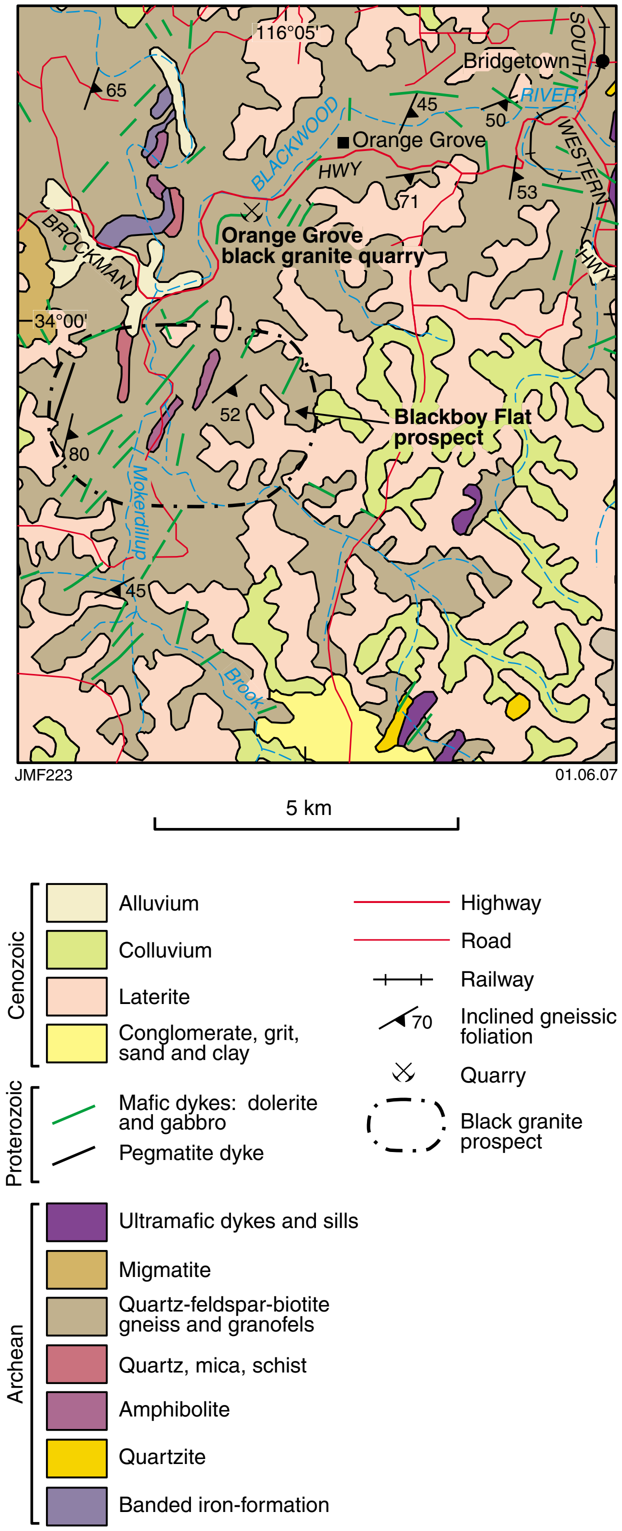

Figure 119. Geology of the area southwest of Bridgetown (modified after Lowry et al., 1983; Wilde and Walker, 1984)

of quartz, similar to those in the sample from the Gwambygine quarry, in a plagioclase-rich host with minor hornblende. The total microcline content is about 20%, with 56% plagioclase, 18% quartz, 3% hornblende, 2% biotite, 1% opaque oxide plus titanite, and minor apatite. This indicates that the quartz monzodiorite is transitional to granodiorite. The microcline has inclusions of plagioclase and quartz, with quartz and opaque oxide in plagioclase, which occurs as laths to 7 mm long.

The quartz is mostly interstitial but some granular quartz (≤7 mm) has possible resorption cavities with feldspar and hornblende. The hornblende is mostly less than 2 mm in grain size, with similar-sized biotite and fine-grained opaque oxide and titanite. Some of the plagioclase has been altered to saussurite, with separate granular epidote, and some of the hornblende contains chlorite and/or epidote, with chlorite also replacing biotite. Small patches of carbonate occur in plagioclase and interstitial patches of pale yellow possible zeolite are evident as in the Gwambygine quarry sample.

Dolerite and gabbro: black granite

Bridgetown

In the Bridgetown region, about 85 km southeast of Bunbury in the southwest of the State, two major swarms of Proterozoic dolerite dykes have intruded large areas of Archean metamorphic rocks that include gneiss, granofels, and migmatite. One dyke swarm has a prominent north-northwesterly trend; the second swarm trends to the north-northeast (Fig. 119). It is this latter set of dolerite dykes in which exploration and quarrying for black granite dimension stone has been concentrated.

Exploration for black granite first took place in the period 1996–97 in the area around Blackboy Flat Road, about 9 km southwest of Bridgetown. In 2004, quarrying of a dolerite dyke for black granite was briefly carried out on the Orange Grove property 6 km west-southwest of the town.

Orange Grove quarry (MGA 414764E 6239472N)

At least five, north-northeasterly trending, almost vertically dipping dolerite dykes are present on the Orange Grove property. These roughly parallel dykes, with individual thicknesses possibly of 10 to 20 m, have intruded a subsequently weathered, cream-pink, metamorphosed granitic rock.

Early in 2004, Coral Marble Pty Ltd opened a quarry in a thick dolerite dyke adjacent to the Brockman Highway (Fig. 120). Although this operation persisted for a comparatively short period, it produced a quantity of high-grade blocks of black granite. The main method of cutting was by using diamond wire sawing to produce extremely smooth-sided primary blocks (Fig. 39), backed up by close-spaced drilling to assist in block separation.

At the quarry site, the dolerite is relatively fresh with minor weathering effects. Jointing appears to be widely spaced with vertical joints at around 2 to 3 m intervals with horizontal, unloading joints ranging from about 1.5 to 3 m spacing. The dolerite is dark grey and massive, and ranges from very fine to medium grained (Appendix 3.22). In some places the rock contains fine, anastomosing veins of a greenish mineral, possibly smectite. Resources of black granite at the quarry site are considerable. Assuming similar rates of weathering in other dolerite veins on the Orange Grove property, the total resource of high-grade black granite in the local area may be substantial. However, further evaluation of these dykes would be required to confirm this.

Petrographic description

This is mostly fine-grained dolerite but has rare grains of orthopyroxene to 2 mm in diameter as well as 54% plagioclase, 42% clinopyroxene, 3% opaque oxide and 1% late magmatic quartz. Sporadic apatite grains are also present. The plagioclase has a pale brown stain, especially in the cores of the grains, suggesting iron staining, and some of the pyroxene has a similar stain. The plagioclase is inequigranular (0.1 – >1 mm in grain size) as is the pyroxene. The opaque oxide, to 0.5 mm in diameter, is commonly rimmed by biotite. Late magmatic quartz is rare but occurs as poikilitic grains to 3 mm in diameter, enclosing plagioclase, pyroxene and prisms of apatite up to 0.8 mm long.

A second, coarser grained sample indicates a more plagioclase-rich dolerite than the previous sample. The visually estimated primary mineralogy of the coarser grained material includes 68% plagioclase, 17% clinopyroxene, 10% olivine, 4% opaque oxide, and <1% K-feldspar and accessory apatite. The plagioclase occurs as zoned euhedral crystals (≤2 mm) with a very pale brown stain. Interstitial clinopyroxene also reaches 2 mm with slightly smaller olivine grains, some of which are intergrown with opaque oxide. Separate opaque oxide grains are partly granular and partly bladed, suggesting titanomagnetite and ilmenite. A sparse mesostasis has sodic plagioclase, minor K-feldspar and small prisms of apatite. There is a narrow crosscutting vein filled with smectite, and adjacent to this vein the olivine has been altered to greenish or brownish smectite. Olivine is rimmed throughout and partly veined by a very pale green probable clay mineral.

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Figure 120. Diamond wire-sawn primary black granite block at Orange Grove quarry

Blackboy Flat prospect area (MGA 412469E 6234878N)

In the late 1990s, Black Magic Granite Pty Ltd carried out exploration for black granite in dolerite dykes in Exploration Licence E70/1597 in the area of Blackboy Flat Road. Twelve sites of interest were identified for sampling, consisting of fine-grained dolerite boulders and small blocks. Samples were removed for cutting and polishing and assessment of their potential as black granite dimension stone. As a result, material from the most prospective site, located at the the grid coordinates above, was re-sampled and polished slabs were distributed locally and overseas for appraisal (Black Magic Granite, 1997).

Wambyn black granite and host monzogranite (MGA 461229E 6470947N)

The Wambyn prospect is sited adjacent to the Great Southern Highway about 3 km east of Mount Observation, and about 20 km west of the town of York. At this locality a swarm of mostly narrow, Proterozoic dolerite dykes trending north-northwesterly, and several larger dykes with a west-northwesterly trend, have intruded a fine-grained, Archean monzogranite (Fig. 121).

Wambyn black granite

In 1988, an exploration site was established on a level crest of a low hill about 750 m south of the highway. This location, on a major west-trending dolerite dyke over 40 m wide, was selected for evaluation as a potential black granite dimension stone resource. During the program three diamond coreholes were drilled to a maximum depth of 95 m into the dyke at a variety of angles to assess stone quality, and attitude and frequency of joint sets.

Results of this exploration in the form of three fully logged coreholes provided detailed lithological and joint-

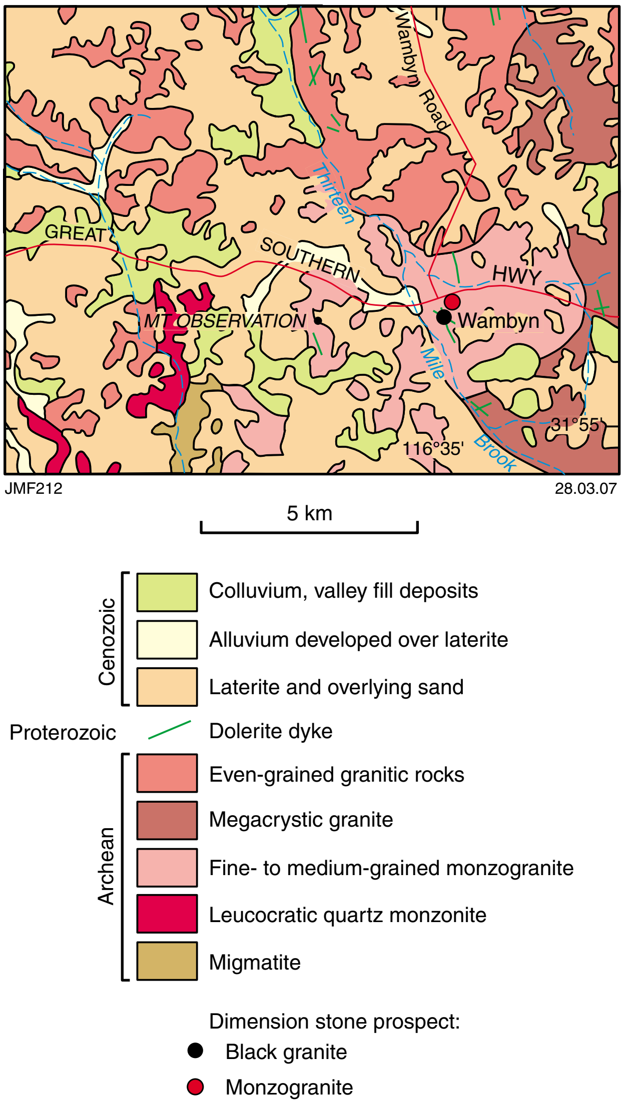

Figure 121. Geology of the Wambyn area (modified after Low et al., 1978)

set data. Joint set analysis indicated that at least two zones, within a potential quarry area occupying about 350 m along strike, could yield marketable-grade black granite blocks with dimensions of 1.0 × 1.0 × 3.0 m. Dolerite in recovered cores was generally medium-grained and ranged from very dark green to dark blue in colour. Estimated resources of marketable monument-grade stone was estimated at 252 000 m^3. No follow-up exploration was carried out (Lipple, 1988).

In 2006, dark blue-grey boulders of extremely hard dolerite, sampled by the author from the same site, were subsequently cut and polished to reveal a medium- to coarse-grained black granite shown in Appendix 3.23.

Petrographic description

This is a medium- to coarse-grained dolerite that contains about 58% plagioclase(–sericite–clinozoisite), 35% pyroxene, 4–5% opaque oxide, 2% granophyre(–late magmatic quartz), 1–2% chlorite(–epidote–actinolite) and trace apatite. The plagioclase occurs as laths to 2.5 mm long with patches of saussuritic alteration (sericite–clinozoisite) with or without chlorite, and is accompanied by mostly prismatic clinopyroxene to 2 mm in grain size, locally with patches of dark green chlorite, and abundant skeletal opaque oxide to 1.5 mm in diameter.

Interstitial patches of quartz(–K-feldspar) are mostly less than 1 mm in diameter and contain very minor apatite. There are also rare aggregates of granular epidote(–chlorite) and some actinolite enclosing ragged patches of sulfide, possibly low-temperature pyrite.

Wambyn monzogranite

Approximately 700 m north of the black granite exploration site and adjacent to the highway, large boulders of the host monzogranite are exposed (Fig. 122). This fine-grained granite is of similar composition to the monzogranite in the historic Mundaring and Mahogany Creek quarries located about 40 km to the west. The Wambyn monzogranite was also assessed by Lipple (1988) as being potentially suitable as a monumental stone.

Although surface samples of the Wambyn monzogranite show some degree of weathering, it is possible that quarry material sourced from depth in the local area may find application as a substitute stone for the historic, even-grained, grey granites used in Perth buildings early in the 20th century (Appendix 3.7, 3.8). In the past, small quantities of monzogranite blocks from Wambyn have been quarried for the construction of local houses. Further exploration would be required to assess resources on a commercial basis.

Petrographic description

In hand specimen this is a fine-grained granite with plagioclase more abundant than K-feldspar and quartz. The visually estimated primary mineralogy includes 38% plagioclase, 28% microcline, 30% quartz, 3% biotite,

Figure 122. Natural joint-bounded block of Wambyn monzogranite of approximately 1.9 m^3

1% titanite, accessory apatite and possible allanite. This indicates fine-grained monzogranite. The grain size varies from 0.2 to 3 mm with subhedral plagioclase but mostly anhedral quartz, microcline, and biotite. Very minor myrmekite is present as well as rare biotite–quartz symplectites. The texture is massive and undeformed. Fine-grained titanite and less abundant apatite are disseminated.

Alteration is strong with saussuritized plagioclase locally containing larger epidote grains and biotite largely replaced by chlorite, epidote and fine-grained secondary titanite(–clay). Primary titanite has been altered to leucoxene or leached and possible allanite has been altered to clays. Veins composed of epidote, chlorite and sericite are present but are very narrow.

Westdale (MGA 476385E 6428702N)

The Westdale prospect is located about 25 km southwest of the town of Beverley in the central wheatbelt. In this area an Archean quartz monzonite and several other granites have been extensively intruded by three generations of Proterozoic dolerite dykes trending west-northwesterly, north-northwesterly, and northeasterly (Fig. 123). In a number of places, dolerite dykes of different generations intersect forming stellate patterns at the point of intersection.

The Westdale prospect is located on a west-northwesterly trending dyke. Advice from local prospectors suggests that the dyke on which the prospect is situated is located close to a stellate dyke intersection some 100 to 200 m to the north. Assuming this information proves correct, it is suggested that the unusual mineralization present at the prospect may be related to geochemical changes in dyke rocks following intersection by successive dykes.

At the prospect, an exploratory costean has been excavated for about 100 m along the length of the dyke. On the costean floor, numerous cream to pale brown masses up to 9 cm in length are seen in discrete zones within the fine-grained, grey dolerite (Fig. 124a). Fresh black dolerite blocks, containing these crystalline masses, have been extracted from the costean and polished into slabs. These reveal a snowflake-like pattern of very large, subeuhedral, cream to pale green, plagioclase phenocrysts, 3–9 cm in diameter (Fig. 124b). Subsequent thin section examination has determined that the plagioclase phenocrysts have been altered by saussuritization to either zoned sericite/muscovite, or clinozoisite(–epidote).

This stone with its unusual pattern of altered, megacrystic plagioclase crystals within fine-grained black dolerite is termed *'Cats Paw'* by local prospectors (Appendix 3.24).

Petrographic description

About 20–25% of this thin section consists of saussuritized large plagioclase phenocrysts to 15 mm in diameter in a less altered dolerite host, which contributes about 40% plagioclase, 30–35% clinopyroxene and smaller

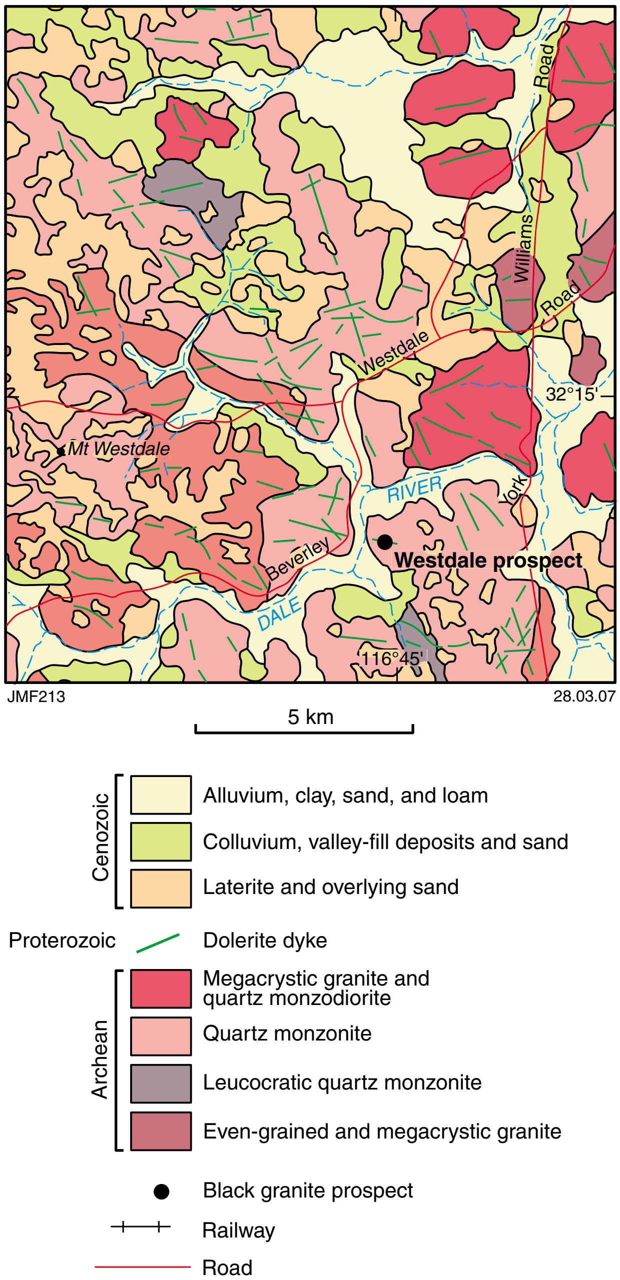

Figure 123. Geology of the Westdale area (modified after Low et al., 1980)

amounts of largely leucoxenized opaque oxide and late magmatic quartz and/or granophyre. The plagioclase phenocrysts were originally euhedral but now have large zoned areas either rich in sericite/muscovite or flooded by clinozoisite(–epidote), with an apparently crenulated or kinked foliation in the mica. The groundmass contains plagioclase (≤1.5 mm) and pyroxene mostly less than 0.8 mm in grain size.

There is also very minor low-Al chlorite replacing the cores of some pyroxene grains (former orthopyroxene or pigeonite) as well as sparse actinolite and epidote replacing pyroxene and plagioclase. Trace apatite is present in late magmatic quartz and granophyre patches.

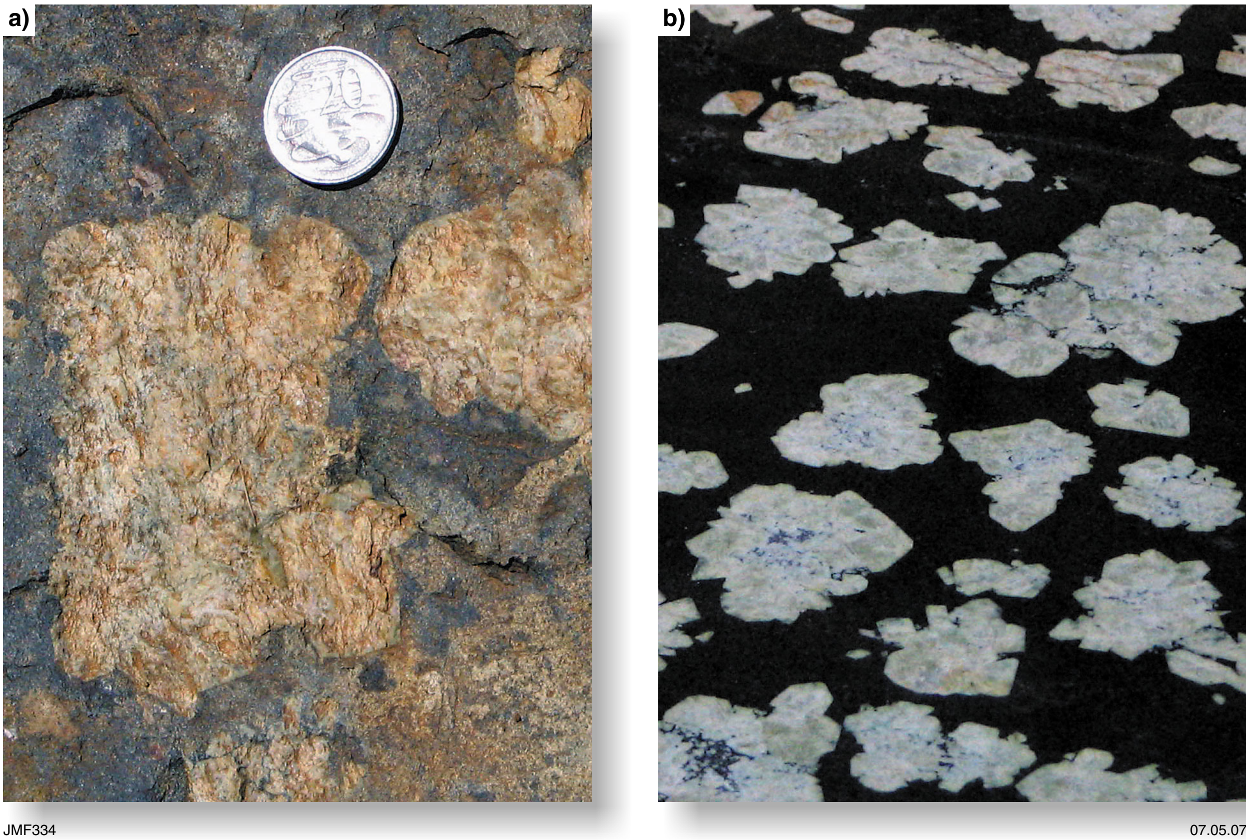

Figure 124. Westdale megacrystic black granite: a) altered plagioclase phenocrysts exposed in the floor of the exploratory costean at Westdale; b) polished slab of Westdale black granite known as *Cats Paw*

Quartzite

Toodyay

An extensive Archean quartzite unit known as *Toodyay Stone* is located in the Darling Range about 65 km northeast of Perth. The quartzite extends in a broad belt, 1 to 2 km wide, from Clackline in the south in a northwesterly direction to the Avon River, a distance of about 40 km (Fig. 125).

The resistant quartzite exists in hilly areas where it forms prominent ridges extending over many kilometres. Major folding ranges from open to isoclinal, with cleavages (interpreted as original bedding) generally steeply dipping between 30 and 85° to the southwest.

Interpreted as orthoquartzite (the metamorphosed equivalent of a sedimentary quartz sandstone or chert), this stone occurs as massive to flaggy bands consisting of interlocking quartz grains, with minor muscovite, fuchsite (chrome-muscovite mica), feldspar and accessory minerals. The pale green fuchsite occurs throughout the unit and is most abundant in flaggy bands where it forms characteristic pale green coatings along cleavage planes (Wilde and Low, 1978).

Toodyay Stone has been mined intermittently for at least 60 years from numerous quarries, mainly located between Clackline and Jimperding Hill, but focused on the area where the quartzite intersects the Toodyay Road about 10 km southwest of Toodyay township. In this area today, there are three semi-active quarries as well as a number of rehabilitated sites that have been worked at times in recent years. Quarries are commonly situated within areas of flaggy, banded quartzite. In these areas, the very well-developed, cleavage planes may be easily split to form almost perfectly flat flagstones.

Prominent cleavage plane surfaces, containing coatings of the pale green fuchsite mica, tend to vary in colour between quarry sites, and also at different levels within the same quarry. Colour variations range from pale green to pale orange-red, mid-brown and dark brown. Colour changes appear to be related to weathering processes, possibly brought about by groundwater penetration into near-surface cleavage planes.

The high-quality quartzite flagstones have been used in many areas of Perth, most commonly as internal and external decorative feature walls in buildings, and walls and non-slip pavers in urban landscaping areas. Also, *Toodyay Stone* has been used in the construction of entire monuments and buildings (Fig. 126).

Salt Valley Road quarry (MGA 446542E 6500089N)

Located about 1 km south-southeast of Gabidene Hill, the Salt Valley Road quarry has been the major quarry supplying stone in recent years. At this site, the glassy, silver-grey, coarse-grained quartzite has a prominent bedding cleavage dipping about 30° to the southwest. The quartzite is thinly bedded with strongly developed parting planes, many of which contain thin coatings of pale green fuchsite mica (Fig. 127).

The flaggy quartzite that has previously been worked has a total thickness of about 40 m. It splits easily into flagstones, commonly up to 0.5 to 1.0 m^2 in area and 5 to 20 cm in thickness (Low, 1960). Higher up on the ridge above the main quarry, there is a smaller quarry in which the quartzite's more exposed cleavage planes have undergone a distinct colour change to a light to mid-brown.

Although the Salt Valley Road quarry has been mined extensively over the years, remaining resources appear to be substantial. It is from the lower quarry that the well-known light green flagstones used in many decorative walls in the Perth region were sourced (Fig. 127; Appendix 3.25).

Petrographic description

This is a quartzite with poorly defined lenticular layers of very coarse through to a lesser medium-grained (irregularly granoblastic) mosaic of quartz. Macroscopically, this sample is a very compact crystalline quartzite, composed of several lenticular interlayers of coarser to finer granular quartz mosaic, enclosing minor pale greenish, discontinuous micaceous foliae. Greenish schistose mica forms a patchy veneer on the 'top' exposed surface. Petrographically, the estimated gross mineralogy is seen to be quartz (90%), very pale greenish mica (10%). The mica is basically muscovite, possibly the subspecies fuchsite with some chromium substitution (Fig. 128).

The dominant quartz forms an extremely compact mosaic, with intricate, sutured intergranular contacts, and with average grain size variations defining the lenticular layering seen in hand specimen. These grains are commonly elongate along the layering. Size range within most poorly defined layers is 0.5 to 2.5 mm but with a more consistent average size of about 0.5 mm in several other layers and lenses (some of which are incorporated within coarser layers). The muscovite occurs mostly as small flakes up to 0.5 mm long, commonly oriented (schistose) throughout various layers, and there are also several continuous (braided) muscovite foliae. There are trace extremely small (<0.1 mm) accessory minerals, possibly rutile and opaques.

