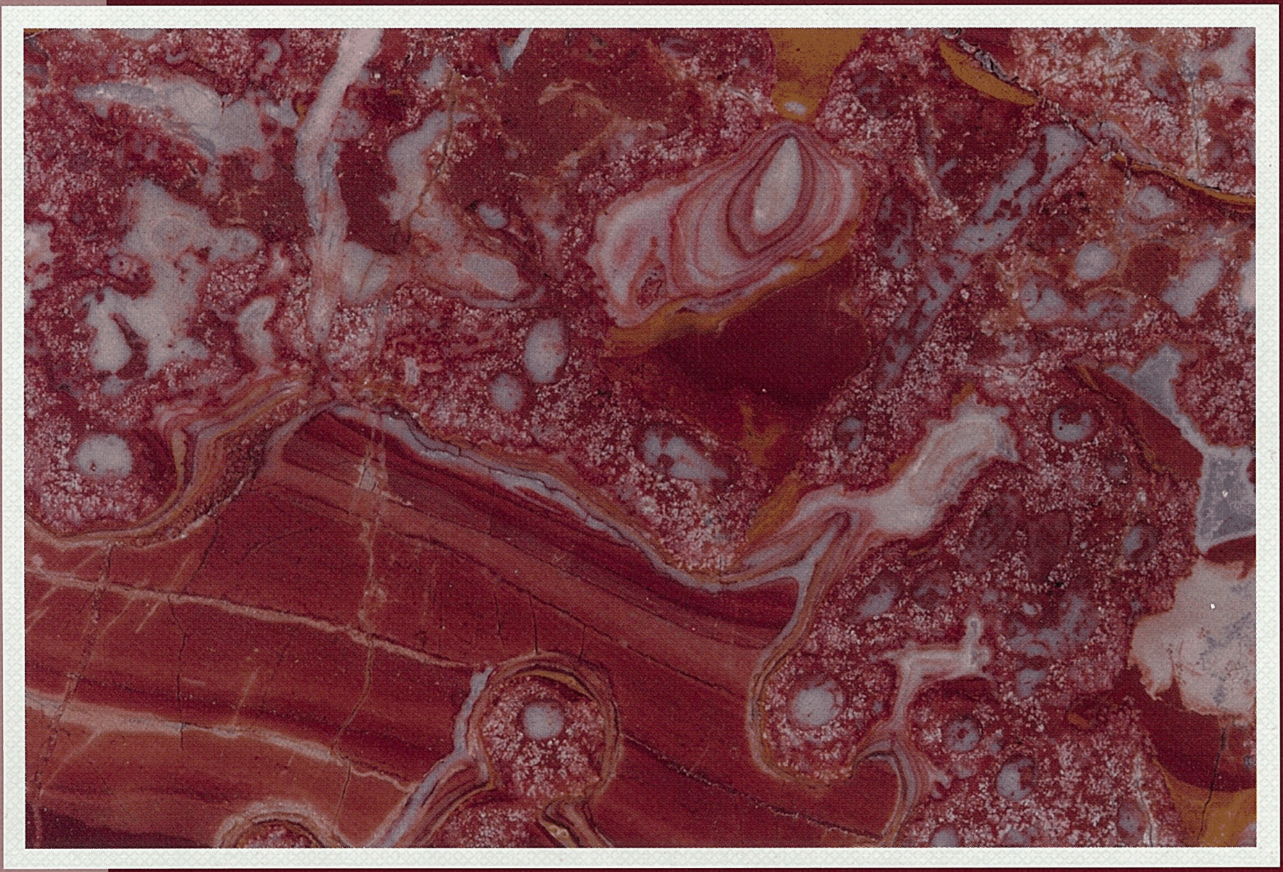
MINERAL RESOURCES BULLETIN 18

GOVERNMENT OF WESTERN AUSTRALIA

LIMESTONE AND LIMESAND RESOURCES OF WESTERN AUSTRALIA

by P. B. Abeysinghe



GEOLOGICAL SURVEY OF WESTERN AUSTRALIA

DEPARTMENT OF MINERALS AND ENERGY

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Cover photograph:
Devonian limestone from the reefal complexes of the Lennard Shelf, Northern Canning Basin.

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Limestone and limesand resources of Western Australia

by

P. B. Abeysinghe

Abstract

Large deposits of high-grade limestone, in excess of several hundred billion tonnes, occur in the Eucla Basin, Cape Range, Dampier Archipelago, and the Perth region. Many localities along the coast of Western Australia, from Geraldton in the north to Augusta in the south, contain extensive deposits of high-grade limesand, the notable localities being Dongara, Cervantes, Jurien, Lancelin, Cockburn Sound, and Boranup. Other major limestone deposits occur on the Lennard Shelf on the northern margin of the Canning Basin, and within the Ord and Bonaparte Basins in the Kimberley region bordering the Northern Territory.

Consumption of limestone in Western Australia during 1995 was approximately 4.64 Mt. This figure includes limestone production of 2.18 Mt (mainly high-grade limestone) reported to the Department of Minerals and Energy (DME), 1.96 Mt of low-grade limestone produced for use as roadbase and in other construction activities (unreported to DME), and 0.3 Mt of imported clinker (equivalent to around 0.5 Mt of high-grade limestone).

Production of high-grade limestone in the State has been mainly from the Perth Metropolitan Region and accounts for approximately 97% of the total production of high-grade material (30 Mt from 1960 to 1995). Other significant production is from Loongana in the Eucla Basin, which yielded 66 086 t in 1995 (0.3 Mt from 1992 to 1995). Approximately 0.5 Mt of high-grade limesand was mined in the Dampier Archipelago from 1974 to 1988, but in recent years production from this area has been minimal.

The main producers of high-grade limestone in the State are Cockburn Cement Limited and Swan Portland Cement Limited. Mining of limestone resources close to the Perth Metropolitan Area is becoming increasingly difficult due to environmental constraints and competing landuses. The main obstacle to the mining of larger deposits located in places such as Cape Range and the Eucla Basin is high transport costs.

KEYWORDS: industrial minerals, industrial materials, aggregates, industrial mineral resources, mineral occurrence, limestone, limesand, calcareous sands, lime, lime industry, economic geology, mineral economics, mineral exploration, mineral processing, mineral industry, mining, Western Australia

Chapter 1

Introduction

Object and scope

Limestone is one of the industrial minerals that will continue to grow in demand in Western Australia, as in many parts of the world, since it is a raw material used in many industries and industrial processes. However, as limestone is a low-priced commodity the economic viability of any mining operation depends on the proximity of the deposit to consumers.

Current annual production of limestone in Western Australia is around 4.64 Mt, 2.68 Mt of which is high-grade material. Department of Minerals and Energy statistics on reported production suggest that approximately 97% of high-grade limestone in Western Australia has been produced from the Perth Metropolitan Region.

Prior to the publication of this Bulletin, patchy information on limestone resources in Western Australia was contained in a variety of unpublished and published reports. The main objective of this Bulletin is to compile all such information in one publication. This Bulletin is not intended to be an exhaustive study of all known deposits but is a guide to regions with potential limestone resources. As this publication is primarily on limestone resources, dolomite resources are not specifically mentioned unless horizons of high-grade limestone are known to be present within large dolomitic bodies (such as the Wittenoom Dolomite), or when dolomite horizons occur in limestone.

Landuse constraints

Limestone mining is severely affected by landuse constraints. Most of the State's limestone resources occur in national parks, nature reserves, or in areas identified for major development projects close to population centres. Therefore, development of limestone resources will often need clearance from various State and local government bodies such as the Department of Minerals and Energy, the Environmental Protection Authority, and the Department of Conservation and Land Management. Figures in this publication do not always indicate such areas because their boundaries are subject to frequent changes (e.g. the planned extensions to Yanchep and Cape Range National Parks).

Sources of information

Information in this Bulletin has been compiled from published and unpublished reports including records, annual reports, technical files, and open-file company data held by the Department of Minerals and Energy. Some major limestone deposits, and others thought to be significant, were visited by the author during September to November 1995. Samples collected were chemically analysed by Amdel Ltd laboratories in Perth. Tests for specific applications were not conducted as this was beyond the scope of this publication. Since samples collected were limited to those from outcrops, quarry faces, cliffs, and limesand dunes the chemistry of individual samples should only be taken as a very approximate guide to the grade of a limestone deposit. More detailed sampling programs involving drilling would be required to determine the economic feasibility of developing individual deposits.

Chemical analyses

In this Bulletin, the percentage of calcium is expressed as either CaO or $CaCO_3$ — conversion between these two is straightforward and based simply on molecular weights. $CaCO_3$ consists of 56% (by weight) CaO. Conversely, the weight percentage of $CaCO_3$ is obtained from the weight percentage CaO by multiplying by a factor of 1.786.

Some of the old (about 30–50 years old) analyses of limestone in this Bulletin are given as total carbonates. The procedure used at that time to obtain this value was a gravimetric method involving digestion of limestone by hydrochloric acid, and measurement of the mass of acid-insoluble material. This mass was subtracted from the sample mass to calculate total acid-soluble carbonate material. D. Herring (Chemistry Centre of Western Australia, pers. comm., 1998) believes that total carbonate figures, quoted with $CaCO_3$ and $MgCO_3$ values, probably represent total acid-soluble carbonate.

Bulletin layout

This Bulletin contains five chapters. After an introductory chapter, Chapter 2 discusses mineralogy, mode of occurrence and uses of limestone. The third chapter outlines production trends in Western Australia. Information within Chapters 2 and 3 is relevant to assessments of the economic viability of any planned project.

Chapter 4 describes the limestone and limesand resources in Western Australia. In accordance with the recent style of Geological Survey of Western Australia (GSWA) Mineral Resources Bulletins, the deposits are grouped by tectonic provinces. These provinces are based on the Survey's Memoir 3 (Geological Survey of Western Australia, 1990). Only relevant aspects of limestone formations within each tectonic unit are discussed. However, for a more detailed description of the geology of these tectonic units the reader should refer to Memoir 3.

Chapter 5 discusses issues related to the future development of limestone-based industries in Western Australia.

Abbreviations

ABARE	Australian Bureau of Agricultural and Resource Economics
DME	Department of Minerals and Energy
Ga	Billion years
GSWA	Geological Survey of Western Australia
K	Thousand
M	Million
Ma	Million years
t	Tonnes
UK	United Kingdom
USA	United States of America

Chapter 2

Mineralogy, mode of occurrence and uses of limestone

Mineralogy

Limestone is a sedimentary rock, consisting chiefly of calcium carbonate, which yields lime when burned. The principal mineral of limestone is calcite, which is the stable form of calcium carbonate at ordinary temperatures. There are gradations from high-calcium limestone (with at least 95% calcite, $CaCO_3$), to high-purity dolomite rock containing around 90% of the mineral dolomite ($CaMg(CO_3)_2$). The common impurities found in limestone include silica, feldspar, clays, pyrite, organic material, ankerite ($Ca_2MgFe(CO_3)_4$), magnesite ($MgCO_3$), and siderite ($FeCO_3$).

The term 'dolomite' refers to the mineral dolomite as well as to the sedimentary rock containing more than 90% of the mineral dolomite and less than 10% calcite. The mineral dolomite has the ideal chemical composition of $CaMg(CO_3)_2$.

The term 'dolostone' is sometimes used instead of the term 'dolomite rock' in order to avoid confusion. Dolomite rock, defined chemically as one having 45.7% magnesium carbonate, usually forms as a replacement product of limestone. It occurs in crystalline and non-crystalline forms, and is often interbedded with limestone.

Classification of limestone

Limestone is classified in many ways; the more common classifications being based on mineralogy and texture. Although such classifications are useful for industrial purposes, a chemical classification is also necessary because many uses of limestone depend on its chemical composition (Folk, 1959, 1962; Leighton and Pendexter, 1962; Dunham, 1962; Bissell and Chilingar, 1967; Carr and Rooney, 1983).

Mineralogical classification

The mineralogical classification of Carr and Rooney (1983) is based on the volumetric proportions of calcite, dolomite (mineral), and non-carbonate materials present in a carbonate rock. Rocks containing more than 90% calcite are classified as limestone, and those containing 50–90% calcite as dolomitic limestone (Fig. 1).

Chemical classification

Literature references to the chemical classification of limestone are rare. A practical chemical classification for industrial requirements would be that rocks containing 97% $CaCO_3$ are ultra-high calcium limestone and those containing 95% $CaCO_3$ are high-calcium limestone. Rocks containing 95% $CaCO_3$ plus $MgCO_3$ are high-purity carbonate rocks and those containing 45.7% $MgCO_3$ are dolomite (Carr and Rooney, 1983).

Textural classification

This type of classification, which is critical for determining the origin of carbonate rocks, relies on identifying and estimating the relative abundances of four textural components: grains, lime mud (micrite), cement, and pores (Leighton and Pendexter, 1962). These components have been described as follows:

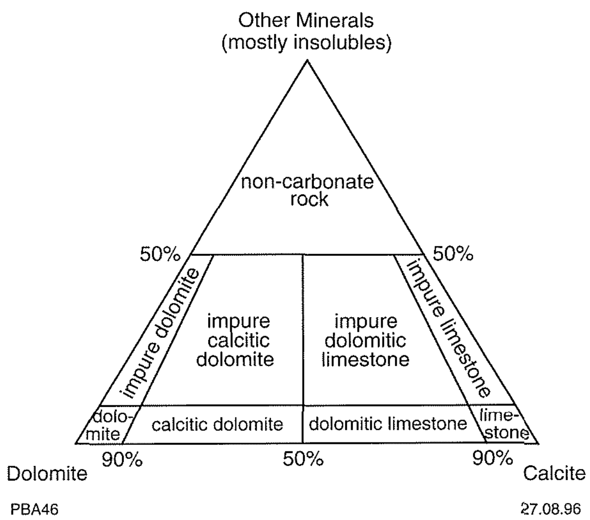

Figure 1. Mineralogical classification of carbonate rocks (after Carr and Rooney, 1983)

Grain/ Micrite Ratio	% Grains	Grain Type					Organic Frame-builders	No Organic Frame-builders
		Detrital Grains	Skeletal Grains	Pellets	Lumps	Coated Grains		
		Detrital Ls	Skeletal Ls	Pellet Ls	Lump Ls	Oolitic Ls Pisolitic Ls Algal en-crusted Ls	Coralline Ls Algal Ls etc.	
9:1	~90%							
		Detrital-micritic Ls	Skeletal-micritic Ls	Pellet-micritic Ls	Lump-micritic Ls	Oolitic-(pisolitic etc.) micritic Ls	Coralline-micritic Ls Algal-micritic Ls etc.	
1:1	~50%							
		Micritic-detrital Ls	Micritic-skeletal Ls	Micritic-pellet Ls	Micritic-lump Ls	Micritic-oolitic (pisolitic etc.) Ls	Micritic-coralline Ls Micritic-algal Ls etc.	Caliche Travertine Tufa
1:9	~10%							
		← Micritic Limestone →						

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Figure 2. Textural classification of limestone (after Leighton and Pendexter, 1962)

(a) Grains — five grain types are recognized (Fig. 2):

1. Detrital grains (made of debris derived from pre-existing rocks);
2. Skeletal grains (the remains of the hard parts secreted by organisms);
3. Pellets (grains of micritic material lacking significant internal structure);
4. Lumps (composite grains typically possessing surficial irregularities and believed to have formed by a process of aggregation);
5. Coated grains (those having concentric or enclosing layers of calcium carbonate around a central nucleus).

(b) Lime mud (micrite) — a common textural component of limestone that ranges from unconsolidated ooze to its lithified equivalent. It refers to ooze or mud of either chemical or mechanical origin and is given an arbitrary upper size limit of 0.03 mm.

(c) Cement — a clear crystalline component that fills the spaces between grains.

(d) Pores — the most important textural component, although pore space changes with the type, roundness, size, shape, sorting and packing of grains, the amount of micritic material, and the amount of cement.

Dunham (1962) classified limestone on the basis of rock or sediment fabric, and the presence of any biological binding. The three main divisions are between limestones which are matrix-supported (mudstone and wackestone), grain-supported (packstone and grainstone), and biologically bound (boundstone). A fourth category, crystalline limestone, is also recognized (Fig. 3).

Another system of classification, based on grain size, is widely used in literature to define three categories. These are calcilutite (grains <62 μm), calcarenite (grains 62 μm to 2 mm), and calcirudite (grains >2 mm) (Tucker et al., 1990).

Origin of limestone

Limestones can be either chemical (organic or inorganic) or mechanical in origin and can occur as detrital, chemical, oolitic, earthy, crystalline, or recrystallized varieties. Many limestones are highly fossiliferous and represent ancient carbonate accumulations in a variety of shallow, deep-marine, and strandline environments. Locally, coral reefs and shell banks are preserved as limestone deposits. During the formation of limestone on shallow sea floors, calcareous organisms may be preserved as readily recognizable fossils such as clams, corals, crinoids, bryozoans, and algae while other shell material is broken up and transported by waves and currents. As a result of such processes, limestones may exhibit diverse textural characteristics such as variable grain size, clasts of reworked limy sediments, faecal pellets, and ooliths embedded in a matrix of micro-crystalline calcite ooze. Limestones have been formed from Precambrian to Recent times, and therefore the types of organisms that have produced them vary from place to place depending on the age of the limestone.

The environment of limestone deposition influences the likelihood of developing an economically viable limestone deposit since this factor determines the size, shape, and purity of a deposit. For example, limestones that form in high-energy environments tend to be high-calcium limestones consisting of sand-size particles with sparry cement; either grainstones free of mud or packstones with only a little mud. Whereas micrite, which accumulates in low-energy environments, is more likely to contain impurities such as clay and silt-size non-carbonate material.

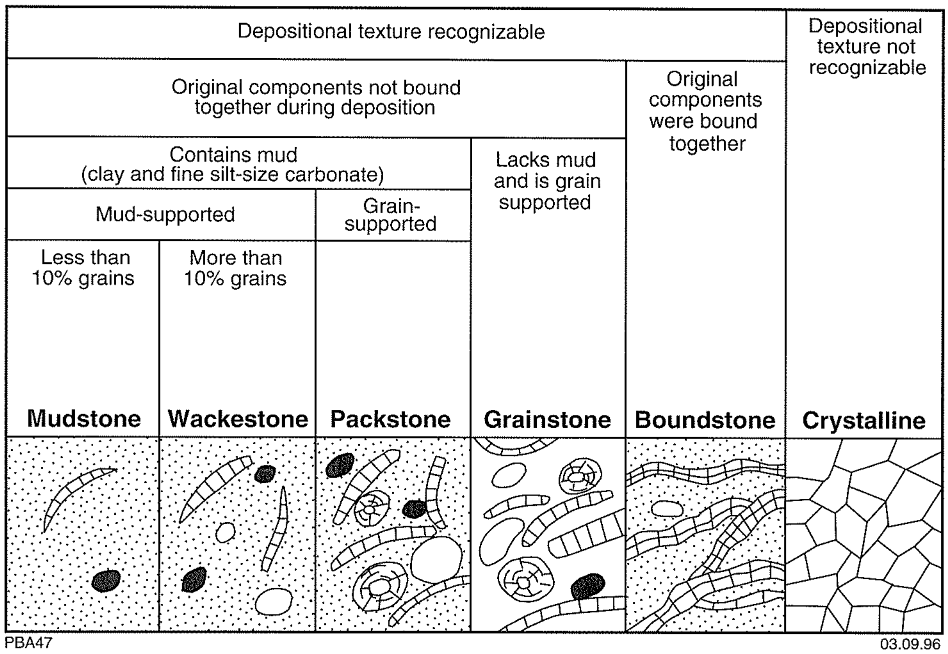

Figure 3. Classification of limestone based on sedimentary fabric and the presence of biological binding (after Dunham, 1962)

Limestone varieties

Varieties of limestone include chalk, marl, travertine, coquina, shells, limesand, aragonite sand, vein calcite, and marble (Carr and Rooney, 1983; Harben and Bates, 1990). Carbonatite, though an igneous rock, consists of almost 100% calcium carbonate and is classified as limestone for industrial-minerals purposes.

Chalk

Chalk is a fine-grained white limestone or micrite containing around 97.5 to 98.5% calcium carbonate, with clay and quartz as the most common impurities. Most chalk is soft and friable. However, the strict usage of the term chalk is for the very fine grained pure-white limestone found in the Upper Cretaceous of Western Europe.

Marl

Marl is a white to buff limy mudstone produced in small lakes. It is intermediate between clay and limestone, and includes all gradations between calcareous claystone and muddy limestone. An ideal environment to form marl would be a landlocked spring-fed basin close to a bedrock of limestone or dolomite.

Travertine

Travertine consists of calcium carbonate formed by rapid chemical precipitation around natural springs and in caves. In texture, travertine forms compact fibrous or concentric bands in a variety of colours ranging from white to shades of pink, red, yellow, and gold.

Coquina

Locally, extensive beds of coquina, made of cemented shell fragments of varying sizes, occur in near-shore and strandline environments. These deposits can be a source of calcium carbonate or building stone, depending on the physical and chemical characteristics of the material. Large deposits of coquina are known to occur in the Shark Bay area of Western Australia.

Shells

Depending on the quality and quantity, naturally occurring shell deposits are sometimes used as a source of calcium carbonate for cement and other industries that require moderate to high percentages of calcium carbonate in their raw materials.

Limesand

Limesand is a term used in Australia for sands rich in calcium carbonate (usually shell fragments). In Western Australia, limesand is a significant source of calcium carbonate for the manufacture of cement and lime, and also a source of agricultural lime.

Aragonite sand

Aragonite sand, consisting of ooliths, is the protolith to oolitic limestone forming in the Bahamas off the south

Florida coast. Formed over the past 5000 years by precipitation from seawater, most ooltihs are ellipsoidal or subspherical grains ranging in size from 75 to 850 µm. The end-product has a $CaCO_3$ content of 96 to 97% with very little organic matter (Harben and Bates, 1990).

Vein calcite

Coarsely crystalline pure calcite occurs in mineralized vein assemblages together with other gangue and ore minerals. Pure clear calcite from such occurrences is used in the production of optical calcite that finds use in the manufacture of optical instruments (such as nicol prisms in optical microscopes). However, due to the small size of these vein deposits, mining of calcite is generally economic only if it is mined as a by-product or co-product of another mineral.

Marble

Marble consists of metamorphosed limestone and dolomite. Marble derived from pure limestone consists mostly of recrystallized calcite. Accessory minerals such as quartz, mica, chlorite, tremolite, graphite, hematite, and limonite may give some marbles desirable characteristics. It should be noted that the term marble, as used by stonemasons, can refer to almost any rock that can be easily polished, and may include non-carbonate rocks.

Carbonatite

Carbonatite is an igneous rock consisting of calcium carbonate, with or without magnesium carbonate, and very rarely strontium carbonate, and is often associated with rare-earth minerals. Although carbonatites are better known as sources of phosphates and rare earths, they are sources of limestone in some parts of the world where limestone is scarce.

The use of limestone depends on its physical or chemical properties or both. Physical properties are more important for uses such as aggregate or building stone where the rock is used 'as is', whereas chemical properties are important if the stone undergoes changes from one form to another such as in the production of lime. The main uses of limestone are discussed in the following section, followed by those of lime, which is a calcined product of limestone.

Commercial applications of limestone

Cement raw material

In the manufacture of cement, a wide of variety of limestones including crystalline limestone, chalk, calcareous earthy marl, shells, and limesand can be used. The grade and amount of limestone used depends on factors such as the type of cement produced and the method of manufacture. The $CaCO_3$ content of limestone used should preferably be above 85% and MgO should be less than 4%, although in some instances lower grade limestone is being used due to non-availability of high-grade material. The limestone should also contain less than 1.5% acid insolubles, less than 0.1% fluorine, and less than 0.5% phosphates, zinc, and lead. The presence of small amounts of shale within limestone may sometimes prove useful as it makes grinding easier, whereas too much quartz increases grinding costs. Minerals such as micas and amphiboles, which are locally present in metamorphosed limestones, may increase the iron oxide and alkali contents to unacceptable levels.

In the manufacture of Portland cement, the essential raw materials are limestone and high-alumina clay or shale. When the alumina content of the clay is too low for the formation of the required mineral phases during sintering of the cement, bauxite is used to upgrade the feed. The suitability of raw bauxite for this application is determined by the ratio of SiO_2 to Al_2O_3 plus Fe_2O_3, which should ideally be in the range 2.6 to 2.8. Another variety of cement produced using bauxite and limestone is high-alumina cement, which consists of calcium aluminates as opposed to aluminosilicates. Concrete made from high-alumina cement is characterized by rapid setting times (2–4 hours) and development of structural strength within 24 hours as compared with conventional Portland cement, which may take several days to gain full strength (Sehnke, 1995). In the case of Portland cement, uncalcined industrial gypsum or 'raw' gypsum is used to control the setting time.

Two types of manufacturing plants using wet or dry processes are used in cement manufacture. Dry processing is a relatively new technology that consumes less energy than the wet process.

Aggregate

Limestone, as an aggregate, can compete with many other rock types, depending on its proximity to the point of consumption, and certain physical and chemical characteristics. As an aggregate, limestone is used for roadstone, cement aggregate, coarse and fine asphalt filler, railway ballast, and for many other construction applications.

When used as roadstone or aggregate, the material must conform to appropriate national standards such as the British Standard Specifications. Main Roads Western Australia has its own specifications for limestone to be used as road sub-base material in Western Australia. For such uses, consideration must be given to critical physical properties and minor chemical aspects of the material. Some of these considerations are strength and hardness, cleanness, particle shape, chemical soundness, and colour. Strength and hardness are related to the density, porosity, and homogeneity of the rock. Cleanness means that the rock should be free from dust and fines such as clay, silt, and soil. Particle shape should be as cubic as possible with no laminations or incipient cracks.

Chemical soundness requires the material to be free from soluble sulfides or organic matter, have a low amorphous silica content, and contain only 0.04 to 0.06% chloride, particularly when the aggregate is used in concrete. Colour is important only when the stone is used for ornamental purposes or when high reflectivity is required (Power, 1985; Harben, 1995).

Roadbase

Low-grade limestone, containing less than 80% calcium carbonate, is widely used as roadbase material in Western Australia due to its widespread geographical distribution and its ability to compete with other materials such as granite and gravel. In the Perth area, although it is used almost exclusively as a sub-base material, it is growing in popularity when used as emulsion-stabilized limestone for the base course overlying the sub-base. This is due to favourable compaction and compression characteristics and its subsequent stability and durability (Landvision, 1996).

Dimension stone

Massive, compact limestones and marble are traditionally used as decorative building or dimension stone, particularly as interior columns, floors, trim, and exterior facing on large buildings. To be used as dimension stone, the rock should be of sufficient strength to withstand blasting, cutting, and polishing, and be able to resist the elements if exposed outside. It must also be able to resist the wear and tear of pedestrian traffic if used as floor or stair tiling. Important characteristics for dimension stone are covered by American Society for Testing and Materials (ASTM) standards that include water absorption and bulk specific gravity (ASTM C 97), modulus of rupture (ASTM C 99), compressive strength (ASTM C 170), abrasion resistance strength (ASTM C 241), and flexural strength (ASTM C 880).

Glass industry

Limestone is used in the manufacture of glass because of its fluxing action on silica sand to form a chemically-fused calcium silicate glass phase. In addition to the fluxing action, the CaO content of limestone also improves the chemical and physical characteristics of glass by increasing the insolubility factor of the finished material. Limestone improves glass strength, reduces brittleness, and contributes a more enduring lustre to the appearance of the finished product.

Specifications for limestone used in the manufacture of colourless glass are rigid to minimize potential colouring impurities such as iron and chromium (Table 1). For use in the flat-glass industry for the manufacture of windows and vehicle glass, limestone should contain greater than 54.84% CaO and less than 0.8% MgO, 0.6% acid insolubles, 0.075% Fe_2O_3, 0.35% Al_2O_3, 0.05% sulfate, 0.1% free carbon, and 0.05% moisture.

Table 1. Specifications for limestone in colourless glass

CaO	>55.2%
$CaCO_3$ equivalent	>98.5%
Fe_2O_3+FeO	<0.035%
Acid insoluble content including silica	<1.0%
Organic matter	<1.0%
Moisture content	<2.0%

* MnO, PbO, P_2O_5, and SO_2 values must be quantitatively declared by the supplier if each exceeds 1%
* Colouring elements, other than iron, should not be present in such quantities as to stain glass
* Specifications for alumina or magnesia are determined by negotiation between buyer and supplier

Particle size distribution

For use in tank furnaces	100%	-4.76 mm	75%	+0.124 mm
For use in pot furnaces	100%	-3.175 mm	95%	+1.20 mm

NOTE: after Power (1985)

The specifications for limestone, for the manufacture of container glass such as bottles and jars, require less than 0.035% total iron. The tinting effects of Fe_2O_3 can to a certain extent be counteracted by the use of selenium, which neutralizes the blue-green tint with its own pinkish colour. In the manufacture of coloured glass, limestone with an iron content of up to 0.1% can be used. Other recommended specifications for container glass are less than 0.001% Cr_2O_3 and 0.1% moisture.

In the manufacture of speciality glass such as optical glasses, the iron content should be very low (0.0013–0.0026% Fe_2O_3).

Another important consideration with regard to usage of limestone in the glass industry is particle size distribution. Container glass generally requires crushed limestone with minimal plus 10 mesh (1.7 mm) material and a minimal amount of fines passing 200 mesh (0.075 mm), to avoid dust problems. The fibreglass industry uses a limestone flour, predominantly minus 200 mesh with a minimum of 2% plus 200 mesh. The speciality glass sector uses a coarser limestone flour with up to 25% plus 200 mesh (Power, 1985).

Pig iron

Limestone has always been the major flux material used in the production of pig iron. Traditionally, iron ore, coke, and limestone are introduced into the top of the blast furnace where various chemical processes occur due to the heat of the furnace. The oxides of calcium and magnesium thus produced combine with the silica and iron impurities from the ore to form a slag. Sulfur, originally derived from the coke fuel, is scavenged by the slag as the molten iron sinks to the bottom of the furnace. The use of much purer iron in recent years has resulted in a much more important role for slag as a sulfur remover in the pig-iron process. Researchers have found that the presence of iron ore, limestone, and coke fines significantly impeded the flow of hot gases through the raw materials, thereby reducing the efficiency of the iron-making process. This impediment was overcome by crushing and screening the ore prior to roasting it with limestone and coke to form irregular 'clinkery' lumps known as sinter.

Although the details of producing sinter in individual iron plants around the world differ, the specifications for limestone appear to favour fine-grained material. British Steel generally specifies limestone crushed to 100% less than 5 mm, a maximum of 95 to 96% less than 3 mm, and around 90% greater than 0.15 mm. Fines less than 0.075 mm are unacceptable as they are picked up by the hot-air draught drawn in by the roasting-plant impellors. The chemical specifications are not particularly stringent, but the higher the $CaCO_3$ content in limestone the better, and silica and other acid-insoluble residues should ideally be below 1%, with negligible sulfur and phosphorus (Power, 1985).

Steel industry

Historically, in the open-hearth process limestone was used for steelmaking, although all other processes in the steel industry use lime. In the open-hearth process, the melt was charged with limestone because the 'lime boil' gave significant metallurgical benefits of stirring the bath. The specifications for steelmaking limestone used in this process were 98% $CaCO_3$, less than 0.1% S, and a 76–305 mm particle size (O'Driscoll, 1988).

Agriculture

Ground limestone is commonly used to correct soil deficiencies. It helps to reduce soil acidity and also increases calcium and magnesium levels. Higher calcium and magnesium levels in soils increase the supply of other nutrients through stimulation of microbiological activity, while increasing organic matter, soil micro-organisms, and the efficiency of fertilizers (Power, 1985).

The usage of limestone as a soil conditioner is mainly governed by its neutralizing value, which is a measure of the material's ability to neutralize weak acidic solutions under standard laboratory conditions. The pulverized limestone must contain less than approximately 10% $MgCO_3$ while the particle size should be less than about 5 mm, with 95% less than about 3 mm. Harben (1995) gave specifications of 85 to 95% $CaCO_3$ with less than 5% MgO and insolubles, and 100% less than 2 mm for use in acid-rain neutralization. These specifications may vary depending on the nature of the soil. Limestone dust produced during the processing of aggregate and chemical-grade limestone is commonly used in agriculture.

Animal feedstuff

Limestone can be added to dry mash or used in pelleted formulations as a calcium nutrient in animal feedstuffs. The chemical purity and particle size are dictated largely by the feed manufacturers in association with limestone suppliers. The material should be high in $CaCO_3$ with minimal amounts of silica, iron, alumina, heavy metals, and moisture. In the case of pig feedstuffs, the MgO content must be low to avoid 'scouring', an effect similar to the purgative action of Epsom salts on humans. Particle size is critical since the material must be of the correct size to be easily eaten and digested by different types of animals, and also the correct size to aid dry-mash feedflow from storage hoppers to animal feed troughs. Egg-laying hens generally require 2.4 to 4 mm granular material free from fines, whereas cattle and pigs normally have pelleted forms made from fine flours (ranging from 100% passing 1.2 mm and 65% minus 63 μm, to around 100% minus 0.5 mm and 13% passing 53 μm).

Filler

Limestone, although only rarely exhibiting a high degree of whiteness, is sometimes used as a cheap filler in latex foam backing for carpets and in PVC floor tiles because of its compressive resistance and wear properties (Power, 1985).

Paper

Calcite is a component of coating slurries used in high-quality printing, as well as in pulp for writing and printing paper. Vidal (1994) stated that for paper coating, calcite with a high percentage of particles less than 2 μm is required. The most widely used grade is 90% finer than 2 μm, which gives an average particle size of around 0.8 μm, a high solids content of around 75%, and a very low level of viscosity (<300 centapoise). The use of calcite slurries for paper coating appears to be replacing the massive use of kaolin, as calcite slurries with good whiteness and low production costs are becoming more widely available. For many paper types, the replacement of kaolin by calcite has brought about a number of

Table 2. Specifications for limestone in coal dust in USA and UK

USA specification			*UK specification*	
Particle size				
100%	-20 mesh	(0.84 mm)	90%	-0.250 mm
70%	-200 mesh	(0.074 mm)	50–70%	-0.063 mm
Silica content				
4% max.			3% max.	
Combustible content				
5% max.			–	
Characteristics				
Light-coloured dust that when wetted does not cake on drying			Dust should be easily dispersed from the air, free from any tendency to cake, and be of uniform colour	

NOTE: after Power (1985)

advantages including a reduction in costs due to the lower cost price of calcite slurry, an improvement in the whiteness of the coating paper, and an improvement in the porosity of high-speed printing paper without diminishing the sheen of printing dyes (Vidal, 1994).

Coal-dust fire dampener

In the coal mining industry, limestone flour is used as a fire dampener to reduce the combustible nature of coal dust during blasting. This is achieved by spreading powdered limestone in mine galleries and along roadways to form an intimate mixture with the coal dust during blasting or an explosion. This mixture reduces the heat capacity properties of coal and prevents combustion. USA and UK specifications for limestone in coal dust are given in Table 2.

Commercial applications of lime

Production

The term lime is used here to mean burnt lime (CaO), also known as quicklime, produced by calcining high-calcium limestone. In the production of lime, high-calcium limestone is calcined in a kiln at temperatures of around 1000°–1100°C. During this process pure limestone loses 44% of its weight, with the reaction being written as:

$$CaCO_3 + \text{heat} \Rightarrow CaO + CO_2$$

The type of kiln used determines the lump size of the raw material to be burnt and therefore the efficiency of the calcination process. Three main types of kiln (vertical, rotary tunnel, and rotary hearth) are in use. Vertical kilns are used in the traditional method of lime manufacture where limestone crushed to 150 mm in size is loaded at the top of the kiln. Rotary tunnel kilns are horizontally disposed kilns which use limestone 40 to 15 mm in size. Rotary hearth kilns, consisting of a circular hearth that rotates on a horizontal axis, can calcine 40 to 12 mm stone without overburning (Power, 1985). Heating within separate zones of the kiln allows sensitive control of calcination. The chemical composition range of commercially produced lime is given in Table 3.

Commercial quicklime is available in a number of sizes (Harben, 1995) as follows:

Lump lime	2.5" (63 mm)
Crushed or pebble lime	0.25 to 2.25" (6.3 to 63 mm)
Ground lime	approximately 100% minus 8 mesh (<2 mm) and 2 to 4% minus 100 mesh (<150 µm)
Pulverized lime	approximately 100% minus 20 mesh (<850 µm)
Pelletized lime	1" (25 mm) pellets or a uniform-size product made by compressing fines

Uses

Steel industry

In the steel industry, lime is added to steel furnaces as a flux that will react with chemical impurities in the melt, enabling them to rise to the surface and form a slag that can be removed before the melt is decanted. The slag thus formed removes or controls the level of acid components (particularly silica, sulfur, and phosphorus) inherent in iron ore, coal, merchant scrap, and alloying agents, to levels tolerable in the later stages of steelmaking. However, technical advances in the steel industry have reduced the quantity of lime required.

The specifications and quantities of lime products used in steel production can vary depending on the market. Table 4 gives a typical UK specification for steelmaking lump lime. The specifications for sulfur and phosphorous in some applications are more stringent than those given in this table.

Environmental applications

Lime has been used to treat liquid wastes for many years, and also to control air pollution caused by acidic gases from metallurgical, chemical, and fuel plants. Lime is used in the flue gas desulfurization (FGD) process to remove sulfur dioxide from flue gases of coal-fired plants.

Table 3. Chemical composition of commercial lime

	%
CaO	86.00–98.00
MgO	0.30–8.00
SiO_2	0.20–1.50
Fe_2O_3	0.10–0.40
Al_2O_3	0.10–0.50
H_2O	0.10–0.90
CO_2	0.40–1.50

NOTE: after O'Driscoll (1988)

Table 4. Specifications for steelmaking lump lime

CaO	mean	95%	min.	93%
LOI	mean	2.5%	max.	4%
S	mean	0.03%	max.	0.04%
SiO_2	mean	1.0%	max.	1.5%
MgO	mean	1.5%		
Reactivity	60°C rise at 2 minutes			
Grading	-38 mm +13 mm 75%; 44 mm max; -7 mm <10%			

SOURCE: O'Driscoll (1988)
NOTE: LOI loss on ignition (% mass lost by sample after heating to 1000°C)

There are three FGD processes using lime; wet scrubbing, dry scrubbing, and dry injection. Lime is mostly used in the dry processes. In the dry-scrubbing process, a lime slurry is showered through the flue gas, neutralizing SO_2 and converting it to a solid. Most of the slurry is then returned to the scrubber to absorb more SO_2, whilst some is separated and filtered to produce a cake for disposal. In the dry-injection process, hydrated lime is injected into a high-temperature zone (1000–1200°C) in a boiler firebox or into the low-temperature zone (150°C) downstream of the boiler. The dry reaction products containing SO_2 are then trapped in particulate collection equipment and discarded.

In the wet-scrubbing process, absorbent slurry is showered through the flue gas. Lime or limestone is added to the slurry to neutralize the acidic SO_2 and convert it to a solid. Most of the neutralized slurry is sent back to absorb more SO_2, while a portion of the slurry is fed into a dewatering system to produce a wet cake for disposal. The advantage of using limestone in preference to lime is its lower cost, which is found to be about one-third that of lime even after taking into consideration lower neutralizing values per tonne, poor utilization, and the higher transport cost of limestone.

Although in the late 1980s a number of countries operated FGD systems using lime, the market has not improved to anticipated levels because of the development of a variety of FGD technologies utilizing a number of minerals other than lime. An advantage of using lime is the smaller capital cost for lime-based FGD equipment, although higher operating costs are involved. For plants with a relatively short lifespan, lime rather than limestone is often more economical (O'Driscoll, 1988; Loughbrough, 1994).

Waste-water treatment

The markets for lime in waste-water treatment are expanding. A well-known method for effluent purification, particularly useful for removing phosphorus, is the use of calcium hydroxide in conjunction with ferrous sulfate. Advantages of this method include effective suspended-solids removal, high reduction of organic matter, relatively low investment costs, and better sludge-dewatering properties in comparison to sludge without chemical addition. Two possible disadvantages are the increased amount of sludge and occasional handling difficulties with lime (O'Driscoll, 1988). When a company has its own disposal facilities, lime is an attractive option.

Calcium hydroxide and lime can also be used for waste-treatment applications involving neutralization of acids such as those in mine tailings. In such applications, lime can precipitate sulfates and heavy-metal ions such as chromium, copper, iron, nickel, and zinc, and also neutralize acids.

Alternative materials for waste-water treatment include magnesium hydroxide and soda ash, both of which are several times more expensive than lime. Calcium hydroxide has advantages over lime in the pollution-control market because of its ease of handling.

Sanitation

Lime is also used both in water and sewage treatment. In water treatment, lime is used to soften water by removing bicarbonate. The high pH caused by this process has an added value as a secondary sterilization agent to chlorine because retention for 3 to 10 hours at a high pH will kill 99% of bacteria and most viruses. The pH is then lowered to acceptable levels by introducing carbon dioxide.

Sugar refining

Lime is used for the refining of both beet and cane sugar, where it assists in purifying the sucrose juices by removing phosphatic and organic-acid compounds as insoluble calcium compounds. Cane-sugar refining consumes around 1.9 to 4.9 kg of lime per tonne of sugar, while that of beet sugar requires an average of around 0.2 tonnes of lime per tonne of sugar. In the production of lime for sugar refining, limestone should contain greater than 96% $CaCO_3$, and less than 1% SiO_2, 1% MgO, and 1% clay, sulfate minerals, and organic matter (O'Driscoll, 1988; Harben, 1995).

Construction industry

Lime is used in the manufacture of dense bricks (sand-lime bricks and blocks) and aerated bricks and blocks. One type of brick manufactured is calcium silicate bricks, made by moulding, under pressure, a mixture of siliceous sand and hydrated lime, which is then subjected to high-pressure steam. Lime for this application should have a high calcium content, with MgO less than 3%, SiO_2 plus Al_2O_3 less than 5%, and a high reactivity to water.

Lime is also used extensively in the production of mortar for use in the building industry. It increases the durability and water resistance of mortars while retaining a degree of elasticity. A typical lime mortar would contain 1 part cement, 1 part lime, and 5–6 parts sand (Ashworth, 1975; Loughbrough, 1994).

Soil stabilization

Lime can be used to stabilize soils that are unsuitable or marginal for use as construction materials. The addition of lime enables such soils to be more easily placed and compacted to form part of temporary or permanent works. Clay must be present in amounts exceeding 10% for lime to react with the available silica and alumina to form complex cementing compounds that will bind the soil into a hard, stable mass that is not sensitive to water saturation. Some of the advantages of soil stabilization by lime include:

- plasticity, shrinkage, and swelling properties are reduced

- compaction is readily achieved
- strength and durability are improved
- erosion by surface water is reduced
- the flow of subsurface moisture is reduced.

In the construction of highways and major airports, clays are often treated with lime, and the technique is widely practised in South Africa, Australia, New Zealand, Germany, Sweden, and France (O'Driscoll, 1988; Loughbrough, 1994).

Paper manufacture

In the manufacture of paper, lime is used in the sulfate pulp-production process to causticize waste sodium carbonate (black liquor) into sodium hydroxide for reuse. The amount of lime used depends on the production process, but an approximate value is 15 to 20 kg of lime per tonne of pulp produced (O'Driscoll, 1988; Loughbrough, 1994).

Precipitated calcium carbonate (PCC) is used as a filler or coating agent for paper. To produce a tonne of PCC, approximately 600 kg of lime is required. After lime is mixed with water to produce calcium hydroxide, carbon dioxide gas is added to produce $CaCO_3$. This reaction has to be controlled to obtain a PCC with the required characteristics. PCC grades that will have applications in the paper industry include those suitable for use as coating pigments and others that are acid tolerant.

Whitings and fillers

The term whiting is now applied to all types of fine-grained flours produced from chalks, limestones, marbles, and calcite, including precipitated calcium carbonate. Whitings are used as fillers in the rubber and plastic industries to reduce the polymer raw material cost, as well as to enhance mechanical, chemical, and electrical performance. Other major markets for calcium carbonate whiting include paint, paper, and floor-covering applications. The physical and chemical characteristics of various whitings produced by ECC Calcium Carbonates Ltd are given in Table 5.

Colour and brightness are the most important characteristics of a whitener. However, the ease of grindability of the rock is an important factor because it decides whether the required fineness can be achieved economically. Careful milling of chalk produces a whiting of much finer and regular particle size than can be achieved by the same degree of processing of harder materials. The process of grinding depends on the relative amount of moisture, and the presence of impurities such as flint in the rock. Dry grinding is more suitable for the harder, more compact, drier chalks and limestones. Where high moisture contents exist, the material is normally slurried and subjected to hydrocyclone separation to separate the fines that are then filtered and milled. Power (1985) listed the following common properties and characteristics expected from most whiting materials:

- a high degree of whiteness and reflectivity
- minute particle size from 10 microns downwards (free from grit, -44 micron)
- a customized particle size distribution
- a particular particle shape and high specific surface area
- known plastic and rheological characteristics
- particular absorption characteristics in regard to oils, inks, and colour pigments
- a relatively inert chemical nature
- extreme purity
- particular specific gravity and bulk density

Chemicals manufacture

About 12% of the lime market is used in the manufacture of chemicals. The main use of lime is in the manufacture of soda ash (Na_2CO_3) by the Solvay process to recover

Table 5. Chemical and physical characteristics of ECC whitings and typical applications in which they are employed

Typical application	*Paint*	*Rubber*	*Paper filler*	*Paper*	*Coating*	*Polish, chemicals, etc.*
$CaCO_3$ (%)	96.15	98.5	96.15	98.5	98.1	96.15
Water-soluble salt content (%)	0.13	0.10	0.13	0.14	–	0.13
Moisture content (%)	0.20	20.0	15	–	–	0.20
Particle size distribution (%)						
+53 microns	0.3	0.02	0.75	0.02	0.01	9.0
+10 microns	18	1.0	18	1.0	1.0	30
+5microns	33	2.5	35	2.5	4.0	53
-2 microns	36	80 (±3%)	40	80 (±3%)	90	28
-1 micron	–	42	–	42	70	–
Specific surface area (m^2/g)	2.70	6.0	2.2	8.0	5–16	1.5
Brightness	85.5	89.0 (±0.7%)	85.5	89.0	96.0	84.7

NOTE: after Power (1985)
ECC ECC Calcium Carbonates Ltd

ammonia. Approximately 580 kg of quicklime is required per tonne of soda ash. In the process, sodium chloride is treated alternately with ammonia and carbon dioxide under pressure to produce ammonium chloride and sodium bicarbonate. Soda ash is then produced by heating the sodium bicarbonate, and ammonia is recovered from the ammonium chloride by reaction with lime. This reaction produces calcium chloride as a by-product, much of which is recovered and sold commercially. Additional lime is used to causticize sodium carbonate solutions to produce sodium hydroxide.

Other chemicals manufactured using lime include mono- , di- , and tricalcium phosphates, pesticides, and paint pigments. Lime is also used in the manufacture of organic chemicals such as ethylene and propylene glycols, calcium-based organic salts, and dyes (O'Driscoll, 1988; Loughbrough, 1994).

Non-ferrous metallurgy

In non-ferrous metallurgical processes, lime prevents the adverse effects of soluble salts on flotation by precipitating them as metal hydroxides, and modifies pH in the beneficiation of metallic ores.

In the manufacture of alumina by the Bayer process, lime is used to causticize sodium carbonate solutions to regenerate sodium hydroxide, which is then recycled.

The carbon-in-pulp (CIP) process, commonly used in Western Australia to extract gold, uses lime to control the pH of cyanide solutions. The amount of lime used varies from around 1 kg per tonne of ore to amounts as high as 4.5 kg per tonne, depending on the nature of the ore.

In the heavy-mineral sands industry, lime is used as a neutralizing agent in the processing of ilmenite to synthetic rutile (SR) and in titanium dioxide (TiO_2) pigment production. Consumption of lime in SR production can vary considerably between individual processing plants, depending on the grades of SR product being produced. The range of consumption recorded has been between 24 and 65 kg of lime per tonne of SR product. In TiO_2 pigment production, it has been estimated that 160 kg of lime per tonne of pigment would be required to neutralize the waste products.

Lime is used extensively as a depressant for pyrite and arsenopyrite during flotation in the beneficiating of copper ore. There is limited use of lime, as a flux, in smelting concentrated copper ores.

Additive for betel-nut chewing

An important use of slaked lime (calcium hydroxide) in many developing countries, mainly in south and southeast Asia, is as an additive for chewing the betel-nut (areca nut). Many people (both male and female) in these countries, especially in rural areas, chew betel leaves and betel-nut, with or without tobacco, and a small amount of slaked lime. This mixture is consumed several times a day, mostly during tea or coffee breaks or after a heavy meal, as a stimulant. Although no proper statistics are available to gauge the amounts of lime consumed, the figure can be considered significant when one considers the vast population in the world who chew betel-nut.

Mining methods

Limestone deposits are mined more commonly by openpit than underground methods.

Openpit mining

Many openpit mining operations generally require the removal of overburden by the use of a bulldozer, dragline, or shovel to expose the limestone bed, which is then mined by drilling and blasting techniques. Broken stone is then loaded into haul trucks and transported to a crushing circuit, which for most uses of limestone includes primary and secondary crushers.

The most important factor in an openpit operation is the depth of the overburden material. Understandably, when the overburden is too thick the deposit may not be economically viable. There is no set limit to the overburden depth that can be mined economically, since this depends on the product's ability to compete with alternate sources. Many producers use the ratio of limestone thickness to overburden as a guide to assessing the viability of an operation. Some consider that if the ratio is greater than three to one the overburden can be removed economically, provided that it is unconsolidated material. However, the same rule cannot be applied when the overburden is thicker or more consolidated. If the overburden material is marketable, such as for aggregate or for the brick and tile industry, then mining of limestone may be more economic.

Underground mining

The mining of limestone by underground methods is economically feasible in some situations, although in general it is not cost-effective because limestone is essentially a low-priced product. Underground mining tends to be more economic when there is a lack of surface limestone deposits near markets, and importing of limestone is more expensive than underground mining. Underground mining might also become feasible when an already existing openpit operation is extended into an underground mine. For example, many underground limestone mines are extensions of surface workings into adjoining hills where overburden is too thick to remove. Another instance would be the mining of deeper levels of a steeply dipping bed of limestone by developing a shaft downdip from the bottom of an already existing openpit. In other instances, limestone could be mined economically by exploiting other commodities found at different levels of the mine, but serviced by a single shaft.

At Quincy in Illinois, USA, the Huber Corporation has developed a very extensive single-level underground limestone mine accessed by an horizontal tunnel at road level. The mine, with workings extending over many square kilometres, consists of an approximately 10 m horizon of thick, horizontal beds of Mississippian (Early Carboniferous) limestone that is mined using the room-and-pillar method. This material is processed to produce micronized-limestone products. Opencut mining is avoided, mainly due to environmental considerations. Mining can continue on a 365-day basis without seasonal considerations (Fetherston, M., 1997, pers. comm.).

Chapter 3

Production and market trends

Limestone is produced in almost all countries of the world, although some countries import high-grade limestone. Australia imported 0.92 Mt of limestone and 1.66 Mt of lime during the 1994–95 financial year (ABARE, 1995), while Australian production during 1992–93 was approximately 16 Mt. During the period 1988–89 to 1992–93, average production figures in individual states of Australia were as follows (McHaffie and Buckley, 1995; Northern Territory Department of Minerals and Energy, pers. comm.):

State	*Production (Mt)*
New South Wales	3.58
Victoria	2.33
Queensland	2.24
Western Australia	1.87 (production reported to DME)
Tasmania	0.92
South Australia	2.03
Northern Territory	0.05 (calendar 1989–1993)

Limestone production in Western Australia

Accurate limestone production statistics in Western Australia are not readily available as some producers do not report production to the DME. This is because limestone is not classified as a mineral under the Mining Act when it is mined on private land. The reported figures cover most of the high-grade limestone produced for the lime and cement industries in the State. Most unreported production is used as roadbase, in building construction, and in the agricultural sector.

Reported Western Australian limestone production from 1960 to 1995 was 31.5 Mt, with production from the Perth Metropolitan Area accounting for 30.5 Mt of this total. The remaining production during this period was primarily from the Pilbara region (566 688 t, mainly from Cleaverville) and Loongana (299 914 t), which started production in 1992. Other areas of the State produced only 98 028 t during the same period (Table 6). Figure 4 illustrates the production of high-grade limestone in Western Australia between 1990 and 1995.

Western Australian limestone production reported in 1995 was 2.18 Mt, with Cockburn Cement Limited (1.65 Mt) and Swan Portland Cement Limited (0.28 Mt) being the major producers. The reported production figure includes most of the high-grade limestone produced in the State. However, current demand for cement and lime exceeds local supply, and therefore 300 000 t per annum of clinker, equivalent to around 500 000 t of high-grade limestone, is imported from Japan and South Australia. In addition, there is an annual production of 1.96 Mt of low-grade limestone used mainly for roadbase material and in other construction activities (Landvision, 1996).

Projected Western Australian demand

Projected Western Australian limestone production for the next 20 years is based on present production levels and using appropriate projections for individual end-use industries. Where specifics are not available a baseline of 3% per year industrial growth has been used. Based on these figures, production could amount to 145 Mt if demand were fully sourced from within the State (Table 7). This would mean a doubling of supply within 15 years to about 8.5 Mt per year.

Market demand in Western Australia

In 1995, approximately 56% of limestone produced in Western Australia was consumed by the cement, alumina, heavy-mineral sands, and gold industries (Fig. 5). These industries virtually consume all the high-grade limestone produced in the State. Roadbase and the construction industry utilize low-quality limestone which, along with the building-block industry and agriculture, consumed 44% of total production in 1995. Accurate statistics for limestone consumption for building block and agricultural uses are not available, but according to the production figures reported to DME, the former consumed approximately 2.8% and the latter 0.6% of the total limestone used in the State in 1995.

Table 6. Limestone production in Western Australia, 1960 to 1995 (tonnes)

Year	*Metro area*	*Loongana*	*Pilbara*	*Rest of state*	*Total*
1960	11 510	–	–	–	**11 510**
1961	14 242	–	–	185	**14 427**
1962	36 589	–	–	478	**37 067**
1963	27 914	–	–	428	**28 342**
1964	31 207	–	–	940	**32 147**
1965	574 374	–	–	536	**574 910**
1966	584 720	–	–	1 981	**586 701**
1967	756 752	–	–	2 008	**758 760**
1968	975 568	–	–	4 002	**979 570**
1969	1 319 475	–	–	4 271	**1 323 746**
1970	1 182 654	–	–	4 951	**1 187 605**
1971	1 301 507	–	–	3 939	**1 305 446**
1972	1 145 574	–	–	2 275	**1 147 849**
1973	1 350 754	–	–	2 825	**1 353 579**
1974	869 037	–	285 454	2 825	**1 157 316**
1975	1 002 670	–	75 264	3 720	**1 081 654**
1976	689 276	–	15 755	–	**705 031**
1977	718 944	–	49 441	1 483	**769 868**
1978	688 420	–	26 360	710	**715 490**
1979	640 387	–	38 879	330	**679 596**
1980	598 753	–	8 359	700	**607 812**
1981	627 846	–	9 004	500	**637 350**
1982	503 692	–	9 212	1 348	**514 252**
1983	336 053	–	8 915	513	**345 481**
1984	178 107	–	6 589	–	**184 696**
1985	184 450	–	5 707	3 354	**193 511**
1986	209 229	–	7 863	–	**217 092**
1987	117 141	–	14 692	33	**131 866**
1988	230 433	–	2 725	6 198	**239 356**
1989	1 801 341	–	397	10 698	**1 812 436**
1990	1 825 814	–	108	2 741	**1 828 663**
1991	1 727 105	–	915	9 964	**1 737 984**
1992	1 967 651	112 281	69	3 845	**2 083 846**
1993	2 034 756	59 526	350	4 475	**2 099 107**
1994	2 154 060	62 021	420	6 410	**2 222 911**
1995	2 106 503	66 086	210	9 362	**2 182 161**
Total	**30 524 508**	**299 914**	**566 688**	**98 028**	**31 489 138**

SOURCE: as reported to DME

The successful promotion in the State of an iron- or steelmaking industry, or both, could have a very significant effect on future limestone and lime demand.

Cement industry

Out of a total of 4.64 Mt (including imports) of limestone consumed in 1995, the cement industry used approximately 1.37 Mt. Projected demand for limestone in the cement industry during the next two decades is around 36.8 Mt, assuming an annual increase in demand of 3% (Table 7). Cement manufacturers are also the major producers of lime for various industrial applications such as those discussed below.

Alumina industry

The alumina industry in Western Australia is based on the Bayer process, in which lime is used during the soda cycle to stabilize the caustic soda solution (Adamson, 1970). The amount of lime required varies depending on the nature of the ore used, and can vary from 50 to 65 kg per tonne of alumina produced.

The amount of lime required to produce Western Australia's 1995 alumina production of approximately 8 Mt, was 0.45 Mt, which is equal to 0.80 Mt of limestone. Alumina-producing companies were Alcoa of Australia (WA) Ltd and Worsley Pty Ltd.

According to surveys carried out by the Department of Resources Development (1994), the outlook for the alumina industry in Western Australia for this decade is bright. However, State production may decline slightly in the immediate future, in response to aluminium quota levels being collectively adopted by world producers to counteract the over-supply situation currently being experienced. A small-scale expansion is currently being put in place at the alumina refinery at Wagerup to add 200 Kt per year to its capacity. Alcoa is currently

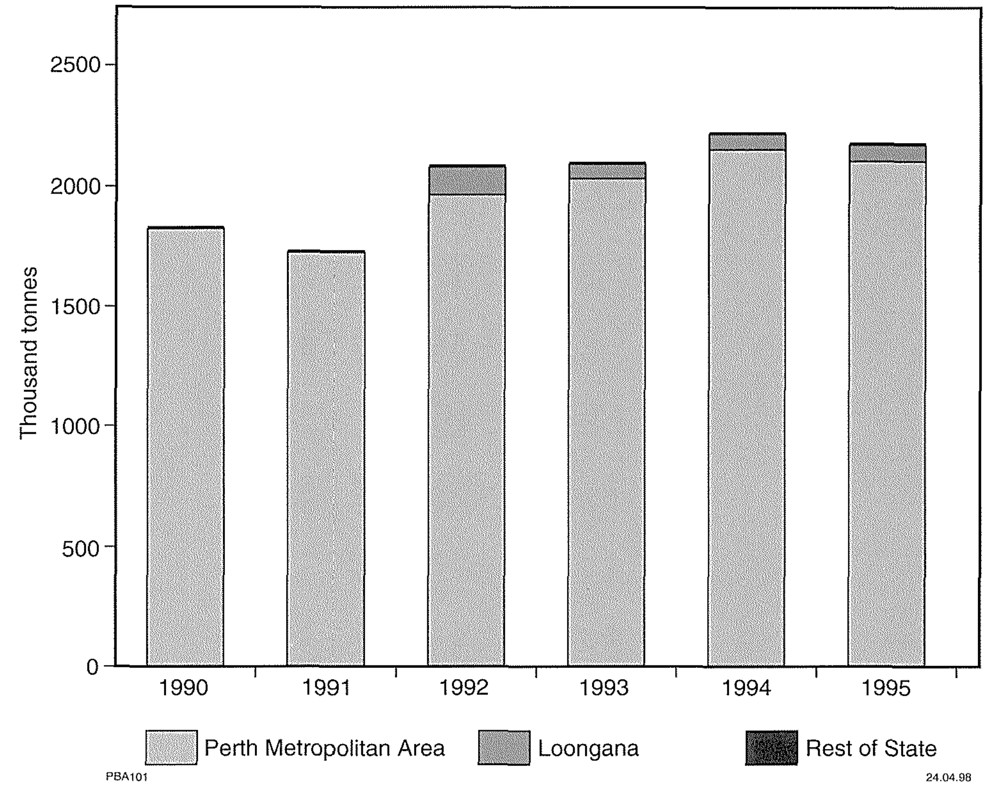

Figure 4. Production of high-grade limestone in Western Australia, 1990–1995. Source: production reported to Department of Minerals and Energy, Western Australia

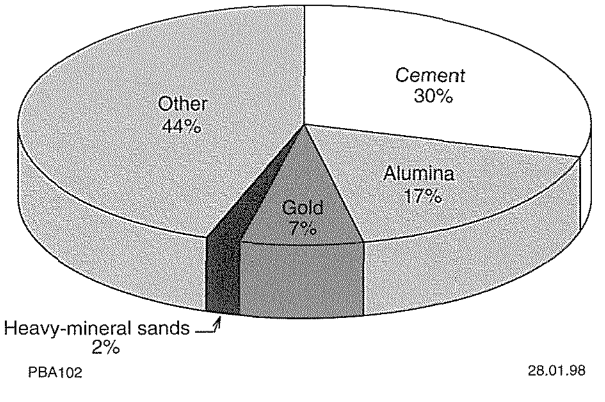

Figure 5. Uses of limestone in Western Australia, 1995. Sources: Department of Minerals and Energy, Western Australia and Landvision (1996)

considering a doubling of capacity at Wagerup to give a total output capacity of 3.3 Mt per year. The Worsley refinery has a tentative plan to add a third line to the refinery, adding 650 Kt per year to its capacity (Preston et al., 1994). Based on these expansions, projected demand for limestone in the alumina industry over the next 20 years would be 19.6 Mt (Table 7). It has been assumed that construction of a new stand-alone alumina refinery facility is unlikely within the period under consideration.

Gold industry

Approximately 90 Mt of ore was processed to produce Western Australia's gold production of 189.4 t in 1995. As the average amount of lime required to process one tonne of ore is around 2.05 kg, 1995 lime consumption by the gold mining industry amounts to 0.185 Mt, which is equivalent to about 0.33 Mt of limestone.

Over the last 5 years, production of gold in Western Australia has reached a plateau of around 180–190 t, with an average treated ore grade of between 2 and 2.5 grams per tonne. Output should remain at around 190 t for the next few years before a slight but progressive decrease. A stabilized production level of 180 t per year of gold, at 2.5 grams per tonne, has been projected after the next 10 years. With an increase in underground production, overall grades may be expected to rise and hence treated ore tonnage should decline (Preston, et al., 1994). Based on this situation, the projected limestone demand for gold processing would be about 6.4 Mt over the next 20 years (Table 7).

Table 7. Projected consumption of high-grade limestone in Western Australia, 1995 to 2014 (million tonnes)

Industry	*1995*	*1996*	*1997*	*1998*	*1999*	*2000*	*2001*	*2002*	*2003*	*2004*	*2005*	*2006*	*2007*	*2008*	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*Total*
Cement	1.37	1.41	1.45	1.50	1.54	1.59	1.63	1.68	1.73	1.79	1.84	1.90	1.95	2.01	2.07	2.13	2.20	2.26	2.33	2.40	**36.79**
Alumina	0.80	0.80	0.83	0.86	0.96	0.99	0.99	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	**19.62**
Gold	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	**6.44**
Mineral sands	0.09	0.09	0.10	0.10	0.10	0.10	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.13	0.13	0.14	0.14	0.15	0.15	0.15	**2.41**
Iron and steel																					
Metallurgical	0.01	0.04	0.24	0.24	0.58	0.54	0.78	0.78	0.78	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	**15.10**
HG metallurgical	–	–	0.12	0.12	0.33	0.33	0.56	0.56	0.56	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	**9.73**
Base metals	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	**0.28**
Building block	0.08	0.08	0.08	0.09	0.09	0.09	0.10	0.10	0.10	0.10	0.11	0.11	0.11	0.12	0.12	0.12	0.13	0.13	0.14	0.14	**2.15**
Roadbase	1.92	1.98	2.04	2.10	2.16	2.23	2.29	2.36	2.43	2.51	2.58	2.66	2.74	2.82	2.90	2.99	3.08	3.17	3.27	3.37	**51.59**
Agriculture	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.05	0.05	0.05	0.05	0.05	0.05	0.05	**0.83**
Total	**(a)4.64**	**4.77**	**5.24**	**5.38**	**6.14**	**6.24**	**6.85**	**7.01**	**7.14**	**7.59**	**7.72**	**7.86**	**7.99**	**8.14**	**8.29**	**8.46**	**8.62**	**8.79**	**8.96**	**9.13**	**144.94**

SOURCE: modified from Preston et al. (1994)
NOTE: (a) includes imported limestone and low-quality limestone
HG high grade

Iron and steel industry

Apart from the Hismelt test plant at Kwinana, there are no iron- or steelmaking facilities in Western Australia and therefore, current lime consumption for this industry is negligible. However, there are many proposals for a variety of processing options for iron ore; from pelletizing, through direct reduction, to fully integrated iron- and steelmaking facilities (Table 8). Both limestone and lime may be used, and the quantity and required characteristics are dependent on the process adopted, but in all cases high-quality metallurgical limestone is required (minimum 92% $CaCO_3$, but preferably above 96%). For high-quality metallurgical processes, a very high quality lime product is required, and is generally used in the steelmaking phase of the process.

In some ferrometallurgical processes, dolomite is substituted for some of the limestone required if there is a need to lower the wear on refractory linings or to control basicity.

If all proposed developments were to eventuate, up to 3 Mt per year of limestone (1.25 Mt of high-quality feedstock) would be required. However, starting from a zero base, it is unrealistic to expect fourteen high-capital, and in some cases fully integrated operations to come to fruition. Very optimistically, the development of four projects over a 20-year period has been projected for the purpose of estimating demand for limestone. These are a pelletizing development, an integrated pelletizing-direct reduction (DR) project in the Pilbara, a second DR project in the Pilbara, and an integrated steelmaking facility in the mid-western or southwestern parts of the State (Preston, et al., 1994). At full capacity, these could be expected to consume about 1 Mt of metallurgical-grade and 0.65 Mt per year of high-grade metallurgical limestone. Over the 20-year period this would amount to 15.1 and 9.7 Mt respectively (Table 7).