Black and Tan quarry (MGA 443590E 6503694N)

The Black and Tan quarry is located approximately 2 km northwest of the Toodyay Road. The quarry is on the side of a northwest-trending ridge beneath a thick overburden

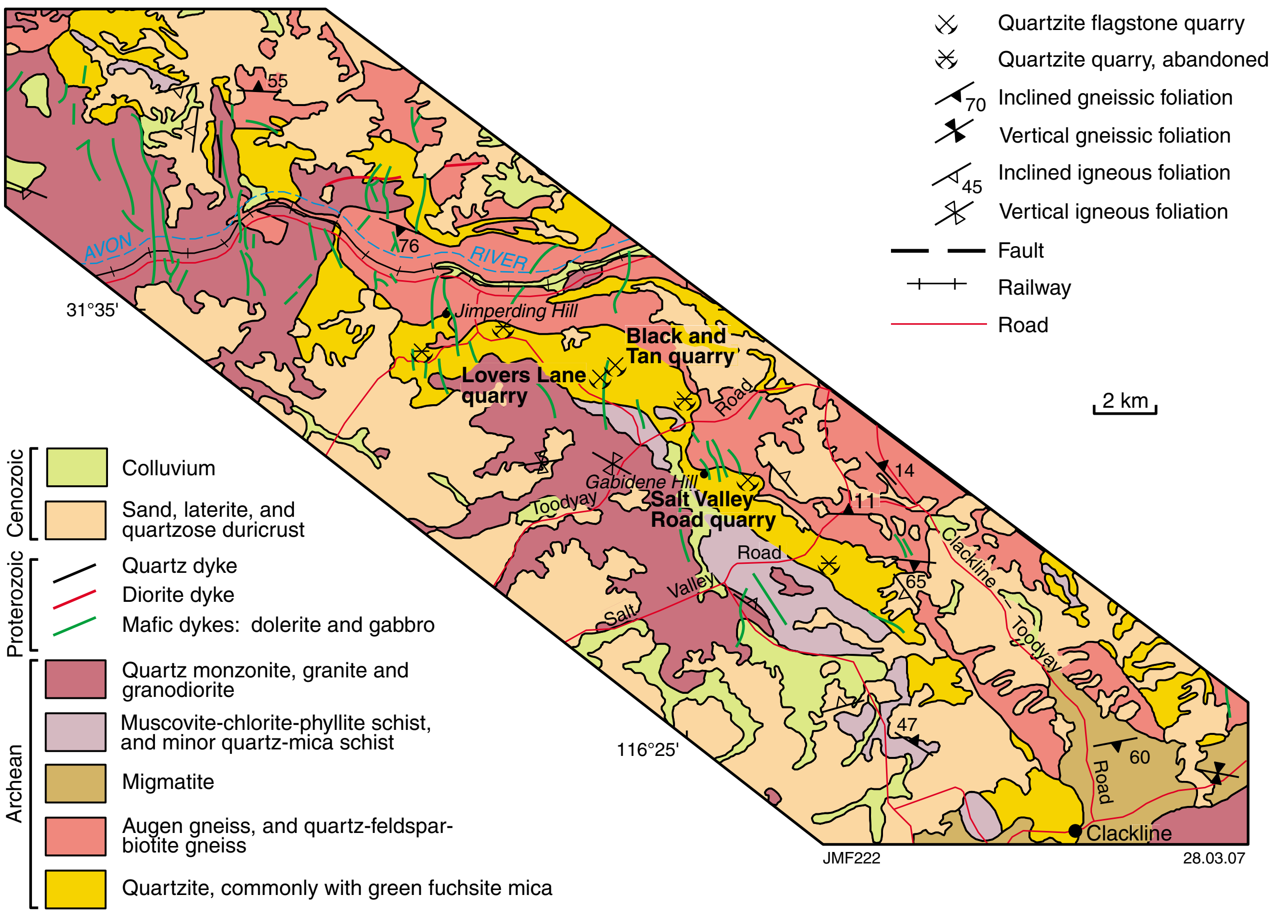

Figure 125. Geology of the area from Clackline northwest to Jimperding Hill and beyond (modified after Low et al., 1978)

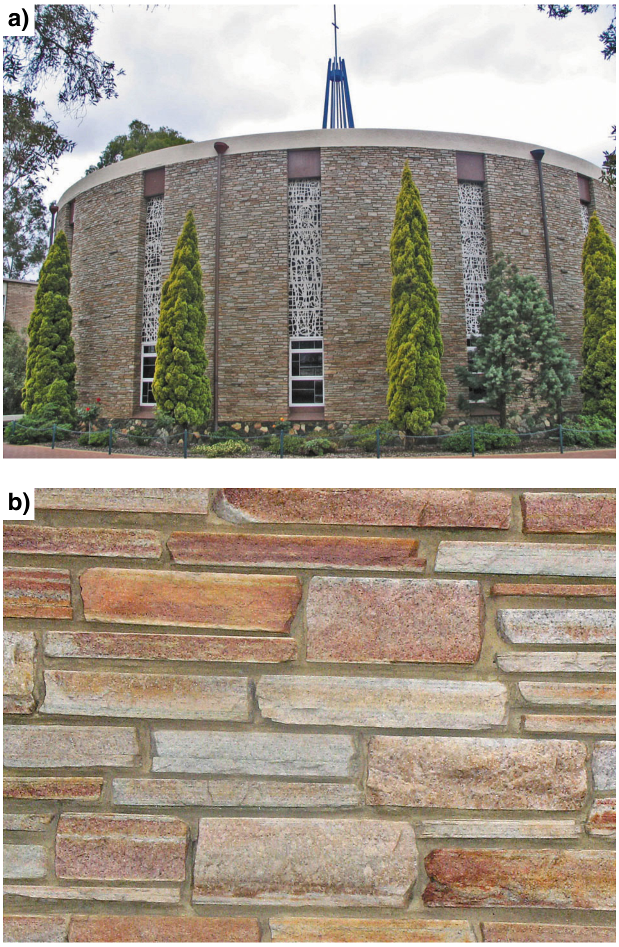

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Figure 126. Dimension stone used in chapel at Trinity College, East Perth: a) circular chapel wall constructed from *Toodyay Stone*: b) detail of mostly pale red-brown *Toodyay Stone* flagstones used in the chapel wall

of micaceous schist that must be removed to access the *Toodyay Stone*. Dip of cleavage at this point appears to be almost horizontal.

The quarry's adopted name, Black and Tan, was applied by Darling Earth Movers, the last operator. The quartzitic material extracted from the quarry is coloured mainly mid- to dark brown, and even some black surfaces are present (Fig. 129; Appendix 3.26). It appears that most of the quarried quartzitic flagstones from this site find use as flaggy, non-slip pavers.

Petrographic description

At this locality the 'quartzite' is represented by a weakly layered or micaceous, schistose, medium-grained metasandstone, or quartz-rich, fine micaceous schist.

Macroscopically, this rock is not specifically a quartzite, especially not in the same sense as the quartzite from Salt Valley quarry. It does have a homogeneous quartzitic (metasandstone) component incorporating weakly laminated schistose mica and minor sericitized feldspar. Estimated mineral abundances are quartz 78%, mica (biotite>muscovite) 15%, original feldspar, now sericitized 7%, and trace detrital zircon, tourmaline, and opaque oxide.

The quartz forms a homogeneous metamorphic mosaic with average size of the subpolygonal grains around 0.2 mm. Minor grains of feldspar form an integral part of this mosaic, but these are now completely pseudomorphically replaced by sericite, with minor sericite extensions being adjacent or intergranular. Flakes of biotite are greater than muscovite and up to 2 mm long as individuals and composites, with some forming short foliae. All micas are commonly oriented to form a foliation or schistosity throughout the fine quartz mosaic. Trace, scattered, resistate detrital grains of zircon are in excess of tourmaline and opaque oxide grains, all to 0.18 mm size.

Lovers Lane quarry (MGA 442970E 6503380N)

The Lovers Lane quarry is located about 750 m southwest of the Black and Tan quarry. It is a small excavation in an

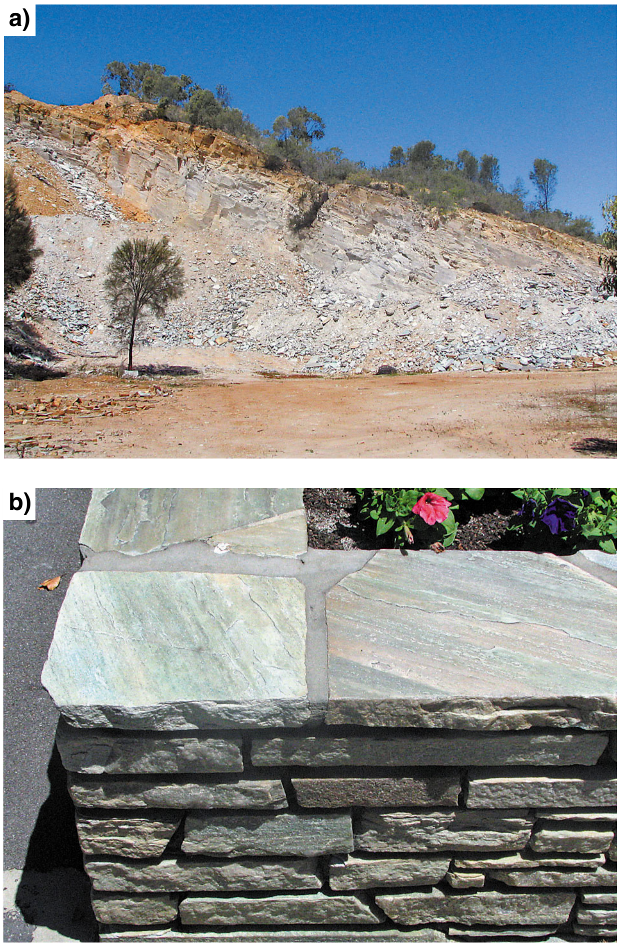

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Figure 127. Principal source and application of *Toodyay Stone* : a) coarse-grained, silver-grey quartzite exposed in the Salt Valley Road quarry; b) quartzite flagstones, exhibiting pale green fuchsite mica coatings on parting planes, used as decorative walls in Stirling Gardens, Perth City.

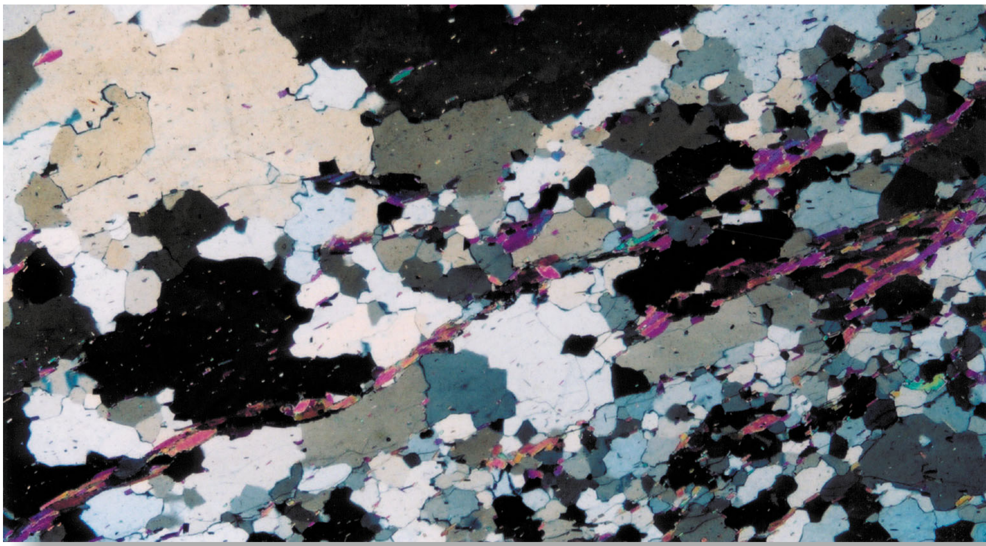

Figure 128. Photomicrograph of *Toodyay Stone.* Photo (polarized light x20) shows lenticular quartzite layers of fine to coarse quartz incorporating foliae and minor flakes of green fuchsite mica that commonly forms pale green coatings on surfaces of the stone (Pontifex, 2005)

Figure 129. A selection of more schistose, quartzitic forms of *Toodyay Stone* from the Black and Tan quarry ranging in colour from pale red-brown, medium brown, to dark brown

area of previous quarrying for quartzite with at least one large rehabilitated quarry about 500 m to the northwest. Quartzite in the Lovers Lane quarry is of the red-brown to mid-brown variety and was last mined in 2004. The quartzite in the quarry has been intruded by a quartz dyke comprising pale pink, saccharoidal, coarse-grained rose quartz (possibly of limited commercial interest). Remaining quartzite resources in the quarry are probably not large, but the surrounding area may have potential for other quartzite quarry sites for future needs.

Pinjarra Orogen – Leeuwin Complex

Gneiss

Woodlands (MGA 317090E 6259730N)

The Woodlands granitic gneiss prospect is located adjacent to Woodlands Road in the Wilyabrup district about 35 km west-southwest of Busselton (Fig. 130). At this locality, gneissic rocks form part of the Proterozoic Leeuwin Complex that extends from Cape Naturaliste south to Cape Leewin in the far southwest of the State.

The prospect, situated on freehold land, is part of an extensive area of outcropping, vertically foliated granitic gneiss. Immediately north, and adjacent to Woodlands Road is a stockpile of large gneissic boulders up to 1 m in length and 0.75 m thick, shown in Figure 31.

The rock has been identified as a hornblende-rich gneissic quartz syenite. Relatively unweathered stockpile

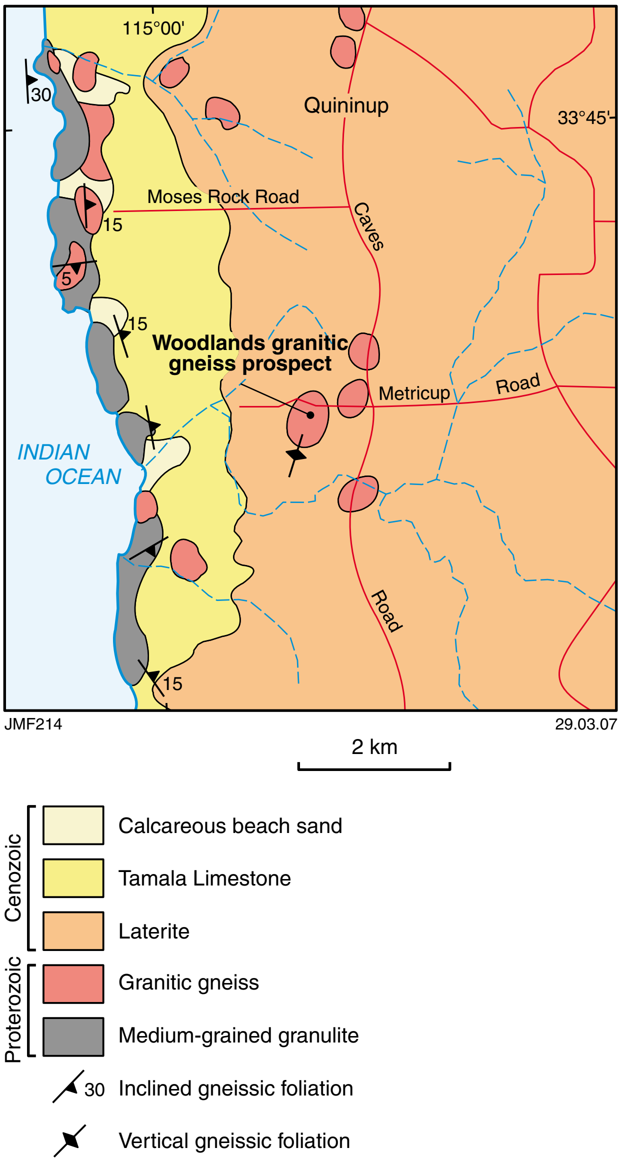

Figure 130. Geology of the Woodlands–Quininup area (modified after Lowry et al., 1967)

specimens are mid-brown in colour and exhibit a foliation defined by thin, roughly parallel, black bands of hornblende (Fig. 131). The cut stone is quite hard and takes a high polish displaying an attractive dark brown hue highlighted by a black linear texture (Appendix 3.27).

Petrographic description

This sample has a weak foliation defined by grains and lenses of hornblende, but is mostly granuloblastic and rich in K-feldspar. The visually estimated primary mineralogy includes 64% K-feldspar, 17% quartz, 12% plagioclase, 6% hornblende. 1% biotite and <1% opaque oxide, as well as myrmekite, apatite and relatively large grains of zircon or monazite. The mineralogy indicates a gneissic quartz syenite. The grain size is mostly less than 5 mm.

The K-feldspar is perthitic but mostly untwinned, apart from occasional grains with twinning in rim zones, suggesting orthoclase passing into microcline. Plagioclase is distributed irregularly and is largely unzoned with minor myrmekite not always adjacent to plagioclase. The quartz is anhedral and only weakly deformed, with subgrains throughout. The hornblende is anhedral and very dark-greenish brown in colour, suggesting titaniferous ferrohastingsite, and is accompanied by minor dark brown biotite and very minor opaque oxide. Most of the apatite occurs in and adjacent to hornblende and biotite, with zircon or monazite to 0.4 mm in grain size. The K-feldspar has a pale brown iron staining and there are microfissures filled with carbonate, but alteration is weak.

Southern Carnarvon Basin

Sandstone

Northampton (MGA 254471E 6865018N position approximate)

The town of Northampton is located on the North West Coastal Highway about 45 km north of Geraldton. An abandoned quarry that supplied sandstone blocks for historic buildings in Northhampton is situated approximately 14 km west-northwest of the town (Fig. 132).

Figure 131. Woodlands hornblende-rich gneissic quartz syenite

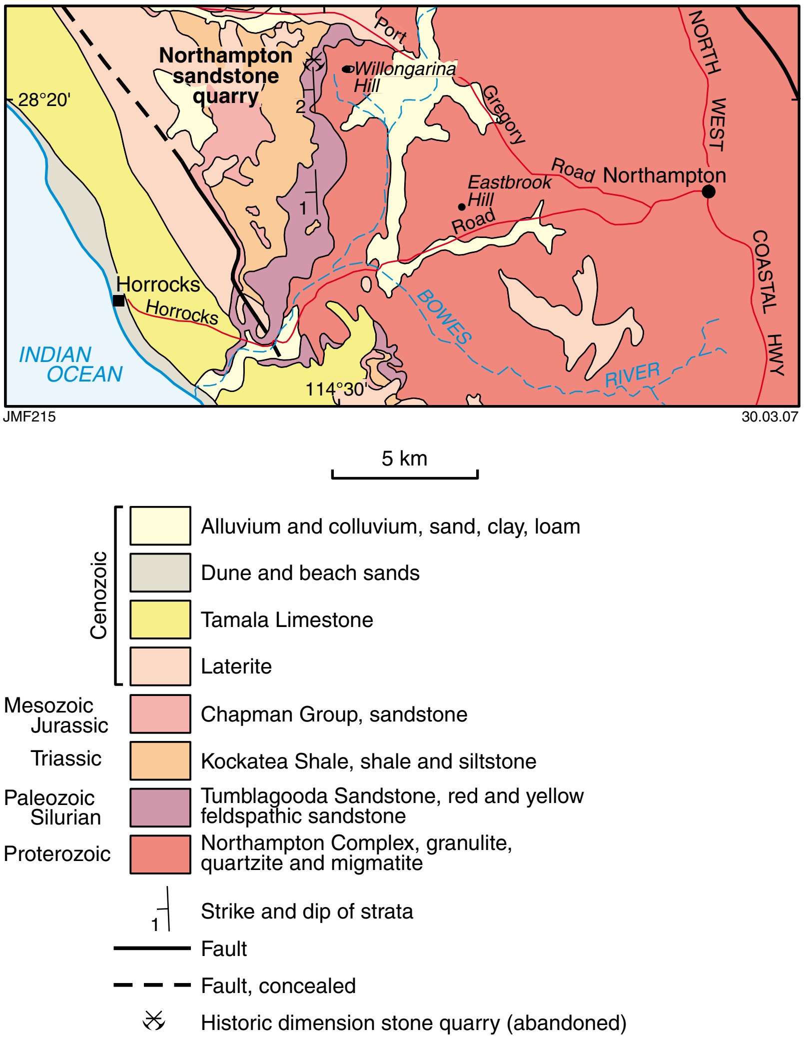

Figure 132. Geology of the Northampton area (modified after Playford et al., 1971)

The old quarry is sited in Silurian Tumblagooda Sandstone, a variably coloured feldspathic sandstone that in the local area comprises two facies of fine- to medium-grained, bioturbated sandstone interbedded with fine- to very coarse grained, poorly to moderately sorted, quartz sandstone (Hocking, 1991).

The quarry site, located on Mineral Claim 31, was inspected by Connolly (1959) who noted that the sandstone beds suitable for use as building stone varied in colour from pink to white, cream, and buff and were almost horizontally bedded with a slight dip of no more than 2° to the west. Fine to coarse, subangular to rounded quartz grains were observed to be cemented by a rather weak siliceous cement leading to a slight friability present only on the edges of the stone. Bedding thicknesses were seen to vary from 5 to over 90 cm over a 12 m section. A conformable pebble conglomerate bed was also noted.

It was thought that uniformity of colour for the pink sandstone could be difficult to attain but that small quantities of this material could possibly find a specialized market. However, there was a very large resource of both cream- and buff-coloured sandstones available for quarrying. It was concluded that because of the slight friability and cracking present in the stone, the overall quality was slightly inferior in quality to the better known Donnybrook Sandstone.

Perth Basin

Basalt

Jules Road and other quarries (MGA 374607E 6303899N)

Bunbury Basalt is currently mined by CSR-Readymix Quarries at a large quarry at Jules Road, Gelorup, 8 km south of Bunbury (Fig. 133). South of Bunbury, the basalt overlies the Yarragadee Formation, having flooded paleovalleys eroded into Yarragadee sedimentary rocks around 136 m.y. ago (Freeman, 1996). The rock is a tholeiitic, highly jointed, columnar, dark grey basalt of early Cretaceous age (Fig. 134).

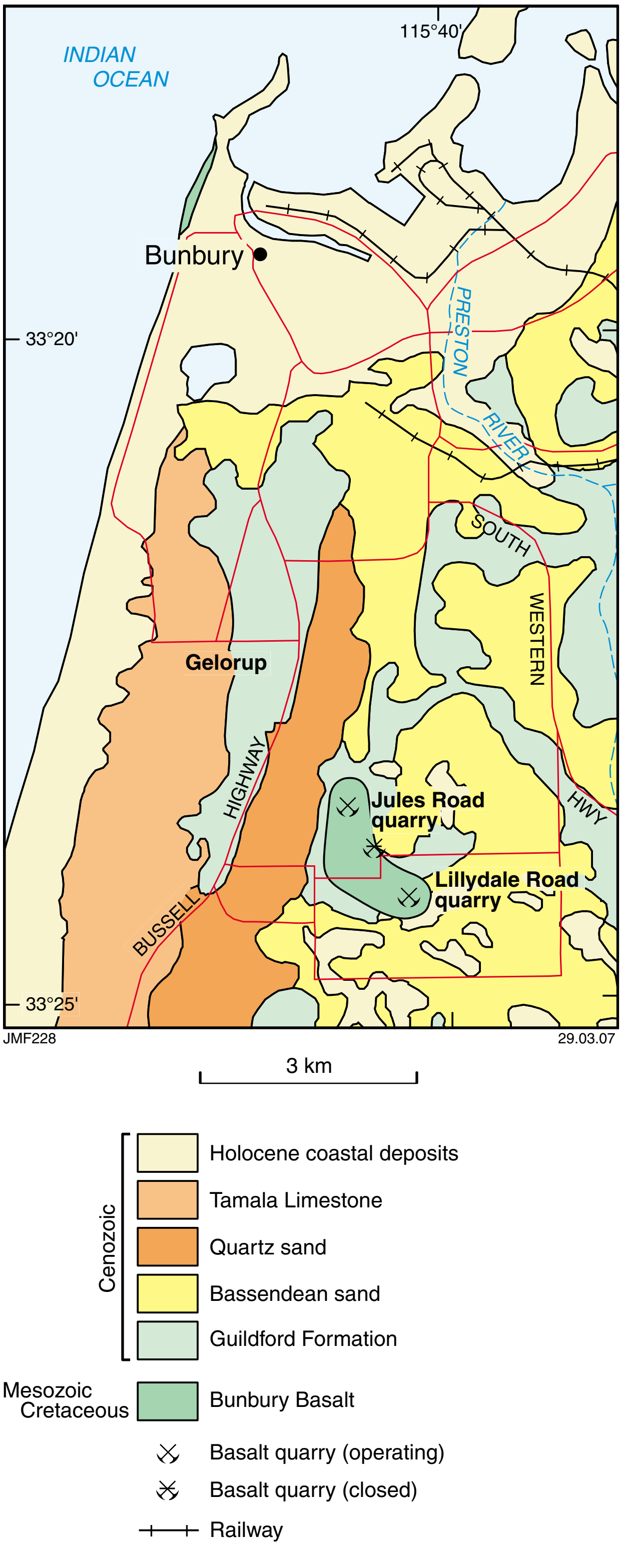

Figure 133. Geology of the Bunbury area (modified after Lowry et al., 1983)

Figure 134. Black, columnar Bunbury Basalt at the Gelorup quarry, 8 km south of Bunbury

Currently, the quarried basalt is crushed on site and is used mainly for road aggregate. However, as in the past, the stone could be used as setts and blocks for ornamental streetscaping projects, and possibly as black, polished blocks up to 30 or 40 cm wide in ornamental walls and memorials (Appendix 3.28).

Two other basalt quarries are also located in the Gelorup area. Another operating quarry, owned by Hanson Construction Materials Pty Ltd, is located about 1.5 km to the southeast of the Readymix quarry at Lillydale Road. A third quarry, formerly owned by Pioneer Concrete (WA), is an abandoned site only several hundred metres southeast of the current Readymix operation.

Petrographic description

This rock appears to be a plagioclase-porphyritic basalt with some alteration to smectite. Disseminated plagioclase phenocrysts make up about 7% of the rock, together with <1% clinopyroxene phenocrysts in a fine-grained groundmass with 52% plagioclase, 33% clinopyroxene, 3% opaque oxide and 5% mostly interstitial brown smectite.

Uncommon larger patches (≤2 mm) of smectite are present and may represent former olivine. The phenocrysts are 1 to 3 mm long with most groundmass plagioclase less than 0.7 mm and very fine grained clinopyroxene (apart from microphenocrysts) 0.3 to 1 mm long. Much of the opaque oxide is platy, suggesting ilmenite, but some magnetite may also be present.

Sandstone

Geraldton

White Peak quarry (MGA 268461E 6828858N)
Chapman Valley Road quarry (MGA 275853E 6823500N)

In the Geraldton area, the abandoned White Peak and Chapman Valley Road quarries are located about 13 km north and northeast of the town respectively (Fig. 135). These quarries, as well as a number of other unknown sites, were extensively mined in the first half of the 20th century to provide sandstone blocks for the construction of historic stone buildings in Geraldton (see Chapter 4).

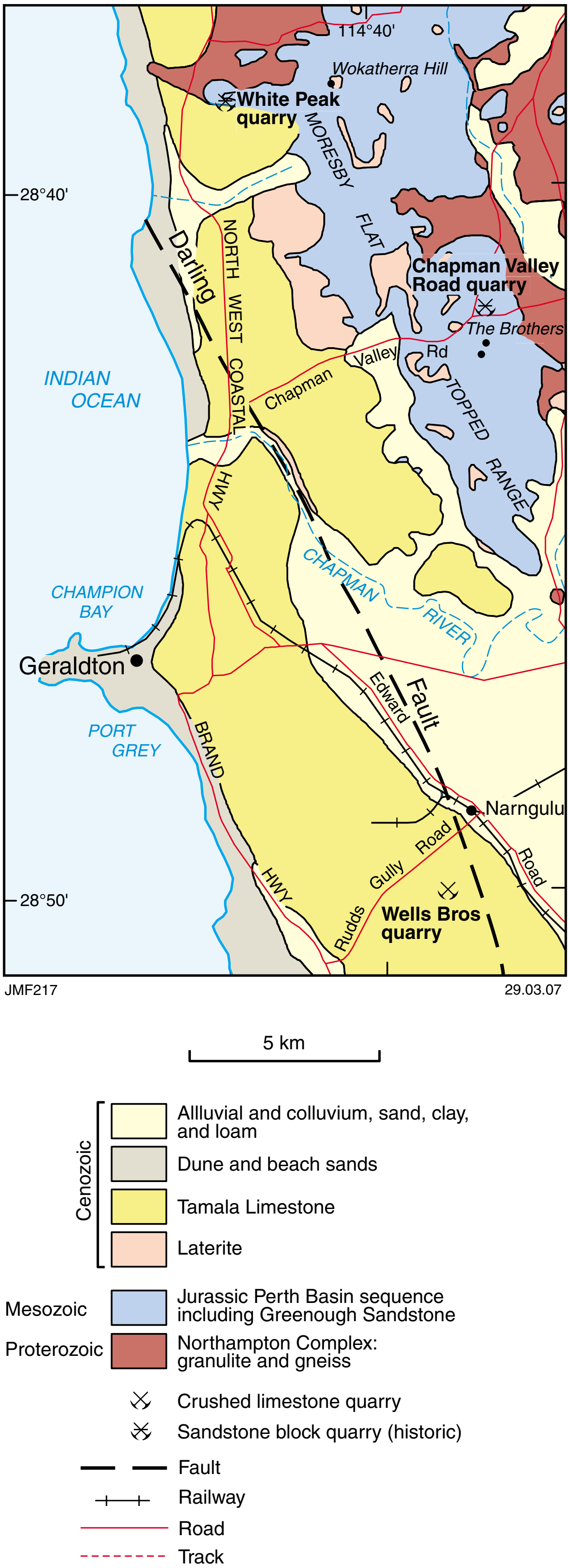

Figure 135. Geology of the Geraldton area (modified after Playford et al., 1971)

Stone from these quarries was derived from the Lower Jurassic Greenough Sandstone, a partially weathered, coarse- to medium-grained, bedded sandstone. This durable and readily worked, slightly ferruginous sandstone has a visually attractive mottled colouring appearing as shades of red, yellow, purple, and white (Playford et al., 1970).

Donnybrook

The multicoloured, Early Cretaceous Donnybrook Sandstone (125 Ma) is located near the town of Donnybrook, about 40 km south-southeast of Bunbury. In this area, the sandstone extends in a narrow, north-trending zone to the north and south of the town. (Fig. 136). It is a shallow marine sandstone that occurs as a series of discontinuous outcrops, consisting of deep pockets of massive sandstone, extending in a narrow northerly trending zone for about 24 km along the western escarpment of the Darling Fault. The formation has a northerly strike, and a dip of 5 to 10° to the west, and comprises sandstone and minor interbedded shales. The unit appears to be of variable thickness (possibly up to 200 m) with information from hillside sandstone exposures indicating thicknesses of at least 60 m. Drillholes in the vicinity of Donnybrook townsite have recorded thicknesses up to 134 m (Wilde and Walker, 1982; Backhouse and Wilson, 1989).

Drillhole data obtained from the vicinity of the Donnybrook Stone quarry, 4 km south of the town, indicate the Donnybrook Sandstone adjacent to the Darling Fault zone unconformably overlies a sequence of Permian claystones up to 165 m thick. These claystones in turn rest unconformably on Archean gneisses, schists, and quartzites of the Yilgarn Craton. Approximately 500 m east of the Donnybrook Stone quarry, a north-trending, inferred fault is indicated (Fig. 136). To the east of this fault, the sandstone appears to have been displaced downwards by around 70 m and may rest directly over the Archean metamorphic rocks (Backhouse and Wilson, 1989). Together with possible differences in local weathering regimes, this interpretation may explain the noticeable difference in colour and lithology between the typically white to beige coloured sandstones in the west, and the more variable, highly coloured sandstones found in the east, particularly in the Beelerup area.

The sandstone was originally described by Simpson (1917) as ‘a feldspathic sandstone whose principal bonding is kaolin or halloysite. In colour it varies from pure white to deep buff or exceptionally deep pink, the paler coloured stone invariably darkening evenly on exposure to air. In grain [size] it varies from very fine to moderately coarse.’ Further work by Carroll (1941), revealed the sandstone to be on average ‘a medium to fine-grained rock consisting of about 75 per cent quartz [rounded to subangular]; the remainder is feldspar, both oligoclase and microcline, kaolinite or other clay mineral supplying the binding.’ Also, some sandstones were shown to contain appreciable amounts of heavy minerals, mainly magnetite, ilmenite, leucoxene and zircon.

The value of the massive, finer grained sandstone as a building material was first recognized in about

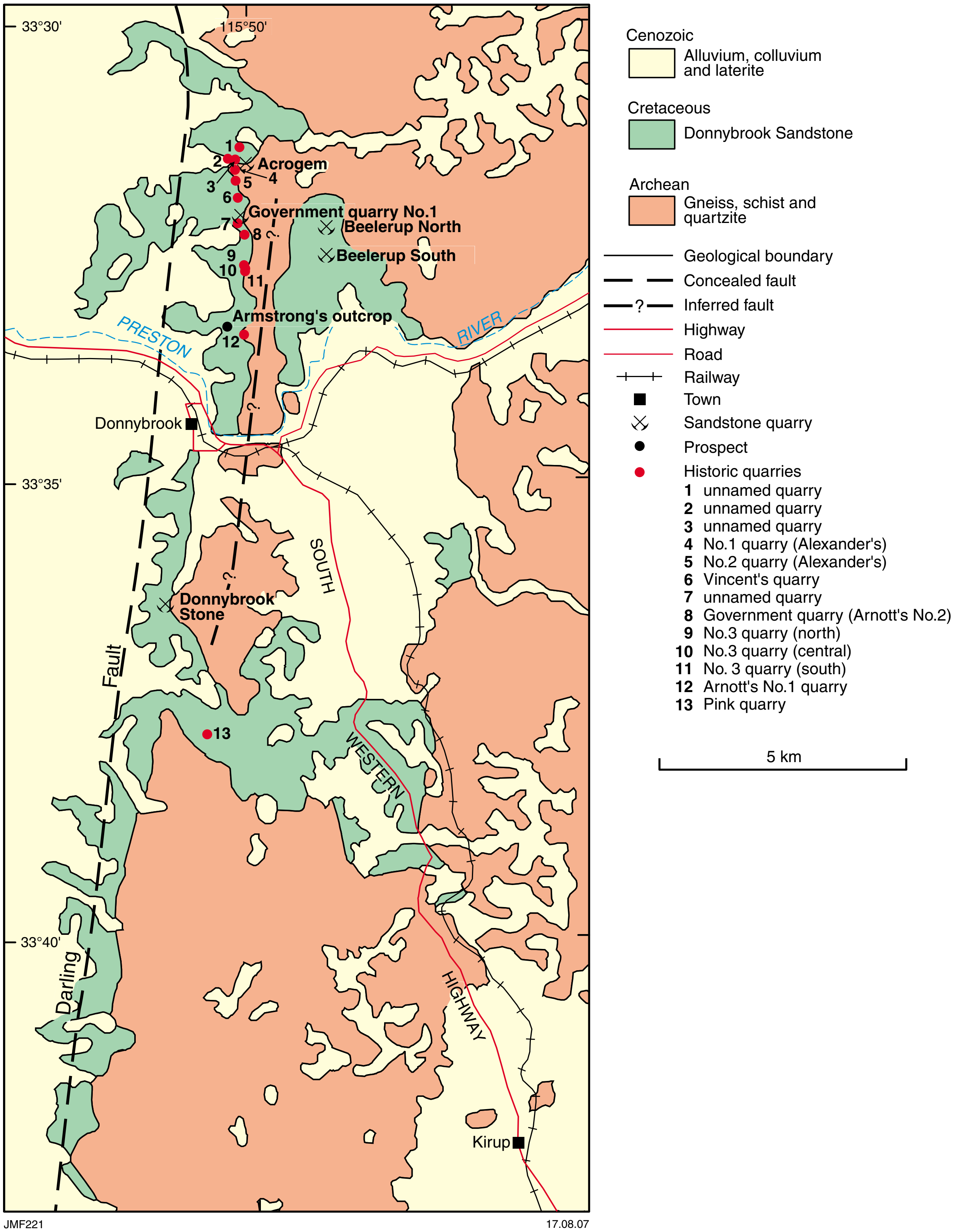

Figure 136. Geology of the Donnybrook area (modified after Lowry et al., 1983)

1895. In addition, the stone's natural hardness as well as its consistency of colour within individual quarries made it a high-quality dimension stone (Fig. 22; cover photograph).

A total of 18 sandstone quarries and one prospect have been identified in the Donnybrook area (Fig. 136). All but five are abandoned quarries that provided sandstone blocks for many of Perth's heritage sandstone buildings mostly during the first three decades of the 20th century (see Chapter 4). Of the currently operating quarries, Acrogem, and Government quarry No. 1 are located about 4 to 5 km north of Donnybrook, Beelerup North and South are located about 4 to 5 km northeast of the town, and Donnybrook Stone quarry is situated 4 km to the south-southwest.

Investigations and sampling by the author indicate that with the possible exception of the white to beige, predominantly fine to moderately coarse grained sandstone from the Acrogem quarry, material obtained from the other active quarries appears to be quite variable depending on the particular horizon from which the rock is sourced. In the west, between the Acrogem and Donnybrook Stone quarries, grain size appears to vary from very fine to coarse with colours ranging from white to off-white, mid-brown and minor pink. By contrast, in the east around Beelerup, the predominance of mottled, yellow to deep pink and golden brown sandstones is noticeable. Throughout the Donnybrook area, many sandstones also display visually attractive, concentric, pale- to golden-brown liesegang ring banding. Consistency of colour is an important feature in any substantial dimension stone project. Over many years of quarrying the Donnybrook Sandstone, it has been demonstrated that the area has adequate resources of high-quality stone of consistent colour to suit most construction projects specifying sandstone blocks or slabs.

The physical properties of this massive, fine-grained sandstone make it particularly suitable for use as a dimension stone. In selected quarries, the massive nature of the stone, combined with the paucity of natural joints or other fracture planes, makes it possible to extract very large blocks using diamond wire saws backed up by lines of vertical or horizontal drillholes as required (Fig. 137a). In general, the use of controlled explosives is not required. Important physical properties of absorption, bulk density, compressive strength, modulus of rupture, and abrasion resistance for the Acrogem and Beelerup sandstones are given in Table 9. Here it may be seen that the sandstones at Donnybrook are of high quality and fall well within the limits for sandstone set by the American Society for Testing and Materials (ASTM).

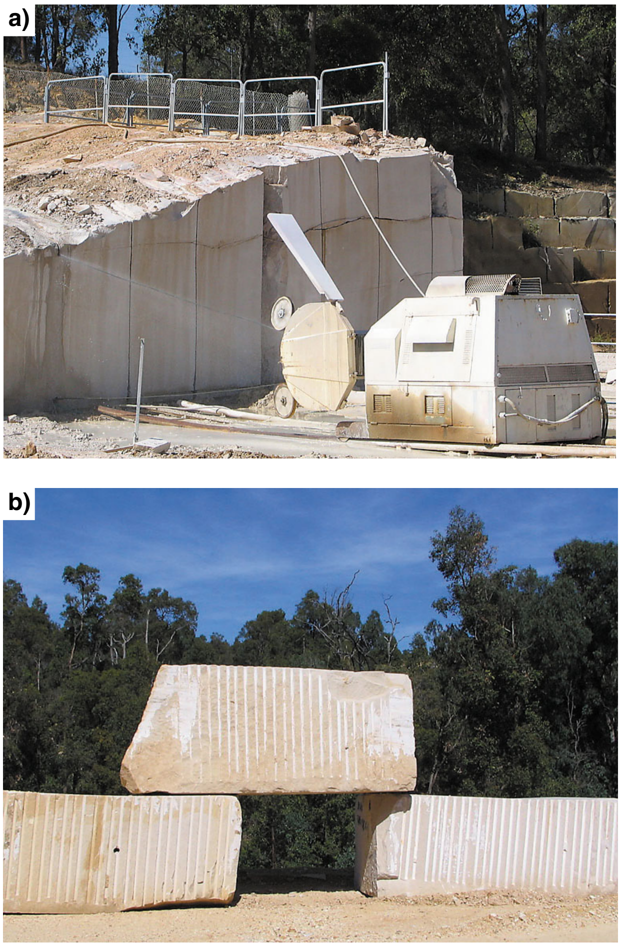

Figure 137. Acrogem quarry operations: a) diamond wire sawing a wall of fine-grained Donnybrook Sandstone into large blocks; b) Ten tonne blocks of fine-grained, off-white sandstone destined for export to Europe

Table 9. Physical properties of the Donnybrook Sandstone and ASTM specifications for sandstone

Donnybrook Sandstone	*Absorption (weight %)*	*Bulk density (t/m³)*	*Compressive strength (MPa, dry)*	*Modulus of rupture (MPa dry)*	*Abrasion resistance (Taber index:Ha)*
ASTM test:	*C97 (max.)*	*C97 (min.)*	*C170 (min.)*	*C99 (min.)*	*C1353 (min.)*
sandstone	*8*	*2.00*	*27.6*	*2.4*	*2*
Acrogem sandstone	3.5	2.4	70.0	12.0	na
Beelerup sandstone (average values)	3.7	2.3	83.0	11.0	20

NOTES: ASTM standard values in italics
na: not available

SOURCE: Data courtesy Gosford Quarries Pty Ltd and Meteor Stone

The natural hardness of these massive sandstones tends to create a brittleness in the stone which may cause blocks to break unevenly at one end during the extraction process. This effect may be seen in one of the export-grade blocks shown in Figure 137b. However, this natural hardness and fine-grained texture of many of the sandstones at Donnybrook gives the stone its long-established reputation as a dimension stone eminently suitable for the production of high-precision cut blocks and slabs, as well as for intricate, high-quality carving, a feature adequately demonstrated in Figure 23.

In 2006, a private consortium carried out a sandstone resource evaluation program in previously unexplored areas north of Donnybrook. At several sites, drillholes returned unbroken cores of high-grade sandstone in excess of three metres. To date, resource estimates indicate the possibility of a substantial resource of mineable stone. Investigations are continuing.

A more complete account of the Donnybrook Sandstone and its application as a dimension stone is given in Fetherston (2005).

Acrogem quarry (MGA 391622E 6289852N)

The Acrogem quarry, operated by Gosford Quarries Pty Ltd is located about 5 km north of Donnybrook (Fig. 136). At this site, the company is continuously extracting large blocks, mainly by diamond wire sawing backed up by close-spaced drilling, from different levels on the side of a hill where sandstone resources appear to be extensive (Fig. 137a). Two high-quality varieties of fine-grained sandstone are quarried; white to off-white, and banded buff to pale brown (Appendix 3.29).

White, 10 t, export-grade blocks are shipped to customers in Europe (Fig. 137b) and the remainder of the production is transported by road to Gosford Quarries processing plant at Somersby near Gosford in New South Wales. At the Somersby plant, slabs of somewhat variable length and breadth (approximately 2 × 1 m) are diamond sawn to 30 mm thickness, and also to thicknesses of 40, 50, 75 mm and upwards, either by diamond wire or gangsawing to produce a smooth or slightly textured finish respectively.

In 2002, a decorative wall of pale beige, medium-grained Donnybrook Sandstone sourced from the Acrogem quarry was built on the grassed area between Old Parliament House and Lake Burley Griffin in Canberra (Fig. 138). This spectacular wall, featuring golden-brown, ring-banded highlights was built into a hillside forming the backdrop to Commonwealth Place. The wall is approximately 100 m in length and reaches a maximum height of about 5 m at its centre where a walkway leads to Reconciliation Place beyond.

Petrographic description

This is a porous, fine- to coarse-grained, quartz-rich sandstone with disseminated K-feldspar and no obvious bedding indicators. Most coarse grains are angular to subrounded, from 0.1 to 0.8 mm long, with single-crystal quartz grains as the most abundant type. Visually estimated mineralogy includes detrital grains of quartz (single grains) 76%, lithic grains (quartz-rich to sericite-rich) 9%, orthoclase 3%, microcline 2%, plagioclase(–sericite) 2%, and accessory tourmaline and zircon in trace amounts. Porosity is estimated at 8% (by volume).

Lithic grains and various feldspar types are also present. The lithic grains include polycrystalline quartz, ranging from granular to foliated, cherty quartz, quartz–sericite schist clasts and mostly massive sericite-rich grains. The feldspars include orthoclase, microcline and variously fresh, partially sericitized or etched/dissolved plagioclase. Rare heavy minerals include tourmaline and zircon to 0.15 mm grain size. The porosity is mostly interstitial with minor clay patches that are also interstitial to the detrital grains.

Government quarry No. 1 (MGA 391346E 6288756N position approximate)

The historic Government quarry No. 1 is located about 4 km north of Donnybrook (Fig. 136). In recent years, selected sites within the main quarry have been worked by a number of operators. For a period during 2003–04, Irishtown Sandstone Pty Ltd produced sandstone blocks in buff, white and pink from this location. Material was targeted at building construction, monumental, and

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Figure 138. Donnybrook Sandstone wall framing the entrance to Reconciliation Place, Canberra

landscaping projects and a winery at Forest Hill near Denmark was constructed from this material. Since that time, it is understood that sandstone products have been produced from stone sourced from existing stockpiles.

Donnybrook Stone quarry (MGA 390091E 6280633N)

The Donnybrook Stone quarry is located about 4 km south of Donnybrook (Fig. 136). At this site, the Donnybrook Stone Company extracts sandstone blocks by close-spaced drilling and diamond wire sawing (Fig.139a). In the quarry, lithological breaks in the sandstone sequence provide near-horizontal breaks commonly used as benches over target stone horizons. The company produces a diverse range of visually attractive, textured stone, ranging from very fine grained white and off-white, through to coarse-grained, banded, golden-brown to mid-brown sandstones (Appendix 3.29). Resources in the area surrounding the quarry may be substantial, although overburden appears to be reasonably thick in places.

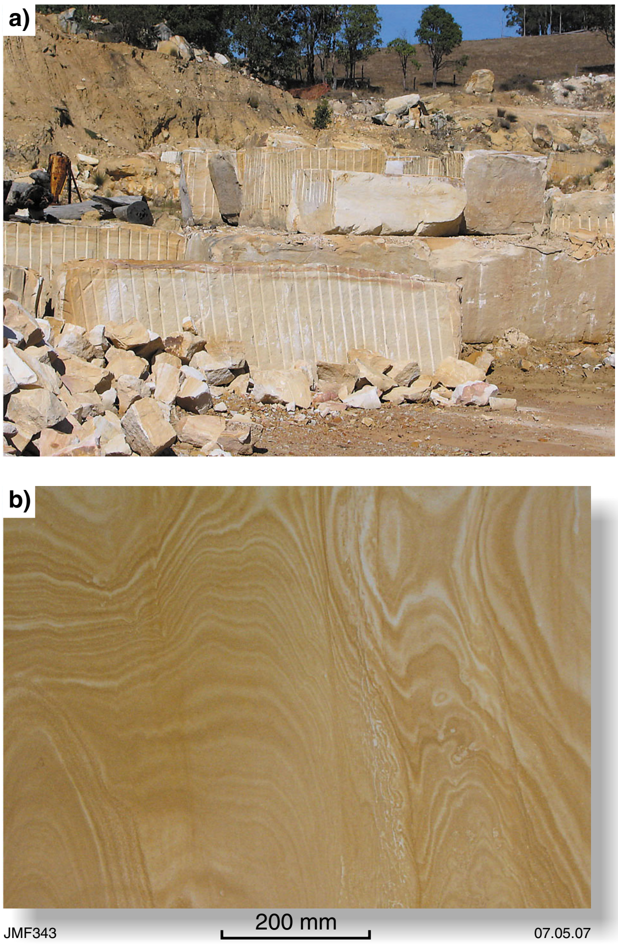


Figure 139. Donnybrook Stone Company operations: a) sandstone blocks in the Donnybrook Stone quarry; b) cut slab of pale brown sandstone displaying an attractive liesegang ring pattern from the company's Donnybrook quarry

At its Bibra Lake processing plant located in Perth, the company produces large slabs up to 3 × 1.5 m in length and breadth, and in thicknesses ranging from 10 mm upward for use in the production of paving blocks and wall cladding slabs, as well as 100 mm thick blocks for solid housing bricks (Fig. 139b). A profiling saw is also used to manufacture sandstone mouldings, skirtings, mantelpieces, door and window surrounds, steps and handrails. Craftsmen also manufacture large sandstone tables, vanity units and kitchen benchtops. Other material is cut for landscaping and stepping stones. In recent years, the company has supplied sandstone blocks for the construction of substantial offices and private homes in suburban Perth.

Petrographic description

This sample is a porous, pale brown, fine- to very coarse grained, quartz-rich sandstone containing minor K-feldspar. Most of the sandstone is poorly sorted with angular to subrounded grains (0.1 – 1.5 mm) but it also contains bedded layers of fine-grained sandstone (<0.25 mm) and medium-grained sandstone (0.25 – 0.5 mm). These layers also contain minor grains exceeding 1 mm in length.

Quartz makes up most of the detrital grains but there are quartz-rich (partly cherty) to sericite or clay-rich, massive to foliated lithic grains. Minor K-feldspar seems to be partly orthoclase and partly microcline with rare, possibly authigenic, adularia. Detrital muscovite is rare and occurs partly as inclusions in quartz. Uncommon zircon crystals occur mostly in the fine- to medium-grained sandstone layers as angular grains up to 0.1 mm in diameter. Visually estimated mineralogy includes detrital grains of quartz (single grains) 75%, lithic grains (sericite/clay-rich to quartz-rich) 9%, orthoclase 2%, microcline 2%, and muscovite <1%, and accessory zircon in trace amounts. Porosity is estimated at 12% (by volume).

Some pores can approach 3 mm in length, whereas others are interstitial to the detrital grains, which seem to lack optically continuous overgrowths. It is possible that sparse interstitial clay may be present, albeit in very small amounts (<1%).

Beelerup quarries

Beelerup North (MGA 393353E 6288384N)
Beelerup South (MGA 393246E 6287801N)

The Beelerup quarries, owned by Meteor Stone, are situated 4 to 5 km northeast of Donnybrook (Fig. 136). Beelerup North quarry site is on the side of a substantial hill where available resources are probably extensive (Fig. 140). Resources may be somewhat reduced at the Beelerup South quarry owing to its proximity to a small watercourse. During mining operations, diamond wire sawn blocks are extracted and transported to Perth to the company's processing plant at Landsdale. During processing, blocks around 2 m in length comprising fine- to medium-grained, off-white to pale brown sandstone, commonly mottled with irregular patches of yellow, pink and deep red are diamond cut into slabs according to

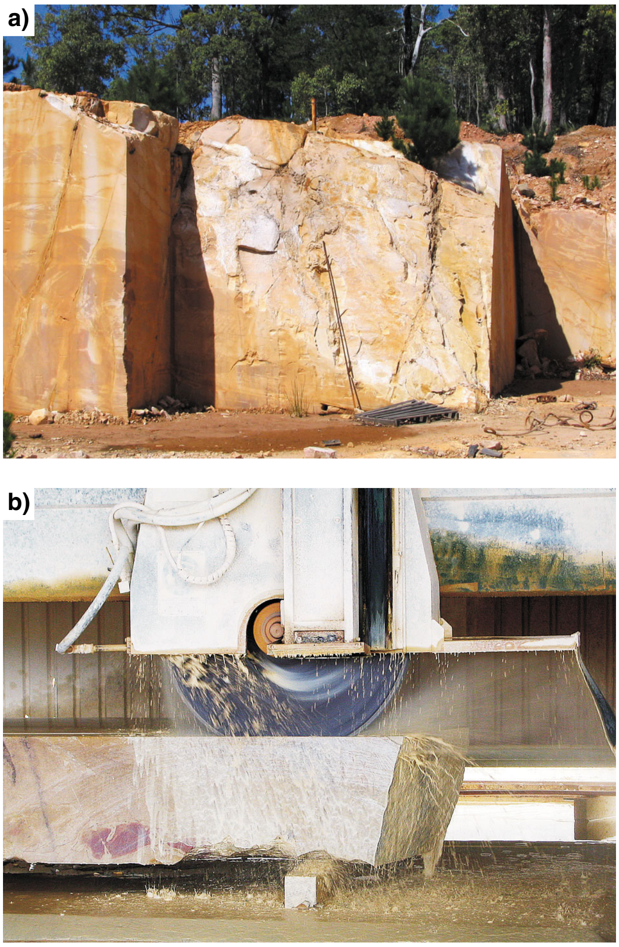


Figure 140. Processing sandstone from Beelerup: a) diamond wire-cut faces in Meteor Stone's Beelerup North quarry; b) slab sawing fine-grained, beige sandstone displaying visually attractive red mottles

customer requirements (Fig. 140). Cladding is usually supplied in lengths of up to 1 m and widths to 0.3 m. Thicknesses generally range from 20 to 30 mm but may reach 50 mm. Meteor Stone supplies cut slabs of this material that are both visually striking and attractive for the creation of wall cladding and landscaping features throughout Australia (Appendix 3.29).

Petrographic description

This is a poorly sorted, quartz-rich sandstone ranging from very fine to coarse grained. The sandstone contains irregular limonite-stained areas together with relatively abundant K-feldspar. No bedding laminations are evident in the thin section and the limonite seems to have affected feldspar grains.

The poorly sorted grains range from 0.05 to 0.5 mm in diameter (very fine to medium grained), with sparse, coarse grains to 0.8 mm. Single-crystal quartz grains are dominant with smaller amounts of K-feldspar (mostly microcline). Sericite-rich lithic grains are also common and appear to be stained with limonite. Some of the quartz has optically continuous overgrowths, including grains showing crystal faces. Interstitial clay, possibly illite(–kaolinite), is disseminated, in places within void spaces. Heavy minerals include leucoxene and tourmaline. Visually estimated mineralogy includes detrital grains of quartz 65%, K-feldspar 15%, sericitic lithic grains with some limonite 12%, interstitial illite(–?kaolinite) 8%, and trace amounts of accessory leucoxene and tourmaline.