Heavy-mineral sands industry

The major companies involved in the heavy-mineral sands industry in Western Australia are RGC Mineral Sands, TiWest Pty Ltd, and Westralian Sands Ltd. In 1992–93, consumption of lime in Western Australia by this industry was 0.048 Mt (Department of Resources Development, 1994). Based on this consumption level, 1995 production of synthetic rutile (SR) and pigment would have consumed 0.053 Mt of lime, which is equivalent to approximately 0.09 Mt of limestone. Westralian Sands has proposed a second SR plant, whilst the TiWest joint venture has developed its fully integrated operation from mine, through synthetic rutile to titanium dioxide production. Westralian Sands Ltd is currently constructing its second synthetic-rutile plant to give it some 240 000 t of synthetic-rutile production capacity. With the development in 1995 of the Jangardup mine on the State's south coast, Cable Sands effectively doubled its capacity to around 500 000 t per year of concentrate. With these expansions lime consumption could reach 0.08 Mt per year (Preston, et al., 1994). With the assumption that a further 250 Kt per year of SR capacity will be installed over the 20-year period, then total limestone requirements for this industry could reach 2.4 Mt over the study period (Table 7).

Base-metal industry

At present, the tonnage of lime required for the base-metal industry in the State is very low. Although exact figures are not available, the amount of lime currently required per year would be around 10 000 t. However, with discoveries of new base-metal deposits, this amount may increase significantly.

Agriculture

According to production figures reported to DME, the amount of limestone and limesand consumed as a soil conditioner by the agricultural sector is only around 0.03 Mt per year. As significant production of limestone for agricultural uses remains unreported, the projected figure of 0.8 Mt (Table 7) for the next 20 years (based on reported production) is at the lower end of the scale of likely consumption.

Building blocks and dimension stone

Most limestone exposed along the coastal belt around the Perth Metropolitan Area is unsuitable for building stone or dimension stone uses because of its friability. During the early years of the Swan River colony, quarries were opened up in the Tamala Limestone on Rottnest Island, and at Cottesloe and Fremantle, to supply the colony's early building needs. Fremantle retains many well-preserved heritage buildings that were mainly constructed of locally produced limestone during the earliest days of the colony. Examples of such buildings include Fremantle Prison, the Warders Quarters (Henderson Street), St John's Anglican Church (Kings Square), and the Fremantle Museum and Arts Centre (Ord Street). In Perth, due to the demolition of older buildings, only a few buildings constructed of limestone remain. These include the Royal Mint (Hay Street), Old Perth Boys' School (St Georges Terrace), the Old Fire Station (Murray Street), and the Geology and Geography Department of the University of Western Australia in Nedlands.

Currently, Tamala Limestone is only rarely used in load-bearing structures in buildings, although it is extensively used for decorative retaining walls and foundation plinths. In 1995, approximately 0.08 Mt of limestone was reported as being used in the building-block industry, but the true figure could be higher than this. On the basis of available figures, limestone demand over the next 20 years would be about 2.2 Mt for the building-block industry (assuming an annual increase in demand of 3%) (Table 7). In addition to the market for sawn blocks of natural limestone, the market for reconstituted limestone, which is produced using Portland

Table 8. Iron- and steelmaking projects under consideration in Western Australia

Project	*Developer(s)*	*Capacity*	*Status*
South Coast			
1. Southdown Pelletizing Project	Portman Mining	2 Mt pa. pellets	In abeyance
South West			
2. Kwinana Hismelt (test plant)	Hismelt Corporation	25–100 Kt pa. metallized iron	Operating
3. Kwinana Hismelt (commercial plant)	Hismelt Corporation	500 Kt pa. metallized iron	No firm plans
4. Rockingham Corex and EAF Steel Plant	Compact Steel Pty Ltd	0.09 Mt pa. rising to 1.7 Mt pa hot-rolled steel products (via DRI)	Feasibility study
5. HBI–Koolyanobbing feedstock	Parmelia Resources Ltd	250 Kt pa. HBI	Conceptual
Mid-West			
7. Tallering Peak–Geraldton DR/Steel Plant	Mid-West Iron and Steel (Kingstream) Resources NL	700 Kt pa. steel products	Feasibility study
Pilbara			
8. Robe River Pellet Plant	Robe River Iron Associates (North Broken Hill–Peko Ltd)	2.5–5 Mt pa. pellets	Feasibility study
9. Port Hedland Sinter Plant	BHP Iron Ore Pty Ltd	4 Mt pa. sinter	Conceptual
10. Port Hedland DRI (HBI) Plant	BHP Iron Ore Pty Ltd	2 Mt pa. DRI (+ ?steel)	Feasibility study
11. WA/China DRI (HBI) Plant	WA Govt/China	2 Mt pa. DRI	Conceptual study completed
12. Fortescue Pellet Project	Mineralogy Pty Ltd	6 Mt pa. DR grade pellets	Feasibility stage
13. Fortescue DRI Project	Mineralogy Pty Ltd	4 Mt pa. DRI (via pelletizing)	Feasibility stage
14. Fortescue EAF Steel Plant	Mineralogy Pty Ltd/Austral Pty Ltd	2 Mt pa. hot-rolled steel product	Conceptual/pre-feasibility stage

NOTE: after Preston et al. (1994)

DR direct reduction
EAF electric-arc furnace
DRI direct-reduced iron
HBI hot-briquetted iron
pa. per annum

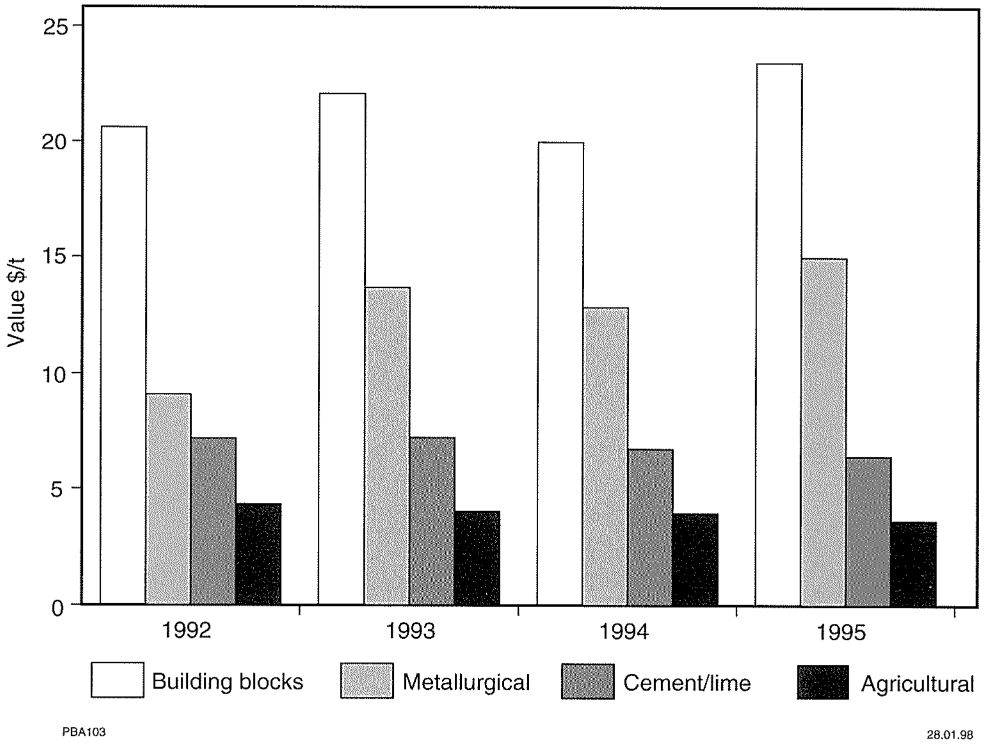

Figure 6. Approximate ex-mine prices of limestone products, 1992–1995

cement and limestone aggregate, is expanding at a considerable rate.

Value of production

The total value of 1995 Western Australian limestone production reported to DME was $14.6 million. On the basis of reported values, the unit price (ex-mine) for different end-uses is as follows:

Usage	*Price ($/tonne)*
Building stone	24.80
Metallurgical grade	15.00
Cement	6.40
Agricultural grade	3.75

The above values are approximate because producers do not provide details of end-use applications. Additionally, in some instances it is suspected that figures quoted are cost-of-production and not strictly the realised prices. The trend of these values during the last four years does not indicate any major variations except for a rise in metallurgical-grade prices from $9.10 in 1992 to $ 13.70 in 1993, and that of building blocks from $ 20.00 in 1994 to $ 23.45 in 1995 (Fig. 6).

Major operating companies

Cockburn Cement Ltd and Swan Portland Cement Ltd are the two major companies that produce cement and lime in Western Australia. Loongana Lime Pty Ltd is also a significant producer of lime, while BGC Transport (a Division of BGC Contracting Pty Ltd) produces cement from cement clinker imported from South Australia.

Other companies involved in limestone or limesand mining are WA Limestone, the Readymix Group (WA), BGC Contracting Pty Ltd, Italia Limestone Co., Boral Resources WA Ltd, Limestone Building Blocks Co. Pty Ltd, Limestone Resources Australia Pty Ltd, Westdeen Holdings Pty Ltd., and Susac Lime Supply Pty Ltd.

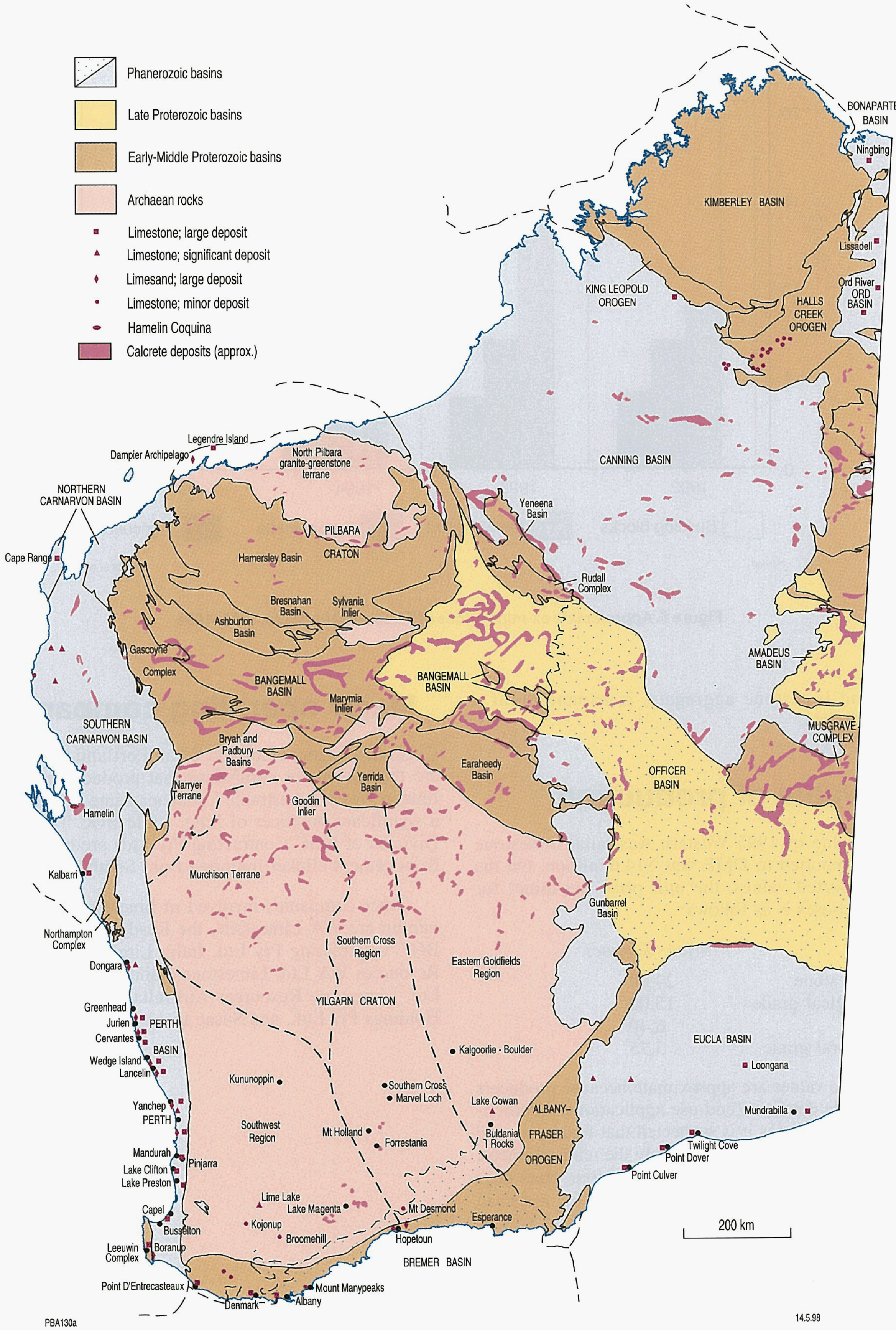

Figure 7. Limestone occurrences in Western Australia

Chapter 4

Limestone resources in Western Australia

The major commercial deposits of limestone and limesand in Western Australia are restricted to the coastal region extending from the Dampier Archipelago in the north to the Eucla Basin in the south of the State (Fig. 7). Other major limestone deposits occur in the Lennard Shelf area of the Canning Basin, and in the Ord and Bonaparte Basins in the Kimberley region bordering the Northern Territory. In the rest of the State, limestone-bearing formations are mainly restricted to calcrete deposits. This Bulletin will therefore focus on limestone resources from the following tectonic units:

Perth Basin
Carnarvon Basin
Eucla Basin
Pilbara Craton
Albany–Fraser Orogen
Canning Basin
Bonaparte and Ord Basins
Other areas

Perth Basin

Regional geology

The Perth Basin is an elongated trough of sedimentary rocks extending for some 1000 km along the south-western coastal belt of Western Australia (Fig. 8). It has a width of about 80 to 175 km onshore, covering an approximate land area of 45 000 km^2. The eastern margin of the basin is defined throughout most of its length by the Darling Fault, while the northern end is bordered to the west by basement rocks constituting the Ajana Ridge. The offshore margins of the basin to the west and south are not precisely defined (Playford et al., 1976a).

Basement underlying the Perth Basin consists of Archaean and Proterozoic igneous and metamorphic rocks forming part of the adjoining Yilgarn Craton, Northampton Block, and Mullingarra Inlier.

Proterozoic and Silurian to Quaternary sequences occur within the Perth Basin as follows:

(a) Proterozoic rocks — the sequence in the Perth Basin is at least 10 000 m thick and consists of mainly siliciclastic rocks, with locally developed volcaniclastic sedimentary rocks.

(b) Silurian rocks — the Tumblagooda Sandstone, with a thickness exceeding 3000 m in the Murchison River valley, is the only probable Silurian unit in the Perth Basin.

(c) Permian rocks — are only exposed in the northern part of the basin. They probably exceed 2600 m in thickness, and consist of a marine and non-marine sequence in the northern part of the basin, and a subsurface non-marine sequence in the southern part.

(d) Triassic rocks — exposures are confined to the Geraldton and Hill River districts but these rocks occur subsurface throughout most of the basin. This sequence may exceed 2500 m and consists of marine and non-marine units in the northern part of the basin, and non-marine units in the south.

(e) Jurassic rocks — this sequence, which is widespread throughout the basin, is mainly non-marine with a thickness of at least 4200 m. Good exposures occur in the Geraldton and Hill River districts.

(f) Cretaceous rocks — reach a total thickness of approximately 12 000 m and are best exposed in the Gingin–Dandaragan area.

(g) Quaternary deposits — cover most of the Perth Basin and consist of mainly Tamala Limestone, Safety Bay Sand, laterite, sand dunes, and alluvium.

Limestone units

The Tamala Limestone, which is exposed along the coastal belt, is the most widespread limestone formation in the Perth Basin, although a number of other limestone and limesand units are recognized as follows:

Age	*Unit*
Quaternary	Muchea Limestone
	Safety Bay Sand
	Peppermint Grove Limestone
	Tamala Limestone
	Herschell Limestone (shell beds) on Rottnest Island
	Rottnest Limestone
	Limestone and beach ridges of the Houtman Abrolhos Islands
Cretaceous	Gingin Chalk
Jurassic	Newmarracarra Limestone

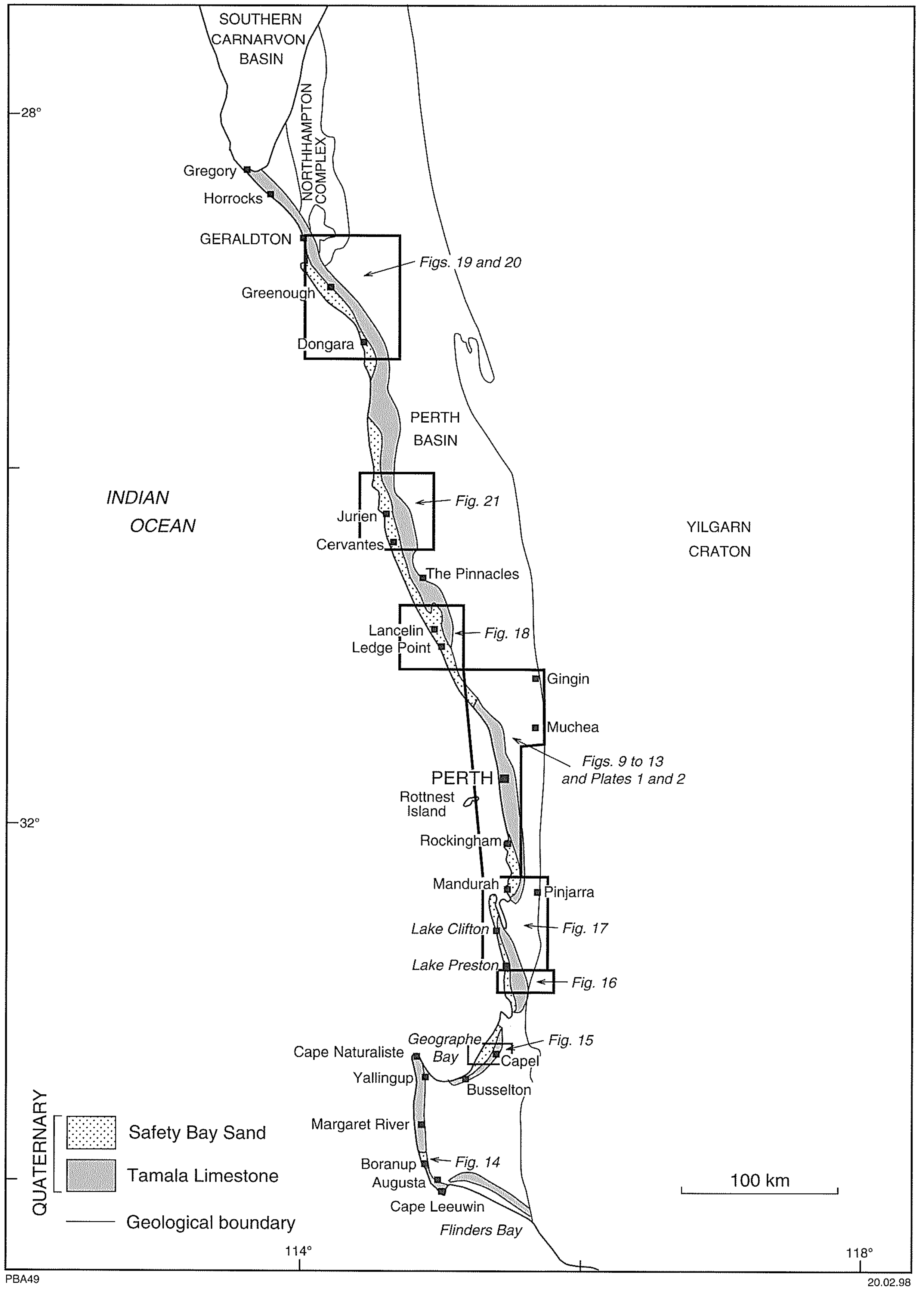

Figure 8. Distribution of Tamala Limestone and Safety Bay Sand in the Perth Basin

Newmarracarra Limestone

The Newmarracarra Limestone, named after the historic Newmarracarra property (one of the first to be established in the Geraldton area), disconformably overlies the Moonyoonooka Sandstone and conformably underlies the Kojarena Sandstone. The type section at Round Hill (Lat. 28°45'31"S, Long. 114°48'23"E) has a thickness of 10 m. Playford et al. (1976a) reported that the thickest section of the unit (11.5 m) occurs on Moonyoonooka Station. The Newmarracarra Limestone contains the richest and best preserved invertebrate fossil fauna known in the Perth Basin (Playford et al., 1970). The dominant fauna are molluscs, with the most common being the bivalve *Trigonia moorei*, which forms coquinoid beds.

The Newmarracarra Limestone is generally an altered, lateritized unit, with lateritization extending to depths of 25 to 30 m. Lateritization has resulted in complete decalcification of the rock, the lime being either replaced by hematite or simply leached out, leaving the insoluble non-carbonate constituents of the original limestone. Where unaffected by lateritization, the unit usually consists of complete or relatively complete shells within a carbonate matrix that locally grades into calcareous sandstone. The limestone is hard, massive, and crudely bedded, typically exposed as large slabs ranging in colour from yellow and grey to bright red. Unaltered exposures are rather limited, with the best outcrops occurring in the Bringo–Moonyoonooka area.

Gingin Chalk

Glauert (1910) named a white, friable, and richly fossiliferous chalk unit between the Molecap and Poison Hill Greensands as Gingin Chalk, and recognized it as Cretaceous in age. Subsequently, Playford et al. (1976a) suggested a Santonian–Campanian age (Late Cretaceous) on the basis of fossils such as *Marsupites* and the foraminiferid *Rugoglobigerina*.

The unit rests, with apparent conformity, on the Molecap Greensand and is overlain by the Poison Hill Greensand. Where the Molecap Greensand is missing, the Gingin Chalk overlies the Dandaragan Sandstone. In its type section at MacIntyre Gully (Lat. 31°19'S, Long. 115°54'E), the unit has a thickness of 19 m, and averages 18 m in thickness overall.

The Gingin Chalk, exposed in the area between Badgingarra and 6 km south of Gingin, commonly contains thin beds of glauconite-rich greensand and a high proportion of coccolith remains. Outcrops, which are commonly kankarized at the surface, lack fossils and glauconite. In the subsurface, chalk is known to occur as far north as Watheroo (Playford et al., 1976a; Wilde and Low, 1978).

Limestone and beach ridges of the Houtman Abrolhos Islands

Pleistocene coralline limestone, overlain by dune limestone that correlates with the Tamala Limestone, occurs on the Houtman Abrolhos Islands in the Indian Ocean, west of Geraldton. These islands and the associated reefal deposits offer unequalled opportunities for studying contemporary and Pleistocene coral-algal reefs, and Quaternary climatic, sea-level, and faunal changes (Playford et al., 1976a).

Rottnest Limestone

Fairbridge (1953) introduced the name Rottnest Limestone or 'Salmon Bay Limestone' for a unit of coral-reef and shell limestone exposed at Salmon Bay on the south coast of Rottnest Island. The unit is overlain by the Tamala Limestone and is underlain by older Pleistocene deposits. Rocks equivalent to this unit are exposed on the Houtman Abrolhos Islands, on the coast at Dongara, and at the mouth of the Greenough River. A coral from the Rottnest Limestone, underlying the Tamala Limestone, was dated at 100 000 ± 20 000 years (Veeh, 1966).

Herschell Limestone

The Herschell Limestone, which outcrops as shell beds along the bottom and margins of salt lakes on Rottnest Island, is thought to represent a series of marine incursions into the Tamala Limestone. The age of the unit is probably Late Pleistocene (Teichert, 1950; Glenister et al., 1959; Wilde and Low, 1980).

Tamala Limestone

Logan (1968) used the name 'Tamala Eolianite' for a unit previously known as 'Coastal Limestone' that is found in the Shark Bay area of the Carnarvon Basin. Playford et al. (1976a) proposed the name Tamala Limestone because the unit consists mostly of limestone, and extended the usage of the name into the Perth Basin. The type section, at Womerangee Hill on the Zuytdorp Cliffs in the Carnarvon Basin, has a thickness of approximately 285 m. In the Perth Basin, Tamala Limestone is late Pleistocene in age.

The Tamala Limestone consists of coarse- to medium-grained calcarenite, composed largely of skeletal fragments of mostly foraminiferids and molluscs, and variable amounts of quartz sand. It is generally well bedded, often exhibiting large-scale cross-bedding, and commonly contains soil horizons and calcified structures. The unit occurs in several belts representing successive lines of late Pleistocene dunes. Within the Perth Basin, the unit is thickest in the Cape Naturaliste region and along the coast south of the Hutt River (north of Geraldton), where it probably exceeds 150 m in thickness in both areas (Fig. 8).

In the coastal region of Busselton and Augusta, the Tamala Limestone consists dominantly of eolian calcarenite with minor occurrences of marine limestone, fossiliferous soil, and beach conglomerate (Lowry, 1967). The eolianite is made up of rounded, frosted quartz sand and 10 to 90% calcium carbonate sand, with accessory amounts of feldspar, sponge spicules, and heavy minerals. Good exposures of limestone occur between Cape Leeuwin and Cape Naturaliste, and also in belts parallel to the coasts of Flinders Bay and Geographe Bay. Lowry (1967) considered that a shelly limestone near Geographe Bay is sufficiently widespread to be mapped as a separate member.

Lowry (1974) concluded that the Tamala Limestone represents a lithified set of dunes, formed when the sea was 2 to 3 m higher than its present level. On prolonged weathering, the unit locally develops a profile consisting of leached quartz sand overlying a hard kankar and indurated limestone caprock 1 to 3 m thick. Subsequent removal of the overlying sand due to eastward wind action results in the exposure of the caprock, which grades down into softer bedded limestone.

Peppermint Grove Limestone

Fairbridge (1953) named the Peppermint Grove Limestone after the Perth suburb of Peppermint Grove. The 5 m-thick type section, exposed on the bank of the Swan River near Scotch College, consists of calcarenite, minor calcirudite, two well-cemented beds, and a shell-rich bed near the top of the unit. The Peppermint Grove Limestone interfingers with the Tamala Limestone.

Safety Bay Sand

The name 'Safety Bay Sand' was introduced by Passmore (1967, 1970) for the Holocene coastal sand dunes and shallow-marine to littoral sands in the Rockingham–Safety Bay area. Playford and Low (1972) extended the usage of this term to include similar sands throughout the Perth Basin (Fig. 8). Passmore (1967) nominated the type section as Rockingham Bore R3 (Lat. 32°16'53"S, Long. 115°42'19"E) from the surface to a depth of 24 m. The unit overlies the Tamala Limestone or other Quaternary units. Some of the older parts of these dunes are lithified, or locally consist of rubbly heaps of friable limestone that have been left behind after the bulk of the dune has blown away. The best example of this process is The Pinnacles, a popular tourist attraction 150 km north of Perth.

The sand commonly consists of shell fragments such as foraminiferids and molluscs, and has variable quartz and minor feldspar. The calcium carbonate content is normally greater than 50%, but higher grade limesand deposits occur within the Safety Bay Sand at a number of localities.

Muchea Limestone

Quaternary units of soft marly limestone, rarely exceeding 1 m in thickness, are locally developed at or near the surface along the eastern side of the central Swan Coastal Plain, in locations such as Muchea, Cannington, and Wungong (Fig. 9) (Wilde and Low, 1978, 1980). This limestone was referred to as Muchea Limestone by Glauert (1911), and the name was later formalized by Fairbridge (1953) who also reported that it contained non-marine gastropod fossils. Playford et al. (1976a) suggested that the limestone originated as a kankar, at least in part, although Fairbridge (1953) suggested that it was of lacustrine origin.

Limestone deposits in the Perth Metropolitan Region

In this Bulletin, the Perth Metropolitan Region refers to an area extending from Seabird to Mandurah, which are located approximately 100 km north and south of Perth respectively. Limestone and limesand production from the metropolitan region accounts for 97% of the State production of these commodities. Cockburn Cement Limited and Swan Portland Cement Limited are the largest producers of cement and lime in the State.

The quality of limestone and limesand deposits in the Perth Metropolitan Region has been investigated by McMath (1952), de la Hunty (1966), Baxter and Rexilius (1974), Gozzard (1987a,b), and by a number of companies. Assays of surface samples collected within the metropolitan region by GSWA, and other assays from open-file data in the Department of Minerals and Energy, are tabulated in Appendix 1 and shown on Plates 1 and 2. Published information on the quality and quantity of available limestone and limesand deposits is scarce, since companies involved in this industry compete for markets. Table 9 gives the known resources and 1993–94 consumption of limestone and limesand in the Perth Metropolitan Region (Landvision, 1996).

Limestone deposits in the metropolitan region occur almost continuously along the coastal region, from Seabird in the north to Mandurah in the south. However, relatively high-grade deposits, containing in excess of 85% $CaCO_3$, are only locally developed around such areas as Parrot Ridge (northeast of Yanchep), Carabooda, State Forest No. 65, north of Flynn Drive in Neerabup, north and south of Wesco Road in Nowergup, west of Lake Pinjar, at Wanneroo, Guilderton, Wilbinga Grove, Coogee, and in various localities north of Mandurah (Plates 1 and 2).

Limestone from around the Nowergup, Parrot Ridge, and Carabooda areas is mainly used for the manufacture of lime and cement, but is also used as roadbase material and, to a lesser extent, for building blocks. Swan Portland Cement Limited obtains most of its limestone requirements for cement manufacture from a quarry at Wesco Road in Nowergup. Most of the limestone produced from quarries and pits located around Wanneroo and Guilderton has been used as roadbase material.

High-grade limestone in areas around Coogee is also a major source of raw material for cement and lime manufacture, and Cockburn Cement Limited obtains a significant amount of limestone from this area. The stretch between Mandurah and Madora is also an active area for limestone mining for various limestone-related industries.

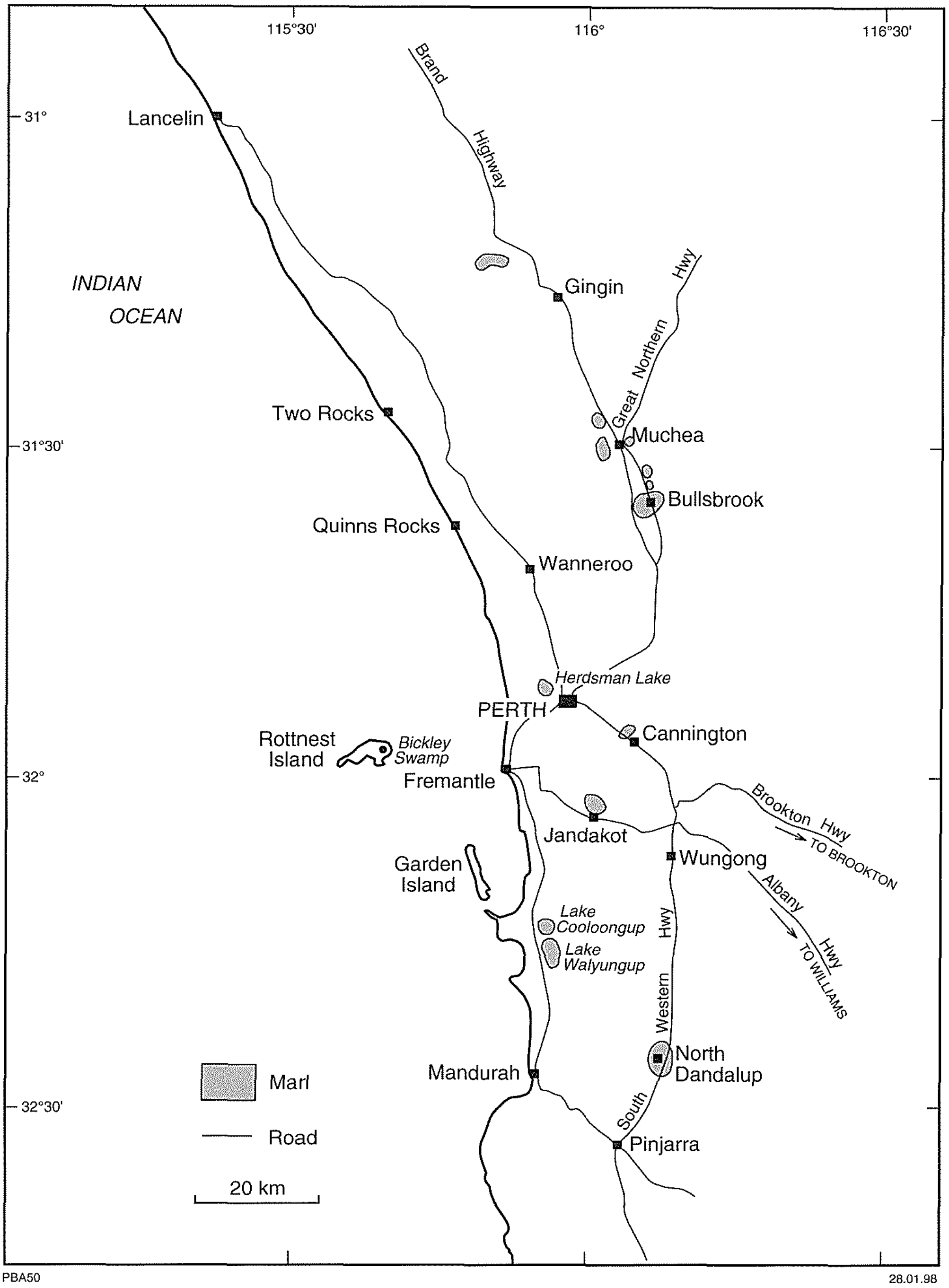

Figure 9. Main marl occurrences in the Perth Metropolitan Region

The area extending from Mullaloo to Fremantle is of minor importance as a source of limestone because of intense urban development. Reabold Hill (82% $CaCO_3$) and Mosman Park (86% $CaCO_3$) are the only two sites in this area known for high-quality limestone, with most other deposits containing only 60 to 70% $CaCO_3$.