Limestone (calcarenite)

In Western Australia, the Pleistocene Tamala Limestone and equivalent units extend, in places both parallel and close to the modern coastline, from Shark Bay on the central west coast south to Cape Leeuwin, and east to Esperance along the south coast. This limestone unit consists mainly of a fine- to coarse-grained, cream to pale brown, eolian calcarenite.

The State's limestone building block industry is located at sites extending from Geraldton in the north, to the Perth Metropolitan area, and south towards Bunbury. Currently, the only areas where natural limestone blocks are quarried from high-grade limestone is in the Carabooda–Nowergup area in the northern fringes of the Perth metropolitan area, and at Moore River in the Guilderton area about 80 km north-northwest of Perth. The overall strength of the calcarenite limestone is governed by the stone's physical properties of compressive and flexural strength that appears to be related to a high calcium carbonate ($CaCO_3$) content in excess of 85% for high-grade building block material (Abeysinghe, 1998).

In other extractive areas, the limestone is mostly too soft for cutting natural stone blocks. This is attributed to the lower strength limestone present in these areas where the calcium carbonate content ranges between a high of 78% and a minimum of 48%. In these areas, lower grade limestone is crushed and used for the manufacture of reconstituted limestone blocks, pavers and other products. This is the case for a number of sites in the Carabooda–Nowergup area, and also in the Yanchep area north of Perth, Hope Valley north of Kwinana, Narngulu southeast of Geraldton, and a number of private operations at Myalup and Kooallup north of Bunbury.

Calcarenite limestone samples collected by the author from selected sites in the region were submitted for chemical analysis and the results are shown in Table 10 together with analytical data from Abeysinghe (1998). In the northern Perth region these analyses mostly bear out the assessment that a high-grade limestone building block's relative strength may commonly be related to its high $CaCO_3$ content.

Perth region

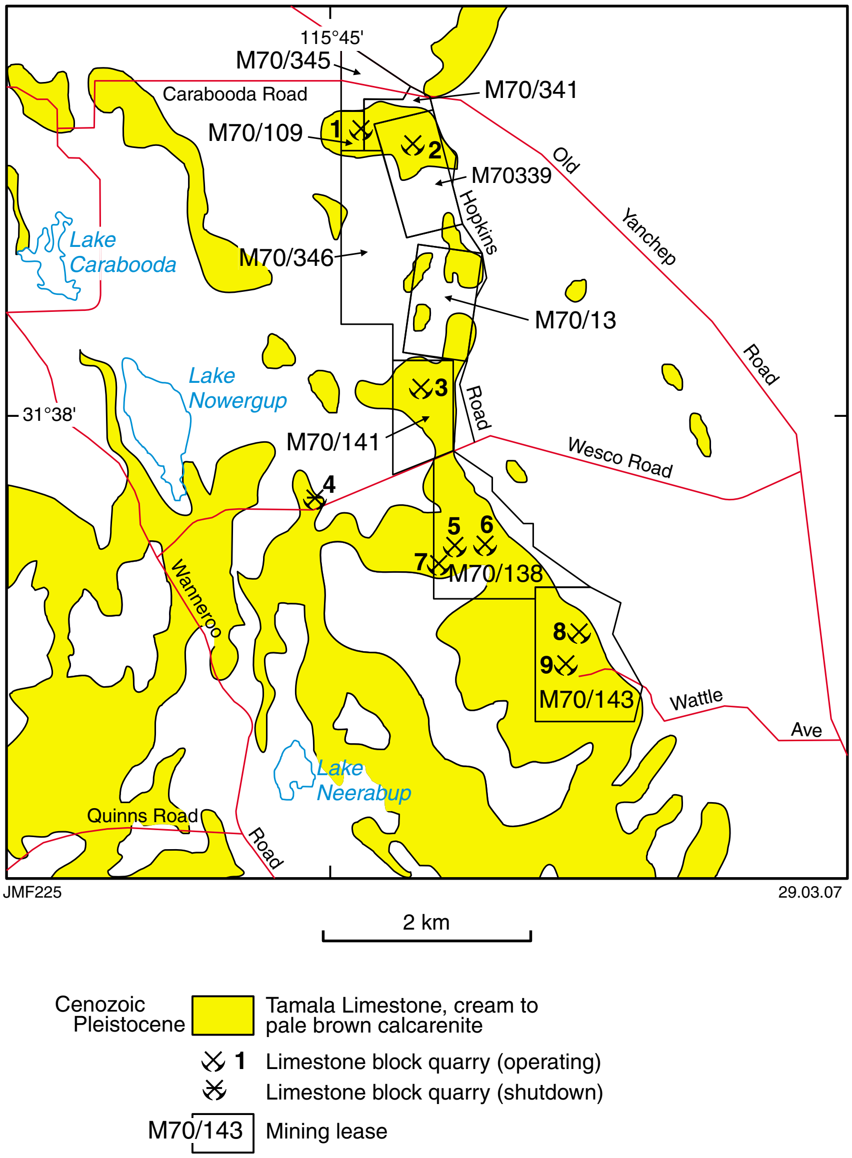
Carabooda–Nowergup

The Carabooda–Nowergup area is in the Wanneroo region of Perth's northern fringes, between 35 and 40 km north-northwest of the city (Fig. 141). In recent

Table 10. Chemical analyses of Tamala Limestone at limestone building block quarries and prospects

Locality	*GSWA sample no.*	SiO_2	Al_2O_3	*CaO*	Fe_2O_3	K_2O	*MgO*	Na_2O	P_2O_5	TiO_2	*MnO*	*LOI (105–1000ºC)*	***Total***	*Estimated $CaCO_3$ content*
							Percentage							
Seabird Road, Seabird[a]	132229	6.13	0.40	48.93	0.01	0.18	0.89	0.16	0.06	0.03	<0.01	42.20	**98.99**	87.38
Lancelin Road, Seabird[a]	132228	17.69	0.57	45.66	0.38	0.25	0.28	0.01	0.05	0.07	<0.01	36.09	**101.05**	81.54
Moore River, Guilderton	178634	33.30	1.63	34.60	0.20	1.07	0.57	0.16	0.049	0.04	<0.01	27.8	**99.43**	61.79
Wilbinga Grove, Wilbinga[a]	132227	23.14	0.53	41.14	0.07	0.29	0.19	0.12	0.09	0.03	<0.01	34.24	**99.84**	73.46
Military Road, Yanchep	178653a	29.40	0.60	37.60	0.15	0.32	0.32	0.06	0.026	0.02	<0.01	30.3	**98.81**	67.14
Cutler Road, Carabooda	178635	8.66	0.66	49.90	0.10	0.37	0.69	0.07	0.053	0.02	<0.01	39.4	**99.93**	89.11
Hopkins Road, Carabooda[a]	132226	10.87	0.79	47.35	0.05	0.27	0.44	<0.01	0.04	0.04	<0.01	39.57	**99.42**	84.55
Wesco Road, Nowergup	178652	10.10	0.79	48.30	0.13	0.42	0.75	0.08	0.064	0.03	<0.01	38.8	**99.47**	86.25
Wattle Avenue, Nowergup	178651	10.20	0.74	48.80	0.11	0.40	0.75	0.08	0.069	0.02	<0.01	38.7	**99.88**	87.14
Postans Road, Hope Valley	178677	18.80	0.75	43.70	0.34	0.36	0.64	0.14	0.073	0.07	<0.01	34.6	**99.48**	78.04
Kooallup Lagoon (Lake Preston)[a]	140305	12.28	0.85	45.48	0.33	0.54	2.09	0.29	0.09	0.05	<0.01	38.75	**100.75**	81.41
Rudds Gully Road, Narngulu	178678	45.40	1.51	27.00	0.79	0.55	1.11	0.15	0.017	0.22	<0.01	22.8	**99.56**	48.21

NOTES: (a) after Abeysinghe (1998)



Carbooda - Nowergup Limestone
Building Block Quarries
(Currently or recently active)

1 Cutler Road: Limestone Resources Australia
2 Hopkins Road: Limestone Building Blocks
3 Wesco Road: Limestone Building Blocks
4 Wesco Road: Meteor Stone No.1
5 Wesco Road: Limestone Natural
6 Wesco Road: Italia Limestone
7 Wesco Road: Meteor Stone No. 2
8 Wattle Avenue: Crown Limestone Supply
9 Wattle Avenue: Limestone Resources Australia

Figure 141. Distribution of Tamala Limestone in the Carabooda–Nowergup area (modified after Abeysinghe, 1998)

years, Carabooda–Nowergup has become the principal production area for limestone blocks in Western Australia. In 2006, there were at least eight quarries in operation with a few producing only natural cut limestone blocks. The majority produced both natural stone blocks and reconstituted limestone blocks sourced from lower grade or waste limestone material.

Apart from the extensive area available for mining, the Carabooda–Nowergup area contains the highest grade Tamala Limestone averaging almost 87% $CaCO_3$ content. It is estimated that in 2003–04, the area produced around 234 000 t of natural cut limestone blocks and about 119 000 t of reconstituted limestone blocks, with a total estimated value of approximately A$6.84 million.

Carabooda quarries
Limestone Resources Australia, Cutler Road (MGA 381794E 6502289N)
Limestone Building Blocks, Hopkins Road (MGA 382271E 6502242N)

In the Carabooda area, two limestone mining companies occupy adjacent sites (Fig. 141). Limestone Building Blocks in Hopkins Road has two mining leases in this area: M70/13 and 339. Current operations are focused on the production of large volumes of mechanically pressed, reconstituted limestone blocks at the rate of several hundred blocks per hour. Block sizes range from 1000 × 350 × 350 mm, to 500 × 245 × 110 mm in colours of natural light brown and pale grey (Fig. 69).

On Cutler Road, Limestone Resources Australia Pty Ltd has four adjacent mining leases at this site: M70/109, 341, 345, and 346. At this location, the company operates a multi-faceted limestone product plant drawing limestone material drawn from a number of quarries. In the first operation, lower grade and waste material are processed on a large open pad to produce substantial quantities of reconstituted limestone blocks very similar in size and appearance to those described above.

The plant's second operation involves the diamond sawing of natural limestone blocks from a number of quarries. In the cutting area, skilled operators manufacture smooth, diamond-cut blocks and housing bricks in standard sizes as well as a large range of speciality products described earlier in Chapter 7.

At this locality, the stone is described as a weakly bedded, porous microfossiliferous limestone with minor scattered quartz and lesser feldspar sandgrains. Chemical analyses indicate that the Carabooda area is one of the sites in district having the highest grade Tamala Limestone available for building blocks, with $CaCO_3$ contents ranging from 85 to 89% (Table 10).

Petrographic description (Limestone Resources Australia quarry)

This weakly bedded, porous microfossiliferous limestone consists of comparatively fine grained, tightly packed microfossils and minor quartz sand grains (0.4 mm) together with intergranular calcareous cement. This results in a porosity of around 40%, shown as black areas in Figure 142.

A visual estimate of the volumetric abundance of these components includes calcareous microfossils as whole tests (shells or exoskeletons) and fragments 55%, single crystal sand grains of quartz 3 to 5%, single crystal sand grains of K-feldspar 1%, and intergranular porosity 40%. Almost all of the microfossils and mineral grains have a size range of 0.1 to 0.5 mm, with an average size of 0.4 mm.

Microfossils consist of clouded cryptocrystalline calcitic limestone, representing complete fossil tests of foraminifera, as well fragments of foraminifera, bryozoa, coral, and possible molluscs. These components are randomly disposed, but generally weakly bedded, especially numerous microplaty fossil fragments, that tend to be commonly oriented along the bedding. The intergranular cryptocrystalline calcareous cement, including rims around the microfossils and some rims on grains of quartz and feldspar, is relatively extensive, albeit sporadic and patchy.

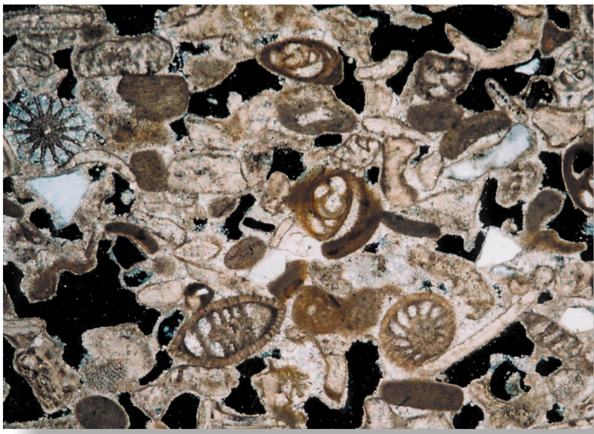


Figure 142. Photomicrograph of Tamala Limestone from the Carabooda–Nowergup area. Photo (polarized light ×50) shows fossil tests of foraminifera together with foraminifera, bryozoan, coral, and possible mollusc fragments, and sporadic white quartz sand grains all interlocked by an intergranular cement of cryptocrystalline calcite. Black areas represent intergranular pore spaces, estimated at 40% by volume (Pontifex, 2005)

Nowergup quarries, Wesco Road
Limestone Building Blocks (MGA 382315E 6499738N)
Meteor Stone No. 1 (MGA 381111E 6498750N)
Limestone Natural (MGA 382701E 6498254N)
Italia Limestone (MGA 382960E 6498382N)
Meteor Stone No. 2 (MGA 382552E 6498049N)

The Wesco Road precinct in Nowergup is the most active area for limestone quarrying in the Carabooda–Nowergup region (Fig. 141). Currently, there are at least four active quarry operations following the recent shutdown of the Meteor Stone No. 1 quarry. These four continuing operations are all located on sites subleased from Cockburn Cement, owner of two mining leases bounded by Wesco Road.

At some quarries there are two simultaneous processing operations. These are the cutting of natural stone blocks and the manufacture of reconstituted limestone blocks. At these sites, natural limestone quarry blocks and bricks are cut from operational floors using multi-blade, tungsten carbide, rotary quarry saws (Fig. 51). This material is either sold as rough cut quarry blocks or is removed to diamond saw cutting plants for added-value processing into many forms of smooth-faced blocks, brick, and other products as shown in Figures 69–71. Waste and low-grade limestone is manufactured into reconstituted limestone blocks either on-site or transported to the company's reconstituted block plant.

On the northern side of Wesco Road, Limestone Building Blocks has a subleased site on mining lease M70/141. Here the company is working two cutting floors to produce large limestone building blocks that are palletized on site for distribution to clients. Low-grade limestone and waste material is crushed and transported to the company's reconstituted limestone block plant at Carabooda for processing.

To the south of Wesco Road, Meteor Stone, Italia Limestone, and Limestone Natural all occupy subleased sites on mining lease M70/138. All three companies have cutting operations on site for the retrieval of natural large quarry blocks and natural cut bricks (Meteor Stone). Waste and low-grade material is crushed and manufactured on site into reconstituted limestone blocks by Meteor Stone, while this same material is apparently crushed for agricultural lime products by Limestone Natural. Both Italia Limestone and Meteor Stone remove a proportion of their quarry cut blocks to their respective sawing plants at Bibra Lake and Landsdale for the manufacture of diamond sawn bricks, blocks, and other limestone products.

Limestone in the Wesco Road area is described as a massive, porous, microfossiliferous limestone, with minor scattered quartz sand grains. Analysis of material from Meteor Stone No. 1 quarry indicates a $CaCO_3$ content estimated at over 86% (Table 10).

Petrographic description (Meteor Stone No. 1 quarry)

This specimen is a porous, calcareous, microfossiliferous limestone with a relative abundance of small, platy to short, stem-like calcareous fossils and fossil fragments seen in thin section to be oriented along bedding (cf. the Carabooda sample). Grain size ranges from 0.1 to 0.5 mm grains with an average diameter around 0.3 mm. Also present, is part of an inherited sedimentary microdyke, composed of calcareous mud (probably original ooze), 3 mm wide × 6 mm long and cutting across incipient layering.

A visual estimate of the volumetric abundance of the essential components (excluding the single calcareous microdyke) includes calcareous microfossils as whole tests and fragments 60%, single crystal sand grains of quartz 3 to 5%, single crystal sand grains of feldspar <1%, and intergranular porosity of 35%.

Nowergup quarries, Wattle Avenue
Crown Limestone Supply (MGA 383889E 6497476N)
Limestone Resources Australia (MGA 383934E 6497054N)

About 2 km south of Wesco Road at Wattle Avenue, two quarries, operated by Limestone Resources Australia Pty Ltd and Crown Limestone Supply, are active on sub-leased areas of Cockburn Cement's mining lease M70/143 (Fig. 141).

On this lease, both companies are cutting natural limestone blocks 1000 × 350 × 350 mm. Limestone Resources Australia is also making a range of smaller sized blocks down to 500 × 350 × 250 mm and the company then transports this material (and possibly some waste for reconstituted limestone) to its Carabooda cutting plant for added-value processing of the highest quality material into diamond sawn blocks, bricks, and other products.

Limestone from Wattle Avenue is described as a massive, porous, microfossiliferous limestone, with minor scattered quartz and feldspar sand grains with an estimated $CaCO_3$ content of 87% (Appendix 3.30; Table 10).

Petrographic description (Limestone Resources Australia quarry)

This specimen is very similar to the microfossiliferous limestone samples from the Carabooda and Wesco Road quarries. A visual estimate of the volumetric abundance of these components includes calcareous microfossils as whole tests and as fragments 55%, single crystal sand grains of quartz 3 to 5%, single crystal sand grains of feldspar <1%, and intergranular porosity 40%.

Size range of quartz sand grains is from 0.1 to 0.5 mm with an average diameter around 0.35 mm. Individual microfossils are mostly equant and commonly internally microcellular (probably mostly foraminifera), with lesser microplaty and weakly bedded fossil fragments. The fossil tests and fragments consist of cryptocrystalline calcite that are randomly disposed to form a massive, loosely packed aggregate. Intergranular porosity is on the same scale as for the previous specimens. A small amount of intergranular, cryptocrystalline, calcitic cement joins adjacent grains at sparse contact points.

Hope Valley – Postans

The Hope Valley – Postans area, located north of Thomas Road, Kwinana and 25 to 30 km south-southwest of Perth, formerly contained a large, mineable resource of Tamala Limestone (Fig. 143). Today, much of this area has been mined out or resumed for other purposes. Currently, a number of limestone quarries are operating on the eastern and southern sides of this area. Most limestone in the area is unsuitable for limestone block cutting and consequently a large proportion is crushed for use as limestone roadbase material and for the manufacture of reconstituted limestone blocks.

Within this area, limestone commonly occurs as a weathered 'capstone' at the surface or under comparatively thin sand cover. The capstone layer is generally 0.5 to 2.0 m thick and is very hard, probably as a result of partial resilicification of the calcarenite during periods of weathering. When broken up, the capstone forms large, irregular boulders 1.0 to 1.5 m in diameter (Fig. 144). These boulders may provide a useful source of armourstone.

Directly beneath the capstone layer, the Tamala Limestone has been weathered to a friable, yellow to pale brown matrix of calcareous, sandy fines containing numerous partially weathered limestone fragments ranging from cobble to pebble size (Fig. 144). Analytical results of this type of material from Stoneridge Quarries in Postans Road is given in Table 10. These results indicate that the weathered, friable limestone from some sites within this area may be used as a future resource for the manufacture of reconstituted limestone blocks.

Stoneridge quarry (MGA 387561E 6438678N)

Stoneridge is a large quarry located on Postans Road, Hope Valley, about 27 km south-southwest of Perth. Owned by Stoneridge Quarries WA, the quarry currently produces crushed limestone from weathered, pale brown, friable limestone containing an estimated 78% $CaCO_3$. This material finds use in the company's reconstituted limestone batching plant, which produces large, mechanically pressed blocks on an extensive pad at the southern end of the quarry (Fig. 145).

Postans prospect (MGA 386849E 6434756N)

The Postans prospect, on Mining Lease M70/555 immediately north of Thomas Road, is owned by Roadstone Quarries Pty Ltd, a subsidiary of Italia Limestone Company (Fig. 143). Investigations by the author show that the prospect is located on a north-trending limestone ridge with exposed capstone underlain by weathered limestone as described above. Despite the area of the mining lease being largely sand covered,

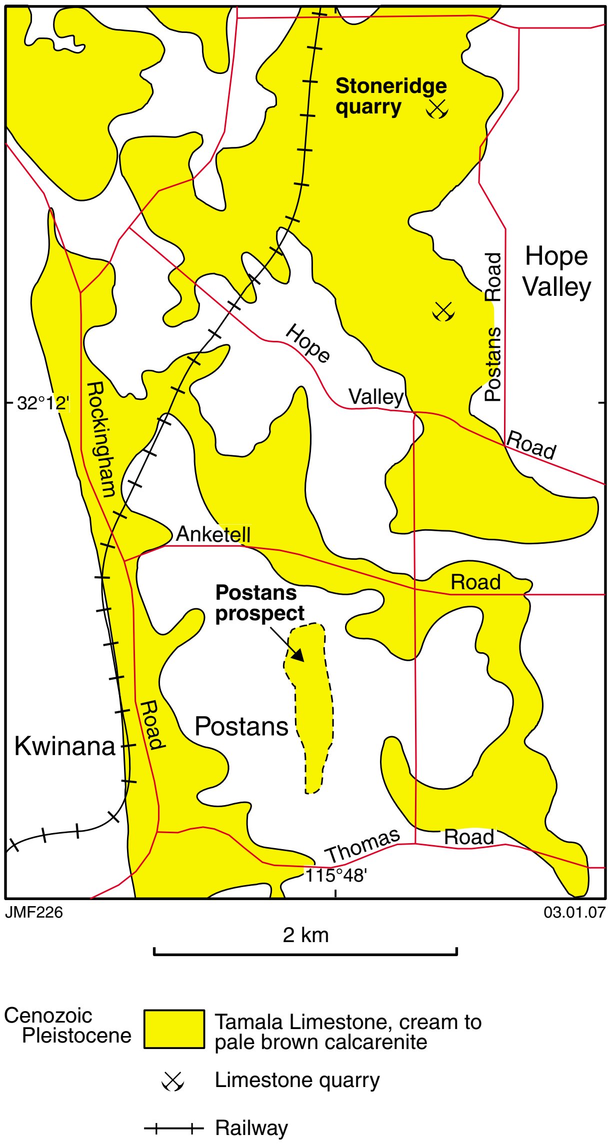


Figure 143. Distribution of Tamala Limestone in the Hope Valley–Postans area (modified after Abeysinghe, 1998)

Figure 144. Tamala Limestone near-surface, 'capstone' profile, Hope Valley–Postans area. Photo shows the upper, hard 'capstone' layer, about 0.5 m thick, overlying friable, light brown, calcareous sand containing numerous limestone pebble and cobble-sized clasts. Previously ripped capstone boulders, 1.0 to 1.5 m in diameter, are stockpiled at surface

Figure 145. Reconstituted limestone block batching plant at Stoneridge quarry, Hope Valley

geological observations from nearby extractive industries indicate that the Postans prospect may contain a valuable limestone resource suitable for the construction industry.

Perth – Rottnest Island

For over 100 years from 1831, Perth was supplied with cut limestone blocks sourced from a number of quarries established along the coast from Scarborough south to Coogee, and also from Rottnest Island. Over this period the quarries provided stone for the construction of many substantial buildings, mainly in Fremantle and Perth city (see Chapter 4).

Today, most of these historic quarries have been rehabilitated to the extent that their exact locations are in some doubt. It is known that some of these quarries operated at Coogee, Fremantle in the vicinity of the public golf course, Buckland Hill in Mosman Park, and at Reabold Hill at City Beach. On Rottnest Island, quarries were situated close to the Thomson Bay settlement, Nancy Cove, and in the vicinity of the army jetty at Thomson Bay.

The only historic limestone block quarry to have been preserved is the Quarry Amphitheatre at Reabold Hill (MGA 384451E 6465682N). In the quarry walls, the manual methods used in block extraction are still clearly visible (Fig. 18).

Moore River
No. 1 quarry (MGA 359130E 6533854N)
No. 2 quarry (MGA 359495E 6532539N)

The Moore River limestone quarrying operation is located 3.5 km north-northeast of the town of Guilderton. At this site, Limestone Resources Australia Pty Ltd is working two quarries adjacent to Guilderton Road. The original No. 1 quarry, situated on Mining Lease M70/193 has been in operation for many years, whereas the No. 2 quarry, on Mining Lease M70/786, was opened early in 2006 as a source of additional limestone block material (Fig. 146).

In 2004, excavation in the No. 1 quarry had reached a depth of 5 to 6 m in massive, pale brown, cross-bedded calcarenite (Fig. 147a). From these operations, the company produces three grades of biscuit-coloured, quarry-cut blocks using tungsten carbide tipped rock saws. The first of these is a high-quality, relatively strong housing brick displaying a natural surface finish of the type often specified in architect-designed housing projects (Fig. 147b; Appendix 3.31). Other types of cut stone include a medium-grade stone for landscaping projects, and large, one metre-long blocks produced mainly for use in retaining walls.

In Table 10 it can be seen that the $CaCO_3$ value obtained from Moore River quarry limestone is comparatively low (~62%) compared with the more common value for limestone building blocks at around 85% $CaCO_3$. It is suggested that the high intergranular porosity of the Moore River limestone of about 50% may be related to the loss of some $CaCO_3$ content, possibly as a result of circulating groundwater. In spite of this loss, the cellular limestone walls surrounding individual pore spaces appear to remain well indurated and the strength of the stone is retained. As a result of this structural property, the Moore River Limestone has been demonstrated to be a comparatively strong and widely used building stone.