Most limestone exploration and mining activities in the Perth Basin are concentrated in the Perth Metropolitan Region because of the relatively low transport costs that are acceptable in associated commodity production. However, continued utilization of high-grade limestone within the metropolitan region is under pressure from competing landuses and environmental constraints. With further urbanization, limestone resources outside the Perth Metropolitan Region will play an increasing role in satisfying the demand for limestone usage in the metropolitan area.

A summary of the information available on the quality and quantity of limestone deposits in the

Table 9. Known resources of limestone and limesand and 1993–94 consumption in the Perth Metropolitan Area

Grade		Metropolitan area	Consumption 1993–94 ('000 tonnes)	[a]Resources ('000 tonnes)	Known resources: [b]Estimated life (years)	[c]Current approved life (years)	Not approved ('000 tonnes)
Cement		North	340	[d]42 800	[e]42	8	[f]41 000
		South	[g]1 750	13 690	[h]61	[h]42	
	Total		**2 090**	**56 490**			**41 000**
Roadbase		North	838	25 000	30	19	[i]60 000
		South	1 120	12 300	11	4.6	9 000
	Total		**1 958**	**37 300**	**19**	**11**	**69 000**

SOURCE: Landvision (1996)

NOTE: (a) Currently known resources
(b) Estimated life based on 1993–94 consumption
(c) Estimated life of approvals based on current production
(d) Includes 40.8 Mt subject to proposed State Agreement Act
(e) Assumes approval of proposed State Agreement Act and anticipated consumption for new plant
(f) Includes 21 Mt in leases within proposed extension to Yanchep National Park
(g) Includes 200 000 t of limesand (cement) and 1 350 000 t of limesand (lime)
(h) Based on 1993–94 consumption and assuming continued availability of shell sands
(i) Includes 50 Mt subject to mining tenement applications in proposed extension to Yanchep National Park

metropolitan region is given below in alphabetical order of locality.

Cape Peron

Cape Peron is located at the end of the long peninsula stretching westward from Rockingham (Plate 2). Impure sandy limestone occurs as weathered, broken, and etched cliffs up to 6 m high around the coastal fringe of the northwestern, western, and southern portions of the tip of the peninsular. Slightly further inland, limestone is capped by dunes of limesand.

Field tests on five samples, collected from several locations at the tip of the peninsular and from various cliff faces, indicate approximately 80 to 90% total carbonate content (locations 219–221 on Plate 2). However, Miles (1945a) stated that the quantity of limestone available at this locality is limited.

Carabooda

Tamala Limestone, suitable for agricultural uses and the manufacture of construction blocks, occurs in localities around Carabooda (Plate 1). Reported production from the area during 1960 to 1993 amounted to 229 700 t valued at $2 032 300.

The limestone is pale-cream to yellow, massive to bedded, laminated, and contains skeletal shell fragments and rounded quartz grains. Quarry and pit exposures reveal a limestone thickness ranging from about 3 to 28 m.

The limestone is suitable for construction, decorative cladding, light foundation work, and also for agricultural uses. Locally, the caprock is of sufficient quality for cement and lime manufacture.

Cockburn Sound

Limestone from cuttings, pits, wells, and cliffs in the onshore area of Cockburn Sound was sampled and assayed in 1944 as part of a reconnaissance survey in the area (Miles, 1945a). Most of the sampling was done in the Groyne Quarry (Fig. 10), located at the limestone cliff south of Russell Road. Assays of these samples are given in Table 10. The locations and assays of other samples collected during the present survey are shown on Figure 10 and Plate 2.

Table 10. Partial chemical analyses of limestone from Groyne Quarry (Cockburn Sound)

Face/sample no.	Depth (m)	$CaCO_3$ (Percentage)	$MgCO_3$ (Percentage)	Ins. (Percentage)
South Face				
1	0–1.5	84.57	3.26	5.72
2	1.5–3.0	83.84	3.51	8.07
3	3.0–4.5	84.41	2.99	9.18
North No. 1 Face				
1	0.6–2.7	84.14	3.78	8.40
2	2.7–4.5	87.30	2.03	7.47
3	4.9–7.0	85.82	1.74	10.61
4	7.0–8.5	85.84	1.65	10.57
5	8.5–10.1	83.41	1.17	12.84
North No. 2 Face				
1	0–1.5	87.34	2.51	7.04
2	1.5–3.0	87.92	2.20	6.63
3	3.0–4.5	85.34	2.76	8.65
4	4.5–6.0	86.0	1.84	9.91
5	6.0–7.6	88.88	1.99	7.55
6	7.6–8.5	84.72	1.28	11.75
North No. 3 Face				
1	0–1.5	71.15	2.59	22.43
2	1.5–3.0	71.90	2.41	22.11
3	3.0–4.5	61.8	1.07	35.03
4	4.5–6.0	67.46	0.65	29.67
5	6.0–7.6	68.40	1.63	28.22
6	7.6–8.5	43.44	1.28	53.22

SOURCE: after Miles (1945a)
NOTE: Ins. insoluble residue (mainly silicates)

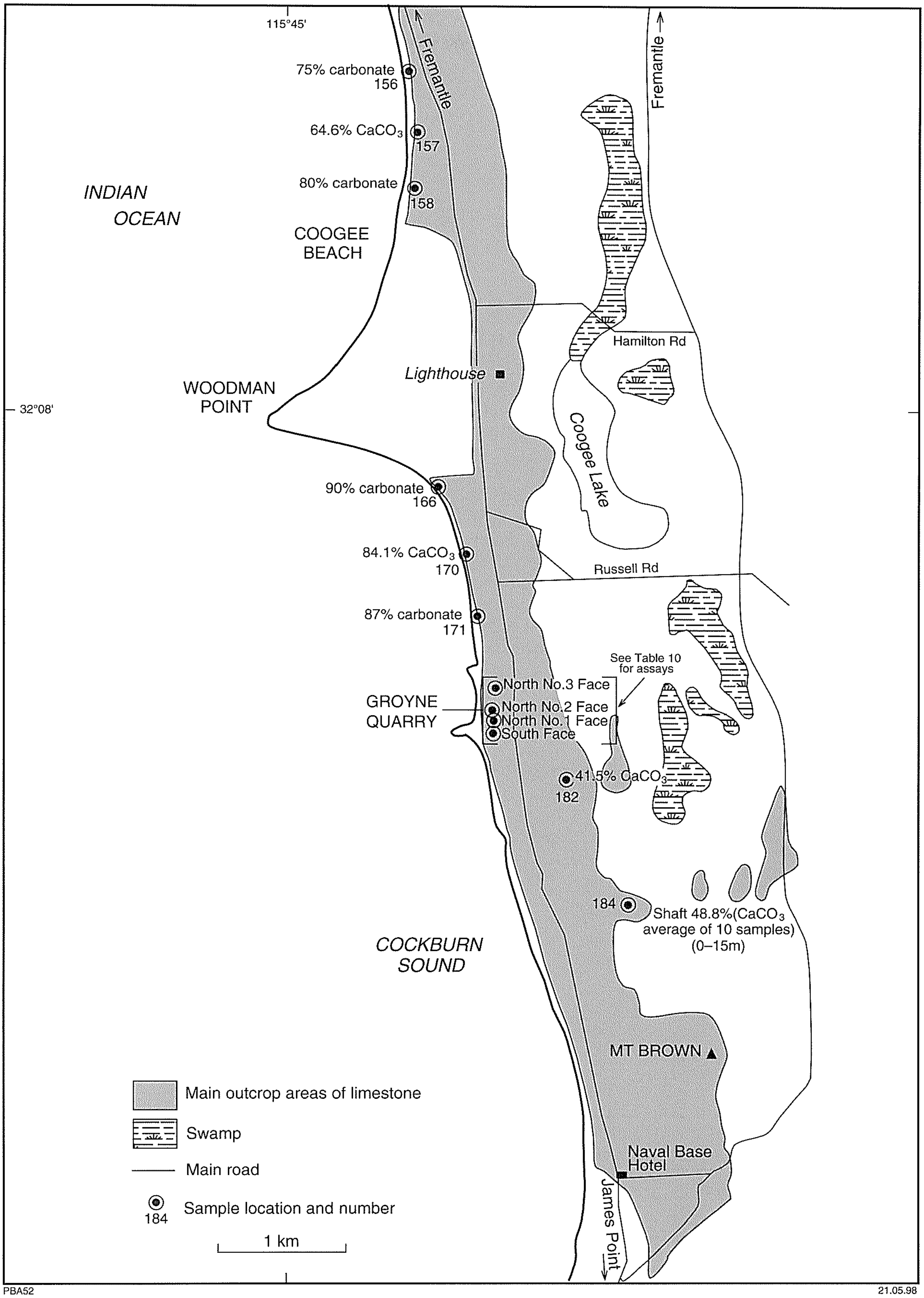

Figure 10. Sample locations and assays of limestone around Groyne Quarry in the onshore Cockburn Sound area (after Miles, 1945a)

Table 11. Calcium carbonate content of limesand from Eglinton Hill

Hole no.	*Intersection (m)*	*Thickness (m)*	*% $CaCO_3$*
1	3.7 – 7.3	3.6	71–78
3	12.2 – 13.7	1.5	70–80
5	6.4 – 7.6	1.2	78
13	0.0 – 2.4	2.4	61–75
72	10.1 – 10.7	0.6	75
74	14.3 – 15.5	1.2	76

SOURCE: after Swan Portland (1971)

On the basis of his sampling program, Miles (1945a) concluded that the limestone, exposed around the Naval Base area and the southern end of the Groyne Quarry, has a high carbonate content. The area immediately south and east of this was recommended for more exploratory work for high-grade limestone.

Samples were also collected from Coogee Beach (north of the Groyne Quarry), a narrow coastal strip extending for about 1.6 km northwards of Woodman Point. Total carbonate values of 80 and 75% respectively were determined for two samples collected from the southern and northern ends of Coogee Beach. Another sample from the centre of the area assayed 64.6% $CaCO_3$ (36.2% CaO), 4% $MgCO_3$, and 28.61% acid insolubles (locations 156–158 on Plate 2).

Eglinton Hill

The area northeast of Eglinton Hill (Plate 2) was explored in 1970 by Swan Portland Cement Ltd for limesand (Swan Portland, 1971). Ninety-seven holes, covering the entire lease, were drilled on a grid of approximately 100 m × 100 m. Only 22 holes were tested for calcium carbonate, and of these, six holes contained limestone assaying 70 to 80% $CaCO_3$ (39.2 to 44.8% CaO) with $MgCO_3$ ranging from 3.5 to 5.5% (Table 11).

Gingin Chalk

In the past, several attempts have been made to develop the Gingin Chalk for commercial applications such as lime burning and the manufacture of cement (Simpson, 1948). With an average of 66.7% $CaCO_3$ and 19.1% silica (Table 12) the chalk is unsuitable for cement manufacture, but Hobson (1948) noted that it was suitable for agricultural uses. The limestone resources available in the Gingin area have been estimated at approximately 9 Mt (Fig. 11; Table 13).

Neerabup

A significant but untested resource of high-grade limestone is available adjacent to Flynn Drive in this area. Samples from locations 114 to 118 (Plate 1) range from 76.9 to 85% $CaCO_3$ (43.1 to 47.6% CaO).

Table 12. Chemical analyses of chalk samples from the Gingin area

Location	*$CaCO_3$*	*$MgCO_3$*	*Fe_2O_3*	*Al_2O_3*	*SiO_2*	*Insol.*	*P_2O_5*	*K_2O*	*MnO*
					Percentage				
Molecap Hill	75.27	2.74	2.02	3.56	13.42	–	–	–	0.11
Molecap Hill	72.35	–	–	–	–	–	0.18	0.36	–
Molecap Hill	70.31	–	–	–	–	19.78	0.48	–	–
Molecap Hill	63.21	2.26	–	–	–	23.96	0.36	–	–
Molecap Hill	61.51	–	–	–	–	24.04	1.84	–	–
Molecap Hill	60.12	–	–	–	–	24.90	1.56	–	–
Molecap Hill	57.78	–	–	–	–	27.23	1.64	–	–
Molecap Hill	56.87	3.10	–	–	–	28.40	3.66	–	–
Molecap Hill	39.64	2.78	–	–	–	32.68	2.28	–	–
1 km south of Molecap	50.77	–	–	–	–	29.65	3.44	–	–
One Tree Hill	77.19	–	–	–	–	15.47	–	–	–
One Tree Hill	77.03	3.17	2.01	1.70	15.23	–	–	–	–
One Tree Hill	76.64	2.07	2.33	2.30	15.25	–	–	–	–
One Tree Hill	76.36	–	–	–	–	16.39	–	–	–
One Tree Hill	75.82	3.19	1.90	1.95	16.72	–	–	–	–
One Tree Hill	70.48	2.66	2.53	3.40	20.28	–	–	–	–
One Tree Hill	65.31	–	–	–	–	25.38	–	–	–
One Tree Hill	62.83	2.38	3.32	3.54	25.56	–	–	–	–
One Tree Hill	61.90	2.42	3.29	4.36	27.04	–	–	–	–
One Tree Hill	61.39	–	–	–	–	27.96	–	–	–
One Tree Hill	58.24	–	–	–	–	29.85	–	–	–
One Tree Hill	55.51	–	–	–	–	31.35	–	–	–
One Tree Hill	54.42	–	–	–	–	33.29	–	–	–
One Tree Hill	53.82	–	–	–	–	33.15	–	–	–

SOURCE: GSWA
NOTE: Insol. insoluble residue

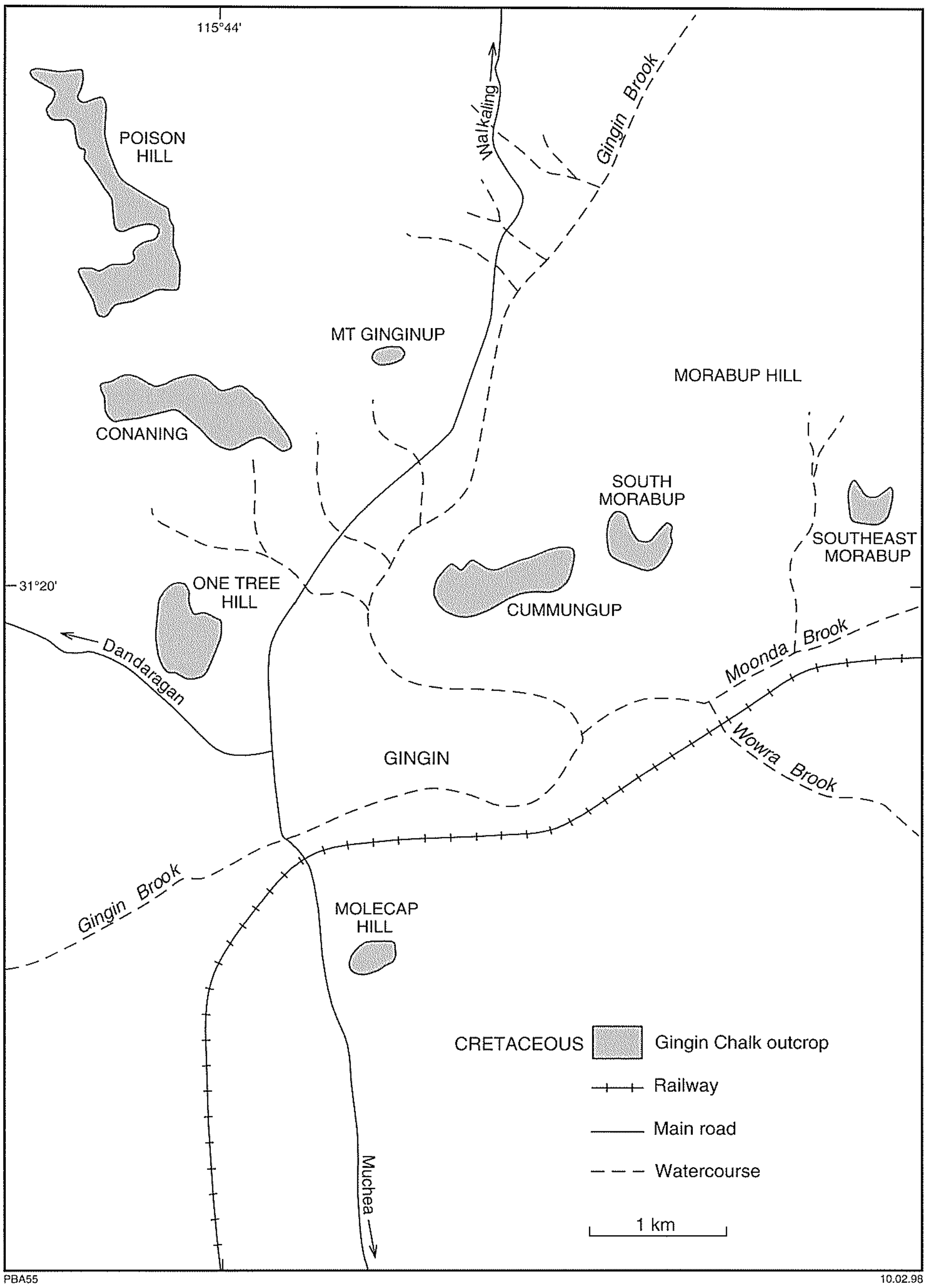

Figure 11. The main exposures of Gingin Chalk around Gingin

Table 13. Resource estimates of chalk in the Gingin area

Locality	*Approximate tonnage*
Molecap Hill	36 000
One Tree Hill	1 440 000
Cummungup	2 600 000
South Morabup	480 000
Southeast Morabup	60 000
Mount Ginginup	12 000
Conaning	2 300 000
Poison Hill	2 800 000

SOURCE: GSWA

Nowergup

A large but untested resource of high-quality limestone occurs in the area around Wesco Road at Nowergup. Samples collected from locations 103 to 109 (Plate 1) have assays ranging from 36.9 to 85.8% $CaCO_3$ (20.7 to 48.0% CaO). Two samples of limestone (132225–26), collected by the author from a limestone building-block quarry at locality 104 (Plate 1), assayed 74.1 and 84.6% $CaCO_3$ (41.5 and 47.4% CaO) respectively (Table 14). The sawing of limestone for building blocks is done from solid rock after preparation of a flat surface (Fig. 12).

Table 14. Chemical analyses of limestone from the Limestone Building Blocks Pty Ltd quarry

Sample no.	*132225*	*132226*
	Percentage	
SiO_2	21.72	10.87
TiO_2	0.02	0.04
Al_2O_3	0.63	0.79
Fe_2O_3	0.04	0.05
MnO	<0.01	<0.01
MgO	0.51	0.44
CaO	41.49	47.35
Na_2O	0.12	<0.01
K_2O	0.35	0.27
P_2O_5	0.08	0.04
LOI	34.71	39.57
Total	**99.67**	**99.42**
CO_2	32.50	37.80
	Parts per million	
As	–	8.9
Ba	75	123
Be	<0.2	1.4
Ce	–	17
Cr	–	16
Ga	–	2.6
La	–	37
Nb	–	2.1
Rb	–	9.5
S	–	<0.01
Sn	–	<5
Sr	–	224
Th	–	4.1
U	–	0.3
V	–	<2
W	–	0.6

NOTE: 132225 Quarry for building blocks at Wesco Road, Lat. 31°36'35"S, Long. 115°45'21"E, Tamala Limestone
132226 Quarry for building blocks at Wesco Road, Lat. 31°36'40"S, Long. 115°45'25"E, Tamala Limestone

A significant resource of high-quality limestone is known to occur within State Forest No. 65 (Plate 1), located south of Parrot Ridge. Surface samples collected from locations 30 and 53 to 57 assayed at greater than 80% $CaCO_3$ (44.8% CaO).

One Tree Hill

In 1976, Universal Milling Company drilled 18 holes to an average depth of 18 m (presumed to be in metres) in an area east of One Tree Hill (Plate 1). Hole numbers 13 and 14 were found to have 8 m of material assaying 79.65% $CaCO_3$ (44.6% CaO) and 10 m of material assaying 72.5% $CaCO_3$ (40.6% CaO) (Universal Milling, 1976). The average grade of the limestone in all holes was 46.5% $CaCO_3$ (26.0% CaO) (Table 15).

Parrot Ridge

A large but untested resource of moderate- to high-grade limestone is known to occur in the Parrot Ridge area, northeast of Yanchep (Plate 1).

Quinns Rocks

The area located east of Quinns Rocks (Plate 1) and north of Quinns Road was explored for limestone by Swan Portland Cement Ltd in 1971 (Swan Portland, 1971).

On Mineral Claim 1958^H, 35 holes were drilled on a grid of approximately 200 m × 200 m, with only nine of these having intersections of 4.5 m or more of limestone that assayed 71.2 to 85.7% total carbonate and 1.2 to 5.2% $MgCO_3$ (Table 16).

Twenty-one holes were drilled on Mineral Claim 1959^H, also on a grid of approximately 200 m × 200 m, but only two of these had intersections of 4.5 m or more of limestone that assayed 75.0 to 84.7% total carbonate and 1.9 to 6.2% $MgCO_3$ (Table 16).

On Mineral Claim 1960^H, 29 holes were drilled on a grid of approximately 200 m × 200 m. Six of these had intersections of 4.5 m or more of limestone that assayed 77.3 to 86.4% total carbonate and 1.0 to 2.0% $MgCO_3$ (Table 16).

Nineteen holes were drilled on Mineral Claim 2103^H, on a grid of approximately 200 m × 200 m, with eight of these having intersections of 4.5 m or more of limestone that assayed 74.7 to 87.5% $CaCO_3$ and 1.5 to 2.4% $MgCO_3$ (Table 16).

Shire View Hill

Mineral Claims 2130^H and 2131^H, located south of Shire View Hill, were explored for high-quality limestone by Swan Portland Cement Ltd (Swan Portland, 1971).

Nineteen holes were drilled on Mineral Claim 2130^H along five east–west lines with variable spacings. Of these, 14 holes intersected limestone thicker than 4.5 m that assayed 70.9 to 83.8% $CaCO_3$ (39.7 to 46.9% CaO), while another 2 holes had intersections thicker than 4.5 m assaying at 70.3 to 83.1% total carbonate (Table 17).

Forty-five holes were drilled in the eastern quarter of Mineral Claim 2131^H on an approximately 80 m × 80 m grid. Another 30 holes in the remaining area were drilled on an approximately 160 m × 160 m grid, with two infill holes on the most northerly line. Of these, 25 holes had intersections thicker than 4.5 m of limestone that assayed 70.5 to 86.3% $CaCO_3$ (39.5 to 48.3% CaO). Ten other holes, with limestone intersections thicker than 4.5 m, assayed at 70.8 to 85.0% total carbonate and around 5.7% $MgCO_3$ (Table 17).

South Fremantle

Twenty-seven samples, collected from five sections (up to a maximum height of about 14 m) of a limestone quarry in South Fremantle at the intersection of Douro and Hampton Roads (then Rockingham Road) (location 153 on Plate 2), contained an average of 91.4% total carbonates (Miles, 1945b). A composite of five samples from one of the above sections (having an average of 90.7% total carbonate) contained 89% $CaCO_3$ (49.8%

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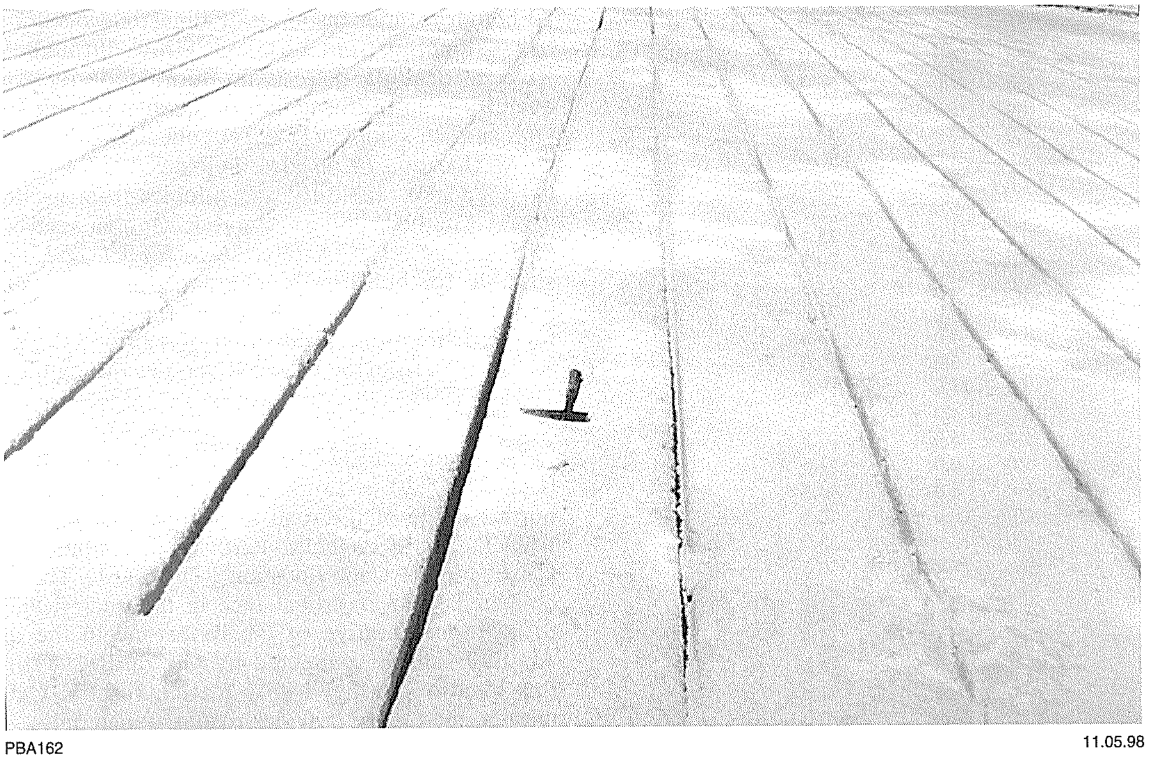

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Figure 12. A limestone quarry (located 3.5 km north of Wesco Road, Nowergup) used for the production of building blocks. Photographs show prepared and partly sawn surfaces

Table 15. Partial chemical analyses of limestone from One Tree Hill

Hole no.	*Depth (m?)*	*%CaCO$_3$*	*Insolubles*
2	1.5 – 4.3	33.3	–
	4.3 – 7.1	43.6	–
	7.1 – 10.1	36.0	–
	10.1 – 11.9	42.4	–
3	1.5 – 5.7	44.9	–
	5.7 – 8.6	37.5	–
	8.6 – 12.6	42.0	–
	12.6 – 16.9	49.5	–
	16.9 – 19.9	70.0	–
	19.9 – 22.8	58.7	–
	22.8 – 25.6	49.0	–
4	5.8 – 10.1	25.0	–
6	1.7 – 3.6	59.0	39.2
	3.6 – 5.3	44.0	55.9
8	2.0 – 3.0	70.0	–
	3.0 – 4.0	74.0	–
	4.0 – 5.0	79.0	–
	5.0 – 6.0	72.0-	–
	6.0 – 7.0	60.0	–
	7.0 – 8.0	67.5	34.5
	8.0 – 9.0	45.0	53.2
	9.0 – 10.0	35.5	62.4
	10.0 – 11.0	25.0	–
	11.0 – 12.0	12.0	–
10	4.0 – 10.0	64.6	–
	10.0 – 14.0	39.0	–
11	1.0 – 5.0	56.0	–
	5.0 – 6.0	55.0	–
	6.0 – 9.0	45.8	–
	9.0 – 10.0	23.3	–
12	1.0 – 2.0	11.0	–
	2.0 – 6.0	33.0	–
	6.0 – 7.0	50.0	–
	7.0 – 8.0	12.0	–
	8.0 – 9.0	55.0	–
13	2.0 – 4.0	90.8	–
	4.0 – 8.0	68.5	–
	8.0 – 9.0	27.5	–
	10.0 – 11.0	35.4	–
14	1.0 – 4.0	70.3	–
	4.0 – 9.0	74.3	–
	9.0 – 10.0	72.8	–
15	4.0 – 7.0	6.0	–
	7.0 – 9.0	30.0	–
	9.0 – 11.0	32.0	–
16	2.0 – 4.0	41.4	–
	4.0 – 5.0	27.5	–
	5.0 – 6.0	51.5	–
	6.0 – 9.0	42.5	–
	9.0 – 10.0	42.5	–
	10.0 – 13.0	33.5	–
	13.0 – 17.0	50.3	–
17	3.0 – 6.0	62.5	–
	6.0 – 9.0	44.5	–
	9.0 – 12.0	42.0	56.1
	12.0 – 13.0	32.0	–
	13.0 – 18.0	41.0	61.2
18	2.0 – 6.0	50.0	–
	6.0 – 9.0	48.0	–
	9.0 – 10.0	51.0	49.5

NOTE: after Universal Milling (1976)

CaO), suggesting that the $MgCO_3$ content of these samples was approximately 1.7%. Two samples collected by Gozzard (1987b) from the same location had an average of 76.4% $CaCO_3$ (42.8% CaO). No estimate of the quantity of available high-grade limestone has been determined for this location.

Wabling Hill

A small area north of Wabling Hill (Lat. 31°24'24"S, Long. 115°41'00"E) was explored in 1971 by Swan Portland Cement Ltd for high-quality limestone. Of forty-five holes drilled on a 160 m × 160 m grid, twenty-one intersected limestone beds of more than 4.5 m thickness that assayed 70.0 to 84.8% total carbonate (Table 18). Thirteen samples from thirteen drillholes contained an average of 1.45% $MgCO_3$ (Swan Portland, 1971).

Limestone in the area south of Wabling Hill is being used for block making. Samples collected from this area suggest that high-grade material, suitable for cement manufacture, could be present. Production of 60 954 t of limestone from the Wabling Hill area, valued at $655 024, was recorded during 1988 to 1993.

Wilbinga Grove–Moore River–Seabird

Although a large resource of limestone occurs in the belt extending from Wilbinga Grove through Moore River to Seabird, there is no information on available quantities, and information on quality is very limited. One surface sample (132227) collected from Wilbinga Grove (location 12 on Plate 1) assayed at 73.4% $CaCO_3$ (41.1% CaO) (Table 19) and samples from locations 6, 7, and 8 in the Wilbinga–Moore River area assayed from 65.3 to 92.0% $CaCO_3$ (36.6 to 51.5% CaO). Limestone suitable for building blocks and dimension stone is known from the Moore River area, and there has been reported limestone production of 123 565 t, valued at $3 731 630, from the Moore River area during the period 1984 to 1993.

A sample (132229), collected from a quarry (Lat. 31°15'20"S, Long. 115°27'38"E) located on the northern side of the road to Seabird that branches off from the main Lancelin–Perth road, contained 86.2% $CaCO_3$ (48.9% CaO) (location 1 on Plate 1). The sample, collected from a vertical face in the quarry, appeared to be representative of the limestone in the quarry. Another sample, collected by Gozzard (1987b) from this location, assayed 85% $CaCO_3$ (47.6% CaO). At present, the quarry provides roadbase material.

Other areas

Samples from the intensively urbanized area between Woodvale and Claremont (Plate 2) assay from 21 to 88% $CaCO_3$. Development of deposits within this area is very unlikely due to competing landuses.