Petrographic description

This sample is a massive, porous, microfossiliferous limestone. Macroscopically (under binocular microscope)

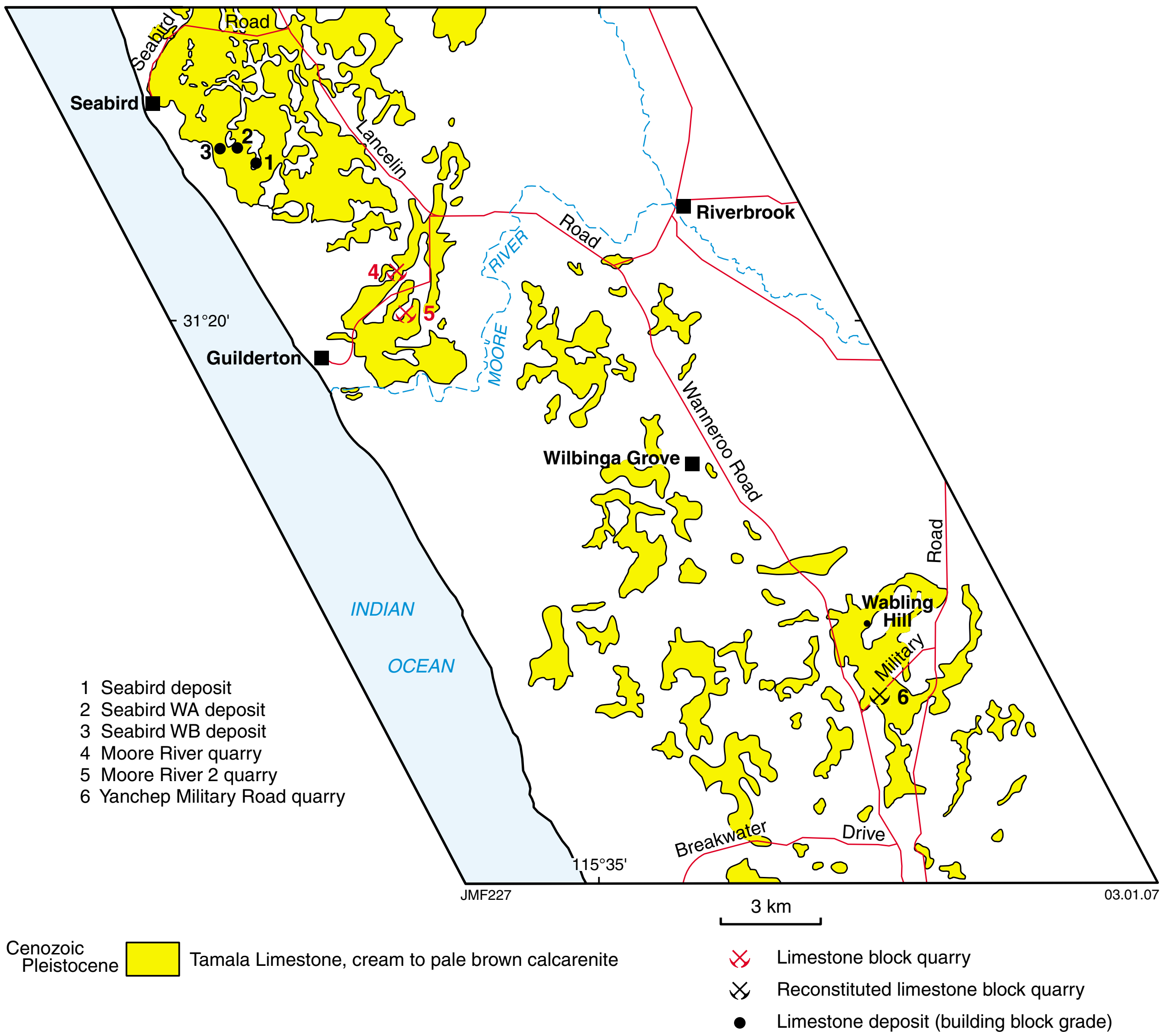


Figure 146. Distribution of Tamala Limestone from Seabird to Yanchep (modified after Abeysinghe, 1998)

it is seen to consist of a homogeneous, massive, very porous aggregate of poorly consolidated grains or fragments of microfossils, with far fewer, similarly coarse, sand-size quartz grains.

In thin section, the sample is seen to consist of a very loosely packed aggregate of randomly disposed calcareous microfossil tests and fossil fragments, together with minor sand grains of quartz and feldspar, and extensive porosity. A visual estimate of the volumetric abundance of these components includes calcareous microfossils as whole tests and fragments 45%, single crystal sand grains of quartz 4%, single crystal sand grains of K-feldspar 1 to 2%, and intergranular porosity 50%.

Almost all grains and fragments possess a variably equant to microplaty shape, and fall within the size range 0.1 to 0.6 mm, with an average of about 0.5 mm. Accessory quartz grains may reach 1 mm in size. Contact between adjacent grains is minimal, giving rise to extensive intergranular porosity that is locally continuous for up to 2.5 mm. The overall aggregate is thus relatively fragile (Fig. 148).

Individual microfossils consist of clouded cryptocrystalline calcite, representing complete fossil tests of foraminifera, as well as foraminifera, bryozoan, coral, and possible mollusc fragments. The cryptocrystalline calcitic composition of the fossils (and the fossil species) is essentially the same as that of the limestone from the Carabooda–Nowergup area, 40 km to the southeast. However, accessory quartz and feldspar grains commonly have very thin (0.05 mm) rims or coatings of cryptocrystalline cement joining adjacent grains of quartz and fossils, resulting in an estimated porosity of 50%.

Myalup–Kooallup Lagoon

There are a number of limestone quarry operations between 25 and 35 km north of Bunbury in the vicinity

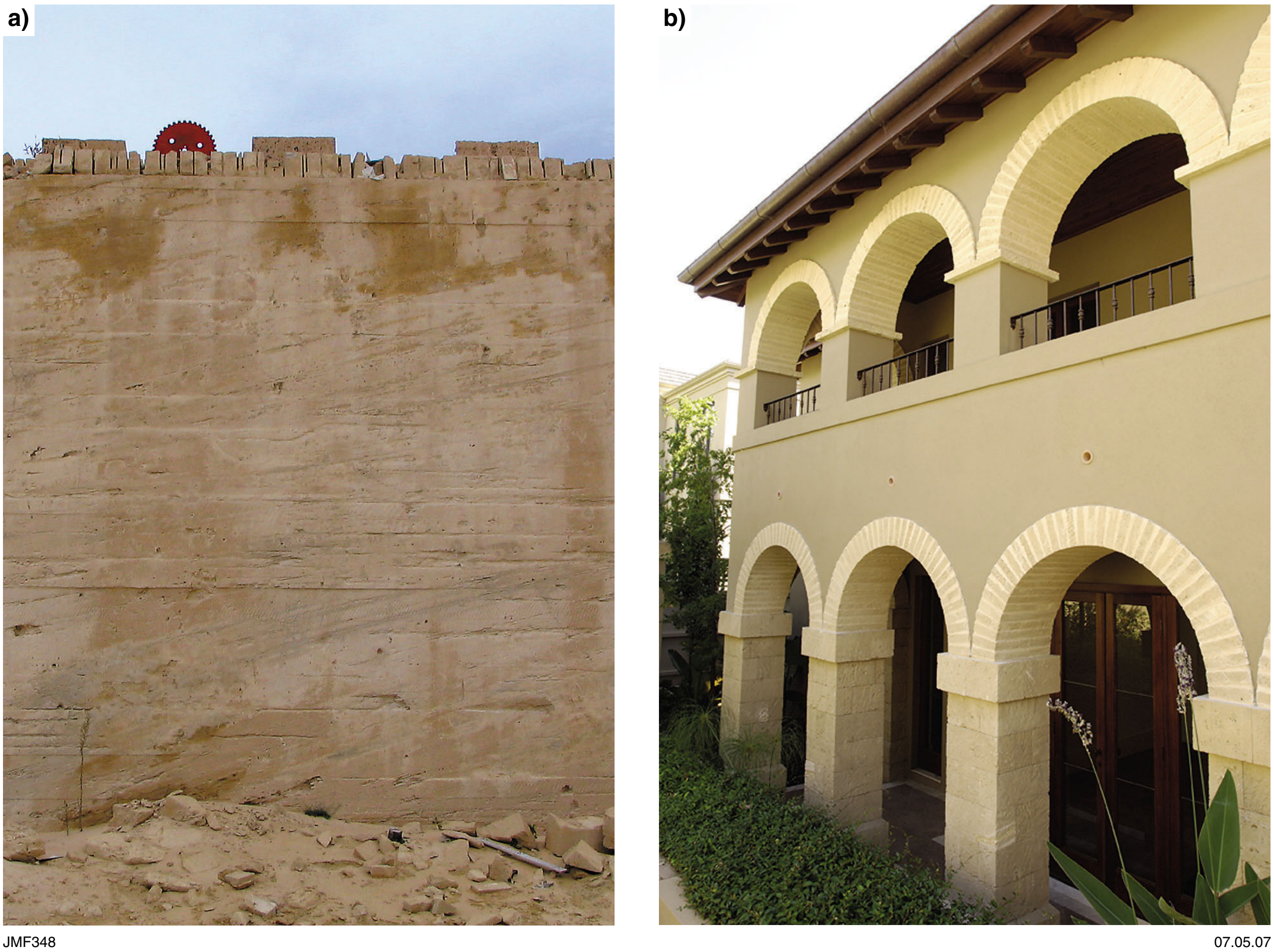


Figure 147. Tamala Limestone from Moore River: a) a six metre-high wall of massive, pale brown, crossbedded calcarenite in the Moore River block quarry; b) Moore River limestone bricks and blocks used in archways and as column cladding in a contemporary Italian-style villa (photo (b) courtesy Limestone Resources Australia, © Discovering Stone, 2006)

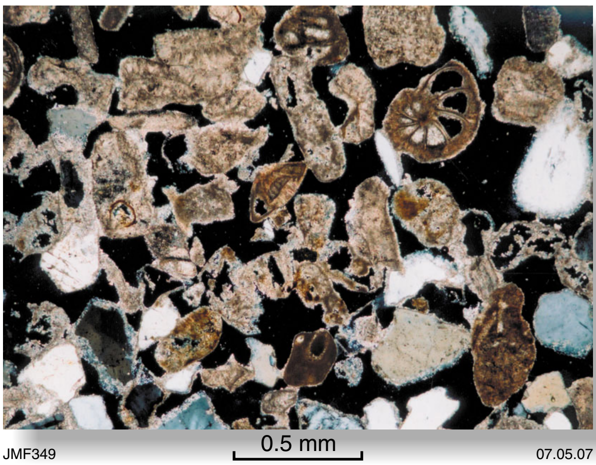


Figure 148. Photomicrograph of Tamala Limestone from Moore River quarry. Photo (polarized light ×50) shows a loose-packed aggregate of cryptocrystalline calcite microfossils together with scattered white and grey quartz and sporadic feldspar sand grains. Black areas represent widespread, discontinuously connected, intergranular pore spaces estimated at 50% by volume (Pontifex, 2005)

of the township of Myalup, and farther north at Kooallup Lagoon adjacent to the eastern shore of Lake Preston (Fig. 149). In this area, Tamala Limestone, mostly beneath a thin sand cover, occurs in a linear, north-trending belt averaging 2.0 km wide (Biggs, 1982). Limestone extracted from these operations is crushed and transported mostly to Bunbury to various limestone processing operations including batch plants that manufacture reconstituted limestone blocks and bricks mainly for sale in the Bunbury and southwest regions of the State.

Myalup

Carbone quarry (MGA 379358E 6334595N)
Giacci quarry (MGA 379203E 6334153N)
Catalano quarry (MGA 379497E 6333856N)

About 2.5 km southeast of the Myalup township there are three limestone quarrying operations in close proximity and operated by Carbone Bros Pty Ltd, G M Family Trust (Giacci), and B & J Catalano.

In 1975, a limestone exploration program was carried out by La Porte Australia Ltd in the area from north of Myalup Beach Road (in the vicinity of the current Myalup operations), south to Binningup Road (Fig. 149).

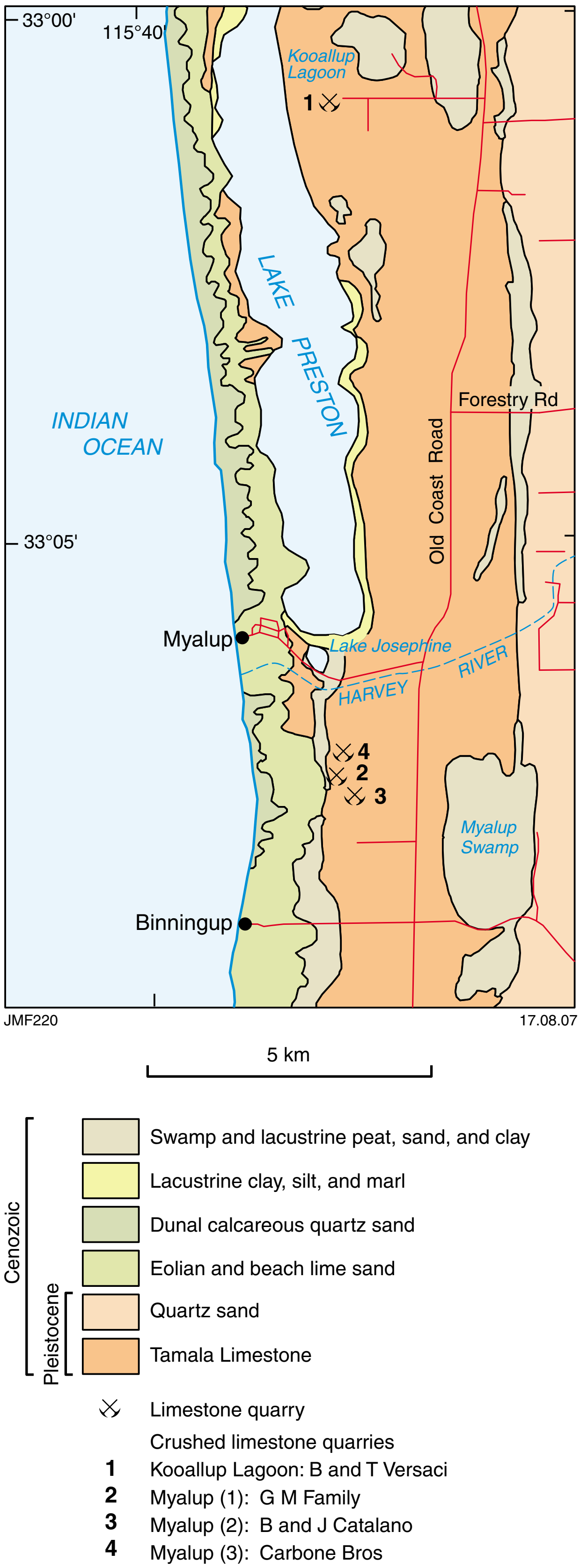


Figure 149. Geology of the Lake Preston to Binningup area (modified after Lowry et al., 1983)

In the north of this area, a total of 57 holes was drilled on Kingswood Park property resulting in a resource estimate of 1.08 Mt of limestone at 69% $CaCO_3$. This figure included 0.67 Mt at 75% $CaCO_3$ and 1.8% $MgCO_3$. In the south of the area, close to Binningup Road, similar results of 1.06 Mt at 65% $CaCO_3$ and 1.0% $MgCO_3$ were obtained on the Crawley Estate from a program of 24 drillholes (Abeysinghe, 1998).

Kooallup Lagoon

Versaci quarry (MGA 379031E 6346120N)

Another quarry producing crushed limestone, adjacent to Kooallup Lagoon and about 1.0 km east of Lake Preston, is operated by B & T Versaci Lime (Fig. 149). Analytical values for three samples from this locality are given by Abeysinghe (1998); $CaCO_3$ values range from approximately 80 to 88%. A set of median values for this locality is given in Table 10.

Narngulu (MGA 274497E 6807697N)

A quarry in the Narngulu area, some 11 km southeast of Geraldton, is operated by Wells Brothers. This quarry produces a variety of basic raw materials including weathered limestone, yellow brick and filling sands, and topsoil (Fig. 135).

Tamala Limestone is present in this quarry as a caprock (1–2 m thick) over a weathered calcareous sand. This powdery sand is creamy brown in colour with pink highlights. Chemical analysis of this material indicates the comparatively low $CaCO_3$ content of 48% (Table 10).

This powdery, weathered limestone is used by Amazzini and Son in their Geraldton plant as a calcareous source material for the manufacture of a range of reconstituted limestone products. These include reconstituted limestone building blocks in various sizes and styles and house bricks in different colours and designs, manufactured for sale both locally and in Perth.

Seabird and other areas north of Perth

Seabird (MGA 353913E 6537580N)

Approximately 85 km north-northwest of Perth, Limestone Resources Australia Pty Ltd have established three mining leases (M70/769, 822, and 865) over several ridges of outcropping high-grade limestone 3 km southeast of the town of Seabird (Fig. 146). It is understood the company plans to retain this area as a potential resource of building-block-grade limestone.

Several limestone samples from the Seabird area have given indications of the high-grade limestone present here (Abeysinghe, 1998). In particular, a sample obtained on Seabird Road 3.5 km to the north of the Seabird deposit gave a very high estimated $CaCO_3$ content of 87.38% (Table 10).

Other areas

Other areas of potential building-block-grade Tamala Limestone north of Perth discussed in Abeysinghe (1998) include the area from Wilbinga Grove north to Seabird

(Fig. 146; Table 10), and coastal areas farther north from Ledge Point to Lancelin and Wedge Island, as well as the areas from Cervantes to Jurien and around Port Denison to Dongara.

Yanchep (MGA 373856E 6521442N)

The Yanchep limestone quarry is located within Mining Lease M70/367 in the Yanchep area about 60 km north-northwest of Perth (Fig. 146). The quarry is owned and operated by Archistone, a manufacturer of reconstituted limestone building block and brick products.

At this location, a 5–6 m-high quarry has been cut into weathered, light brown Tamala Limestone (Fig. 150a). During mining operations, the friable limestone breaks comparatively easily into its component parts. These consist of a substantial proportion of small, rounded sandy limestone particles and fines containing numerous, light brown calcarenite cobbles, commonly 10 × 15 cm, and displaying a slightly subrounded and partially weathered appearance (Fig. 150b). This effect may indicate partial dissolution of the limestone by groundwater, but petrographic examination of the calcarenite cobbles indicates that their internal structure, composed mainly of microfossils, is still largely intact. Chemical analysis shows that the $CaCO_3$ remains comparatively high at about 67% (Table 10).

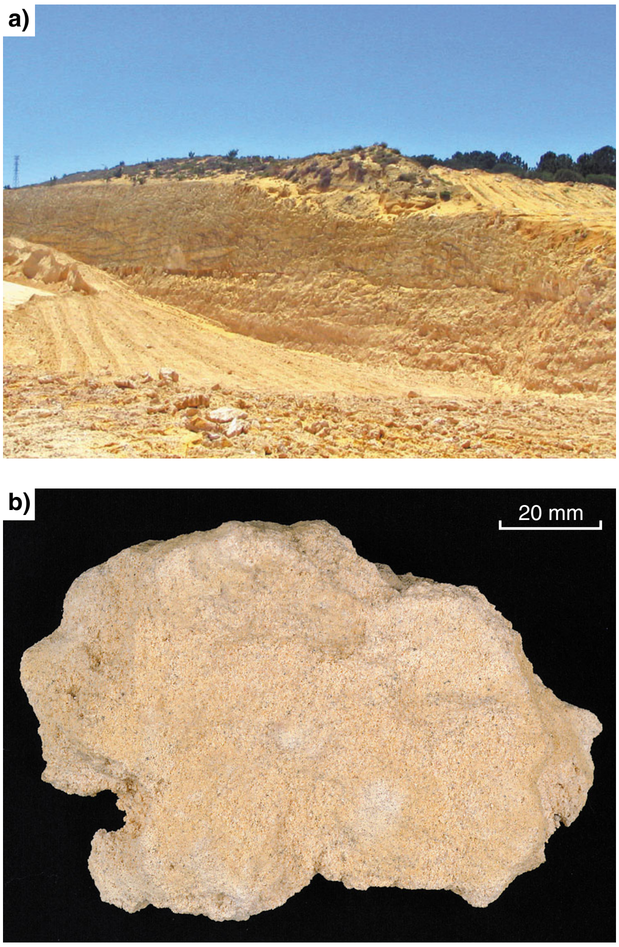


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Figure 150. Yanchep reconstituted limestone quarry: a) main quarry wall (5–6 m high) cut into weathered, friable, light brown Tamala Limestone; b) cobble-sized, subrounded, partially weathered limestone clast from quarry wall

The quarried material is fed through a series of crushers. The coarser material is processed by primary crusher to -20 mm grain size for use as a feedstock for pressing into large blocks intended for use as free-standing and retaining walls. Finer material is fed through a secondary crusher to produce a final crushed limestone product of less than 10 mm diameter. This finer material is used in the manufacture of wall blocks, pavers and other products by the wet casting process. Both processes have already been described in Chapter 8.

Petrographic description (calcarenite cobble)

Macroscopic and initial petrographic examination of this sample indicates a homogeneous, massive and very porous microfossiliferous limestone. In this sample, scattered quartz grains are slightly coarser and slightly more abundant than in the limestone samples previously described.

Visually estimated primary mineralogy (volume percent) is somewhat variable and includes calcareous microfossils as whole tests and fragments 60 to 70%, single-crystal quartz sand grains 10 to 12%, single-crystal feldspar sand grains 3%, and intergranular porosity 20 to 25%. The size range of equant fossils and calcareous fragments is 0.1 to 0.6 mm, although some of the small platy to reed-like fossils measure up to 0.2 mm wide × 1.3 mm long, and these have a random to weakly bedded distribution. Quartz and lesser feldspar grains range in size from 0.1 to 1.2 mm with an average diameter of 0.65 mm.

Rims or coatings of cryptocrystalline calcareous cement seem to be slighty more widespread than in other limestone samples previously described. This greater infill of cavities results in a reduction of porosity of both intergranular and internal pore space within individual fossils tests. The increase in cryptocrystalline calcareous cement and the corresponding reduction in porosity may be attributed to the movement of groundwater as part of the weathering process.

Diatomite

Gingin (MGA 393674E 6530479N position approximate)

On the Swan Coastal Plain north of Perth there are many small, scattered swamps containing deposits of diatomite. To the west of Gingin and Dandaragan, numerous small deposits exist in parallel chains of north-northwesterly trending swamps. In the Gingin area, about 60 km north-northeast of Perth, a grey to beige and pale yellow coloured material of Holocene age, varying from clayey diatomite to diatomaceous clay, has been quarried from a number of unknown sites along Gingin Brook between 1 and 7 km to the west and northwest of the town

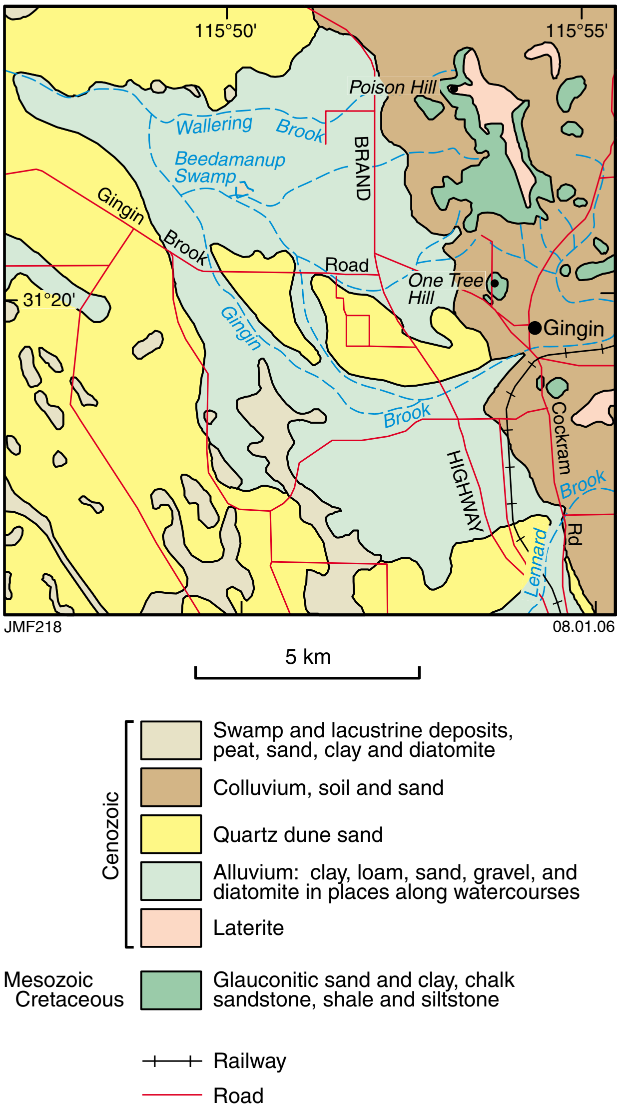

Figure 151. Geology of the Gingin area (modified after Low et al., 1978)

(Fig. 151). This diatomaceous material, locally known as *Casuarina Stone* was used as a cut building stone between the 1860s and the early 1900s to construct buildings in Gingin and Dandaragan (Hocking et al., 1975; Udell, 1979). The historical use of this stone has been more fully described in Chapter 4 and is illustrated in Figure 29 and Appendix 3.32.

Recent petrographic examination indicates that *Casuarina Stone* is a massive to weakly layered diatomite, composed predominantly of a silty claystone containing fine, compact masses of siliceous diatoms contained in an ultrafine opaline, siliceous matrix (Fig. 152).

Chemical analysis by X-ray fluorescence spectroscopy (XRF) indicates that this material is composed predominantly of silica (90.9%), with lesser quantities of iron oxide (Fe_2O_3 at 2.82%), alumina (Al_2O_3 at 1.31%), and volatiles (water and organic matter at 4.52%). All other oxides return trace values.

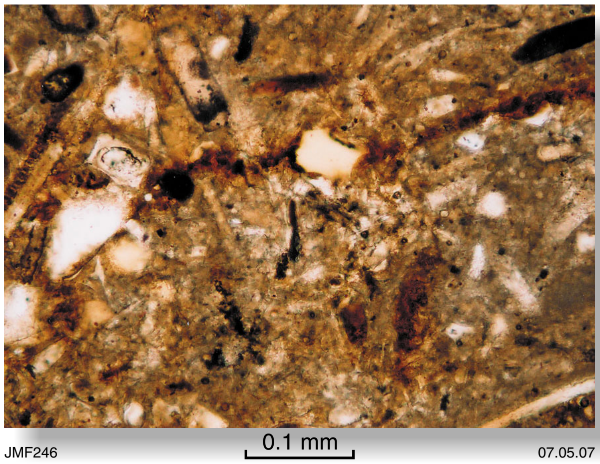

Figure 152. Photomicrograph of *Casuarina Stone* from Gingin. Photo (plane light ×200) shows a compact mass of siliceous diatoms in a limonite-stained ultrafine, opaline siliceous matrix (Pontifex, 2005)

Petrographic description

Macroscopically, this sample has the appearance of a compact, indistinctly fine layered claystone. It is soft, friable and readily scratched, beige coloured, weakly iron-stained, and microscopically very porous. Its lack of reaction to diluted HCl indicates that it is not calcareous.

On initial petrographic examination at least 90% of the material appears as an irregularly iron-stained and lenticular-layered, somewhat silty claystone, with up to 10% randomly scattered subangular quartz sand grains 0.2 to 1.0 mm in size. However, more detailed examination reveals abundant individual microscopic, single-celled and stem-like, fossil fragments mostly <0.1 mm long. Although limonite-clouded, these are isotropic (viewed through crossed nicols) and almost certainly composed of amorphous silica. They are aggregated to form a compact structureless mass, with the more clearly defined fragments randomly dispersed. An indefinite, even finer scale (clouded) matrix is also universally isotropic and also identified as amorphous ultrafine silica.

The collective evidence indicates a sample of diatomaceous earth, formed from a diatomaceous ooze. The dried, fine-powdered equivalent of this material is diatomite. Clay is not specifically recognized, but ultrafine clay may be intricately mixed within the matrix and should be investigated by X-ray diffraction analysis (XRD).

Chapter 11

Summary

Dimension stone is a natural rock material quarried for the purpose of obtaining blocks or slabs that meet specifications as to size (width, length, and thickness) and shape. The term encompasses natural stone prepared for use as building stone, ornamental stone, and monumental stone. Most rocks commonly used for dimension stone tend to fall into six major commercial categories. These are granite, black granite, sandstone, limestone, marble, and slate. Other commercial categories include metamorphosed granitic rocks, quartzite, trachyte, bluestone, multicolour, basalt or 'trap rock', flagstone, and greenstone.