Table 16. Partial chemical analyses of limestone from Quinns Rocks

Hole no.	*Intersection (m)*	*Thickness (m)*	*Total carbonate (%)*	*$MgCO_3$ (%)*	*$CaCO_3$ (%)*
Mineral Claim 1958H					
1	3.8 – 12.2	8.4	85.7	2.5	83.2
2	0.8 – 6.1	5.3	78.2	5.2	73.0
8	3.0 – 8.4	5.3	82.8	1.2	80.3
9	3.8 – 18.3	14.5	85.0	3.0	82.0
16	6.9 – 9.9	3.0	76.9	1.7	75.2
	9.9 – 13.7	3.8	82.1	1.7	80.4
17	3.8 – 9.9	6.1	84.6	1.7	82.9
22	8.4 – 10.7	2.3	75.6	2.4	73.2
	10.7 – 15.2	4.6	81.5	2.4	79.1
23	2.3 – 19.1	16.8	84.2	2.9	81.3
26	7.6 – 16.8	9.1	71.2	2.2	69.0
Mineral Claim 1959H					
3	16.0 – 19.1	3.0	84.1	1.9	82.2
	21.3 – 25.1	3.8	84.7	1.9	82.8
17	0 – 9.1	9.1	83.9	6.2	77.7
	9.1 – 16.0	6.9	75.0	–	–
Mineral Claim 1960H					
3	12.2 – 19.8	7.6	85.9	2.0	83.9
6	18.3 – 21.3	3.0	81.9	1.5	80.4
	22.1 – 26.7	4.6	86.4	1.5	84.9
8	14.5 – 21.3	6.9	78.7	1.7	77.0
	21.3 – 22.1	0.8	85.6	–	–
11	12.2 – 18.3	6.1	77.3	1.0	76.3
	18.3 – 22.9	4.6	80.8	1.0	79.8
15	15.2 – 22.1	6.9	86.0	1.3	84.7
16	16.0 – 20.6	4.6	83.4	2.0	81.4
Mineral Claim 2103H					
1	10.7 – 16.0	5.3	81.7	1.9	79.8
2	12.2 – 19.0	6.9	87.5	2.4	85.1
3	6.9 – 9.1	2.3	76.8	–	–
	9.1 – 11.4	2.3	84.4	1.5	82.9
6	13.0 – 17.5	4.6	82.9	2.4	80.5
8	9.1 – 20.6	11.4	85.4	2.4	83.0
10	1.5 – 6.1	4.6	74.7	–	–
12	11.4 – 26.7	15.2	87.2	2.3	84.9
13	13.0 – 25.2	12.2	85.6	1.7	83.9

SOURCE: Swan Portland (1971)

Limesand deposits in the Perth Metropolitan Region

Limesand deposits in the metropolitan region occur in many areas along the coast from Seabird in the north, to Mandurah in the south, but relatively high-grade deposits containing in excess of 85% $CaCO_3$ (47.6% CaO) appear to be localized in areas around Yanchep Beach, Cockburn Sound, and Garden Island (Plates 1 and 2).

The high-grade deposit in Cockburn Sound is currently one of the major sources of raw material for cement and lime manufacture in the State.

Cockburn Sound

A reconnaissance survey carried out in 1944 in the Cockburn Sound offshore area by Dr K. R. Miles indicated the presence of extensive limesand deposits. The total carbonate content of limesand from these deposits ranged from 55 to 90%. The most promising areas recommended by Miles (1945a) were the area immediately south of Woodman Point and between James Point and the Naval Base (Plate 2).

Extensive exploration drilling activities carried out since the early 1970s by Cockburn Cement Limited at Cockburn Sound (offshore) have led to the delineation of a significant resource of high-grade limesand. This is the largest proven deposit of high-quality limesand in the State. However, environmental and other landuse constraints impose severe restrictions on the continued extraction of this resource.

Garden Island

Garden Island, located approximately 6 km west of Kwinana, is nearly 10 km long and has a width that varies

Table 17. Partial chemical analyses of limestone from Shire View Hill

Hole no.	*Intersection (m)*	*Thickness (m)*	*Total carbonate (%)*	*$CaCO_3$ (%)*
Mineral Claim 2130[II]				
19	3.8 – 13.0	9.2	–	74.2
20	2.3 – 15.2	12.9	–	76.1
21	6.9 – 19.8	12.9	–	74.1
22	0.0 – 3.8	3.8	83.1	–
	6.1 – 9.1	3.0	78.6	–
	11.4 – 17.5	6.1	81.2	–
24	0.0 – 0.8	0.8	–	83.8
	1.5 – 2.3	0.8	–	70.9
	2.3 – 19.1	16.8	–	80.0
	20.6 – 27.4	6.8	–	80.1
	27.4 – 28.2	0.8	–	72.6
37	0.8 – 19.8	19.0	–	80.7
50	0.0 – 8.4	8.4	77.5	–
	9.1 – 16.0	6.9	70.3	–
51	0.0 – 15.2	15.2	–	74.4
52	2.3 – 16.0	13.7	–	76.8
	16.0 – 19.1	3.1	–	72.6
55	6.9 – 11.4	4.5	–	78.7
	12.2 – 23.6	11.4	–	74.6
56	2.3 – 22.1	19.8	–	75.3
57	4.6 – 17.5	12.9	–	76.5
	18.3 – 23.6	5.3	–	73.1
58	5.3 – 20.6	15.3	–	72.3
74	5.3 – 11.4	6.1	–	79.8
	11.4 – 18.3	6.9	–	72.2
75	2.3 – 16.0	13.7	–	76.7
	16.0 – 21.3	5.3	–	72.3
76	4.9 – 13.7	8.8	–	76.4
Mineral Claim 2131[II]				
1	0.0 – 0.8	0.8	–	74.4
	0.8 – 13.7	12.9	–	80.8
	14.5 – 22.9	8.4	–	80.5
	22.9 – 31.2	8.3	–	74.5
2	0.0 – 9.1	9.1	–	80.9
	9.1 – 26.7	17.6	–	75.7
3	0.0 – 1.5	1.5	78.4	–
	3.8 – 6.9	3.1	81.6	–
	9.9 – 22.1	12.2	78.5	–
	22.1 – 23.6	1.5	70.8	–
4	0.0 – 0.8	0.8	–	73.8
	0.8 – 9.9	9.1	–	81.1
	9.9 – 22.1	12.2	–	77.4
5	0.0 – 2.3	2.3	–	82.7
	3.8 – 16.0	12.2	–	80.9
	16.0 – 17.5	1.5	–	72.4
6	5.3 – 14.5	9.2	–	79.9
	14.5 – 15.2	0.7	–	70.5
7	0.8 – 3.8	3.0	–	72.1
	3.8 – 13.0	9.2	–	77.9
8	0.0 – 11.4	11.4	–	74.7
10	1.5 – 9.1	7.6	73.1	–
11	0.0 – 6.9	6.9	79.4	–
15	0.8 – 11.4	10.6	–	82.4
	12.2 – 17.5	5.3	–	80.1
	17.5 – 29.7	12.2	–	73.8
16	0.0 – 0.8	0.8	–	86.3
	0.8 – 11.4	10.6	–	81.3
17	0.0 – 1.5	1.5	–	78.4
	3.8 – 20.6	16.8	–	78.9
Mineral Claim 2131[II]				
	21.3 – 22.9	1.6	–	79.2
	23.6 – 24.4	0.8	–	78.9
18	0.8 – 9.9	9.1	–	71.5
	9.9 – 16.0	6.1	–	79.2
25	0.0 – 12.2	12.2	–	82.0
	12.2 – 25.1	12.9	–	77.0
26	0.0 – 6.7	6.7	–	80.8
	15.2 – 18.3	3.1	–	79.3
27	0.0 – 9.1	9.1	77.1	–
	13.0 – 16.8	3.8	80.0	–
28	0.8 – 6.9	6.1	71.6	–
29	0.8 – 3.0	2.2	74.8	–
	3.8 – 8.4	4.6	71.9	–
38	0.0 – 14.5	14.5	–	78.9
	14.5 – 15.2	0.7	–	73.5
39	0.0 – 1.5	1.5	–	71.5
	1.5 – 13.0	11.5	–	80.0
40	2.3 – 8.4	6.1	–	79.9
41	1.5 – 13.0	11.5	–	81.2
42	0.0 – 10.7	10.7	–	78.7
43	0.0 – 0.8	0.8	–	82.4
	5.3 – 9.9	4.6	–	79.5
60	0.8 – 10.7	9.9	–	79.5
	12.2 – 16.0	3.8	–	80.4
61	0.0 – 16.8	16.8	–	80.9
	16.8 – 17.5	0.7	–	71.4
62	0.8 – 14.5	13.7	–	80.5
63	3.0 – 8.4	5.4	72.5	–
70	0.8 – 1.5	0.7	85.0	–
	.3.8 – 9.1	5.3	76.9	–
	9.9 – 14.5	4.6	72.7	–
71	0.0 – 12.2	12.2	78.5	–
72	0.0 – 10.7	10.7	–	80.0
	10.7 – 11.4	0.7	–	74.4
77	0.0 – 8.4	8.4	–	80.2
78	0.0 – 0.8	0.8	78.8	–
	4.6 – 13.0	8.4	80.0	–
79	0.0 – 9.9	9.9	–	80.1
80	3.2 – 8.4	5.2	–	78.9
86	2.3 – 10.7	8.4	–	76.2
	10.7 – 11.4	0.7	–	70.5
87	6.9 – 9.9	3.0	–	80.8
	9.9 – 11.4	1.5	–	75.0
88	1.5 – 3.0	1.5	–	82.3
	4.6 – 8.4	3.8	–	75.0
	9.9 – 13.7	3.8	–	78.0
89	2.4 – 3.2	0.8	–	74.5
	3.2 – 14.6	11.4	–	77.9
90	0.0 – 2.3	2.3	–	77.4
	2.3 – 14.5	12.2	–	81.4
	14.5 – 16.0	1.5	–	77.0
91	4.1 – 12.0	7.9	–	79.2
	0.0 – 10.7	10.7	–	77.5
	10.7 – 15.2	4.5	–	75.0
93	1.4 – 9.0	7.6	–	82.0
	9.0 – 12.0	3.0	–	78.4
	12.0 – 12.8	0.8	–	70.9
94	2.1 – 9.8	7.7	–	77.0
95	10.1 – 16.2	6.1	–	74.9
	16.9 – 21.4	4.5	–	76.6

SOURCE: Swan Portland (1971)

Table 18. Partial chemical analyses of limestone from Wabling Hill

Hole no.	*Intersection (m)*	*Thickness (m)*	*Total carbonate (%)*
2	0.0 – 13.7	13.7	72.4 – 79.5
3	0.0 – 3.8	3.8	72.0 – 79.1
	13.0 – 19.1	6.1	73.6 – 74.3
6	0.0 – 13.0	13.0	80.1 – 83.7
7	0.0 – 13.7	13.7	77.0 – 84.3
8	2.3 – 24.4	22.1	72.1 – 77.0
9	0.0 – 6.9	6.9	73.9 – 76.0
11	0.0 – 13.0	13.0	78.6 – 83.5
12	0.0 – 18.3	18.3	73.8 – 82.4
14	5.3 – 13.7	8.4	70.4 – 72.5
16	0.0 – 12.2	12.2	75.5 – 79.1
17	0.0 – 3.0	3.0	72.0
	6.1 – 7.6	1.5	70.0
	10.7 – 14.5	3.8	79.4
18	2.3 – 11.4	9.1	72.7 – 75.2
21	0.0 – 12.2	12.2	74.6 – 79.7
26	0.8 – 11.4	10.6	80.1 – 83.0
31	0.0 – 12.2	12.2	76.4 – 82.6
32	3.8 – 15.2	11.4	70.4 – 80.4
37	0.8 – 11.4	10.6	81.3 – 84.5
42	1.5 – 7.6	6.1	80.7
	7.6 – 11.4	3.8	70.3 – 76.9
43	0.0 – 14.5	14.5	78.2 – 83.0
48	0.0 – 15.2	15.2	78.8 – 84.8
49	0.0 – 4.6	4.6	77.5
	13.7 – 16.8	3.1	74.2

SOURCE: Swan Portland (1971)

Table 19. Chemical analyses of limestone and limesand from the Wilbinga Grove, Moore River, and Seabird areas

Sample no.	*132227*	*132228*	*132229*	*132230*
		Percentage		
SiO_2	23.14	17.69	6.13	13.95
TiO_2	0.03	0.07	0.03	0.01
Al_2O_3	0.53	0.57	0.40	0.35
Fe_2O_3	0.07	0.38	0.01	0.07
MnO	<0.01	<0.01	<0.01	<0.01
MgO	0.19	0.28	0.89	2.90
CaO	41.14	45.66	48.93	42.52
Na_2O	0.12	0.01	0.16	0.42
K_2O	0.29	0.25	0.18	0.28
P_2O_5	0.09	0.05	0.06	0.12
LOI	34.24	36.09	42.20	38.59
Total	**99.84**	**101.05**	**98.99**	**99.21**
CO_2	33.30	34.10	42.00	37.20
		Parts per million		
Ba	63	82	51	50
Be	<0.2	<0.2	<0.2	0.7

NOTE:
132227 Wilbinga Grove, Lat. 31°22'32"S, Long. 115°37'10"E, Tamala Limestone
132228 8 km north of Moore River, Lat. 31°15'57"S, Long. 115°29'31"E, Tamala Limestone
132229 Quarry, 1.7 km north of main road towards Seabird, Lat. 31°15'20"S, Long. 115°27'38"E, Tamala Limestone
132230 Seabird, Lat. 31°17'05"S, Long. 115°26'36"E, limesand

from 1 to 1.6 km. Although a large resource of high-quality limesand occurs on the island, it has not yet been used commercially since Garden Island is under Commonwealth jurisdiction and hosts a military base.

Geology

Flat-lying Tamala Limestone, which forms the basement to Garden Island, is exposed in prominent cliffs at the southern end of the island, but elsewhere is covered by sandplains and dunes. The eastern coastal strip and the northern and southern portions of the island consist predominantly of sandplains with minor sand dunes. The central area from Mount Stewart to north of Mount Moke is mostly hilly due to the development of dunes, some of which are the highest coastal features from Fremantle to Rockingham, having elevations of more than 60 m. Most dunes are aligned in a westerly or southwesterly direction.

The best developed limesand deposits are in the central portion of the island, between north of Mount Stewart and south of Gilbert and Cliff Points.

Exploration

Initial interest in Garden Island limesand was due to a proposal by Broken Hill Pty Co. Ltd (BHP) to develop a steelworks at Kwinana. The proposed steelworks required a limestone or limesand resource of approximately 10 Mt containing less than 5% SiO_2, which was within 50 km of Kwinana. Although limestone of suitable quality was not available within the area, the few published analytical data on Garden Island limesand, from Mount Haycock and from the southern end of the island, suggested that the limesand would be of appropriate grade. In 1963, BHP identified an area stretching from Mount Stewart to a kilometre north of Mount Moke as suitable for more detailed prospecting. This was subsequently described by McEwen and Whitehead (1964).

Preliminary sampling in 1963 by BHP involved the collection of 32 samples including eight samples from 1.6 m-deep auger holes and eight surface samples. Assays of these samples suggested that the northern portion of the dune area contained the best-quality limesand, and that mobile dunes contained markedly lower silica and alumina than fixed dunes.

The exploration described by McEwen and Whitehead (1964) involved 16 percussion drillholes in the northern portion of the area (Fig. 13). Material from the entire length of the percussion drillholes was sampled and chemically analysed (Table 20). A few samples were also collected for beneficiation tests.

The aim of the exploration program was to identify a limesand resource containing less than 5% SiO_2. Chemical analyses of samples, most of which contained less than 5% SiO_2, showed the following range of chemical compositions:

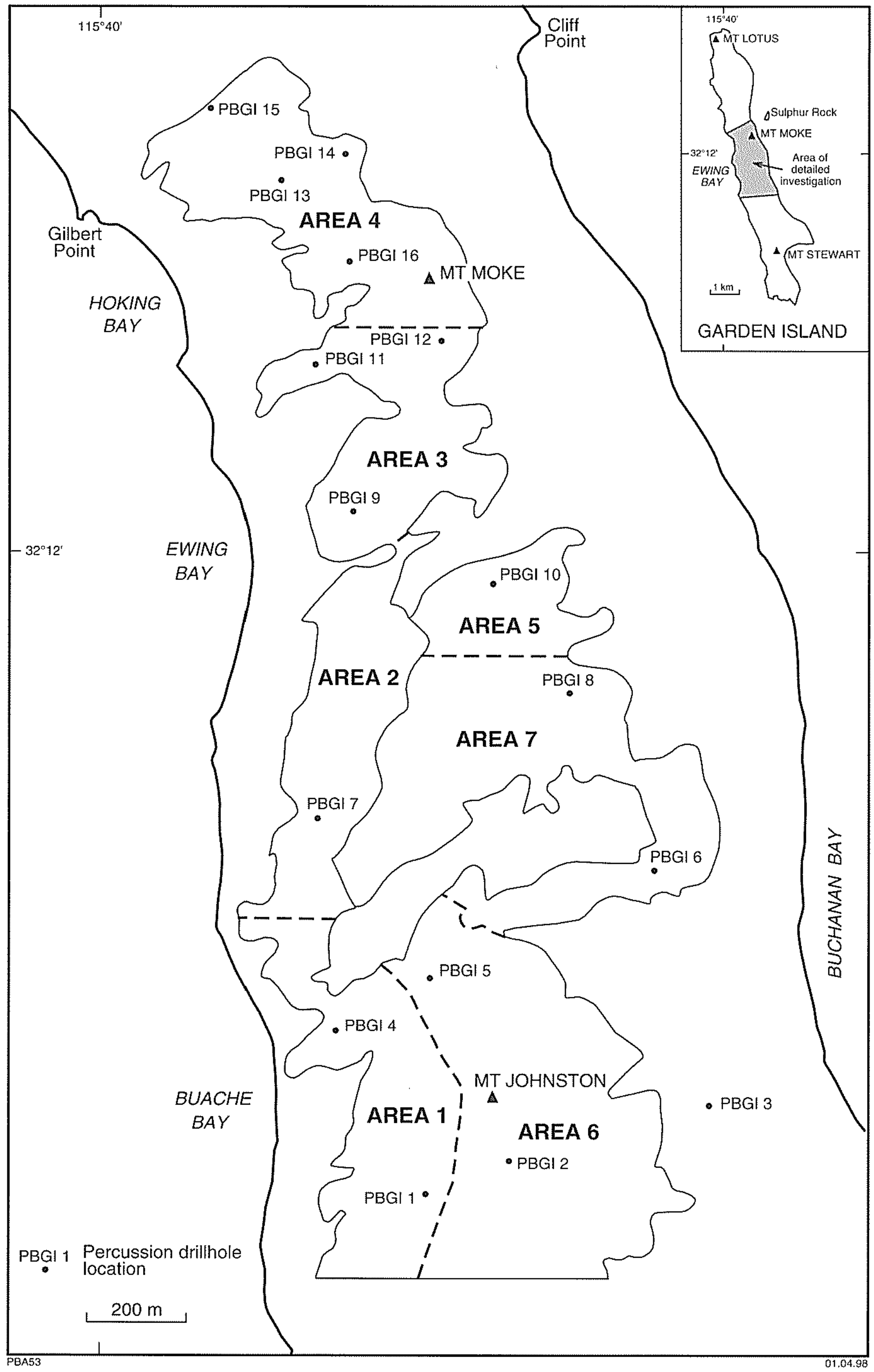


Figure 13. Drillhole locations on Garden Island (after McEwen and Whitehead, 1964)

	%
CaO	40.34 – 51.55
MgO	0.68 – 3.27
SiO_2	1.40 – 19.80
Al_2O_3	0.02 – 1.36
P	0.02 – 0.06
S	0.04 – 0.21
Na_2O	0.16 – 0.57

The average CaO content of the limesand was 49.0% and MgO was 2.7%. Drillholes PBGI 1, 4, 9, 11, 12, 13, and 16 contained an average of less than 5% SiO_2, while drillholes 9, 11, and 12 contained an average of less than 3.73% SiO_2.

In 1965, four seismic-refraction traverses (totalling 1.5 km), aimed at establishing bedrock topography, were completed within the northern portion of the limesand.

Table 20. Chemical analyses of limesand from Garden Island

Bore no.	Depth (m)	Interval (m)	SiO_2	Al_2O_3	P	S	CaO	MgO	CO_2	LOI	Na_2O	H_2O
						Percentage						
PBGI 1	00.00–07.62	7.62	3.40	0.19	0.04	0.12	48.78	2.00	40.14	42.70	0.38	0.13
	07.62–15.24	7.62	3.26	0.20	0.04	0.14	49.09	2.61	19.95	42.61	0.30	0.14
	15.24–19.81	4.57	7.78	0.40	0.04	0.15	46.92	2.55	38.05	40.80	0.35	0.20
	19.81–20.42	0.61	18.80	1.36	0.04	0.08	41.62	0.68	34.35	34.78	0.16	0.39
PBGI 2	00.00–07.62	7.62	4.75	0.26	0.05	0.07	48.27	2.61	40.51	42.41	0.38	0.16
	07.62–15.24	7.62	6.02	0.36	0.04	0.08	47.54	2.60	41.45	41.76	0.41	0.26
	15.24–22.86	7.62	4.82	0.36	0.04	0.04	48.37	2.61	39.77	42.66	0.36	0.22
	22.86–25.30	2.44	5.80	0.35	0.04	0.16	47.75	2.47	40.42	41.87	0.36	0.26
	25.30–25.91	0.61	15.40	1.30	0.04	0.12	43.21	1.19	35.27	37.53	0.30	0.43
PBGI 3	00.00–07.62	7.62	5.46	0.34	0.04	0.11	47.84	2.30	40.65	42.71	0.41	0.24
	07.62–11.58	3.96	5.46	0.38	0.04	0.20	47.52	2.74	39.96	42.46	0.49	0.26
	11.58–11.73	0.15	4.86	0.46	0.04	0.18	47.63	2.82	40.42	42.83	0.50	0.25
PBGI 4	00.00–07.62	7.62	2.76	0.10	0.04	0.17	49.44	2.83	42.08	43.26	0.40	0.10
	07.62–15.24	7.62	3.16	0.19	0.04	0.16	49.44	2.83	41.90	43.65	0.40	0.15
	15.24–22.86	7.62	4.06	0.20	0.04	0.12	48.82	3.13	41.93	43.00	0.37	0.15
	22.86–30.48	7.62	7.88	0.22	0.04	0.11	47.08	2.53	40.02	41.22	0.35	0.17
	30.48–32.00	1.52	19.80	0.10	0.04	0.14	40.34	2.91	34.90	35.51	0.23	0.15
PBGI 5	00.00–07.62	7.62	4.98	0.28	0.04	0.19	47.63	2.80	40.64	42.39	0.36	0.14
	07.62–15.24	7.62	5.12	0.32	0.04	0.16	48.25	2.59	40.70	42.21	0.41	0.24
	15.24–22.86	7.62	5.46	0.42	0.04	0.14	47.63	2.67	40.39	41.95	0.35	0.22
	22.86–30.48	7.62	5.86	0.34	0.04	0.17	47.63	2.22	40.30	41.68	0.38	0.25
	30.48–39.62	9.14	6.40	0.52	0.04	0.16	47.20	2.27	40.06	41.31	0.41	0.30
PBGI 6	00.00–07.62	7.62	6.62	0.24	0.04	0.15	47.56	2.31	40.04	41.35	0.28	0.20
	07.62–15.24	7.62	7.40	0.34	0.04	0.15	46.95	2.83	39.79	40.97	0.32	0.23
	15.24–22.25	7.01	5.80	0.27	0.04	0.14	47.05	3.06	40.07	41.13	0.31	0.20
	22.25–22.86	0.61	7.40	0.40	0.03	0.16	47.15	2.24	39.08	41.19	0.44	0.33
PBGI 7	00.00–07.62	7.62	4.10	0.24	0.04	0.15	49.00	2.60	41.40	42.90	0.37	0.16
	07.62–15.24	7.62	3.84	0.26	0.04	0.14	49.28	2.22	41.03	42.91	0.38	0.19
	15.24–22.86	7.62	4.44	0.30	0.04	0.14	47.84	2.30	40.70	42.24	0.38	0.23
	22.86–30.48	7.62	5.74	0.40	0.04	0.11	47.70	2.45	40.55	42.32	0.57	0.55
	30.48–38.10	7.62	7.54	0.23	0.04	0.11	47.25	2.69	40.05	40.86	0.31	0.18
PBGI 8	00.00–07.62	7.62	7.34	0.36	0.04	0.16	47.20	2.15	39.48	40.56	0.28	0.19
	07.62–15.24	7.62	6.20	0.26	0.03	0.16	49.35	2.05	41.02	41.36	0.30	0.21
	15.24–22.86	7.62	6.52	0.34	0.03	0.14	48.45	1.80	40.54	41.39	0.35	0.18
	22.86–30.48	7.62	6.40	0.30	0.03	0.15	47.99	2.54	39.86	41.42	0.33	0.20
PBGI 9	00.00–07.62	7.62	3.32	0.28	0.04	0.18	49.07	2.82	41.55	43.68	0.46	0.12
	7.62–15.24	7.62	3.60	0.32	0.04	0.14	49.37	2.52	41.68	43.18	0.37	0.13
	15.24–22.86	7.62	3.53	0.28	0.04	0.10	48.56	3.04	41.35	43.17	0.39	0.15
	22.86–30.48	7.62	3.72	0.26	0.04	0.11	49.58	2.30	41.73	43.06	0.39	0.15
	30.48–38.10	7.62	4.48	0.26	0.04	0.18	48.25	3.11	39.55	42.82	0.35	0.16
PBGI 10	00.00–07.62	7.62	5.60	0.40	0.04	0.10	48.02	2.67	41.00	42.45	0.45	0.25
	07.62–15.24	7.62	5.52	0.32	0.04	0.10	48.43	2.82	41.00	42.13	0.35	0.22
	15.24–22.86	7.62	6.07	0.30	0.04	0.10	48.04	2.52	40.80	42.13	0.30	0.15
	22.86–30.48	7.62	4.86	0.26	0.04	0.15	48.42	2.45	40.95	41.77	0.34	0.24
	30.48–33.53	3.05	6.20	0.36	0.04	0.14	47.22	2.37	39.68	41.33	0.32	0.26
PBGI 11	00.00–07.62	7.62	5.56	0.24	0.04	0.21	48.61	2.83	41.02	43.31	0.48	0.14
	07.62–15.24	7.62	2.80	0.24	0.04	0.17	49.23	2.76	41.37	43.57	0.40	0.15
	15.24–22.86	7.62	2.72	0.26	0.04	0.12	49.44	2.46	41.68	43.63	0.44	0.17
	22.86–30.48	7.62	3.00	0.19	0.04	0.16	49.99	2.25	41.80	43.68	0.45	0.15
	30.48–31.09	0.61	4.10	0.02	0.04	0.13	49.48	2.07	41.00	43.20	0.45	0.17
	31.09–31.39	0.30	14.60	1.22	0.05	0.15	42.47	1.33	34.28	37.25	0.40	0.43
PBGI 12	00.00–07.62	7.62	4.40	0.26	0.04	0.09	49.00	2.44	40.95	43.06	0.40	0.14
	07.62–15.24	7.62	3.20	0.26	0.04	0.11	49.48	2.74	41.70	43.30	0.40	0.14
	15.24–22.86	7.62	2.73	0.22	0.04	0.15	49.28	2.96	41.95	43.54	0.40	0.12
	22.86–30.48	7.62	2.32	0.24	0.04	0.20	49.47	2.90	42.03	43.77	0.46	0.11
	30.48–36.58	6.10	4.08	0.36	0.04	0.10	48.86	2.37	40.58	43.18	0.46	0.18
PBGI 13	00.00–07.62	7.62	4.20	0.26	0.04	0.21	48.33	3.19	41.49	42.77	0.40	0.16
	07.62–15.24	7.62	5.08	0.24	0.04	0.17	48.25	3.11	41.59	42.08	0.29	0.16
	15.24–22.86	7.62	4.70	0.30	0.04	0.17	48.04	3.27	41.46	42.32	0.31	0.18
	22.86–30.48	7.62	5.24	0.32	0.04	0.19	48.04	2.67	40.25	42.07	0.33	0.20
	30.48–30.78	0.30	5.00	0.28	0.06	0.18	48.63	2.82	40.70	42.14	0.33	0.19
PBGI 14	00.00–07.62	7.62	5.00	0.28	0.04	0.17	48.33	2.82	41.01	42.11	0.29	0.20
	07.62–15.24	7.62	6.26	0.46	0.04	0.11	47.50	2.96	40.49	41.46	0.32	0.23
	15.24–22.56	7.32	5.76	0.50	0.04	0.16	47.93	2.82	40.82	41.68	0.35	0.32
	22.56–22.86	0.30	11.09	0.48	0.03	0.13	44.33	1.85	36.34	38.59	0.39	0.40
PBGI 15	00.00–03.35	3.35	5.86	0.42	0.05	0.12	47.01	2.37	39.66	41.51	0.31	0.26
	03.35–03.96	0.61	11.64	1.12	0.04	0.09	44.12	1.63	36.58	38.84	0.26	0.39
	03.96–04.27	0.30	1.40	0.14	0.02	0.09	51.55	1.78	42.43	44.10	0.24	0.09
PBGI 16	00.00–07.62	7.62	2.78	0.32	0.04	0.15	50.31	2.52	42.07	43.59	0.39	0.15
	07.62–15.24	7.62	5.64	0.40	0.06	0.14	48.04	3.11	41.02	42.01	0.34	0.21
	15.24–22.86	7.62	5.52	0.42	0.04	0.16	48.64	2.52	41.07	41.89	0.24	0.18
	22.86–30.48	7.62	5.28	0.34	0.04	0.06	48.00	2.96	41.02	41.71	0.26	0.14
	30.48–38.10	7.62	5.28	0.44	0.04	0.13	48.33	2.82	41.50	41.93	0.27	0.15

NOTE: after McEwen and Whitehead (1964). Locations of bores are shown on Figure 13

Table 21. Limesand resources on Garden Island

Area	*Drillhole numbers*	*Mt (density 1.993 tonnes/m³)*	*Mt (density 1.435 tonnes/m³)*	*SiO_2%*
1	1, 4	4.63	3.33	<5
2	7	3.76	2.71	<5
3	9, 11, 12	3.78	2.72	<5
4	13, 14, 15, 16	4.96	3.57	5–6
5	10	1.95	1.40	5–6
6	2, 3, 5	8.23	5.93	5–6
7	6, 8	6.74	4.85	>6

NOTE: after McEwen and Whitehead (1964)

These profiles indicated that bedrock varied between 5.2 m below Australian Height Datum (AHD) to 11.3 m above AHD, with an average depth of 4.6 m above AHD.

Reserves

In order to calculate limesand reserves, seven areas were defined (Fig. 13), with an average limesand thickness of 15.2 m. Reserves were calculated using densities of 1.993 and 1.435 tonnes/m^3, since the density of unconsolidated limesand varies within this range (Table 21). The extent of the resource, based on these two densities, was 12.17 and 8.76 Mt (<5% SiO_2), 15.14 and 10.90 Mt (5–6% SiO_2) ,and 6.74 and 4.85 Mt (>6% SiO_2) respectively (McEwen and Whitehead, 1964).

Only 32% of the resource is considered to be of proven category, and falls within Area 3 defined by drillholes PBGI 9, 11, and 12. The remaining 68% is in the inferred category as the estimate is based on widely spaced holes and the grade is variable.

South Yanchep Beach

Two areas, on Leases DC 236 and DC 237 located south of Yanchep, were explored for limesand by Swan Portland Cement Limited in 1971 (Swan Portland, 1971). Of the 14 holes drilled within Lease DC 236, 10 had intersections of limesand assaying 71.4 to 79.0% total carbonate, and 2.0 to 6.1% $MgCO_3$ (Table 22). The spacing and exact drillhole locations within the lease are not available. Within Lease DC 237, 16 holes were drilled with 11 of these having intersections of limesand assaying 72.1 to 82.0% total carbonate, and 4.9 to 7.5% $MgCO_3$ (Table 22). The spacing and exact drillhole locations within this lease are also not available.

Seabird

A limesand sample (132230) collected on the coast south of Seabird assayed 75.9% $CaCO_3$ (42.5% CaO) (location 3 on Plate 1; Table 19).