Apart from size specifications for blocks and slabs, it is the stone's physical properties that determine its commercial success in the marketplace. Combined with contemporary architectural trends, it is the visual properties of any stone, particularly colour, texture and structure, that largely influence customer demand. Behind the more obvious visual properties, it is the technical properties of any dimension stone that will ultimately determine its success in the environment in which the stone is placed forming part of a building, landscape feature, or monument. The most common set of testing standards used by industry for dimension stone are those devised by the American Society for Testing and Materials (ASTM). Standard ASTM tests include absorption and bulk density, durability, and strength tests such as compressive strength, modulus of rupture, and flexural strength. Other standard tests are those of hardness, abrasion resistance, and linear thermal expansion.

Since the dawn of civilized society, man has identified numerous rock types for use as dimension stone in many areas around the world. As a general rule, from pre-historic times until the invention of mechanized transport, rock material with suitable physical properties for block manufacture were sourced from rocks in the local area for use in building projects ranging from simple stone shelters and walls through to large stone bridges and major buildings such as defensive castles. Exceptions to this are found in major civilizations such as ancient Egypt, Greece, and Rome that had the economic means and the manpower to obtain large stone blocks with more attractive colours or superior physical properties from locations at great distances from construction sites. This is evident in the variety of stone used in their massive monuments, gigantic statues, temples, and mausoleums. Other early civilizations which used vast quantities of dimension stone for their cities and monuments included the Mayan peoples of Mexico, the Incas of Peru, the Khmer Empire in South East Asia, and European civilizations of the Middle Ages.

During the Renaissance Period in Europe, the use of dimension stone, especially marble, reached its zenith. About the same time, outstanding stone structures such as the Great Wall of China, and the Taj Mahal at Agra in India were completed. Subsequently, from the early18th century, many cities and towns in different parts of the world were built wholly or partly from local stone.

By the 19th century, dimension stone extraction for civil engineering projects became a well established industry and many European countries, especially Italy, France, Spain and Greece, became large producers to satisfy the growing demand. This trend continued to expand into the 20th century in many countries throughout the developed world until the 1930s, when the industry slipped into a decline largely attributed to the invention of artificial building materials such bulk concrete for major project construction. This trend continued until the 1980s, when architects rediscovered stone as a building material and began by cladding large buildings both inside and out with pre-cut stone slabs.

Australia's capital cities were settled in the late 18th and early 19th centuries. A few years after initial establishment, the search was on in each local area to find stone suitable for the construction of substantial, weatherproof structures such as government buildings, warehouses, churches, banks, and large houses. Other stone requirements were for the construction of port facilities, bridges, and main roads. Western Australia was settled at Albany in 1826 and three years later in the Swan River Colony, later to become the City of Perth. This was followed by the larger regional centres in the State such as Bunbury, Geraldton, and Kalgoorlie. As was the case in the eastern states, the search was soon underway to find local stone and, initially, each city used the closest suitable stone in their construction works.

In recent times, it has become necessary to select a site accessible for quarrying within an economic distance of a port or processing plant for a successful dimension stone operation. The potential site must contain stone with the right properties and sufficient resources to satisfy customer requirements on a consistent and continuing basis. Surface expressions of potential deposits may appear to be far more extensive than the subsurface stone resource that ultimately turns out to be suitable for quarrying. In practice, it is often difficult to locate large resources of durable material with uniform grade for the production of 10–25 t blocks on a commercial basis.

Once all of the required resource estimation, quarry design, marketing, and feasibility studies and financial assessment have been finalised for the selected site and have been found to be favourable for the dimension stone project to proceed, it is necessary to progress to the project approvals stage. This involves working with government, local government, and landholders to get the project under way. Operations may commence when all of the required licences and approvals have been granted. The design of a quarry is based on the local topography together with the size, structural elements, and physical properties of the stone resource to be recovered. If the site has not been quarried in the past, the overburden overlying the stone deposit will usually require removal. In general, there are four basic types of quarry from which spring numerous variations. At a later stage in the life of a quarry, when initial resources are depleted, the quarry design may change in order to maintain production at that site.

In contemporary dimension stone quarries there are essentially two methods of stone extraction. The first method (known as the Finnish method) is commonly applied to rocks ranging from very hard granite, gneiss, and quartzite, through basalt and indurated sandstone, to moderately hard types including marble and limestone. This method involves extraction of large primary blocks, commonly 400–900 t as feedstock for the production of transportable 10–25 t quarry blocks. The second extractive method applies to soft rocks such as calcarenite and semi-indurated sandstone. In this process quite different methods are used to acquire a variety of smaller sized quarry blocks.

In today's competitive market, Australian dimension stone processing plants tend to be centralized and located in or close to a major city, with a ready market close at hand. Companies commonly extract a variety of medium to hard rocks from their own quarries, but also select stone from privately owned operations in widely separated locations across Australia or from overseas. Principal stages of hard-rock dimension stone processing include quarry block trimming and primary sawing, followed by a variety of surface-finishing processes including polishing and the application of artificial surface textures. Slabs then undergo secondary sawing to final size, and blocks may be profiled using computer-guided saws into intricate shapes according to architectural specifications. Secondary stone processing industries, operated by monumental masons and artisans, generally make use of pre-cut stone for the production of stone memorials and carved artworks.

Other forms of processing are employed by specialist suppliers of a single type of stone. In this situation, processing plants are located close to those quarries that produce typically softer varieties of high-quality sandstone and limestone mainly for local use in the building construction, paving, and landscaping industries. In Western Australia, it is the calcarenite limestone processing industry of the Perth region that supplies high-quality limestone blocks, slabs, bricks and other products for building and construction projects.

In 2004, world production of dimension stone by 25 countries was estimated at 89.5 Mt. This figure together with estimates for another six producing countries with unrecorded production for that year, estimated at around 2.5 Mt, provides a world production estimate for 2004 of approximately 92 Mt. China remains the world's largest producer at 20.6 Mt followed by India, Italy, and Iran (11.2, 10.6, and 10.4 Mt respectively). The Australian national estimate for 2003–04 is approximately 0.41 Mt. It is estimated that more than 5000 varieties and colours of dimension stone are produced worldwide.

Prices for blocks and slabs on world markets are normally quoted in US dollars, either as US$ per tonne or US$ per cubic metre. A survey of prices (see Table 7), mainly from large-scale producers in 13 countries, indicates an average world price for dimension stone of around US$244/t. Today, international applications for dimension stone are dominated by stone flooring products at 38%, followed by interior and exterior building cladding totalling 20%, and material supplied to the mortuary industry of 15%.

Australian Bureau of Statistics figures reveal that over a three-year period Australian dimension stone exports experienced a 20% increase in monetary returns from A$12.21 million in 2001 to A$14.64 million in 2003. Total returns for the three-year period were A$37.68 million. Estimates for 2003–04 show that Western Australia is the largest producer of cut limestone blocks in Australia at almost 234 000 t valued at approximately A$4.57 million. Also, production figures for granite and sandstone (8342 and 5385 t respectively) have been substantially increased as, for the most part, they are obtained from extractive quarries for which official records are not usually maintained. These estimates show that in that year Western Australia was Australia's largest dimension stone producer at over 248 000 t valued at approximately A$7.81 million.

In today's competitive international markets for the building and paving industries, a number of materials have been developed as substitutes for dimension stone in certain applications. These include brick, ceramic tile, concrete, glass, plastics, resin-agglomerated stone, aluminium, and steel. In Western Australia, the reconstituted limestone industry has developed not only as a byproduct of, but also as a substitute for, natural stone blocks and slabs.

Once any stone has been removed from its rock mass in a quarry, it is in a state of disequilibrium as part of a stone structure in a new environment. As the stone re-attempts to reach a state of equilibrium it may be subject to a wide range of weathering and decay processes. These processes may affect the durability of a stone resulting in reduced strength, cohesion, and bulk density as well as increased volume, surface area, and permeability. Even with the most modern maintenance, conservation, and replacement programs, it is virtually impossible to completely restore partially weathered or decaying stone. Accordingly, stone restoration is the process of treating stone so it appears similar to stone in its original state while preserving its aesthetic qualities and enhancing its future integrity.

Currently, in the southwest of Western Australia centred on the Perth region, there are numerous dimension stone quarries (both operating, and in care and maintenance), prospects, and historic sites. These include high-grade limestone and sandstone resources from the Phanerozoic Perth and Southern Carnarvon Basins. Perth Basin resources lie mainly on the Swan Coastal Plain, extending southwards from Geraldton, through the economically significant outer Perth metropolitan area, to the Bunbury–Donnybrook district in the south. Also included is high-quality granitic, mafic, and metamorphic dimension stone from the South West Terrane of the Archean Yilgarn Craton, and the Proterozoic Leeuwin Complex, within a radius of 300 km from Perth.

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Appendix 1

Key websites accessed in this publication

ASTM International	www.astm.org/cgi-bin/SoftCart.exe/DATABASE.CART/REDLINE_PAGES/C1528.htm?E+mystone
Australian Museum	www.amonline.net.au/geoscience/events/event-heritage-sandstone.htm
Benetti Macchine	asp.thetisweb.com/benetti/store/listprod.asp?idCategory=74
Brick Industry Association	www.bia.org/BIA/technotes/t6a.htm
CaesarStone	www.caesarstone.com.au/aboutus/theprocess.html
Casa Editrice Bonechi	www.arca.net/db/musei/giotto.htm
Castle Tools Tyrolit Pty Ltd	www.castletools.com.au/new/diamondwire.htm
City of Sydney, Cadman's Cottage	www.cityofsydney.nsw.gov.au/AboutSydney/HistoryAndArchives/SydneyHistory/HistoricBuildings/CadmansCottage.asp
Dee Concrete Accessories	www.deeconcrete.com/concretehistory5.html
Discovery Channel, Stonehenge	www.exn.ca/mysticplaces/construction.asp
findStone.com	www.findstone.com/country-stone.htm
Finska Stenindustri Ab	finska.gsf.fi/stonesto.htm
Fisa s.r.l	www.fisa.it/cutting.html
India Travel Agents, Taj Mahal	www.tajmahalindia.net
Internazionale Marmi e Macchine Carrara SpA	www.immcarrara.com/stat/english-version/index-en.html
Johnson Tiles	www.johnson-tiles.com/page.cfm?LANGUAGE=eng&pageID=28
Koirala, D.	homepages.wmich.edu/~d3koiral/electives.htm#rock
Megalithia, Carnac	www.megalithia.com/brittany/carnac
Melocco Stone	www.melocco.com.au
Methodo S.r.l.	www.methodo.com/English/Cosa.htm
North Carolina Geological Survey, Division of Land Resources	www.geology.enr.state.nc.us/Mineral%20resources/Mineral_Resources.html
Our Australia, Richmond	www.our-australia.com/Tasmania/richmond.shtml
PCpedras	www.pcpedras.com.br
Pedrini SpA.	www.pedrini.it
Pellegrini Mechanica SpA	www.pellegrinispa.it/stonepages/ing-gruppo.html
Pierre Bleue Belge	www.pierrebleuebelge.be/archi/en/2_0_0_product_result.cfm
PIRSA Minerals, Primary Industries and Resources SA	www.pir.sa.gov.au/pages/minerals/commodity/dimension_stone.htm:sectID=245&tempID=7
Publicaciones Litos S. L.	www.litosonline.com/
Rodrigues, J. D.	www.csarmento.uminho.pt/docs/ncr/historical_constructions/page%2003-14_DDelgado.pdf
SlabUSA	www.slabusa.com/surfacefinishing.php
Socomac S.r.l.	www.socomac.it/ing/home-ing.htm
Sumitomo Osaka Cement Co. Ltd	www.soc.co.jp/sumitomo_e/business/const/s-mite.html
Tour Egypt!, Pyramids of Giza	www.touregypt.net/gizaindex.htm
Travel China Guide	www.travelchinaguide.com/china_great_wall
The Bathstone Quarry Research Group	bathstonequarries.mysite.wanadoo-members.co.uk/
Trade International Inc.	jbmatthews.home.mindspring.com/limestone2001.doc
U.S. Geological Survey Mineral Commodity Summaries	minerals.usgs.gov/minerals/pubs/commodity/stone_dimension/stdimmcs06.pdf
U.S. Geological Survey Minerals Yearbook	minerals.usgs.gov/minerals/pubs/commodity/stone_dimension/dstonmyb04.pdf
Walkabout, Brisbane	www.walkabout.com.au/locations/QLDBrisbane.shtml
Wikipedia, Cholula	en.wikipedia.org/wiki/Great_Pyramid_of_Cholula
World-Mysteries, Teotihuacan	www.world-mysteries.com/mpl_7.htm

Appendix 2

Location of quarries, prospects, and historic sites in Western Australia

Name	Operation	Status	Location	MGA Zone 50 Eastings	MGA Zone 50 Northings	Owner	Tenement/licence
Granite and granitic gneiss							
Austral Coffee	Quarry	Operating	20 km SSE of Bruce Rock	612039	6451251	AustralAsian Granite	EQL
Austral Juperana	Quarry	Operating	20 km SSE of Bruce Rock	613719	6454019	AustralAsian Granite	EQL
Austral Waterfall	Quarry	Operating	20 km SSE of Bruce Rock	613378	6453655	AustralAsian Granite	EQL
Carrido Spring	Quarry	Abandoned	23 km east of Mingenew	371591	6773794	Unknown	None
Doodlakine	Quarry	Operating	14 km ENE of Kellerberrin	580996	6502065	Public Transport Authority	Railway reserve
Greenmount	Quarry	Historic site	20 km east of Perth	411321	6468607	Unknown	None
Gwambygine	Quarry	Care and maintenance	9 km SSE of York	481491	6464373	Unknown	EQL
Karlgarin	Quarry	Care and maintenance	2 km ESE of Karlgarin	662357	6402698	Unknown	None
Mahogany Creek	Quarry	Historic site	2 km SSE of Mahogany Creek	419464	6468388	Unknown	None
Meckering	Quarry	Operating	3 km WSW of Meckering	497731	6499741	Public Transport Authority	Railway reserve
Merredin	Quarry	Abandoned	4 km east of Merredin	624995	6516386	Unknown	None
Mulroy Green	Quarry	Care and maintenance	10 km south of Watheroo	409679	6638521	Unknown	EQL
Mundaring	Quarry	Historic site	1.5 km NW of Mundaring	419915	6471207	Private ownership	None
Namban Green	Prospect		9 km south of Watheroo	410149	6639487	Unknown	None
Namban Red	Quarry	Care and maintenance	5 km SSW of Watheroo	408759	6643604	Unknown	None
Roelands	Quarry	Care and maintenance	20 km ENE of Bunbury	393264	6316295	Government reserve	EQL
Valmere Green	Quarry	Care and maintenance	2 km NNW of Watheroo	408475	6649865	Unknown	EQL
Verde Lope	Quarry	Care and maintenance	4 km SE of Watheroo	412106	6644732	Granites of Australia	EQL
Waterhatch Road	Quarry	Care and maintenance	13 km west of Beverley	480132	6446558	Unknown	EQL
Watheroo Red	Quarry	Care and maintenance	4 km NW of Watheroo	406804	6650086	Unknown	EQL
Winchester	Quarry	Operating	3 km SE of Carnamah	394656	6712457	Winchester Industries	EQL
Woodlands	Prospect		35 km WSW of Busselton	317090	6259730	Unknown	None
Black granite							
Blackboy Flat	Prospect		9 km SW of Bridgetown	412469	6234878	Unknown	None
Orange Grove	Quarry	Care and maintenance	6 km WSW of Bridgetown	414764	6239472	Coral Marble	EQL
Wambyn	Prospect		20 km west of York	461229	6470947	Unknown	None
Westdale	Prospect		25 km SW of Beverley	476385	6428702	Unknown	None
Quartzite							
Black and Tan	Quarry	Care and maintenance	8 km SW of Toodyay	443590	6503694	Darling Earth Movers	EQL
Lovers Lane	Quarry	Care and maintenance	10 km SW of Toodyay	442970	6503380	Darling Earth Movers	EQL
Salt Valley Road	Quarry	Care and maintenance	10 km SSW of Toodyay	446542	6500089	Unknown	EQL
Basalt							
Jules Road, Gelorup	Quarry	Operating	8 km south of Bunbury	374607	6303899	CSR-Readymix Quarries	EQL
Lillydale Road, Gelorup	Quarry	Operating	9 km SSE of Bunbury	375601	6302912	Hanson Construction Materials	EQL
Sandstone							
Acrogem	Quarry	Operating	5 km north of Donnybrook	391622	6289852	Gosford Quarries	EQL
Beelerup North	Quarry	Operating	5 km NE of Donnybrook	393353	6288384	Meteor Stone	EQL
Beelerup South	Quarry	Operating	4 km NE of Donnybrook	393246	6287801	Meteor Stone	EQL
Chapman Valley Road	Quarry	Historic site	13 km NE of Geraldton	275853	6823500	Unknown	None
Donnybrook Stone	Quarry	Operating	4 km south of Donnybrook	390091	6280633	Donnybrook Stone Company	EQL

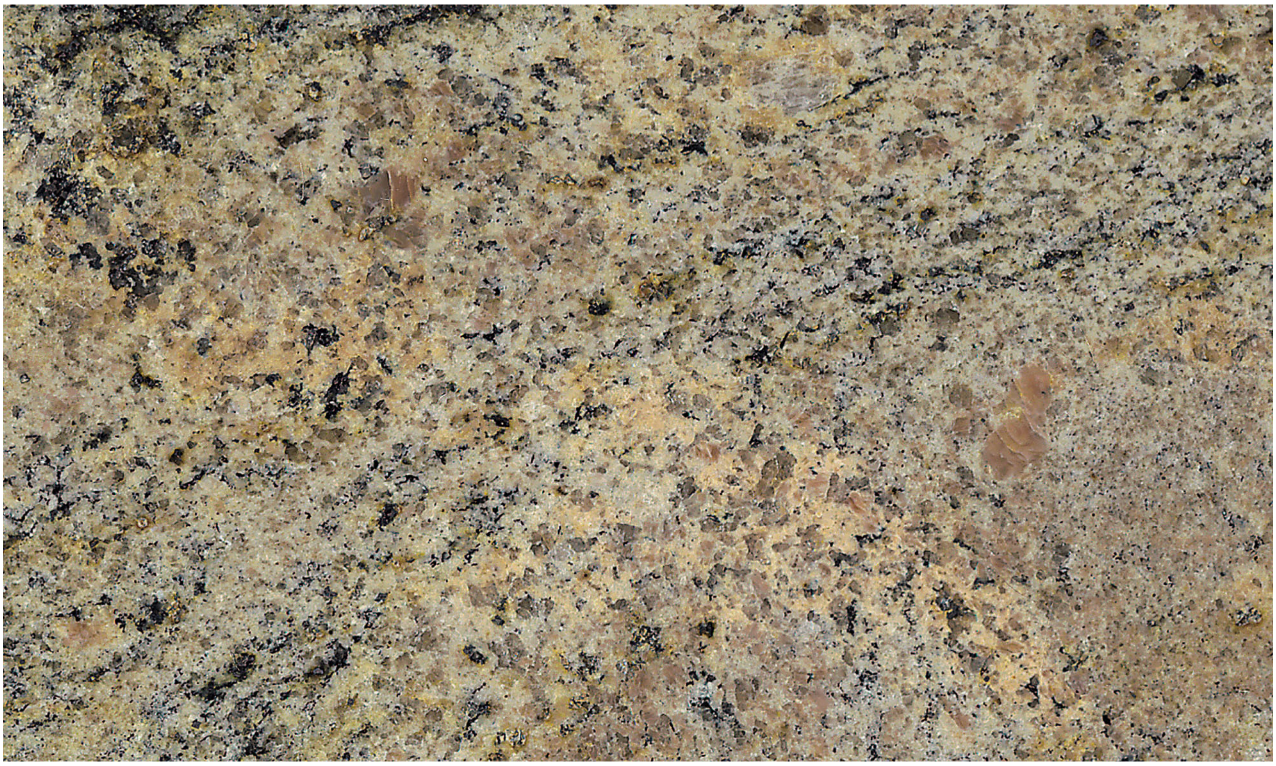
Appendix 2 (continued)

Name	Operation	Status	Location	MGA Zone 50 Eastings	MGA Zone 50 Northings	Owner	Tenement/licence
Government Quarry No. 1	Quarry	Care and maintenance	4 km north of Donnybrook	391346	6288756	Irishtown Sandstone	M70/862
Northampton	Quarry	Historic site	14 km WNW of Northampton	254471 (pos. approx.)	6865018	Unknown	None
White Peak	Quarry	Historic site	13 km north of Geraldton	268461	6828858	Unknown	None
Limestone							
Cutler Road, Carabooda	Quarry	Operating	40 km NNW of Perth	381794	6502289	Limestone Resources Australia	M70/109, M70/341, M70/345, and M70/346
Hopkins Road, Carabooda	Quarry	Operating	40 km NNW of Perth	382271	6502242	Limestone Building Blocks	M70/13 and M70/339
Kooallup Lagoon	Quarry	Operating	1.0 km east of Lake Preston	379031	6346120	B & T Versaci Lime	EQL
Moore River No. 1	Quarry	Operating	3.5 km NNE of Guilderton	359130	6533854	Limestone Resources Australia	M70/193
Moore River No. 2	Quarry	Operating	3.5 km NNE of Guilderton	359495	6532539	Limestone Resources Australia	M70/786
Myalup, Giacci	Quarry	Operating	2.5 km SE of Myalup	379203	6334153	G M Family Trust (Giacci)	EQL
Myalup, Carbone	Quarry	Operating	2.5 km SE of Myalup	379358	6334595	Carbone Bros	EQL
Myalup, Catalano	Quarry	Operating	2.5 km SE of Myalup	379497	6333856	B & J Catalano	EQL
Narngulu	Quarry	Operating	11 km SE of Geraldton	274497	6807697	Wells Brothers/ Amazzini & Son	EQL
Postans	Prospect		30 km SSW of Perth	386849	6434756	Roadstone Quarries	M70/555
Reabold Hill, City Beach	Quarry	Historic site	8 km WNW of Perth	384451	6465682	Unknown	None
Seabird	Prospect		85 km NNW of Perth	353913	6537580	Limestone Resources Australia	M70/769, M70/822, M70/865
Stoneridge, Hope Valley	Quarry	Operating	27 km SSW of Perth	387561	6438678	Stoneridge Quarries WA	EQL
Wattle Avenue 8	Quarry	Operating	35 km NNW of Perth	383889	6497476	Crown Limestone Supply	Sublease on M70/143
Wattle Avenue 9	Quarry	Operating	35 km NNW of Perth	383934	6497054	Limestone Resources Australia	Sublease on M70/143
Wesco Road, Nowergup 3	Quarry	Operating	37 km NNW of Perth	382315	6499738	Limestone Building Blocks	Sublease on M70/141
Wesco Road, Nowergup 4	Quarry	Care and maintenance	37 km NNW of Perth	381111	6498750	Meteor Stone	EQL
Wesco Road, Nowergup 5	Quarry	Operating	37 km NNW of Perth	382701	6498254	Limestone Natural	Sublease on M70/138
Wesco Road, Nowergup 6	Quarry	Operating	37 km NNW of Perth	382960	6498382	Italia Limestone	Sublease on M70/138
Wesco Road, Nowergup 7	Quarry	Operating	37 km NNW of Perth	382552	6498049	Meteor Stone	Sublease on M70/138
Yanchep	Quarry	Operating	60 km NNW of Perth	373856	6521442	Archistone	M70/367
Diatomite							
Gingin	Quarries[c]	Historic site	1–7 km west and NW of Gingin	393674 (pos. approx.)	6530479	Unknown	None

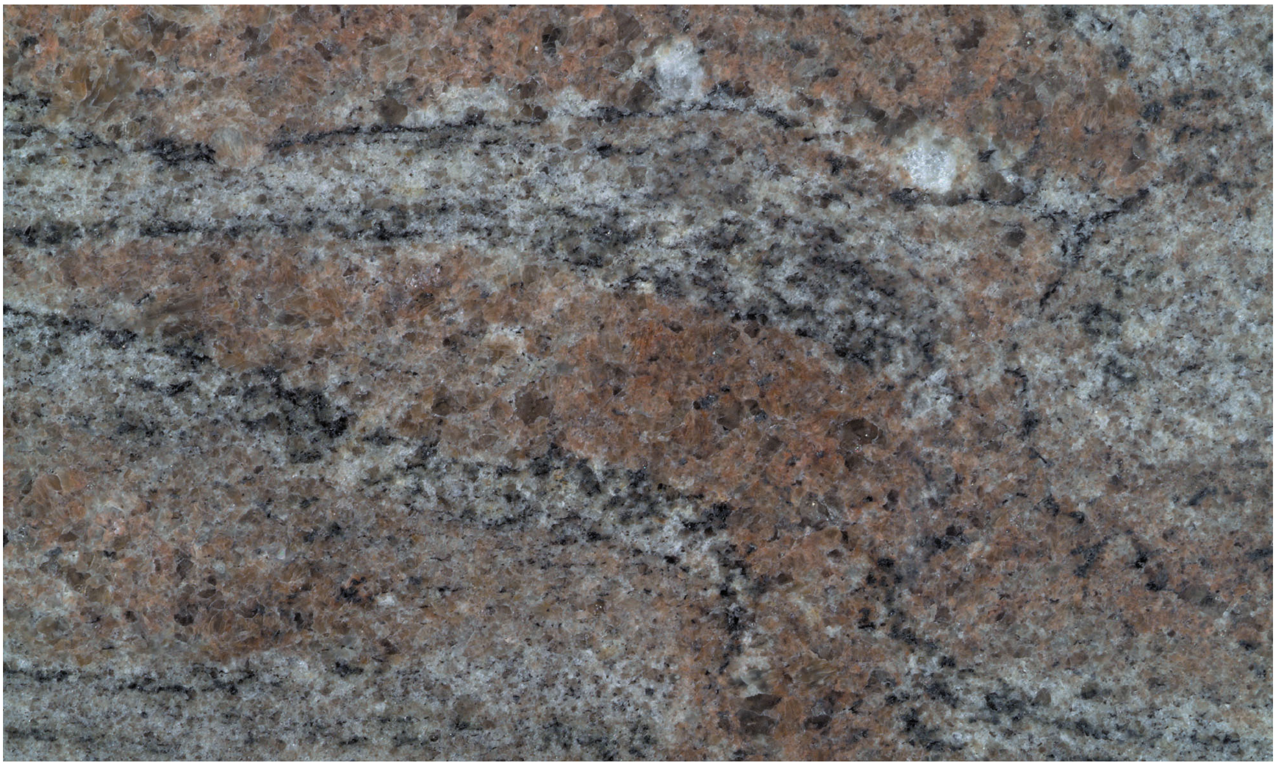
NOTES: All sites are listed in the Department of Industry and Resources online MINEDEX mines and mineral deposits database
M: mining lease
EQL: extractive quarry licence