Table 22. Partial chemical analyses of limesand from South Yanchep Beach

Hole no.	*Intersection (m)*	*Thickness (m)*	*Total carbonate (%)*	*$MgCO_3$ (%)*	*$CaCO_3$ (%)*
Lease DC 236					
C. 0	0.8 – 16.0	15.2	74.1	4.7	69.4
C. 6	0.0 – 15.2	15.2	71.4	5.1	66.3
C. 18	0.8 – 16.0	15.2	76.4	2.0	74.4
C. 24A	0.0 – 27.4	27.4	75.5	4.9	70.6
C. 30	4.6 – 17.5	13.0	78.4	4.9	73.5
B. 51	0.0 – 12.2	12.2	77.6	5.9	71.7
B. 54	0.8 – 8.4	6.1	79.0	5.9	73.1
B. 60	0.8 – 19.8	19.1	76.9	5.4	71.5
B. 66	0.8 – 10.7	9.1	76.3	5.9	70.4
B. 72	0.0 – 18.3	18.3	76.0	6.1	69.9
Lease DC 237					
B. 0	2.3 – 16.0	13.7	72.1	–	66.1
A. 6	0.0 – 7.6	7.6	78.2	6.4	71.8
A. 6	7.6 – 12.2	4.6	82.0	7.5	74.5
B. 6	0.8 – 13.7	13.0	72.9	6.3	66.6
B. 12	0.0 – 14.5	14.5	75.6	5.6	70.0
A. 18	0.0 – 7.6	7.6	73.8	5.8	68.0
B. 18	0.0 – 19.8	19.8	74.9	6.8	68.1
B. 30	0.0 – 5.3	5.3	74.7	4.9	69.8
A. 36	0.0 – 15.2	15.2	78.1	5.3	72.8
B. 36	0.0 – 7.6	7.6	72.1	–	66.1
A. 42	0.8 – 10.0	9.1	76.0	–	70.0
B. 48	0.0 – 7.6	7.6	76.9	–	70.9

SOURCE: after Swan Portland (1971)

Marl occurrences in the Perth Metropolitan Region

Numerous marl deposits occur in lakes and swamps within the metropolitan region of Perth (Fig. 9). A few of the more notable occurrences are described in the following section.

Bullsbrook–Muchea

The many small, surficial marl deposits that occur on the coastal plain around Bullsbrook and Muchea (Simpson, 1948) may have developed from Muchea Limestone. While the surface of the exposures generally consists of a hardened duricrust layer, the material below can be crumbled by hand. The marl is granular, cream to greyish in colour and occurs as beds with an approximate thickness of 1.5 to 3.5 m, often containing pockets of loose sand. In the past, there has been production of good-quality lime from some of these occurrences. The CaO content of eight samples varied from 36.01 to 53.11%, and SiO_2 from 3.38 to 26.18% (Simpson, 1948).

Cannington

Simpson (1948) noted that several small banks of marl occur in the Cannington area. A sample from Lacey Street that contained 52.0% CaO (92.9% $CaCO_3$) may be developed from the Muchea Limestone that is exposed in the area.

Herdsman Lake

A major part of the bed of Herdsman Lake, now drained, contains a marl bed 0.5 to 2 m thick (Simpson, 1948). Although the material is highly charged with water, areas holding 60 to 70% water are still firm enough to walk over. A sample of dried marl contained 50% $CaCO_3$ (28.0% CaO), 30% SiO_2, and 20% organic matter. Another sample, thought to represent high-grade carbonate lake material, contained 59.8% $CaCO_3$ (33.5% CaO) (Simpson, 1948).

Jandakot

A marl sample from Jandakot townsite contained 24.7% CaO (44.1% $CaCO_3$), 3.0% Al_2O_3, 2.0% Fe_2O_3, and 36.2% insolubles (Simpson, 1948). A firm, greyish-white marl, just south of Jandakot, contained 92.2% $CaCO_3$ (51.6% CaO).

Lake Cooloongup and Lake Walyungup

Marl occurs in a number of lacustrine environments such as at Lake Cooloongup (White Lake) and Lake Walyungup (Salt Lake). One sample from east of Lake Cooloongup contained 87% $CaCO_3$ (48.7% CaO) (Plate 2), and five samples from Lake Walyungup had $CaCO_3$ contents varying from 68 to 98% (38.1 to 54.9% CaO) (Gozzard, 1987c).

Simpson (1948) gave analyses of six samples collected from the bed and at the edge of Lake Walyungup. These contained CaO varying from 24.2 to 35.2% (43.2 to 62.9% $CaCO_3$) and MgO from 1.3 to 36.4%. Another sample of white 'crusty' marl at the southern end of this lake contained 46.2% CaO (82.5% $CaCO_3$), 2.8% MgO, 2.5% Al_2O_3 plus Fe_2O_3, and 3.2% insolubles. A sample from between the two lakes assayed 76.5% $CaCO_3$. A surface sample from a large area of marl at the southern end of Lake Cooloongup assayed 96.4% $CaCO_3$.

The marl at Lake Walyungup has been used as roadbase material (Wilde and Low, 1980).

North Dandalup

Two samples of marl from an exposure near North Dandalup were found to contain 46.8 and 50.0% CaO (83.6 and 89.3% $CaCO_3$), and 10.3 and 4.0% insolubles respectively.

Rottnest Island

A sample from a bed of marl, between limesand and Tamala Limestone in Bickley Swamp, contained 45.7% CaO (81.6% $CaCO_3$), 6.09% MgO, 1.07% SiO_2, and 0.51% Fe_2O_3 plus Al_2O_3 (Simpson, 1948).

Deposits south of the Perth Metropolitan Region

Many localities between Mandurah and Augusta contain large deposits of moderate- to high-quality limestone or limesand. Below is a summary of the information that is available on the quality and quantity of material from some of these localities.

Boranup

The Boranup limesand deposit was briefly investigated by Blatchford in 1931 as part of an investigation of coastal limesand deposits (Blatchford, 1932). This limesand deposit is situated close to Hamelin Bay, approximately 15 km northwest of Augusta. Almost the entire deposit is contained within Reserve 26493 that was created in 1962. In 1970, Reserve 30656 was created for limesand and vested in the Shire of Augusta–Margaret River. These two reserves and other areas in the vicinity were recommended by the Environmental Protection Authority (EPA) to be included in a national park. Subsequent developments resulted in the cancellation of Reserve 26493 in 1985 and the release of the northwest portion of this reserve to create the A Class Reserve 35036 (Leeuwin–Naturaliste National Park) (Fig. 14).

Due to these developments, a range of mineral claims and prospecting licence applications in the area, by a number of companies, were refused.

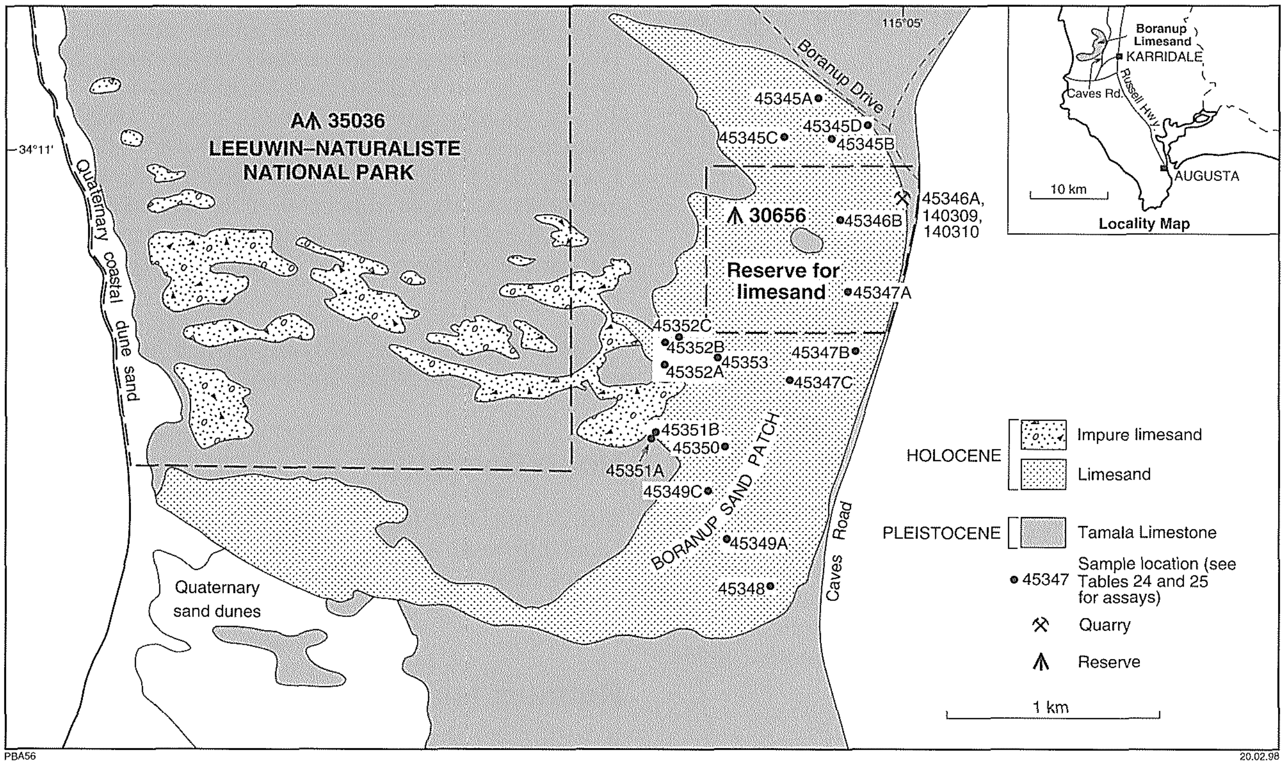


Figure 14. Distribution of limestone and limesand in the Boranup Sand Patch area (after Denman, 1977)

Exploration

Preliminary investigations by Blatchford in 1931 revealed that the limesand at Boranup forms a huge dune several kilometres in length and width, with a depth of 60 m in several places. Samples collected by Blatchford (1932) had an average analysis of 85.2% total carbonate.

The initial quantitative assessment of this deposit was carried out by Denman (1977), in response to a recommendation by the EPA that Mineral Reserve 26493 be incorporated into the Leeuwin–Naturaliste National Park.

The main objectives of the program initiated by Denman (1977) were to:

1. Produce a geological map of the Boranup limesand deposit and mineral reserve;
2. Estimate the limesand resource of the deposit;
3. Assess the overall quality and delineate any lower grade areas.

About 50% of the deposit was inspected in the field and the remainder mapped using aerial photographs (1:15 480 and 1:40 000). Since topographic maps of the area were not available, a sketch map was produced using an aneroid barometer on closed traverses from base stations. The elevation of the deposit was found to vary from 40 to 180 m above AHD, with surface contours being visually estimated by stereoscopic means. The accuracy of volumes and tonnages is considered to be within 30% of the true figure.

Geology

Approximately 90% of the limesand is located on the western side of Caves Road, with the remainder in the southern end of Reserve A 35036 (Fig. 14). A veneer of lower quality limesand occurs, as a series of dunes, between the main deposit in the east and the coast. Pleistocene Tamala Limestone outcrops along the coast and also inland east of the coastal beach and dune sand.

Large-scale cross-bedding can be seen in the quarry and along the western flank of the main deposit. The lower 10–20 m of the deposit, as seen in the western flank, appears to be poorly cemented along bedding planes, and the lower part of the unit commonly contains root-stem casts of lithified carbonate sand.

Reserves

Volume estimates for the main deposit are given in Table 23. On a dry basis (assuming a density of 1.542 tonnes/m^3), the total tonnage of the deposit is 108 Mt. On the same basis, the southwestern deposit (southern part of Reserve A 35036) is estimated to contain 13 Mt. Volume estimates for this deposit are also given in Table 23.

Table 23. Volume estimates for the Boranup limesand deposit

Isopach range (m)	*Area (m^2)*	*Assumed thickness (m)*	*Volume (m^3)*
Main deposit			
0–50	958 306	7.6	7 283 125
50–100	1 115 326	23	25 652 489
100–150	641 029	37	23 718 071
150+	268 858	51	13 456 752
		Total	**70 110 437**
Southwestern deposit			
0–50	357 746	7.6	2 718 869
50–100	160 257	23	3 685 916
100+	48 563	37	1 796 824
		Total	**8 201 609**

The maximum error involved in these estimates was considered to be plus or minus 30%, and is mainly due to the lack of topographic data for the base of the deposit. Another source of error, probably minor, is the uncertainty of the geology in the thickly vegetated northwestern and the southwestern parts of the deposit.

Quality

Partial chemical analyses of 19 limesand samples (Table 24) collected by Denman (1977) from the main deposit contained an average of 78.8% $CaCO_3$ (44.1% CaO), 6.3% $MgCO_3$, and 12.5% insolubles. Two samples of limesand (140309–10) collected from the Boranup Sand Patch quarry by the author contained an average of 79.6% $CaCO_3$ (42.9% CaO) and 6.1% $MgCO_3$ (2.9% MgO) (Table 25; Fig. 14).

Table 24. Partial chemical analyses of Boranup limesand

Sample no.	*H_2O^-*	*$CaCO_3$*	*$MgCO_3$*	*Acid insolubles*	*LOI[a]*
			Percentage		
45346 A	0.36	77.1	6.34	13.1	38.7
45346 B	0.30	83.7	6.55	8.82	40.6
45345 A	0.26	79.1	6.53	11.8	39.3
45345 B	0.26	78.5	6.04	14.2	38.2
45345 C	0.27	77.5	6.13	13.3	38.6
45345 D	0.25	80.5	6.40	10.3	40.0
45347 A	0.25	82.6	6.67	8.38	41.0
45347 B	0.23	83.2	7.24	7.36	41.6
45347 C	0.24	84.9	6.61	8.12	41.2
45348	0.23	80.3	6.94	9.40	40.6
45349 A	0.27	78.0	5.56	13.3	38.7
45349 C	0.23	76.9	6.19	13.7	38.5
45350	0.20	85.1	7.63	4.27	42.9
45351 A	0.20	45.3	4.04	46.7	23.4
45351 B	0.24	75.8	5.92	16.1	37.3
45352 A	0.25	80.5	5.84	12.1	39.2
45352 B	0.23	72.3	5.71	19.6	35.6
45352 C	0.36	89.9	6.82	2.45	43.7
45353	0.37	86.4	7.24	4.62	42.6
Average	**0.26**	**78.82**	**6.34**	**12.51**	**39.04**

NOTE: after Denman (1977)
(a) LOI loss on ignition

Table 25. Chemical analyses of limestone and limesand from the Boranup area

Sample no.	*140309*	*140310*	*140311*
		Percentage	
SiO_2	14.54	11.80	2.01
TiO_2	0.05	0.03	0.01
Al_2O_3	1.23	1.15	0.12
Fe_2O_3	0.20	0.15	<0.01
MnO	0.01	0.01	<0.01
MgO	2.80	2.99	0.41
CaO	42.05	43.75	54.46
Na_2O	0.46	0.43	0.04
K_2O	0.57	0.50	0.09
P_2O_5	0.10	0.10	0.07
LOI	36.92	38.46	42.36
Total	**98.93**	**99.37**	**99.57**
CO_2	33.70	34.80	40.40

NOTE: 140309 Quarry at Boranup Sand Patch (western wall), Lat. 34°11'18"S, Long. 115°04'38"E, limesand
140310 Quarry at Boranup Sand Patch (western wall), Lat. 34°11'18"S, Long. 115°04'38"E, limesand
140311 Boranup Drive, within national park, Lat. 34°06'38"S, Long. 115°03'02"E, Tamala Limestone
The locations of samples 140309 and 140310 are shown on Figure 14

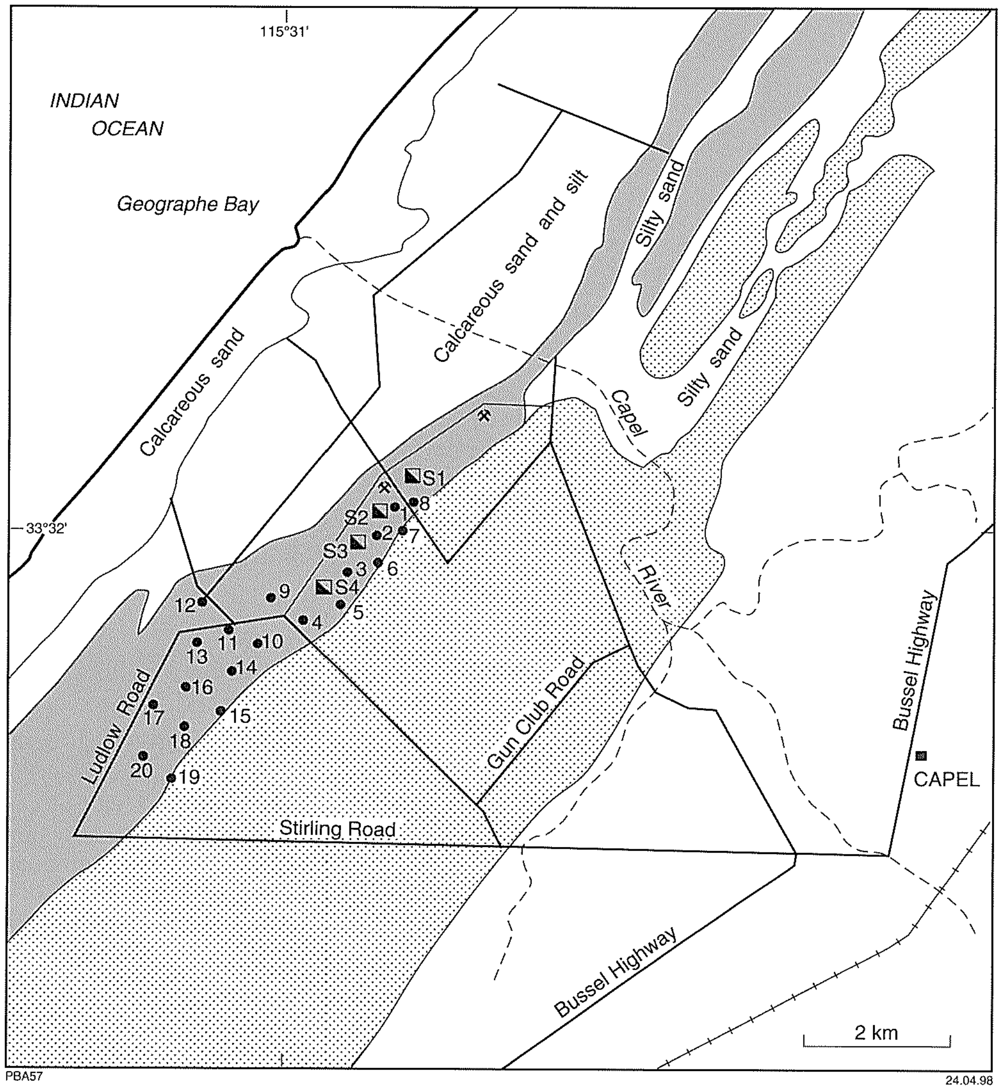
One surface sample (140311) of compact massive limestone collected from Boranup Drive (Lat. 34°06'38"S, Long. 115°03'02"E) assayed 97.3% $CaCO_3$ (CaO 54.5%) (Table 25) and is one of the best quality limestones found in the South West region. Such high-quality limestone appears to be widespread in the area, but is mostly confined to the Leeuwin–Naturaliste National Park.

Capel

In the past, limestone from a large deposit of fossiliferous limestone, approximately 5 km west of Capel, has been burnt to produce lime (Simpson, 1948).

In 1950, an investigation for limestone within an 80 km radius of Bunbury, found that a locality approximately 8 km northwest of Capel (Fig. 15) was the only area worthy of detailed examination (Johnson, 1953). In this locality, the extent of limestone exposure was greater at the northern end than the southern, and the thickness of soil cover was less than a metre (Lord, 1953a). The deposit was initially considered to be a fossil reef by Johnson (1953), but later work suggested that it is sandy limestone (Lord, 1953a). The average $CaCO_3$ and SiO_2 contents of 13 samples collected from four pits, ranging in depth from less than a metre to about 2.2 m, were 85.7 and 7.7% respectively.

The deposit was further investigated in 1951 (Lord, 1953b) following a request by the Department of Industrial Development to assess the suitability of this limestone for cement manufacture. During this program, 4 test shafts and 20 boreholes, varying in depth from 2.5 to 4.0 m, were completed (Fig. 15).



HOLOCENE		Mainly sand derived from limestone
PLEISTOCENE		White to cream, fine-grained limestone
	• 20	Location of borehole
	S4	Location of shaft
		Limestone quarry
		Geological boundary
		Railway
		Road
		River

Figure 15. Locations of exploration boreholes and shafts northwest of Capel (after Lord, 1953b)

Table 26. Partial chemical analyses of limestone from northwest of Capel

Location	$CaCO_3$	SiO_2	$MgCO_3$	Al_2O_3	Fe_2O_3
			Percentage		
Shaft 1	80.96	12.55	2.48	1.01	0.46
Shaft 2	72.55	20.49	1.74	1.58	0.95
Shaft 4	76.42	17.55	1.98	2.18	0.95
Bore 1	77.06	15.75	2.60	1.16	0.52
Bore 2	80.05	9.04	2.66	0.77	0.74
Bore 3	75.86	12.51	3.35	0.98	0.69
Bore 4	72.39	21.27	2.24	1.49	0.63
Bore 5	81.66	13.67	0.79	1.10	0.52
Bore 7	71.03	21.89	1.02	1.95	0.66
Bore 8	70.04	22.34	2.31	1.68	0.42
Bore 10	74.64	18.54	–	–	–
Bore 11	56.61	36.85	–	–	–
Bore 12	59.76	31.77	–	–	–
Bore 13	74.57	19.60	1.55	1.19	0.86
Bore 15	76.50	17.25	1.30	3.26	1.02
Bore 17	70.91	24.33	0.54	1.47	1.10
Bore 18	69.68	25.23	0.86	3.12	0.76
Bore 20	62.56	31.88	0.65	3.24	0.96
Average	**72.40**	**20.70**	**1.45**	**1.45**	**0.62**

NOTE: after Lord (1953b)

Within the area tested, the limestone had an average composition of 72.4% $CaCO_3$ (40.5% CaO) and 1.5% $MgCO_3$ (Table 26), and was considered to be unsuitable for use as a raw material for cement manufacture.

Cape Naturaliste – Cape Leeuwin

Johnson (1953) found that eolian limestone, mostly containing 14 to 30% SiO_2, occurs on the western side of the ridge from Cape Naturaliste to Cape Leeuwin (Fig. 8). This sandy limestone is about 150 m thick and has a capping of pure limestone of variable thickness, rarely exceeding 0.6 m. The limestone occurs above Precambrian rocks to a height of about 230 m AHD (Johnson, 1953; Lowry, 1967). Simpson (1948) noted that Cape Naturaliste consists of limestone at a height of about 110 m AHD rising to about 210 m AHD at the trigonometric station. There are rapidly encroaching sand dunes on the southwestern side of the limestone.

The hills around Yallingup are composed of hard cavernous limestone. At the mouth of Quininup Brook, located about 11 km south of Yallingup, there are extensive dunes of sand containing varying amounts of quartz and foraminifers (Simpson, 1948; Blatchford, 1932). Blatchford (1932) noted that the deposit on the southern edge of the high ground, north of the brook, does not contain a large tonnage of limesand. However, a deposit about a kilometre southwest contained a much larger quantity, although a single grab sample containing 70.7% $CaCO_3$ (39.6% CaO and total carbonates of 78.2%) suggests that the quality of the deposit needs further assessment. Six samples of limesand from both locations had an average of 76.5% $CaCO_3$ (42.8% CaO), 6.0% $MgCO_3$, and 0.2% P_2O_5.

In 1923, limestone caprock from Margaret River was partially analysed to determine its suitability for agricultural uses (Simpson, 1948). The samples contained an average of 89.5% $CaCO_3$, 2.0 % $MgCO_3$, 5.9% SiO_2, and 0.5% Fe_2O_3 plus Al_2O_3. Lowry (1967) concluded that this limestone deposit is unlikely to be of commercial value because of variations in thickness and grade.

Kingswood Park – Crawlea Estate

In 1975, La Porte Australia Ltd carried out an exploration program for limestone of neutralizing quality (minimum 60% $CaCO_3$ equivalent) in an area approximately 2–4 km south of Lake Preston, where limestone occurs in a linear belt, extending from north of Myalup Beach Road to south of Binningup Road (Fig. 16). The width of the belt between Binningup and Myalup Beach Roads varies from about 400 to 1500 m.

Exploration was confined to Kingswood Park (57 holes, 339 m) and Crawlea Estate (24 holes, 169 m) (Layton and Associates, 1975). Thirty-five drillholes were also sunk in a pastoral property close to the coast, but landowners objected to exploitation of the limestone.

A total resource of over 2 Mt of approximately 70% $CaCO_3$ was estimated in the following:

(a) Kingswood Park — 1.08 Mt containing 69% $CaCO_3$, including 0.67 Mt containing 75% $CaCO_3$ and 1.8% $MgCO_3$;

(b) Crawlea Estate — 1.06 Mt of 65% $CaCO_3$ and 1.0% $MgCO_3$;

(c) Coastal pastoral property — contained a narrow zone of limestone assaying 64–78% $CaCO_3$ that

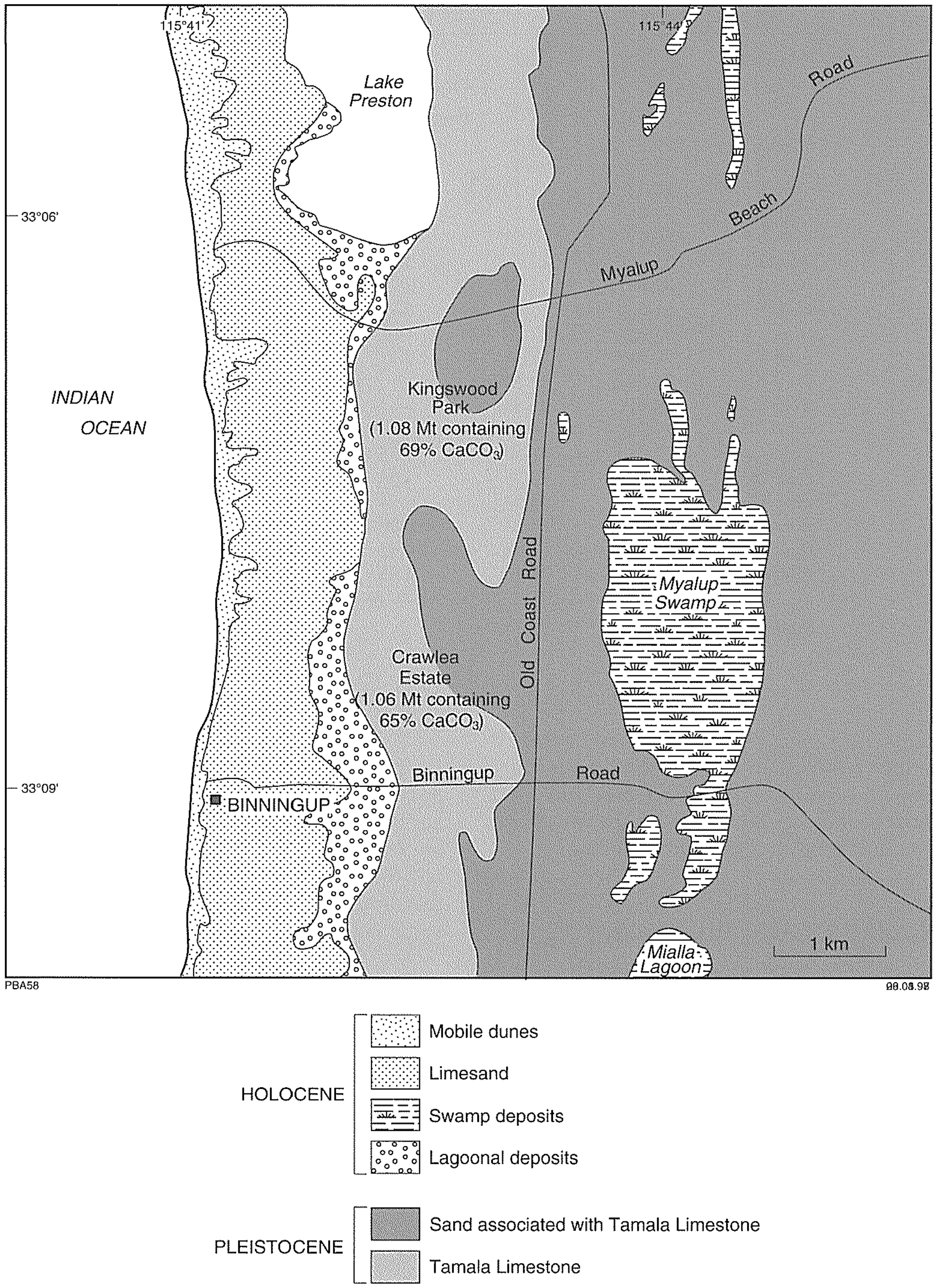


Figure 16. Distribution of Tamala Limestone and limesand in Kingswood Park and Crawlea Estate (geology after Biggs, 1982)

varied in thickness from 2–4 m and had a resource of 0.12–0.15 Mt.

Mandurah to Lake Preston

The distribution of limestone and limesand, with assays of samples collected from a number of locations along the coastal stretch from north of Mandurah to south of Lake Preston, is given on Figure 17. The $CaCO_3$ content of the samples was found to range from 68.0 to 82.3% (38.1 to 46.1% CaO) (Table 27).

An area located in Yalgorup National Park, east of Lake Preston (Fig. 17), was explored for limestone by Lord & Associates Pty Ltd (1983) for Swinford (W.A.) Pty Ltd. Approximately 70% of the area consisted of outcrops of Pleistocene Tamala Limestone with a thin, locally developed soil cover.

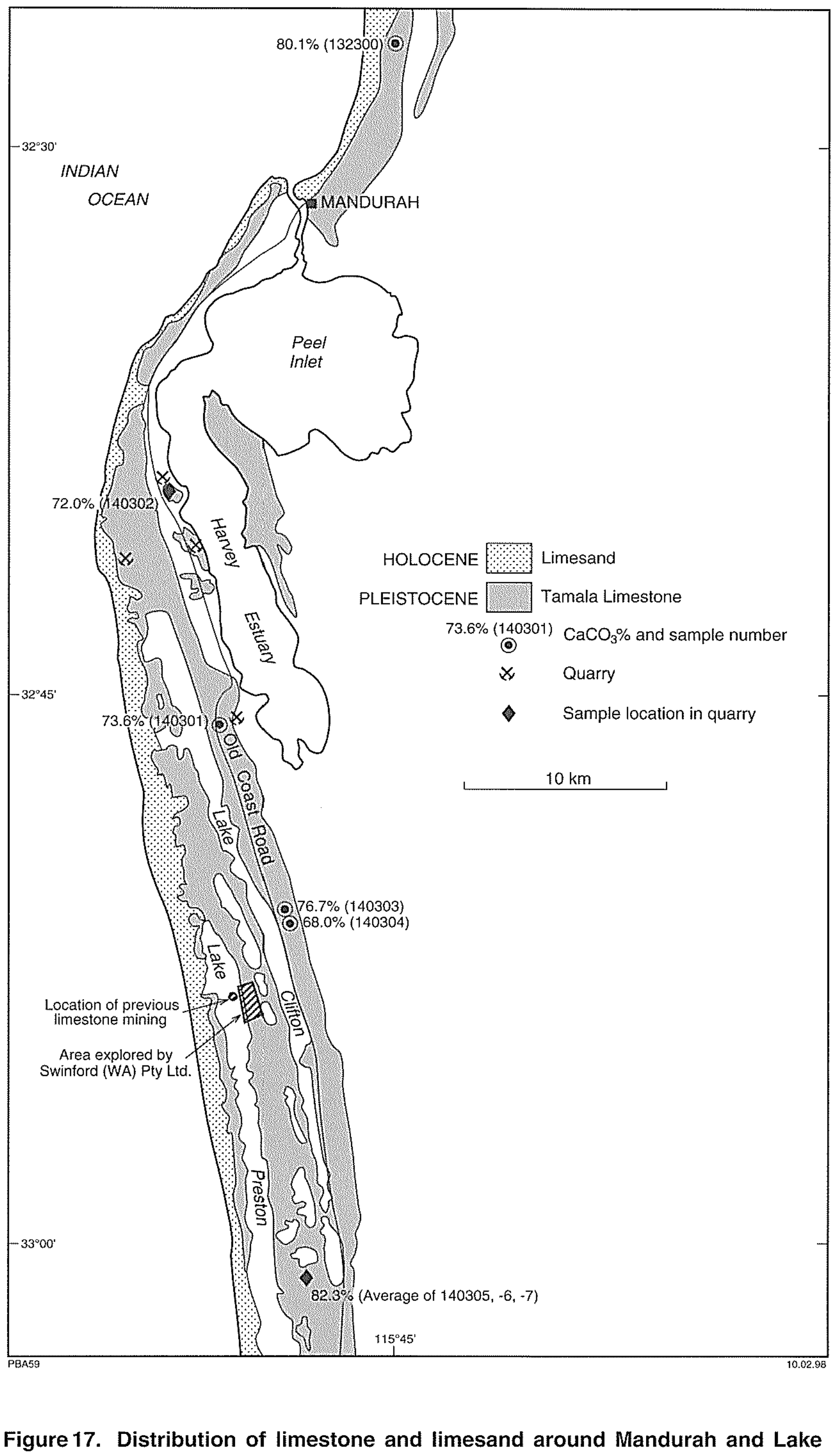


Figure 17. Distribution of limestone and limesand around Mandurah and Lake Preston, with assays of some surface samples (geology after Low et al., 1980)

The area was initially investigated by surface sampling (59 samples), followed by the drilling of 21 holes. Surface sampling identified areas containing in excess of 83% $CaCO_3$ (46.5% CaO) (21 samples), 76–83% $CaCO_3$ (42.6–46.5% CaO) (27 samples), and 62–76% $CaCO_3$ (34.7–42.3% CaO). The drilling indicated that samples below 6 m in depth generally contained 70% $CaCO_3$ (39.2% CaO) or less, and usually the high-grade (>85% $CaCO_3$) limestone was restricted to caprock that was less than 2 m thick.

It was concluded that further drilling could locate zones having 76–78% $CaCO_3$ (42.6–43.7% CaO) to an average depth of 5 to 7 m. However, since the mineral claims are in a national park, restrictions could be imposed on future development activities.

Table 27. Chemical analyses of limestone and limesand from Mandurah to Lake Preston

Sample no.	*132300*	*140301*	*140302*	*140303*	*140304*	*140305*	*140306*	*140307*
				Percentage				
SiO_2	14.56	19.46	24.03	17.83	24.69	12.28	14.59	7.16
TiO_2	0.10	0.22	0.11	0.14	0.22	0.05	0.06	0.03
Al_2O_3	0.90	1.50	1.30	1.15	1.70	0.85	0.75	0.45
Fe_2O_3	0.28	0.42	0.40	0.21	0.49	0.33	0.36	0.12
MnO	<0.01	0.01	<0.01	<0.01	0.01	<0.01	<0.01	<0.01
MgO	0.53	0.70	0.56	0.57	0.60	2.09	1.87	1.13
CaO	44.88	41.24	40.29	42.93	38.09	45.48	43.53	49.21
Na_2O	0.12	0.17	0.13	0.13	0.15	0.29	0.26	0.12
K_2O	0.45	0.76	0.79	0.79	1.05	0.54	0.52	0.28
P_2O_5	0.06	0.03	0.06	0.03	0.03	0.09	0.08	0.06
LOI	37.42	34.27	32.79	35.46	33.05	38.75	37.22	41.42
Total	**99.30**	**98.78**	**100.46**	**99.24**	**100.08**	**100.75**	**99.24**	**99.98**
CO_2	36.20	32.60	30.70	33.80	31.30	34.80	34.40	37.50
				Parts per million				
As	–	–	5.3	–	–	3	–	4.1
Ba	–	–	193	–	–	138	–	81
Be	–	–	<0.2	–	–	0.4	–	<0.2
Ce	–	–	8.6	–	–	4.3	–	1.99
Cr	–	–	58	–	–	37	–	17
Ga	–	–	6.3	–	–	3.7	–	2.8
La	–	–	15	–	–	4.7	–	2.4
Nb	–	–	4.4	–	–	1.4	–	0.8
Rb	–	–	18	–	–	12	–	8
S	–	–	<0.01	–	–	<0.01	–	<0.01
Sn	–	–	1.3	–	–	0.4	–	0.4
Sr	–	–	460	–	–	1 744	–	1 211
Th	–	–	3	–	–	1.03	–	0.47
U	–	–	0.68	–	–	0.88	–	0.5
V	–	–	<2	–	–	<2	–	<2
W	–	–	0.2	–	–	<0.1	–	<0.1

NOTE:
132300 Madora, on the way to farm, Lat. 32°28'12"S, Long. 115°45'37"E, Tamala Limestone
140301 Lake Clifton, close to W.A. Limestone quarry, Lat. 32°46'11"S, Long. 115°40'02"E, Tamala Limestone
140302 Lake Clifton, Dawesville pit, Lat. 32°39'23"S, Long. 115°38'32"E, Tamala Limestone
140303 Lake Clifton, Nightingale Road, Lat. 32°51'05"S, Long. 115°42'04"E, Tamala Limestone
140304 Lake Clifton, along Old Coast Road, Lat. 32°51'19"S, Long. 115°42'16"E, Tamala Limestone
140305 Quarry of Lance Lime Company, Lake Preston, Lat. 33°01'21"S, Long.115°42'16"E, Tamala Limestone
140306 Quarry of Lance Lime Company, Lake Preston, Lat. 33°01'21"S, Long.115°42'16"E, Tamala Limestone
140307 Quarry of Lance Lime Company, Lake Preston, Lat. 33°01'21"S, Long.115°42'16"E, Tamala Limestone

During the period 1969 to 1978, 1017 t of limestone was mined from a location a few hundred metres west of the above area.

Pinjarra

A minor deposit of soft limestone (?Muchea Limestone) is exposed over approximately 25 hectares on a local property. The property is located approximately 1.5 km north-northwest of Pinjarra on the eastern side of the railway line (Woodward, 1912; Simpson, 1948). Some of the caprock to the limestone has been quarried for building blocks and lime burning. Boreholes at this location indicate that the limestone is approximately 0.5 to 2.5 m thick, with an overburden of a few centimetres to about 1.5 m. Analyses of three caprock samples indicated 82, 94, and 96% $CaCO_3$ (45.9, 52.6, and 53.8% CaO), while two underlying samples of marl contained 51.5 and 88% $CaCO_3$ (28.8 and 49.3% CaO), suggesting that the caprock is generally of higher grade than the underlying marl.

Busselton

Blatchford (1932) noted that a considerable amount of limesand occurs in the vicinity of Busselton Cemetery, and at the terminus of the railway yards. The average $CaCO_3$ content of ten samples collected was 66.1% (total carbonate 71.4%) and that of $MgCO_3$ was 6%. Partial analysis of a sample of fossiliferous limestone from the landward side of the town indicated 88.3% $CaCO_3$ and 2.9% $MgCO_3$ (Simpson, 1948)

Deposits north of the Perth Metropolitan Region

Ledge Point–Lancelin–Wedge Island

The coastal area extending from Ledge Point through Lancelin and up to Wedge Island is covered with large deposits of limesand. The $CaCO_3$ content of seven widely spaced surface samples of limestone and limesand,

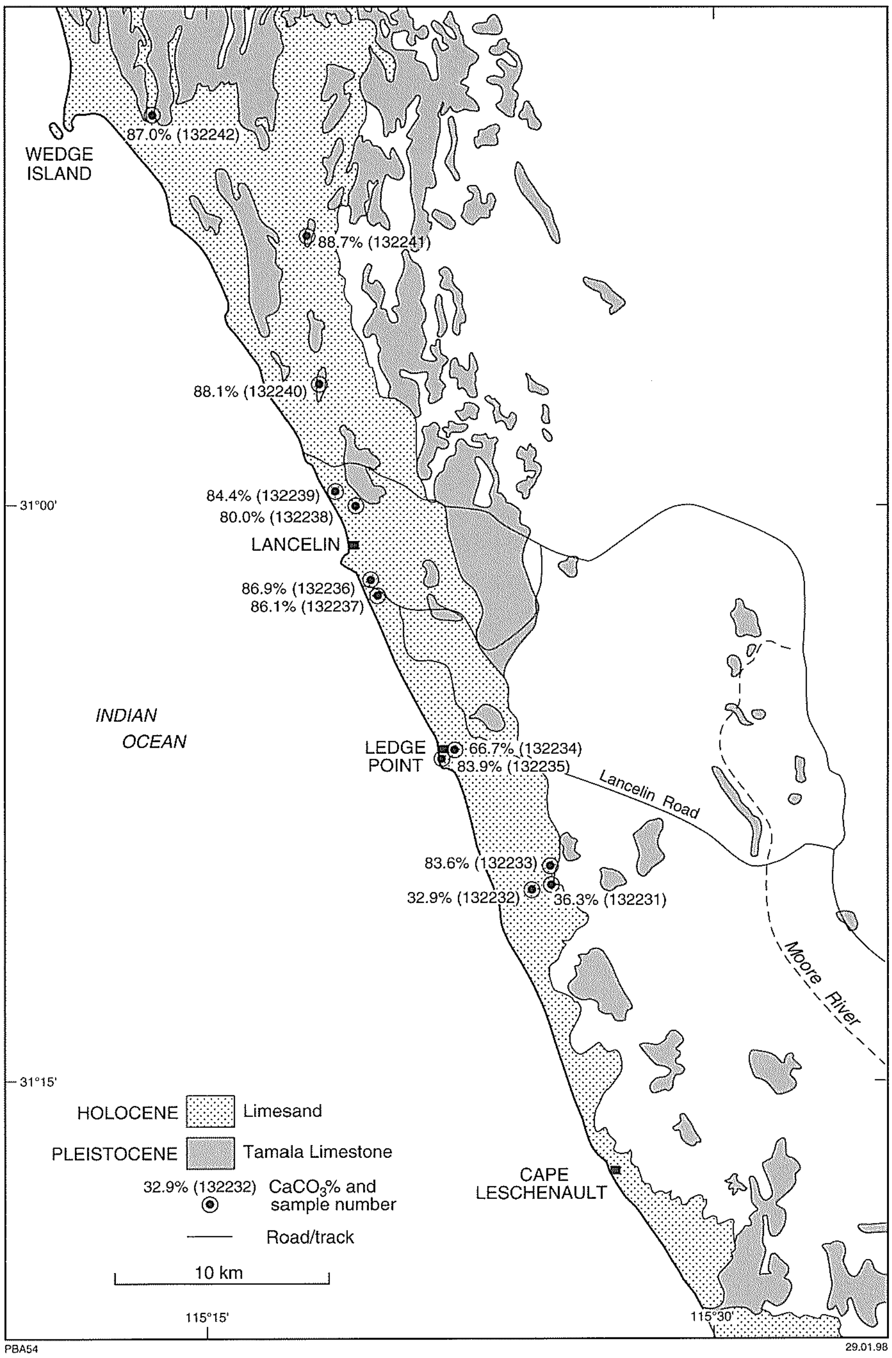


Figure 18. Distribution of limestone and limesand around Lancelin, with assays of some surface samples (geology after Low et al., 1978; Lowry et al., 1973)

collected by the author between Wedge Island and north of Ledge Point, assayed between 80.0 and 88.7% $CaCO_3$ (44.8 and 49.7% CaO) (Fig 18; Table 28), suggesting the presence of several hundred million tonnes of relatively high-grade limestone or limesand within a coastal strip more than 30 km in length. Westdeen Holdings Pty Ltd has proved a resource of 70 Mt of limesand at a location 1 km east of Lancelin.

A limesand resource of approximately 30 Mt, containing greater than 80% acid-soluble carbonates (including greater than 2% $MgCO_3$), was estimated by Baxter (1979) after a brief inspection of the area around Ledge Point. He suggested that the limesand and limestone occurrences could be 100 m thick along the coast. However, the quality quoted above is based on only a few samples, and a more detailed investigation would be necessary to confirm these estimates. Assays of four surface samples of limestone or limesand, collected by the author between Ledge Point and a few kilometres to the south, gave $CaCO_3$ values ranging from 32.9 to 83.9% (18.4 to 47.0% CaO).

Table 28. Chemical analyses of limestone and limesand on the coastal belt from Ledge Point through Lancelin to Wedge Island

Sample no.	*132231*	*132232*	*132233*	*132234*	*132235*	*132236*	*132237*	*132238*	*132239*	*132240*	*132241*	*132242*
							Percentage					
SiO_2	58.75	62.95	12.24	23.39	5.77	1.79	2.48	9.57	4.56	7.09	4.48	1.84
TiO_2	0.06	0.06	0.08	0.01	0.02	0.00	0.01	0.02	0.00	0.02	0.02	0.01
Al_2O_3	0.46	0.43	0.71	0.41	0.28	0.11	0.14	0.23	0.19	0.29	0.30	0.10
Fe_2O_3	0.08	0.04	0.10	<0.01	0.05	0.09	0.07	<0.01	0.07	0.02	<0.01	0.07
MnO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
MgO	1.17	1.06	0.47	2.69	3.01	3.23	3.22	3.01	2.98	0.69	0.88	3.40
CaO	20.35	18.35	46.82	37.37	46.96	48.64	48.20	44.78	47.26	49.34	49.72	48.72
Na_2O	0.19	0.21	0.18	0.37	0.59	0.54	0.71	0.33	0.59	0.21	0.49	0.61
K_2O	0.30	0.32	0.41	0.36	0.27	0.17	0.23	0.14	0.17	0.23	0.18	0.20
P_2O_5	0.07	0.06	0.05	0.12	0.12	0.11	0.12	0.12	0.11	0.07	0.06	0.13
LOI	18.11	15.90	36.94	33.72	42.11	44.13	43.71	40.08	42.67	41.06	42.97	44.01
Total	**99.54**	**99.38**	**98.00**	**98.44**	**99.18**	**98.81**	**98.89**	**98.28**	**98.60**	**99.02**	**99.10**	**99.09**
CO_2	16.90	14.70	37.50	31.90	40.30	42.00	41.10	37.70	40.30	40.00	42.40	42.70
							Parts per million					
Ba	59	57	96	67	46	25	31	42	33	42	44	25
Be	<0.2	0.8	0.5	1	1.1	0.9	1.6	1.4	<0.2	0.7	0.6	1.5

NOTE:
132231 East of Ledge Point, Lat. 31°10'39"S, Long. 115°25'56"E, limesand
132232 East of Ledge Point, Lat. 31°11'06"S, Long. 115°25'46"E, limesand
132233 East of Ledge Point, Lat. 31°09'03"S, Long. 115°25'36"E, Tamala Limestone
132234 Ledge Point, Lat. 31°06'36"S, Long. 115°23'39"E, limesand
132235 Ledge Point, Lat. 31°06'49"S, Long. 115°22'21"E, limesand
132236 Southern end of Lancelin, Lat. 31°02'03"S, Long. 115°20'06"E, limesand
132237 South of Lancelin, Lat. 31°02'07"S, Long. 115°20'11"E, limesand
132238 Northeast of Lancelin, Lat. 30°59'47"S, Long. 115°19'26"E, limesand
132239 North of Lancelin, Lat. 30°59'21"S, Long. 115°19'15"E, limesand
132240 North of Lancelin, Lat. 30°56'10"S, Long. 115°18'39"E, Tamala Limestone
132241 Between Lancelin and Wedge Point, Lat. 30°52'35"S, Long. 115°18'28"E, Tamala Limestone
132242 Wedge Point, Lat. 30°49'27"S, Long. 115°13'22"E, limesand

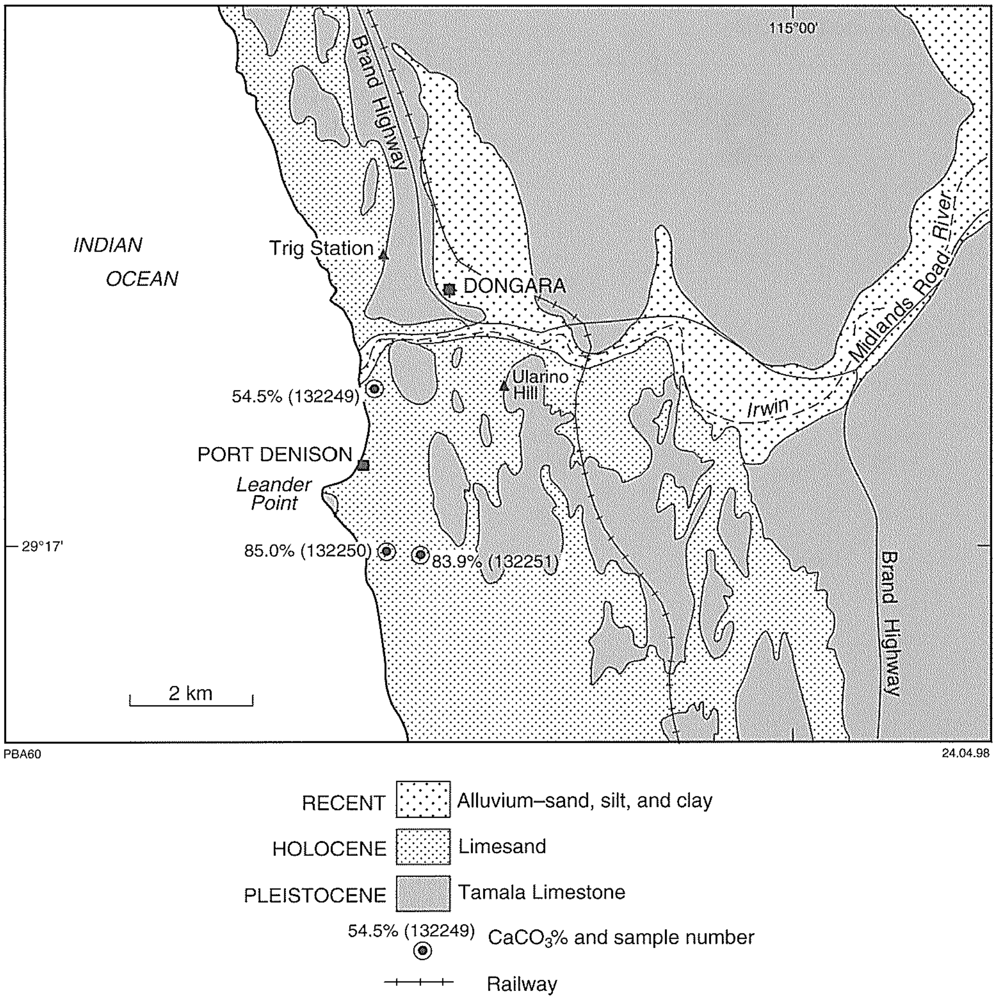


Figure 19. Limestone and limesand distribution in the Dongara–Port Denison region, with assays of some surface samples (geology after Mory, 1995)

From 1985 to 1993, there was a recorded production of 64 146 t of limestone or limesand, valued at $250 953, from the Ledge Point and Lancelin areas, mainly for use as a soil conditioner.

Port Denison–Dongara–Geraldton

Woodward (1915a) identified limesand deposits in the Dongara area in three localities; Ularino Hill, Dongara Trig. Station Hill, and Crown Land around Port Denison (Fig. 19). The sand in these deposits is composed almost entirely of minute shells of foraminifers.

Ularino Hill, an area of about 1 km by 0.5 km, rises abruptly to a height of about 30 m from the south bank of the Irwin River. Six samples taken from this location contained an average of 82.2% $CaCO_3$ and 5.8% $MgCO_3$ (Table 29).

Dongara Trig. Station Hill is a ridge of hills, located west of Dongara railway station, with a maximum height of about 35 m. Two samples from these hills had an average assay of 81.3% $CaCO_3$ and 5.1% $MgCO_3$.

Table 29. Partial chemical analyses of limestone and limesand from Port Denison and Dongara

Location	*Ularino Hill (average of) 6 samples*	*Port Denison Crown Land (average of) 4 samples*	*Dongara Trig. Ridge (average of) 2 samples*
		Percentage	
$CaCO_3$	82.20	86.25	81.30
$MgCO_3$	5.80	6.70	5.11
$FeCO_3$	1.30	0.43	1.42
Al_2O_3	0.40	0.12	1.05
SiO_2	7.70	2.95	9.09
P_2O_5	0.11	0.09	0.11
NaCl	0.06	0.05	0.03
Organics	1.76	2.77	1.34
Moisture	0.52	0.53	0.40

The Crown Land near Port Denison, located east of Leander Point, consists of a belt of dunes that are parallel to the coast south of the Irwin River. The highest dune

Table 30. Whole-rock chemical analyses of limestone and limesand from Port Denison and Dongara

Sample no.	*132249*	*132250*	*132251*
		Percentage	
SiO_2	38.46	3.48	4.25
TiO_2	0.05	0.01	<0.01
Al_2O_3	0.98	0.14	0.19
Fe_2O_3	0.07	0.07	0.03
MnO	<0.01	<0.01	<0.01
MgO	1.49	3.16	3.01
CaO	30.49	47.58	47.01
Na_2O	0.72	2.56	3.30
K_2O	0.49	0.12	0.09
P_2O_5	0.11	0.13	0.12
LOI	26.68	43.30	42.81
Total	**99.54**	**100.55**	**100.81**
CO_2	25.20	41.40	38.90
		Parts per million	
As	–	–	<0.5
Ba	123	26	34
Be	<0.2	<0.2	0.9
Ce	–	–	3.1
Cr	–	–	14
Ga	–	–	0.61
La	–	–	4.5
Nb	–	–	<0.5
Rb	–	–	3.2
S	–	–	<0.01
Sn	–	–	<5
Sr	–	–	2 432
Th	–	–	0.74
U	–	–	1.3
V	–	–	<2

NOTE: 132249 Dongara, Lat. 29°15'46"S, Long. 114°55'15"E, limesand
132250 Port Denison, Lat. 29°17'14"S, Long. 114°55'21"E, limesand
132251 South of Port Denison, Lat. 29°17'41"S, Long. 114°55'55"E, limesand

is about 20 m in elevation. The limesand deposit at this location is larger in tonnage and better in quality than those at Dongara Trig. Station Hill and Ularino Hill. The average composition of four samples was 86.3% $CaCO_3$ and 6.7% $MgCO_3$. Two samples (132250–51) collected by the author from the Crown Land near Port Denison had an average of 84.5% $CaCO_3$ (47.3% CaO) and 6.5% $MgCO_3$ (3.1% MgO), while another sample (132249), collected from the limesand at the mouth of the Irwin River contained only 54.5% $CaCO_3$ (30.5% CaO) and 3.1% $MgCO_3$ (1.5% MgO) (Table 30).

In the absence of published figures, a conservative estimate of several hundred million tonnes of moderate- to high-grade limesand could be placed on the resource in the area south of Port Denison.

The limestone and limesand deposits in the Dongara and Port Denison area extend continuously to the north of Geraldton (Fig. 20). The coast between the Greenough and Chapman Rivers has large areas covered with limesand dunes that contain a variable amount of non-carbonate material. Partial analyses of six samples collected from these coastal dunes are given in Table 31. While three samples assayed 73.50 to 84.43% $CaCO_3$

Table 31. Chemical analyses of limesand from the Geraldton area

Location	*1*	*2*	*3*	*4*	*5*	*6*
			Percentage			
$CaCO_3$	73.50	–	84.43	–	–	81.44
$MgCO_3$	–	–	6.52	–	–	3.01
$FeCO_3$	–	–	1.36	–	–	1.36
Al_2O_3	–	–	1.36	–	–	2.06
SiO_2 + Ins.	17.88	22.19	(a)2.06	24.67	49.68	(a)7.10
P_2O_5	–	–	0.13	–	–	0.14

NOTE: after Woodward (1915a)
Sample 1 1.6 km south of Greenough River
Sample 2 1.6 km north of Greenough River
Sample 3 Mahomets Flat, 2.5 km south of Mount Scott
Sample 4 1 km north of Mount Scott
Sample 5 Bluff Point
Sample 6 Rifle range
Ins. insoluble residue
(a) SiO_2 only

(41.16 to 47.28% CaO), the other three samples contained a large percentage of silica and insolubles and were not analysed for $CaCO_3$. $MgCO_3$ in the samples analysed varied from 3.01 to 6.52% (Woodward, 1915a; Simpson, 1948). Sample 132253 collected by the author from the mouth of Greenough River assayed 76.6% $CaCO_3$ (42.9% CaO) (Table 32).

Cervantes–Jurien–Green Head

Although large deposits (possibly several hundred million tonnes) of moderate- to high-grade limesand or limestone occur along the coastal stretch from Cervantes through Jurien to Green Head (Fig. 21), there are no published resource figures available, and the information on quality is very limited. Three surface samples (132243–45) collected from the Cervantes area contained

Table 32. Chemical analysis of limesand from Greenough River

Sample no.	*132253*
	Percentage
SiO_2	12.50
TiO_2	0.05
Al_2O_3	0.38
Fe_2O_3	0.05
MnO	<0.01
MgO	2.94
CaO	42.94
Na_2O	1.55
K_2O	0.22
P_2O_5	0.13
LOI	38.85
Total	**99.61**
CO_2	37.90
	Parts per million
Ba	53
Be	<0.2

NOTE: Mouth of the Greenough River,
Lat. 28°51'57"S, Long. 114°38'06"E

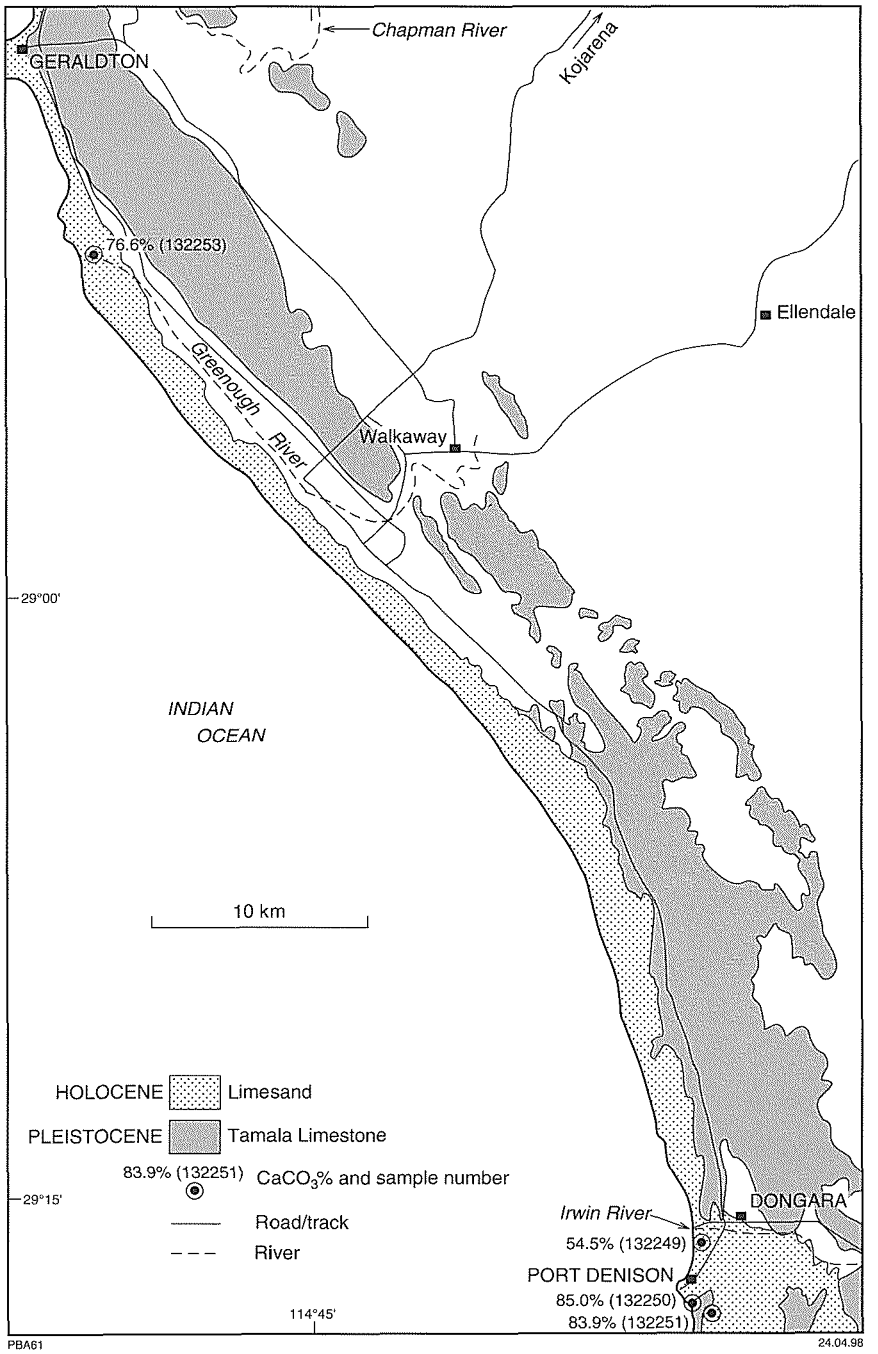


Figure 20. Distribution of limestone and limesand in the area south of Geraldton, with assays of some surface samples (geology after Lowry et al., 1973; Playford et al., 1971)

79.70, 85.71, and 88.48% $CaCO_3$ (44.63, 48.00, and 49.55% CaO) respectively. Two surface samples (132246–47) from an area north of Jurien assayed 76.79 and 81.86% $CaCO_3$ (43.00 and 45.84% CaO) respectively. Another surface sample (132248), from the coast at Green Head, contained only 76.12% $CaCO_3$ (42.63% CaO) (Table 33).

Carnarvon Basin

The Carnarvon Basin has an onshore width ranging from about 50 to 300 km, and extends lengthwise for a distance of about 1000 km, from Geraldton to Karratha, along the western and northwestern coastline of Western Australia. Sediments in the basin range in age from

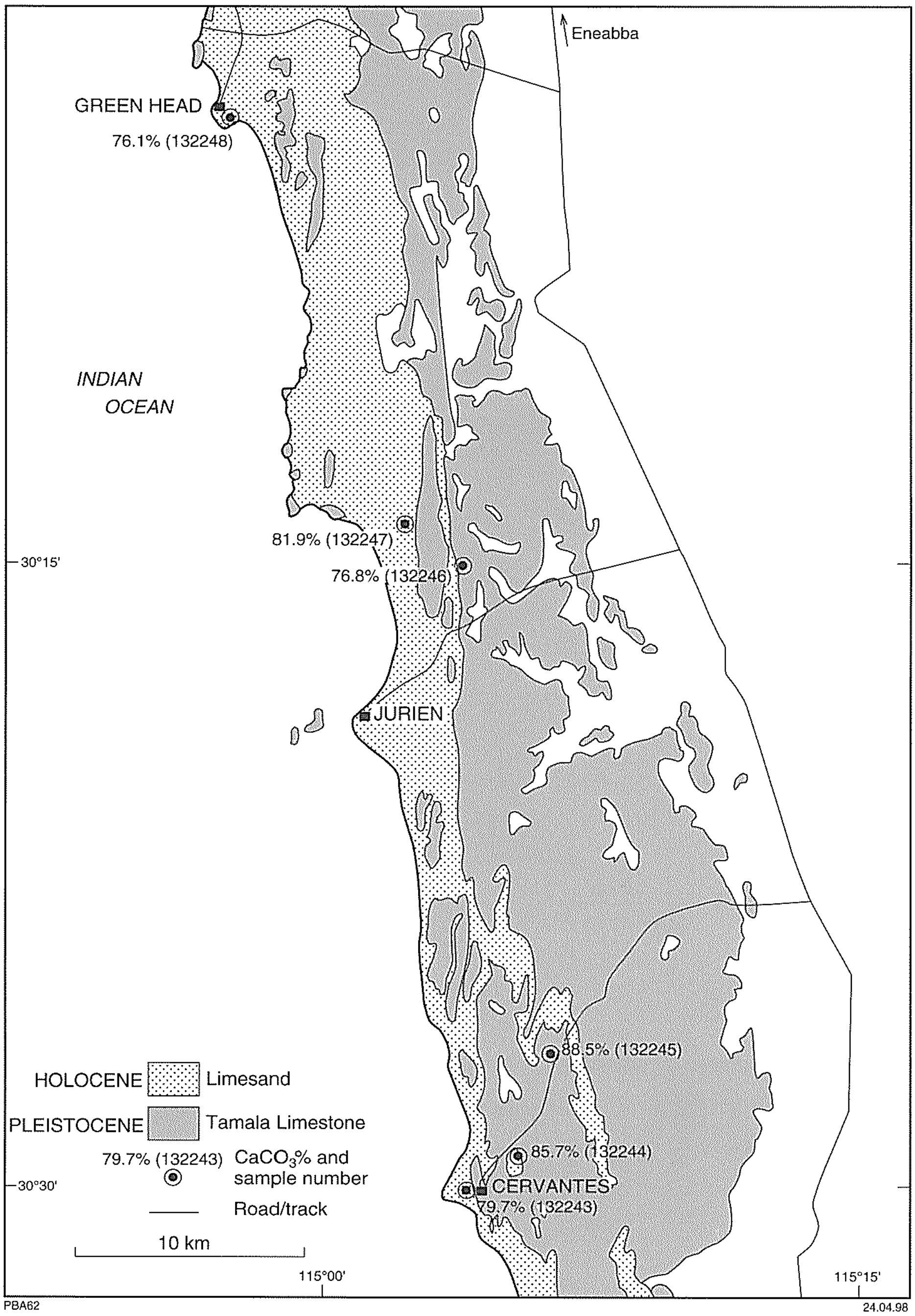


Figure 21. Distribution of limestone and limesand between Cervantes and Green Head, with assays of some surface samples (geology after Lowry et al., 1973)

Silurian to Holocene (Fig. 22), with the limestone formations associated with sediments of varying ages. A detailed description of the geology of the basin may be found in Hocking et al. (1987).

Limestone formations

Limestone deposits in the Carnarvon Basin include the following:

Age	*Unit*
Quaternary	Coral-reef deposits Calcrete Hamelin Coquina Bibra Limestone Dampier Limestone Tamala Limestone
Miocene	Trealla Limestone Tulki Limestone

Age	*Unit*
Miocene – Oligocene	Mandu Limestone
	Bullara Limestone
Cretaceous	Toolonga Calcilutite
Early Carboniferous	Moogooree Limestone

Moogooree Limestone

The Early Carboniferous Moogooree Limestone, a carbonate sequence containing minimal terrigenous material, was named by Teichert (1949) and defined by Condon (1965). Although limestone is the dominant rock type, dolomite is more abundant than suggested by Condon (1965), and in some areas more than half of the section consists of dolomite beds. While fossil algae are common throughout the limestone, shelly fossils are largely absent. Horizons of sandy carbonate occur locally at various levels within the unit.