Appendix 3

Photo image gallery of dimension stones from the Perth Region

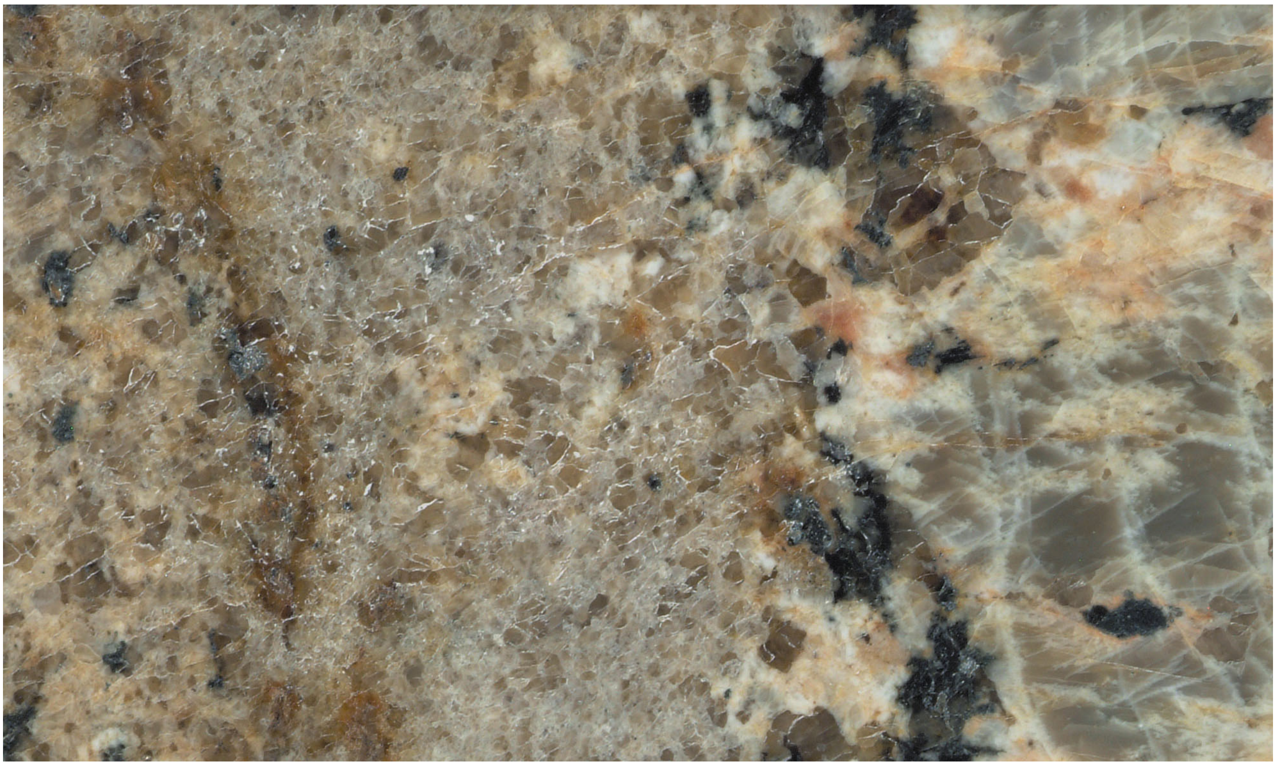


Appendix 3.1. ***Austral Juperana*: leucocratic quartz syenite granofels. Bruce Rock (courtesy Melocco Pty Ltd, and © Discovering Stone, 2004)**



10 mm

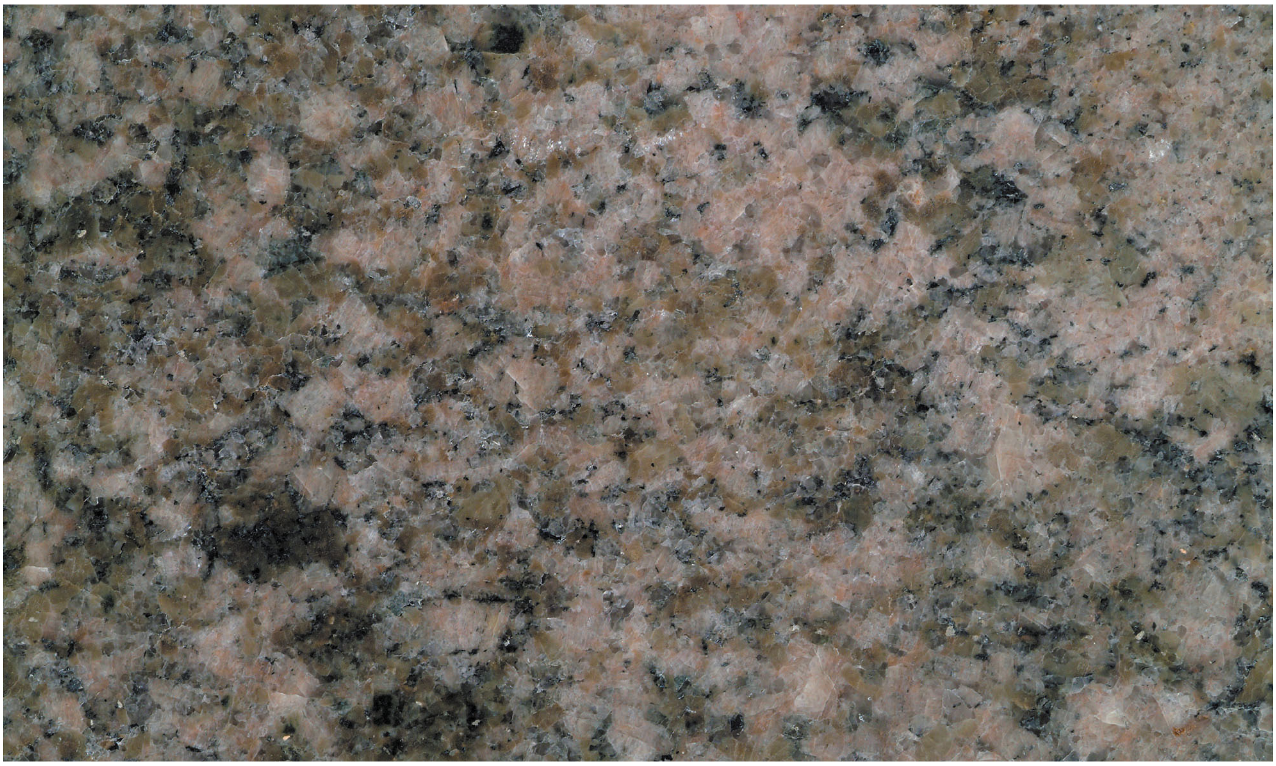
Appendix 3.2. *Austral Waterfall*: leucocratic quartz monzonite granofels, Bruce Rock



JMF352

10 mm

Appendix 3.3. *Austral Coffee*: granodiorite granofels with an interfingering monzogranite pegmatite, Bruce Rock



10 mm

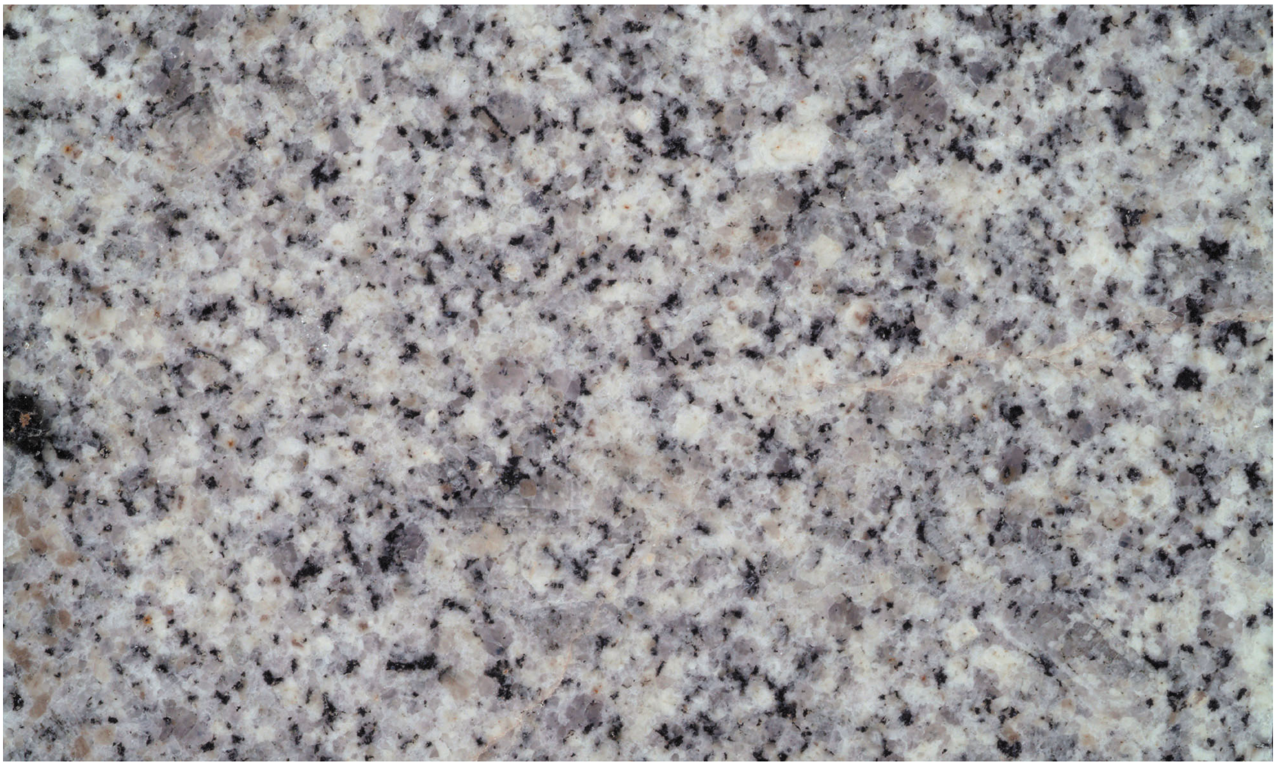
Appendix 3.4. Carnamah granite: leucocratic, biotite monzogranite, Winchester quarry, Carnamah

JMF353

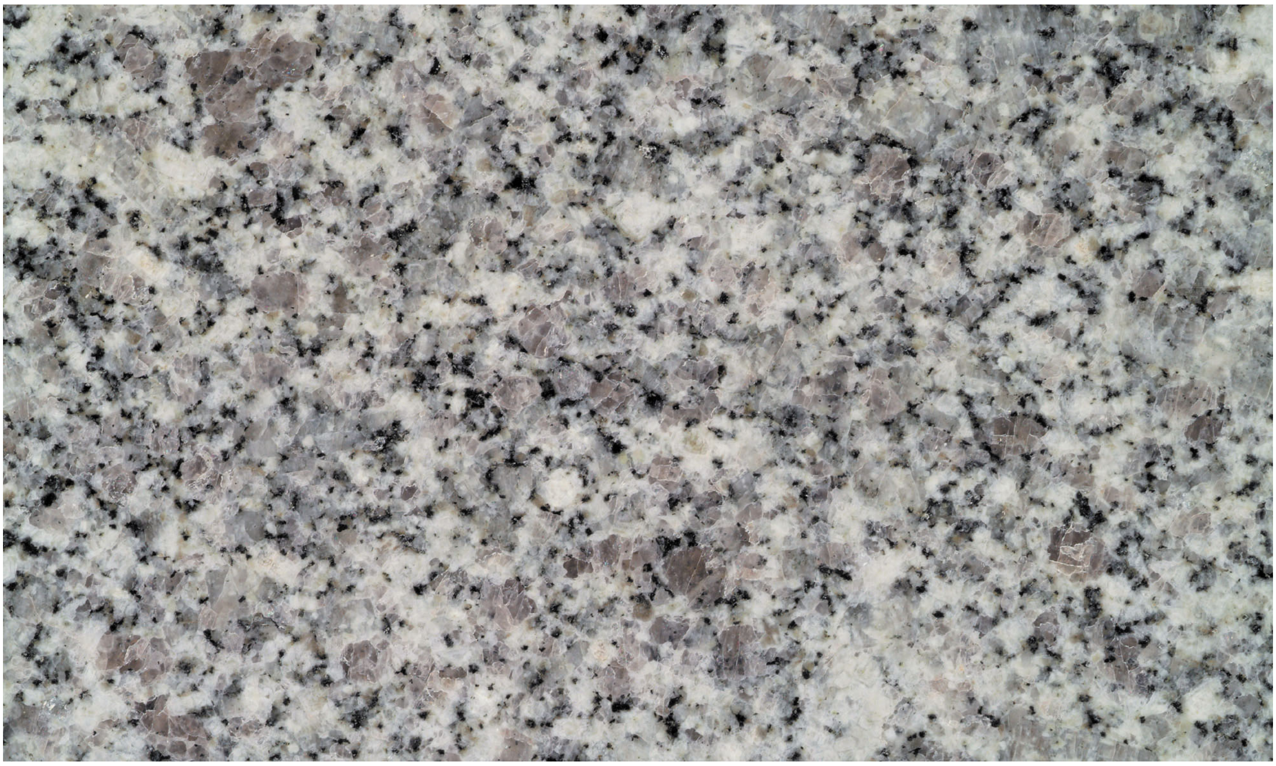
50 mm

Appendix 3.5. Carrido Spring gneiss: gneissic tonalite, Carrido Spring quarry

Appendix 3.6. Greenmount granite: weakly deformed monzogranite, Greenmount Hill quarry



Appendix 3.7. Mahogany Creek granite: even-grained monzogranite, Mahogany Creek quarry



Appendix 3.8. Mundaring granite: inequigranular monzogranite, Mundaring quarry

JMF356 10 mm

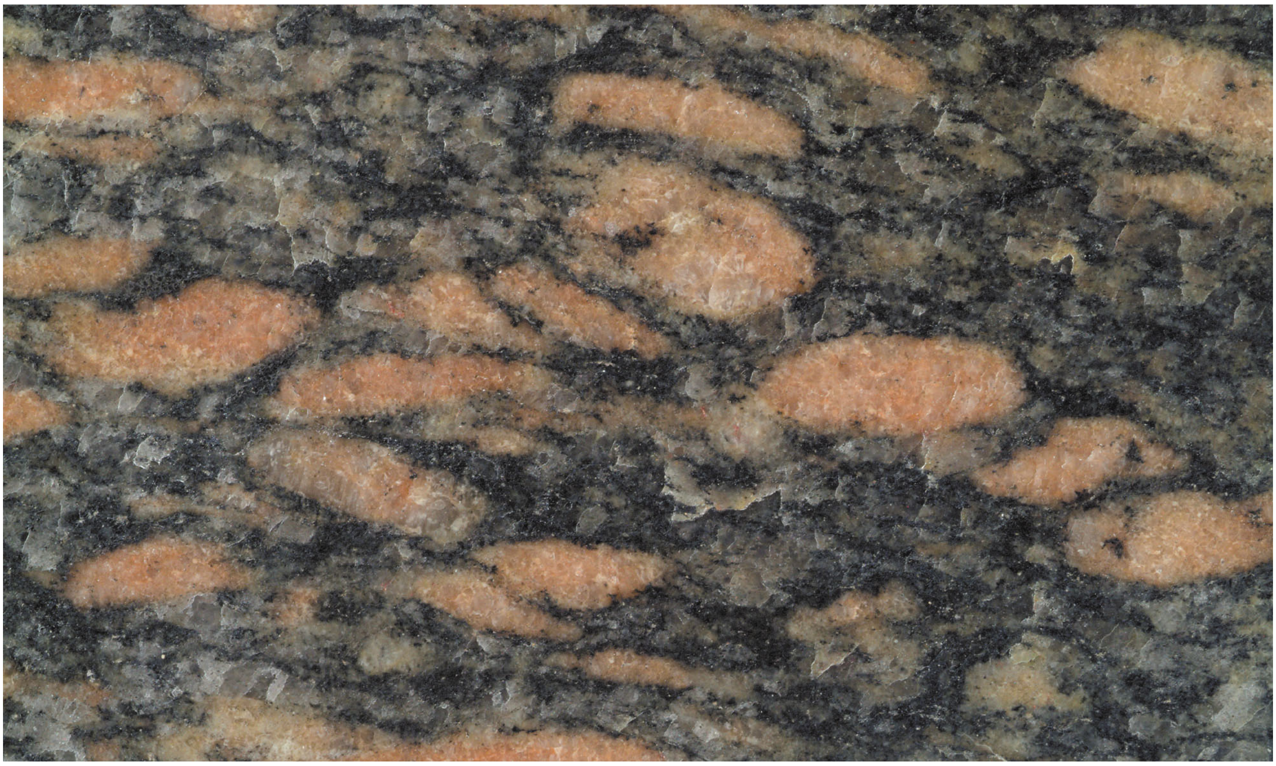
Appendix 3.9. Karlgarin granite gneiss: biotite syenogranite gneiss, Karlgarin quarry

Appendix 3.10. Kellerberrin granite: hornblende–biotite monzogranite, Doodlakine quarry

Appendix 3.11. Meckering granite: fine-grained, grey, uniform, biotite–quartz monzodiorite, Meckering quarry

JMF358 10 mm

Appendix 3.12. Roelands gneiss: layered biotite monzogranite gneiss, Roelands quarry



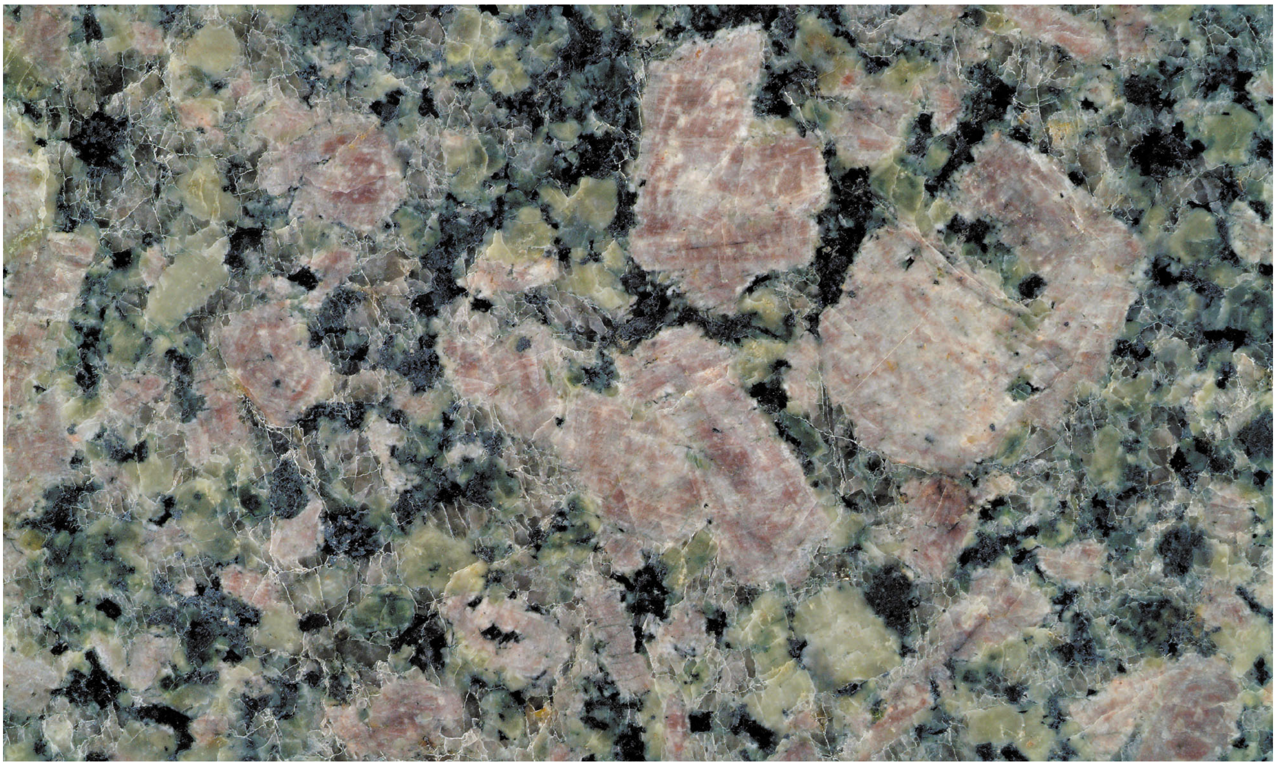
10 mm

Appendix 3.13. Roelands gneiss: lenticular-layered biotite monzogranite gneiss, Roelands quarry

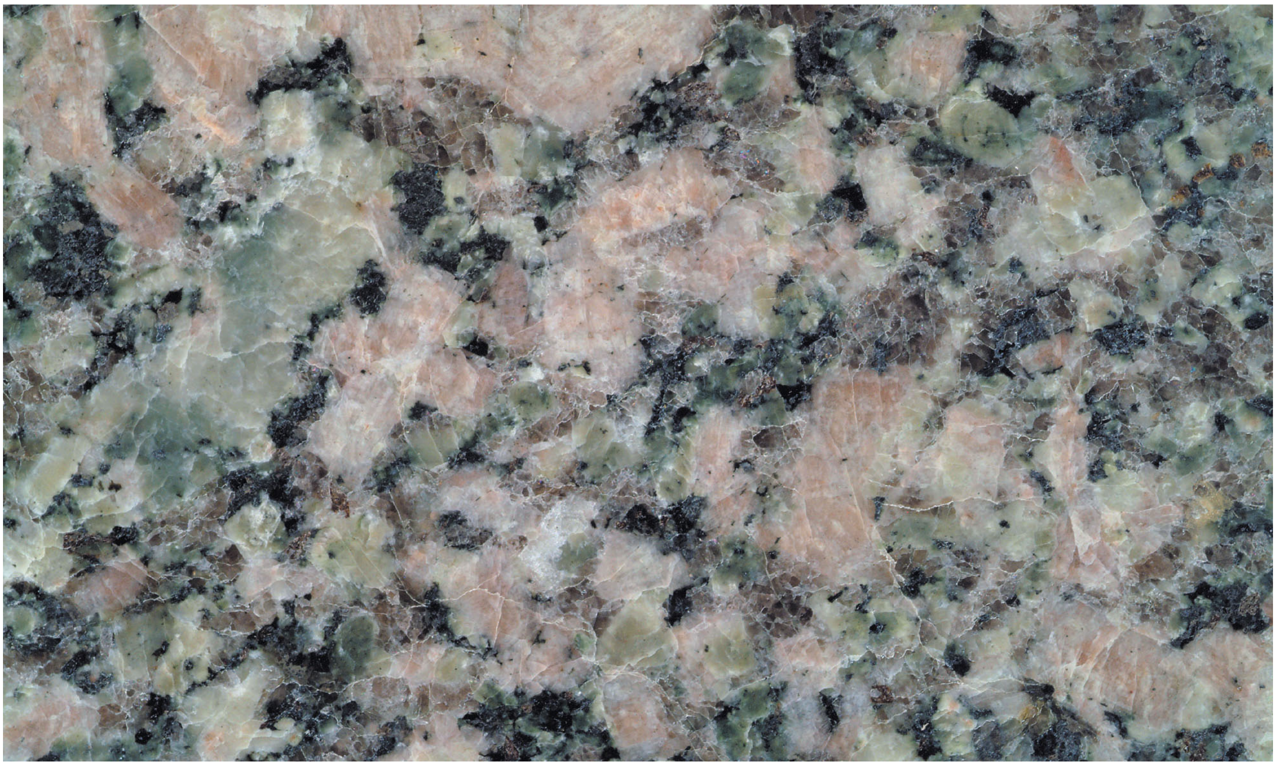
JMF359

10 mm

Appendix 3.14. Roelands gneiss: heterogeneous biotite monzogranite gneiss, Roelands quarry

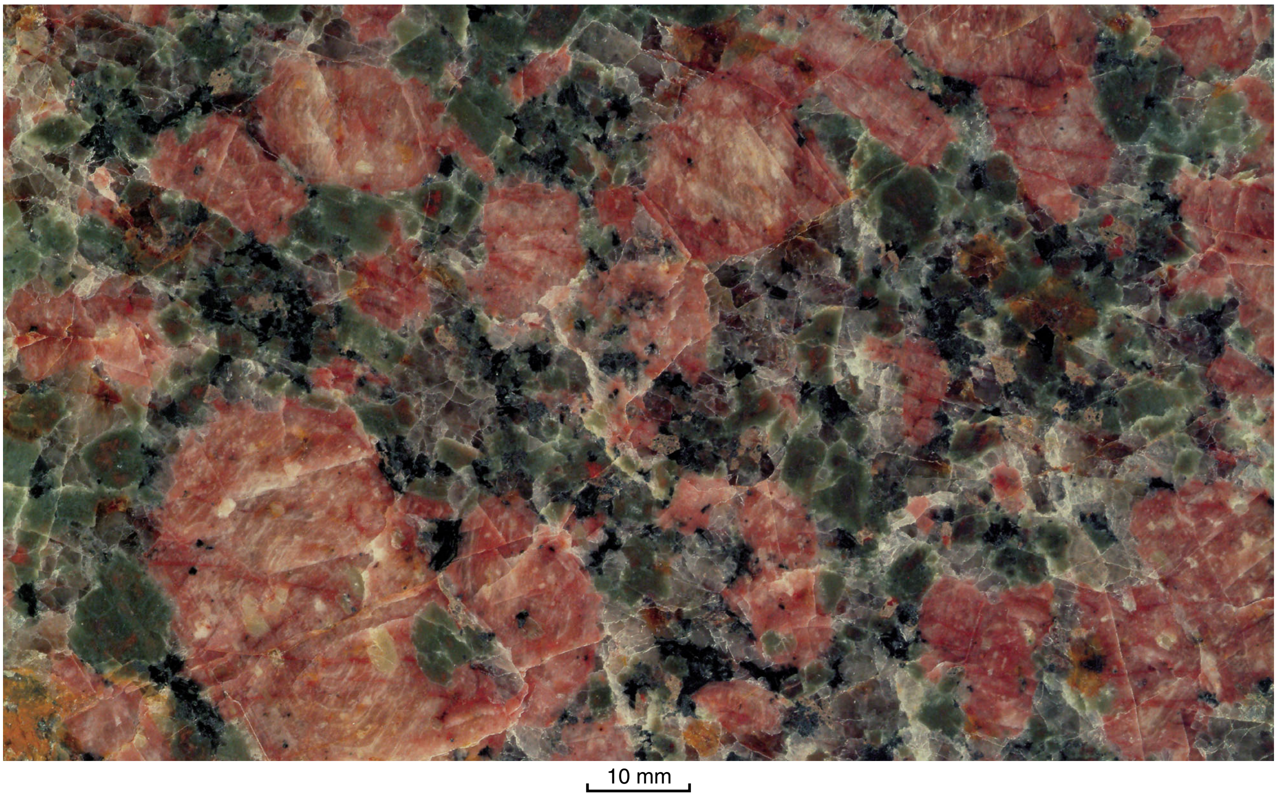


Appendix 3.15. ***Valmere Green*** **granite: coarse-grained, heterogeneous, quartz monzonite, Watheroo**



JMF360

Appendix 3.16. ***Verde Lope*** **granite: coarse-grained, megacrystic, hornblende–biotite monzogranite, Watheroo**



Appendix 3.17. ***Watheroo Red*** **granite: coarse-grained biotite monzogranite, Watheroo**

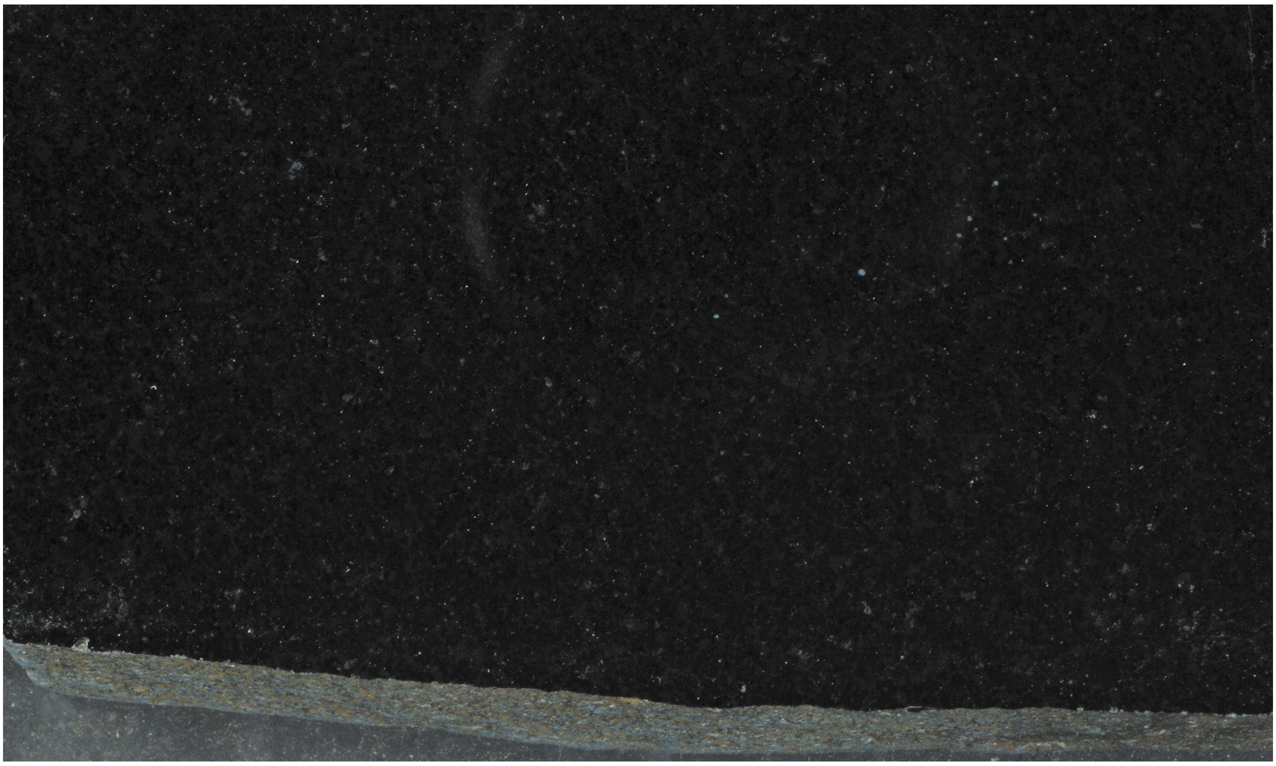
Appendix 3.18. ***Mulroy Green*** **granite: coarse-grained monzogranite, Namban**

Appendix 3.19. *Namban Red*: coarse-grained quartz syenite, Namban

Appendix 3.20. ***York Granite*****: megacrystic quartz monzodiorite, Gwambygine quarry, York**

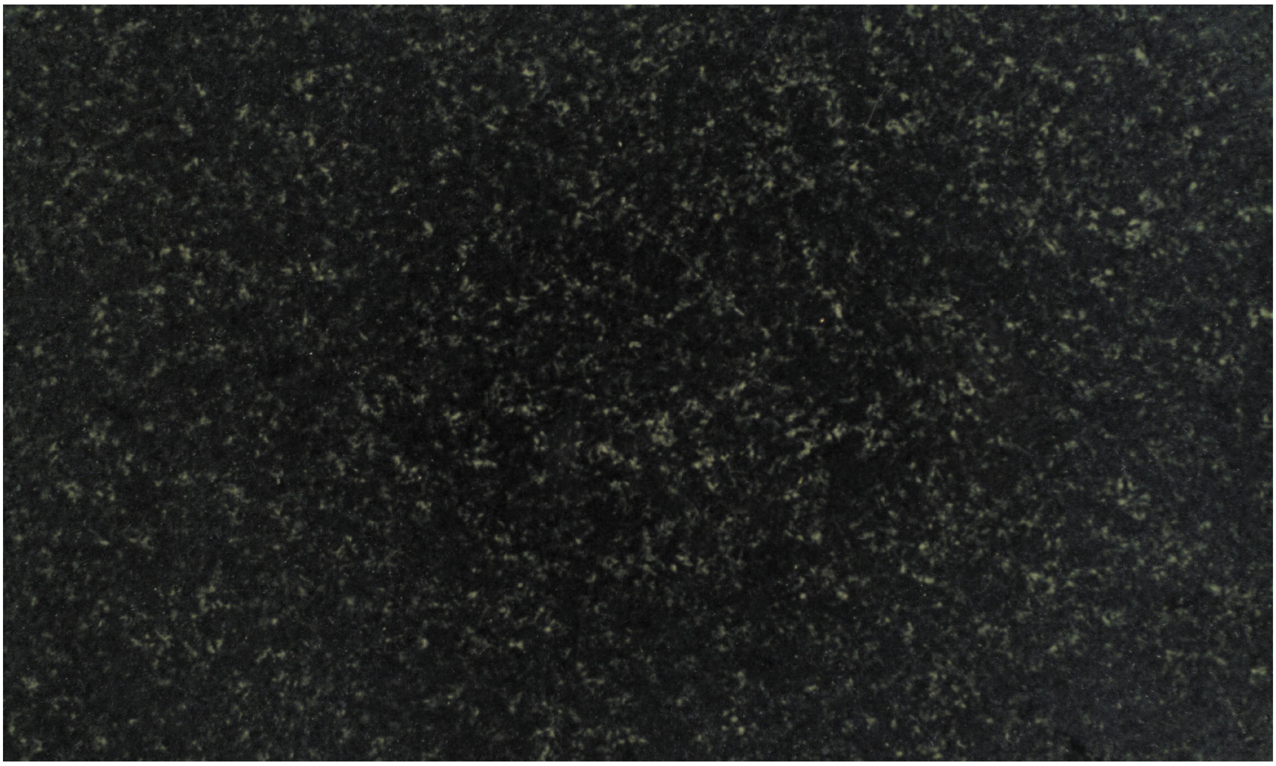
JMF363

Appendix 3.21. ***York Granite*****: megacrystic hornblende–quartz monzodiorite, Waterhatch Road quarry, Beverley district**



10 mm

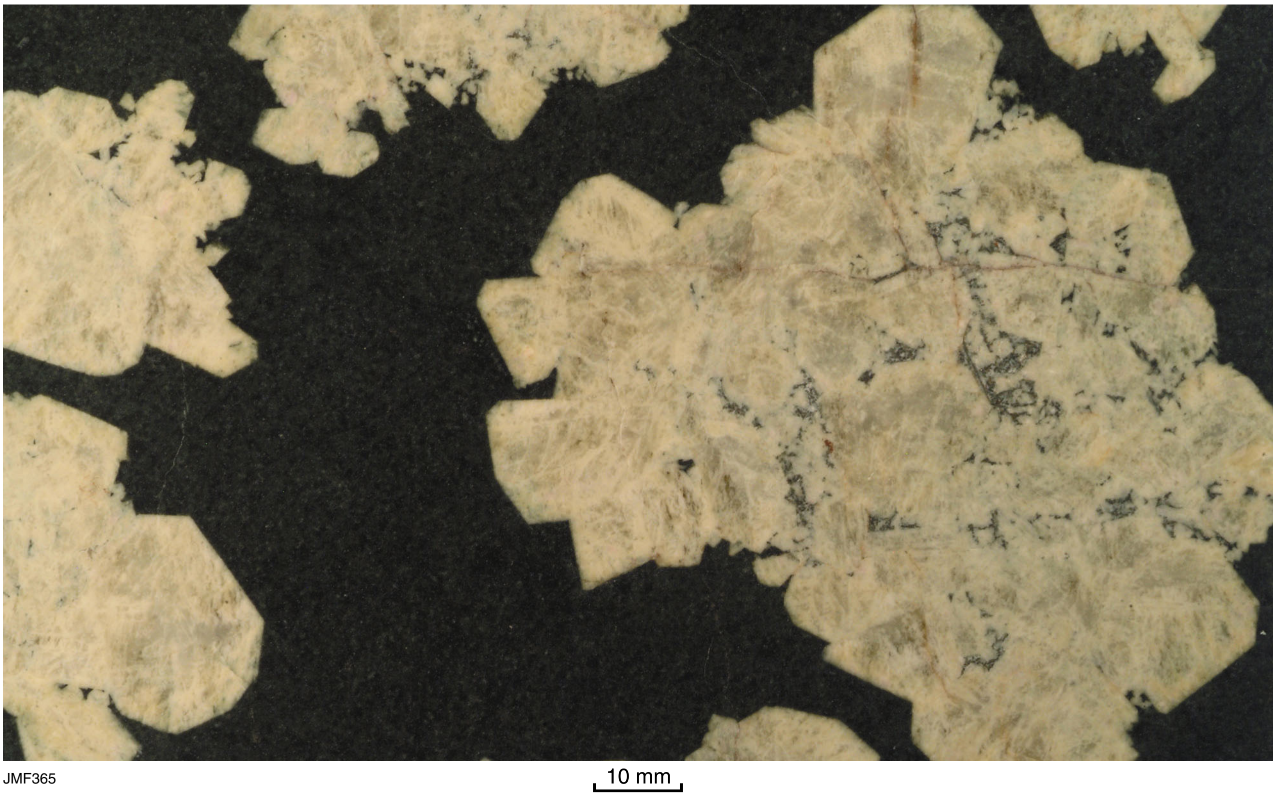
Appendix 3.22. Orange Grove black granite: fine-grained dolerite, Orange Grove quarry, Bridgetown



JMF364

10 mm

Appendix 3.23. Wambyn black granite: medium- to coarse-grained dolerite, Wambyn prospect, York district

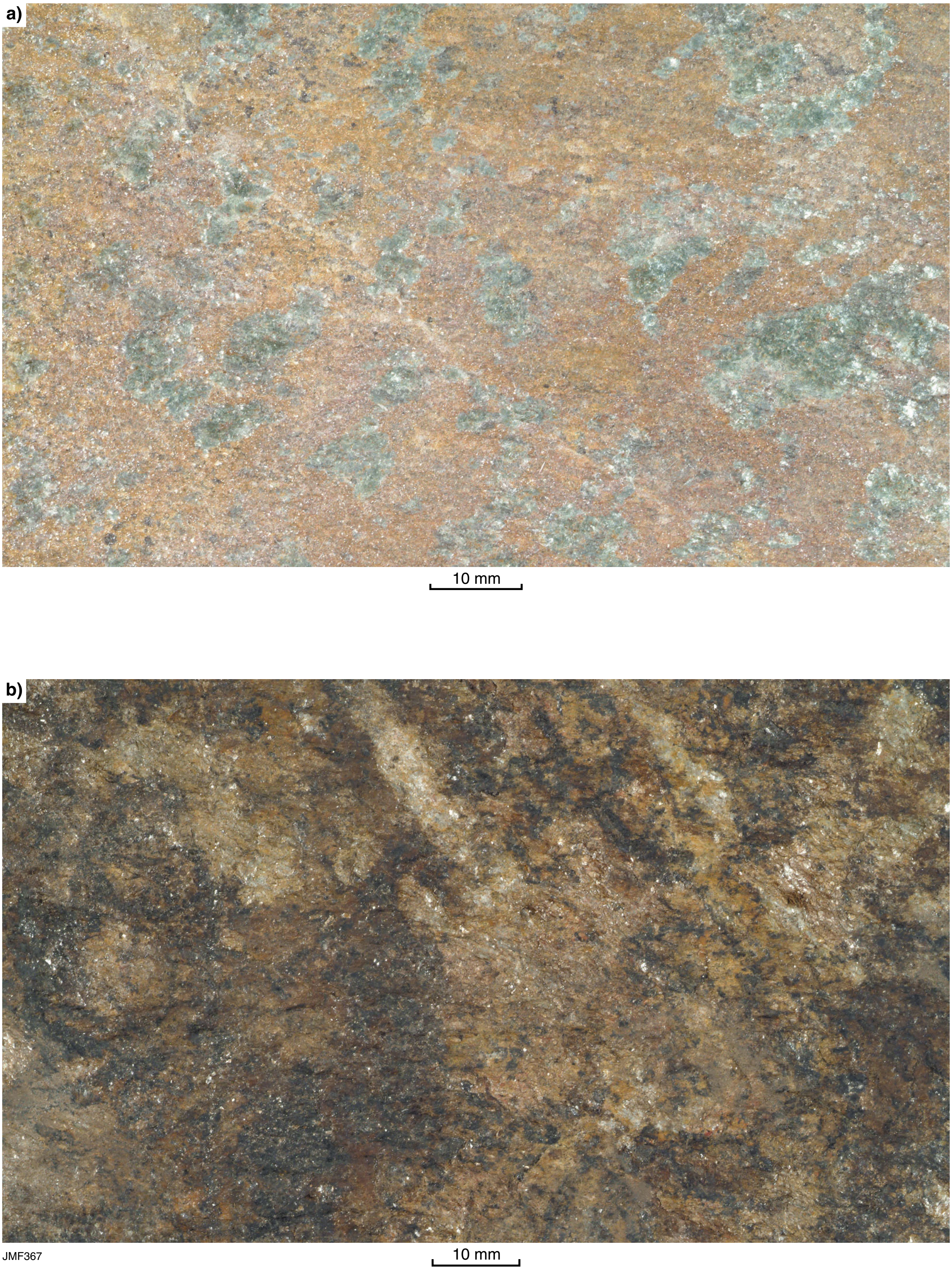


JMF365

Appendix 3.24. Westdale black granite; megacrystic dolerite. Westdale prospect, Beverley district

JMF366

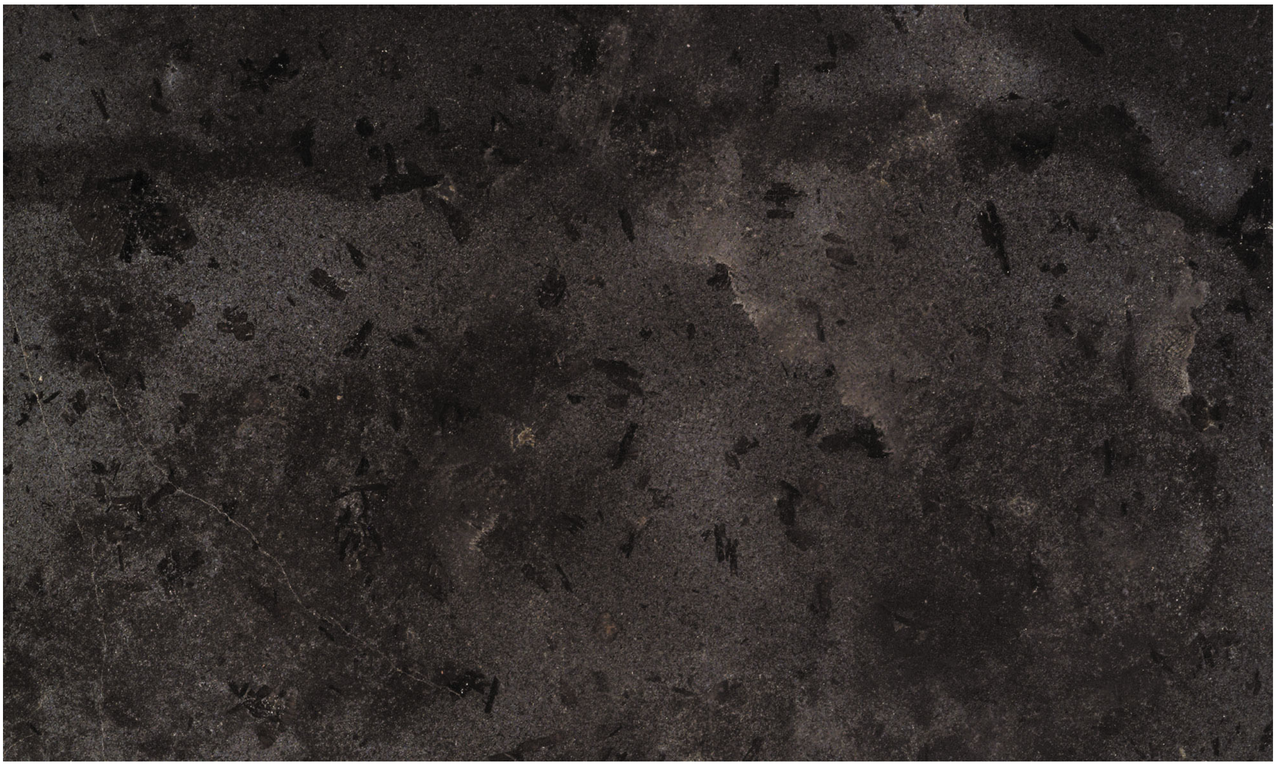
Appendix 3.25. ***Toodyay Stone*: a) silver-grey, coarse-grained quartzite; b) coarse-grained quartzite with pale green fuchsite mica coatings on parting planes, Salt Valley Road quarry, Toodyay**



Appendix 3.26. ***Toodyay Stone*: schistose, medium-grained metasandstone: a) mid-brown variety with pale green fuchsite patches on parting plane; b) variegated, mid- to dark brown variety, Black and Tan quarry, Toodyay**

10 mm

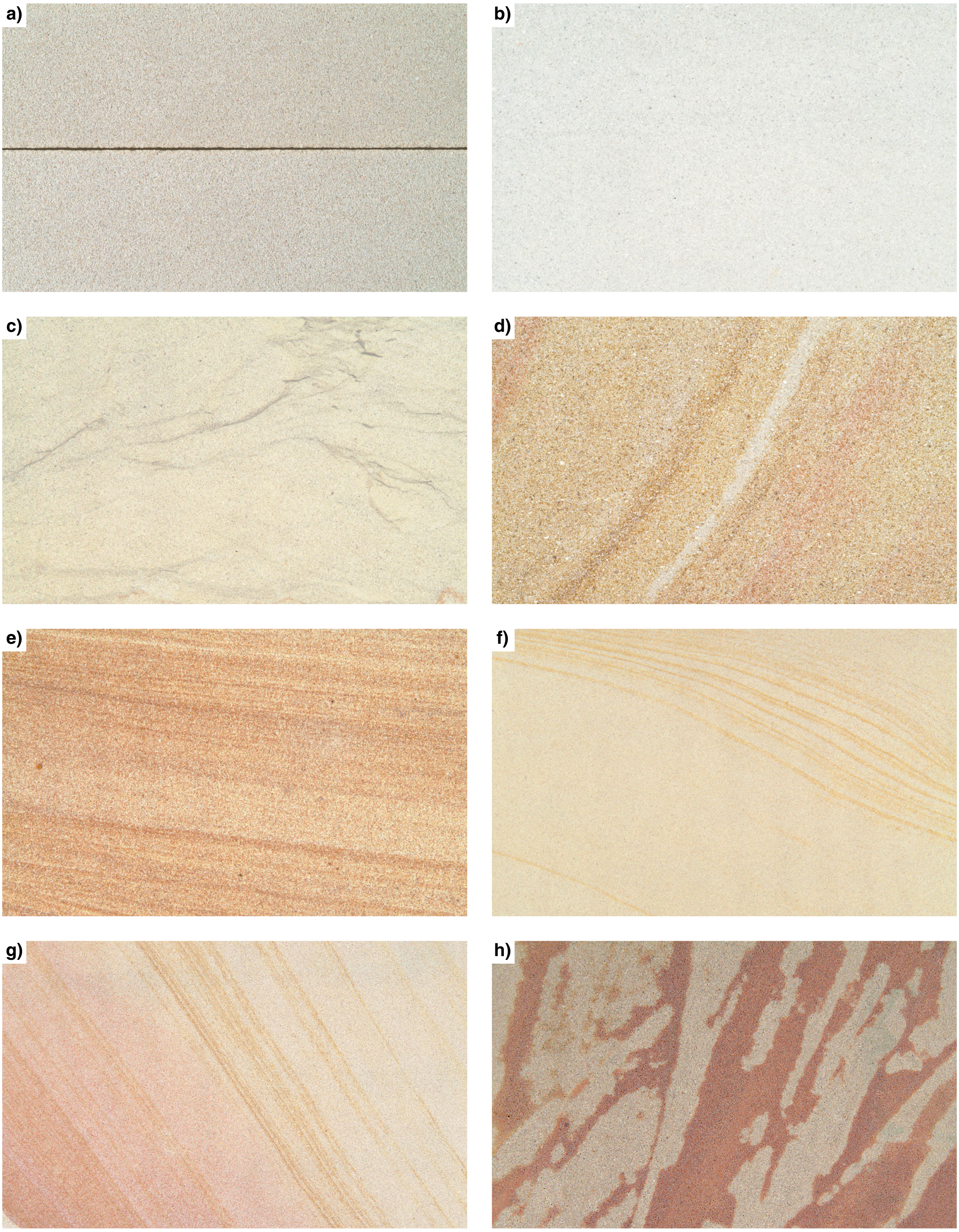
Appendix 3.27. Wooodlands granitic gneiss: gneissic quartz syenite, Woodlands prospect, Wilyabrup district



JMF368

10 mm

Appendix 3.28. Bunbury Basalt: dark grey porphyritic basalt, Jules Road quarry, Gelorup



JMF369

Appendix 3.29. Donnybrook Sandstone: very fine to coarse-grained, feldspathic sandstone: a) Acrogem quarry: fine-grained, off-white sandstone; b–e) Donnybrook Stone quarry: fine- to coarse-grained sandstones ranging from plain white, to off-white, and brown-banded varieties; f–h) Beelerup quarries: fine- to medium-grained sandstones ranging from banded pink to pale beige, and red mottled varieties, Donnybrook area (photos (a) 70% natural scale, (b) natural scale; (c)–(h) approximately 50% natural scale)

10 mm

Appendix 3.30. Tamala Limestone: cream to pale brown, massive, porous, microfossiliferous limestone. A typical example of high-grade limestone building block material from the Carabooda–Nowergup area, Wattle Avenue quarry, Nowergup

JMF370

10 mm

Appendix 3.31. Tamala Limestone: biscuit-coloured, massive, very porous, microfossiliferous building block limestone, Moore River quarry, near Guilderton

JMF371

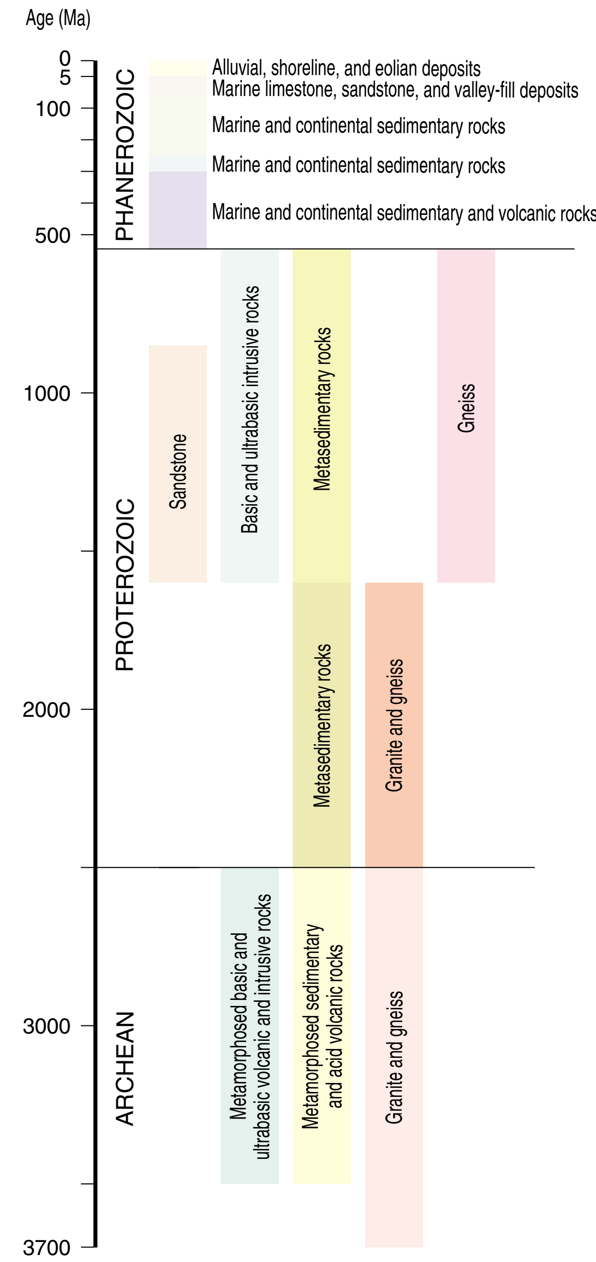
Appendix 3.32. ***Casuarina Stone*****: massive to weakly layered diatomite, predominantly composed of silty claystone, Gingin Brook environs, Gingin**

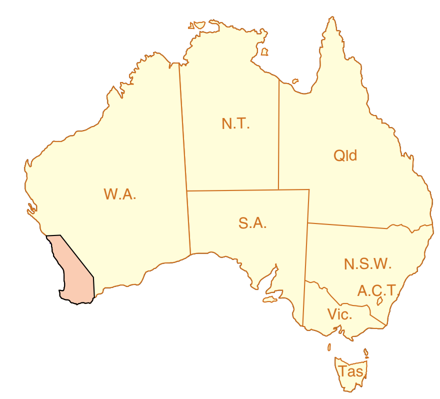
Volume 1 of this Bulletin covers much of the published and unpublished data on dimension stone quarries, prospects, and historical sites in the southwest region of Western Australia. Currently, the largest dimension stone operations, producing substantial quantities of limestone building blocks, are located in the Carabooda–Nowergup and Moore River areas to the north of Perth. Smaller operations producing high-quality blocks and slabs are at Donnybrook (sandstone) and Bruce Rock (granite). This detailed study includes the history of dimension stone, the rock types and their physical properties, and quarry design and operation. Accounts of added-value stone processing, world production and markets, and restoration techniques for weathered stone round out this work.

Further details of geological publications and maps produced by the Geological Survey of Western Australia are available from:

Information Centre
Department of Industry and Resources
100 Plain Street
East Perth, WA 6004
Phone: (08) 9222 3459   Fax: (08) 9222 3444

www.doir.wa.gov.au/GSWA/publications





Department of Industry and Resources

Geological Survey of Western Australia

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MINISTER FOR STATE DEVELOPMENT

TIM GRIFFIN
EXECUTIVE DIRECTOR

SCALE 1:2 000 000

0 20 40 60 80 100

Kilometres

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
MINERAL RESOURCES BULLETIN 23 PLATE 1

DIMENSION STONE IN SOUTHWEST WESTERN AUSTRALIA

Compiled by JM Fetherston 2006

Geology by Myers JM, and Hocking RM, 1998, Geological map of Western Australia, 1:2 500 000 (13th edition): Geological Survey of Western Australia.
Tectonic units by Tyler IM, and Hocking RM, 2002, Tectonic units of Western Australia (1:500 000 scale) preliminary release: Geological Survey of Western Australia.

Edited by N Tetlaw, H Caldon, and B Williams

Cartography by M Prause

Further information on mineral localities in WA can be obtained from MINEDEX database, Department of Industry and Resources.

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Phone (08) 9222 3459, Fax (08) 9222 3444
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Printed by Haymarket Pty Ltd, Perth.

The recommended reference for this map is:
Fetherston, JM, 2007, Dimension stone in southwest Western Australia Volume 1. Industry review and dimension stones of the southwest region *by* JM Fetherston, Geological Survey of Western Australia, Mineral Resources Bulletin 23, Plate 1.