The Moogooree Limestone is almost continuously exposed for a distance of about 55 km at the eastern border of the Carnarvon Basin (Fig. 23), from 20 km south of Moogooree Homestead to 8 km north of Williambury Homestead. Isolated outcrops occur further west of Harris Bore.

The limestone probably unconformably overlies the Willaraddie Formation and is conformably overlain by the Williambury Formation. Both of these formations consist of immature sandstone and conglomerate.

Toolonga Calcilutite

The Toolonga Calcilutite is generally massive, fossiliferous, greenish-grey to white-weathering, slightly clayey calcilutite containing some greenish flint nodules. The unit is dated as Santonian to Campanian (Hocking et al., 1987), extending locally into the Maastrichtian (McWhae et al., 1958), and was largely deposited in a shallow-marine environment.

The Toolonga Calcilutite is exposed in the lower Murchison River area (eg. Pillawarra Hill), the Hill Springs area west of the Kennedy Range, and a few kilometres east of Cardabia Creek (Fig. 23). In the area south of Carnarvon, the unit is recognized in waterbores and in exposures as far east as Yalbalgo Station (Denman et al., 1985). Toolonga Calcilutite is also exposed at Flint Cliff where it contains irregular chert nodules, and small outcrops are common along the east coast of Hamelin Pool in Shark Bay.

The type section is 2 km north of Yalthoo Bore (Lat. 27°35'59"S, Long. 114°13'35"E). Generally, the unit is between 50 to 100 m thick onshore, although locally it may be as much as 290 m thick. In areas north of Carnarvon, Toolonga Calcilutite varies in thickness from 135 m at Cape Cuvier to 290 m in Brickhouse 2 (Denman and van de Graaff, 1982). A maximum thickness of 600 m for the unit is reached offshore in Trimouille 1 (Hocking et al., 1987), although it thins to between 60 and 80 m over the Rankin Platform.

Bullara Limestone

The Bullara Limestone, a variably sorted, medium- to coarse-grained, bioclastic foraminiferal grainstone with some packstone, has only been recognized in the Rough Range area. The unit is coarser grained and purer than the Mandu Limestone, which is its lateral equivalent.

Table 33. Chemical analyses of limestone and limesand from Cervantes, Jurien, and Green Head

Sample no.	*132243*	*132244*	*132245*	*132246*	*132247*	*132248*
			Percentage			
SiO_2	8.95	3.38	0.61	16.39	7.84	14.03
TiO_2	0.02	0.00	0.00	0.06	0.01	0.01
Al_2O_3	0.28	0.16	0.07	1.04	0.26	0.27
Fe_2O_3	0.05	0.09	0.08	0.13	0.08	0.04
MnO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
MgO	3.38	3.02	3.09	0.69	3.10	3.07
CaO	44.63	48.00	49.55	43.00	45.84	42.63
Na_2O	0.42	0.55	0.30	0.22	2.17	0.37
K_2O	0.23	0.16	0.11	0.53	0.21	0.22
P_2O_5	0.13	0.12	0.06	0.05	0.13	0.13
LOI	40.77	43.15	45.23	37.40	41.00	38.33
Total	**98.86**	**98.63**	**99.10**	**99.51**	**100.64**	**99.10**
CO_2	39.80	41.80	44.20	36.70	40.00	36.10
			Parts per million			
Ba	39	29	60	192	42	42
Be	0.8	0.4	0.2	0.3	<0.2	<0.2

NOTE:
132243 Cervantes, Lat. 30°30'37"S, Long. 115°03'39"E, limesand
132244 East of Cervantes, Lat. 30°29'33"S, Long. 115°05'29"E, limesand
132245 East of Cervantes, Lat. 30°28'45"S, Long. 115°05'54"E, Tamala Limestone
132246 Northeast of Jurien, Lat. 30°15'09"S, Long. 115°05'16"E, Tamala Limestone
132247 Quarry northeast of Jurien, Lat. 30°14'29"S, Long. 115°02'05"E, limesand
132248 Green Head, Lat. 30°04'16"S, Long. 114°57'47"E, limesand

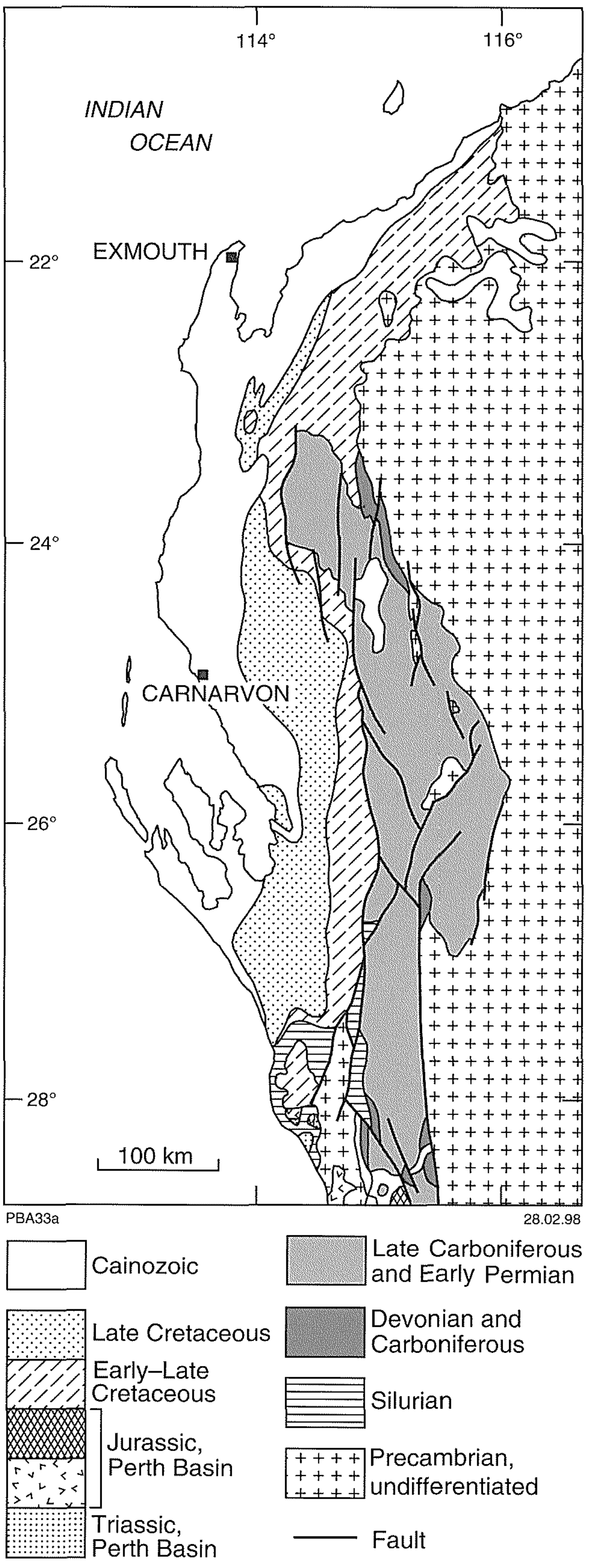


Figure 22. Geology of the Carnarvon Basin (after Hocking et al., 1987)

The Bullara Limestone is between 220 and 306 m thick in its type section in Rough Range South 1 and is considered to be Late Oligocene in age (Chaproniere, 1975, 1976, 1984).

Mandu Limestone

The Mandu Limestone is richly fossiliferous in outcrop, with large lepidocyclinid foraminifers, bivalves, echinoids, bryozoans, sponges, and crustacean fragments. The base of the limestone is dated as Late Oligocene and the top as Early Miocene. It disconformably overlies the Giralia Calcarenite or Walcott Formation, and is overlain conformably by the Tulki Limestone in the Cape Range area, or by the Trealla Limestone elsewhere (Hocking et al., 1987).

The type section for the Mandu Limestone is 76 m thick and occurs on the south side of Badjirrajirra Creek (Lat. 22°06'10"S, Long. 114°02'00"E). In the Cape Range area, the unit appears to be generally more than 300 m thick, and is thicker again over the Rankin Platform, with 724 m in Pueblo 1, 571 m in Goodwyn 6, and 596 m in Fisher 1 (Hocking et al., 1987).

The Mandu Limestone is present throughout the Barrow and Dampier Sub-basins, located offshore in the northern part of the Carnarvon Basin. In the Cape Range area, the Mandu Limestone consists of friable, largely impermeable, white to cream, chalky to marly calcarenite, calcisiltite, and calcilutite. The calcarenite ranges from packstone to wackestone, and the grains are mainly bioclastic, with moderate amounts of quartz.

Tulki Limestone

The Tulki Limestone is exposed mainly in the Cape Range area (Fig. 23), where it consists predominantly of cream to reddish-coloured foraminiferal calcarenite (packstone) (van de Graaff et al., 1982). The type section of the unit, located in Badjirrajirra Creek (Lat. 22°06'00"S, Long. 114°02'00"E), has a thickness of 95 m and conformably overlies the Mandu Limestone. A rich fauna, dominated by foraminifers, indicates an Early Miocene age (van de Graaff, et al., 1980) for the unit. The uppermost part of the Tulki Limestone is commonly recrystallized (Chaproniere, 1975) and exhibits a disconformable contact with the overlying Trealla Limestone.

Trealla Limestone

The Trealla Limestone is a thin- to massive-bedded, hard limestone that disconformably overlies the Tulki Limestone and Giralia Calcarenite. The type section of the unit is at Mount Lefroy (Lat. 22°13'10"S, Long. 114°00'30"E). Foraminiferal faunas indicate an Early Miocene to Middle Miocene age for the unit, which was probably deposited in a lagoonal coastal environment.

On the western side of Cape Range, the Trealla Limestone grades laterally into the Pilgramunna

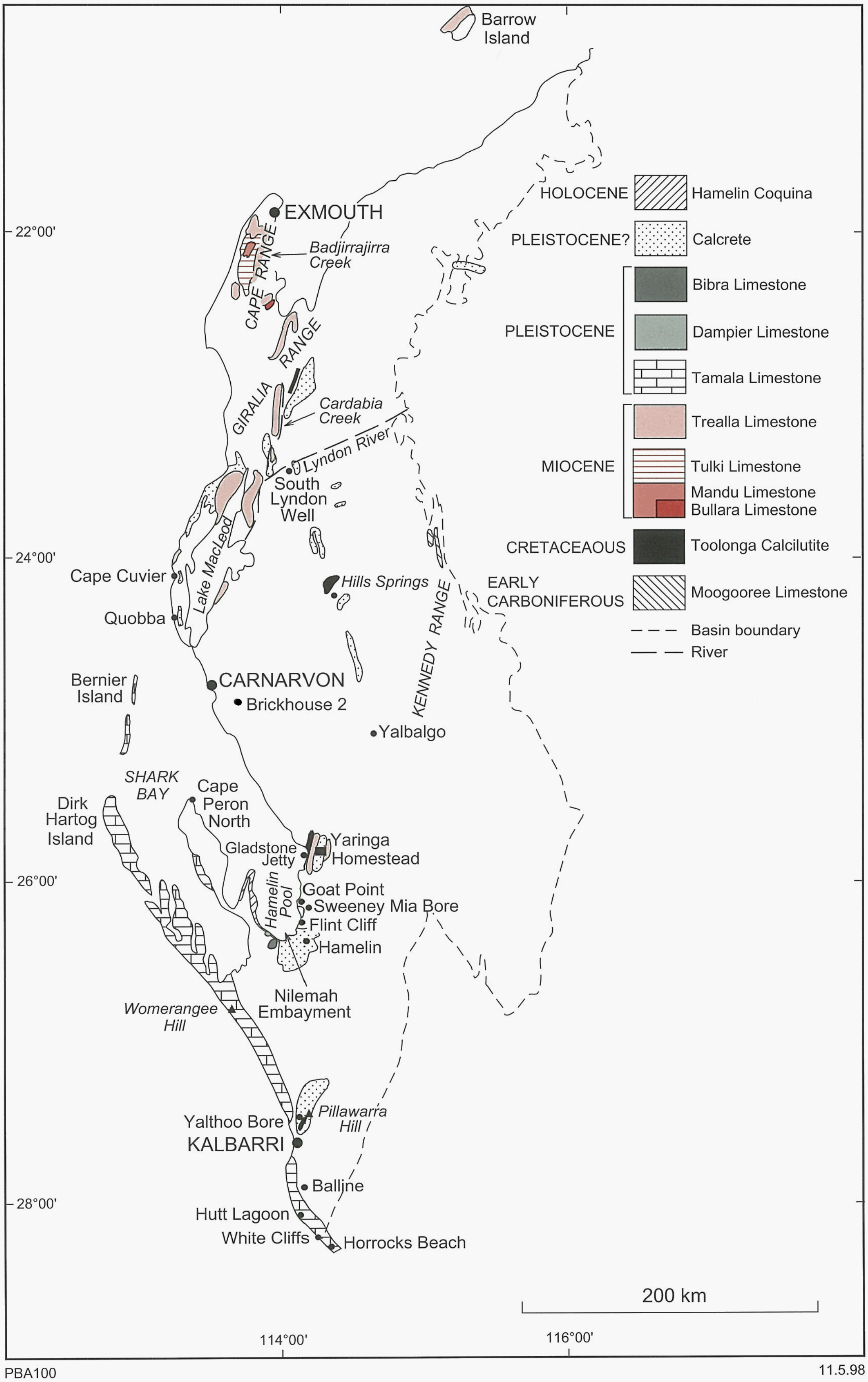


Figure 23. Distribution of limestone in the Carnarvon Basin

Formation, which differs from the Trealla Limestone in its admixture of silt-to-granule sized quartz. The purer limestone deposits of the Trealla Limestone characteristically give rise to very sharp karst features (van de Graaff et al., 1980).

The lower 13 m of a 25 m-thick section of Trealla Limestone exposed at Cape Cuvier includes two thin units of red soil and a laminated dolomite unit with 'birdseye' structures (Denman and van de Graaff, 1982). The remaining 12 m of the section consists of fossiliferous white bioclastic packstone and grainstone, typical of Trealla Limestone exposed elsewhere.

In the Giralia Range area, Trealla Limestone conformably overlies, and in places may grade into, the Lamont Sandstone. In the Giralia Anticline, the unit was deposited on a moderate-energy, shallow-marine shelf with little terrigenous contamination. To the east, near South Lyndon Well, silt and quartz-sand contamination increases (Hocking et al., 1985a).

Trealla Limestone is also known to occur at Yaringa Homestead, a few kilometres to the north of Yaringa. However, differentiating this unit from Toolonga Calcilutite is difficult due to development of calcrete duricrust (van de Graaff et al., 1983). Denman et al. (1985) stated that Trealla Limestone in this area is unlike the 'normal' Trealla Limestone exposed from Quobba northwards (Fig. 23), where it is a white, pure packstone to grainstone, commonly very fossiliferous. Limestone similar to Trealla Limestone is also known from Barrow Island (Kriewaldt, 1964).

Tamala Limestone

The type section for the Tamala Limestone is at Womerangee Hill on Tamala Station, where the unit is approximately 285 m thick. The Tamala Limestone, from south of Kalbarri to Dirk Hartog Island (Fig. 23), consists of medium- to coarse-grained, strongly consolidated to unconsolidated, locally quartzose calcarenite containing skeletal fragments. In lithified portions, the cement is predominantly calcite with subordinate dolomite. Lithification is most intense in calcreted, exposed parts of older dunes.

In the Balline area, the Tamala Limestone is composed of at least two generations of lithified dunes. A low scarp south of Wagoe Ridge Farm may represent an old shoreline cliff similar to the one east of Hutt Lagoon (Hocking et al., 1982).

Two outcrops of shelly limestone, occurring at the mouth of the Murchison River at Kalbarri (a few kilometres north of the above locations), are probably equivalent to the Dampier and Bibra Limestones of the Shark Bay area.

In the Geraldton coastal area, the unit is composed of eolianite extending up to 8 km inland, and it is very thick north of Horrocks Beach. At White Cliffs, there are spectacular cliffs exposing Tamala Limestone rising up to 75 m from the sea (Playford et al., 1970).

Dampier Limestone

The Dampier Limestone is a shallow-marine to supratidal unit of bivalve- and foraminifer-rich coquinite, which is extensively calcreted on upper surfaces (Butcher et al., 1984). The Carbla Oolite Member of the unit, exposed along the eastern shore of Hamelin Pool (Fig. 23), has its type section at Goat Point. It is predominantly an ooid grainstone with a fossiliferous basal conglomerate. It is overlain by a sequence of unfossiliferous, very well sorted ooid grainstone occurring in distinct ridge-like bodies (van de Graaff et al., 1983).

The minimum age of the Dampier Limestone is likely to be about 240 000 years (van de Graaff et al., 1983; Kukla, 1977).

Bibra Limestone

The Bibra Limestone, which overlies the Dampier Limestone, is considered to be 120 000 to 130 000 years old. The unit consists of predominantly shelly calcirudite (coquinite) that was deposited in beach-ridge, tidal-flat and subtidal environments. Beach-ridge type deposits are exposed 1 km east of Hamelin Post Office, 5 km west of Sweeney Mia Bore, south of Nilemah Embayment, and at Gladstone Jetty (van de Graaff et al., 1983; Denman et al., 1985).

Fossils in the Bibra and Dampier Limestones indicate that during the Pleistocene salinities in the Hamelin Pool area were at near-oceanic levels, and unlike the present-day hypersaline conditions.

Hamelin Coquina

Hamelin Coquina is a beach-ridge complex, consisting predominantly of small shells of *Fragum erugatum*, which has been deposited in Hamelin Pool (Fig. 23). During storms, these shells are swept from the sublittoral platform, across the stromatolite belt, and onto the shore (van de Graaff et al., 1983).

Calcrete

Extensive deposits of calcrete are found associated with limestone and as valley calcrete in different parts of the Carnarvon Basin (Fig. 23). Brief descriptions of calcrete occurrences within various 1:250 000 geological map sheet areas covering the Carnarvon Basin are as follows:

YANREY–NINGALOO*: thick calcrete profiles are presently developing in alluvial and colluvial deposits in the eastern part of the area, while in the west all calcareous units have undergone calcretization (van de Graaff et al., 1980).

WINNING POOL–MINILYA: calcrete is extensively developed both as duricrust on the Korojon Calcarenite and other calcareous units, and as valley-fill calcrete in Precambrian areas. Duricrust calcrete probably formed

* Capitalized names refer to standard 1:250 000 map sheets.

in the Pliocene, whereas valley calcrete is probably younger (Hocking et al., 1985a).

QUOBBA: calcrete commonly caps the eolianite dunes on the Quobba ridge and on Bernier Island.

AJANA: calcrete is extensively developed as a duricrust over the Pillawarra Plateau on the Toolonga Calcilutite, and also as valley-fill calcrete in older alluvium in eastern areas of the sheet. Field evidence suggests a general Pliocene to Pleistocene age for the duricrust calcrete. Valley-fill calcrete is considered to be a product of groundwater percolation. Minor calcrete of Late Pleistocene to Holocene age has also developed on the Tamala Limestone (Hocking et al., 1982).

YARINGA, KENNEDY RANGE, and WOORAMEL: the upper part of the Dampier Limestone is marked by solution pipes and intense calcrete development. The presence of this profile is useful in differentiating the Dampier Limestone from the overlying Bibra Limestone. Calcrete development on Bibra Limestone is less advanced than on Dampier Limestone (van de Graaff et al., 1983).

Mature calcrete duricrust, post-dating laterite and silcrete, has often developed on exposures of Toolonga Calcilutite (van de Graaff et al., 1983; Denman et al., 1985, Hocking et al., 1985b). Valley calcrete occurs in the major palaeodrainage on the eastern part of YARINGA and KENNEDY RANGE.

The limestone quarried at Lat. 26°00'10"S, Long. 114°18'30"E is considered to be either calcreted lacustrine limestone, coeval with calcrete duricrust, or a very thick, pure calcrete deposit.

ONSLOW: poorly developed calcrete, as shallow as 0.5 m, is commonly present in the eastern part of the area although it is rarely seen at the surface. The $CaCO_3$ content generally increases downward, and the thickness of the calcrete may be similar to that of the host sediment (van de Graaff et al., 1982).

Coral-reef deposits

Van de Graaff et al. (1982) noted that living coral reefs, consisting of coralgal boundstone, occur along the western and northern shores of Cape Range peninsula and around islands in Exmouth Gulf. Most of these reefs are now within the Ningaloo Reef Marine Park.

Limestone deposits

Currently, limestone resources in the region are mainly used in the local construction industry or as road-metal. Although a number of locations have been investigated in some detail, for uses such as the manufacture of cement and lime, much of the resource is yet to be explored.

Based on exploration activities in limited areas, Whitecrest Enterprises, in joint venture with Swan Portland Cement Limited, has put forward a proposal to manufacture clinker and lime using limestone sourced from the Cape Range area. This indicates that the transport of limestone from remote locations is becoming more economic. If this trend continues, and resources closer to markets are exhausted or sterilized, then it is likely that demand for high-grade limestone from remote locations could increase in the longer term. Furthermore, planned steel-manufacturing industries, utilizing the vast resources of iron ore in the Pilbara region, will require high-quality metallurgical-grade limestone. The Cape Range limestone resource would be an obvious choice for development, if the proposed steel manufacturing becomes a reality. Preliminary exploration indicates the presence of a large resource of high-grade metallurgical limestone in the Cape Range and a number of other areas in the Carnarvon Basin.

In many areas, environmental concerns are a serious impediment to the development of limestone resources. This is a common occurrence when the limestone lies within a national park or in areas under consideration for inclusion in national parks. These matters are being addressed by various government bodies, local shires, and other interested parties, and it is hoped that some resources can be identified and set aside for future usage.

Past and present exploration activities, and current uses of limestone in the Carnarvon Basin, are discussed below.

Cape Range

Cape Range, located approximately 750 km north of Perth, has undulating topography that rises from a height of about 100 m AHD at the northern end to 314 m at Mount Hollister (Fig. 24).

The range is underlain by about 10 000 m of Phanerozoic sedimentary rocks, with the Miocene to Late Oligocene shallow-marine sedimentary rocks of the Cape Range Group (Fig. 25) being the oldest exposed rocks in the area. Mandu Limestone, exposed in the lower parts of the major gorges and forming the base of the Cape Range Group, is overlain by the Tulki Limestone, which outcrops widely in Cape Range. In the western part of Cape Range, Tulki Limestone is disconformably overlain by the Trealla Limestone.

Exploration activities

During 1961–1964 and 1973–1974, BHP explored an area within temporary reserve TR 5980 (Fig. 24), which either bordered or was within the Cape Range National Park. The work involved reconnaissance drilling and geological mapping of the Tulki and Trealla Limestones.

Subsequent work involved a feasibility study by the MHL Syndicate (Marubeni/Hancock and Wright/Lewis, Tomich, and Hammond) on the possibility of supplying crushed limestone to the alumina industry. However, this project did not go ahead, although three rotary holes were drilled and approximately 8 t of Trealla Limestone was quarried for various tests.

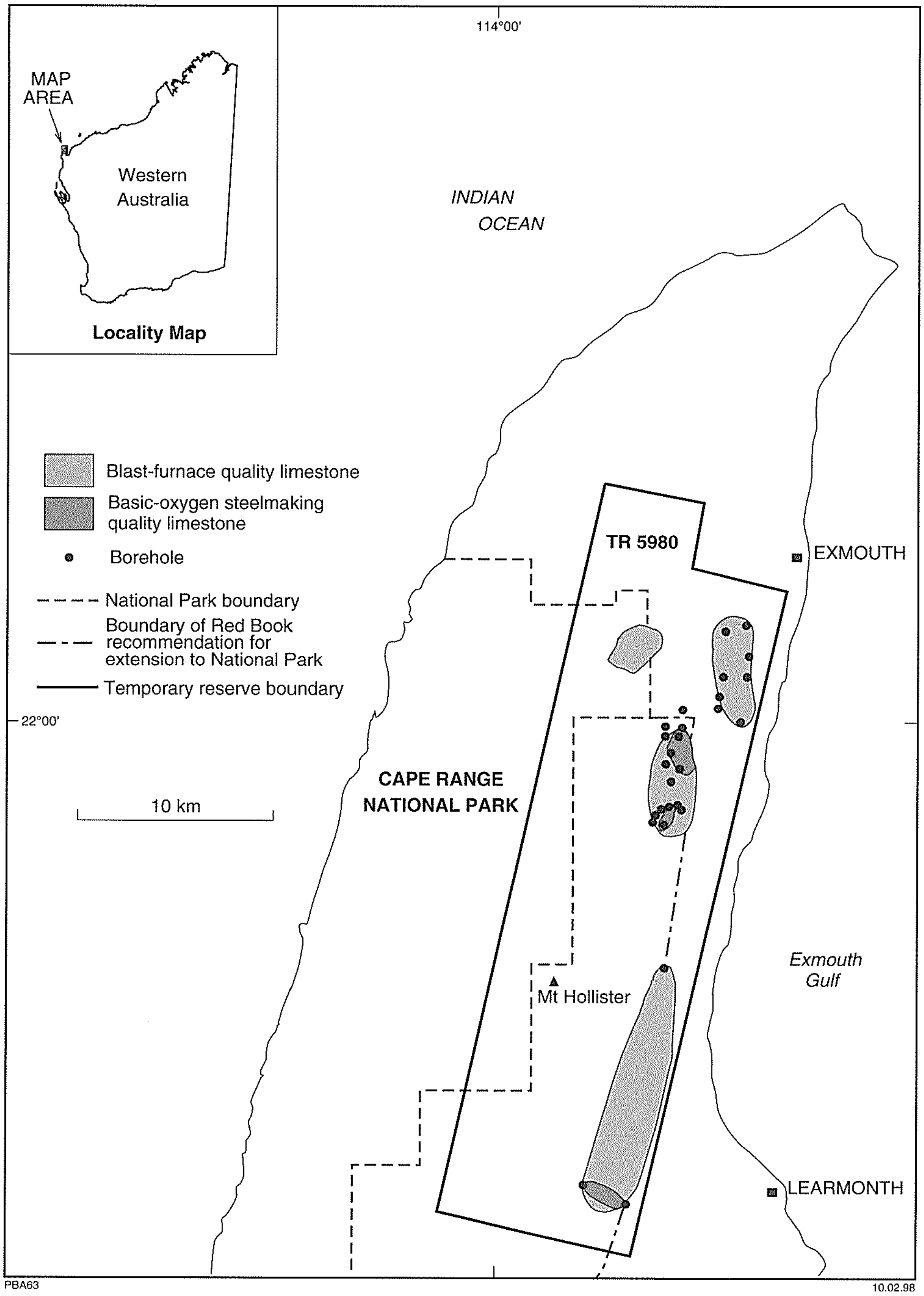


Figure 24. High-grade limestone areas identified by BHP in the Cape Range (after Kojan et al., 1995)

In 1993, Whitecrest Enterprises sampled earlier BHP drill cuttings, as well as carrying out geological mapping, and completed a major new sampling program involving cliff faces and surface samples collected along selected lines. The area explored was about 10 km^2.

Quality and resources

A typical high-quality limestone from the Cape Range area was found to contain 54.7% CaO (97.7% $CaCO_3$), 0.8% SiO_2, and 0.2% MgO (0.4 $MgCO_3$), whereas a typical sample of poor-quality dolomitic limestone from this area assayed 34.4% CaO (61.4% $CaCO_3$), 0.8% SiO_2, and 17.2% MgO (36.0% $MgCO_3$) (Hocking, et al., 1987). Phosphorus levels are commonly below 0.02%. The samples supplied by MHL Syndicate to ICI Australia indicated that the material was mechanically stable during calcination and yielded a very reactive lime.

In defining a resource of 70 Mt of blast-furnace quality limestone in four areas (Fig. 24), BHP delineated subareas containing 15 Mt of basic-oxygen steelmaking (BOS) quality limestone with a high stability index (Kojan et al., 1995). BHP's investigations also revealed

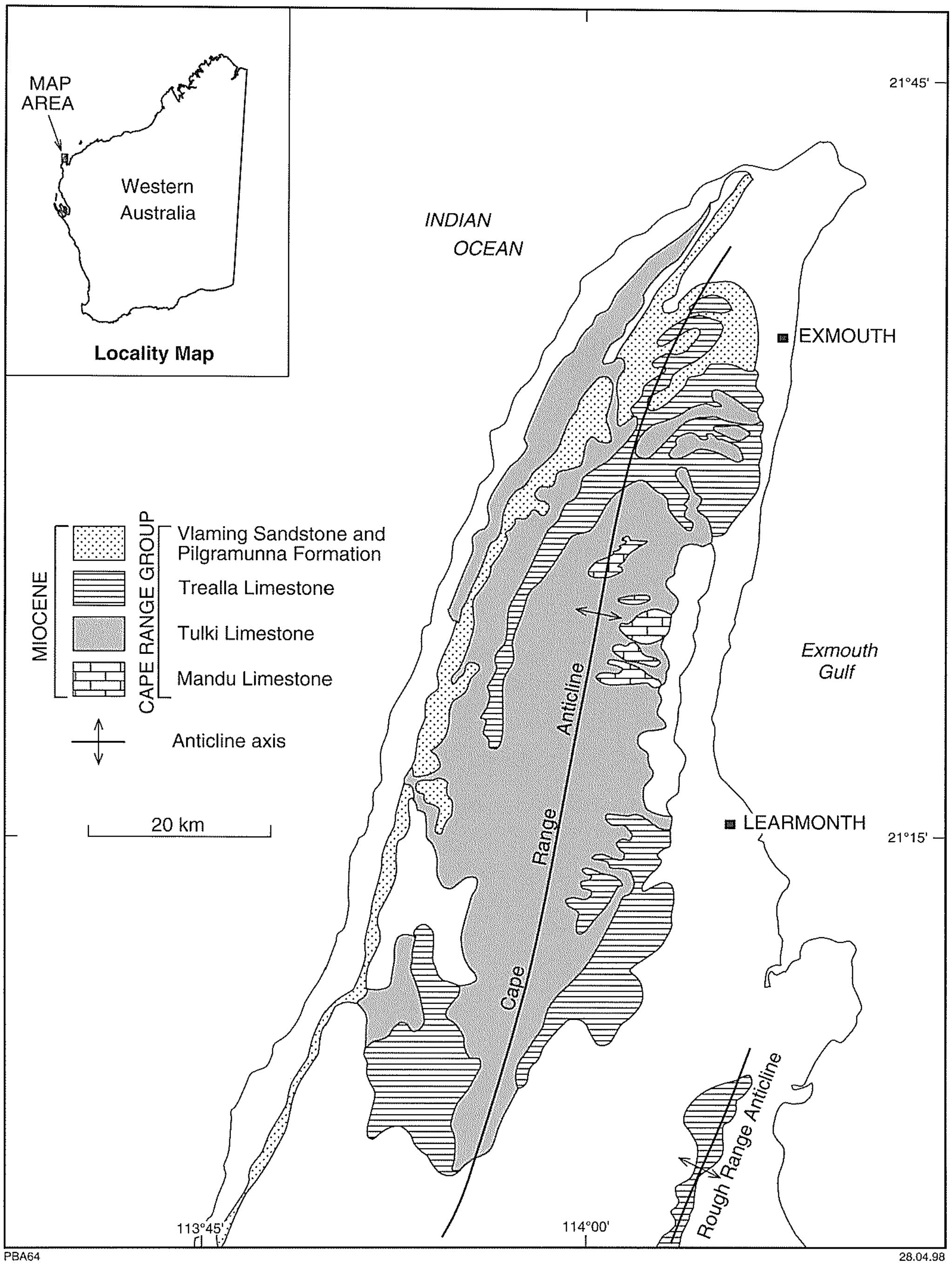


Figure 25. Distribution of the Cape Range Group in the Cape Range area (after Allen, 1993)

the presence of a large resource of high-grade limestone to a depth of 20 m.

Further assessment of the area was carried out by DME (Kojan, et al., 1995). During this program, samples were collected from a cliff section and from three boreholes drilled by the Water Authority of Western Australia (Fig. 26). Based on this sampling program and previous work by BHP, an inferred resource of 4000 Mt of high-grade limestone, assaying 55.3% CaO (98.7% $CaCO_3$), 0.4% MgO (0.8% $MgCO_3$), and 0.6% SiO_2, was calculated for the sampled area.

Kojan et al. (1995) noted that dolomite is prevalent in the eastern side of the sampled area. The geological section given in Figure 27 indicates that dolomite also occurs in hole R23 in the northern part of the sampled area. However, two boreholes in the southern part of the sampled area did intersect limestone suitable for basic-oxygen steelmaking, although generally limestone in these holes was only of medium grade due to the presence of clay bands. The limestone between the clay bands is of high grade. Quicklime produced from 20 composite samples demonstrated an available lime content generally in excess of 90%, and sometimes as

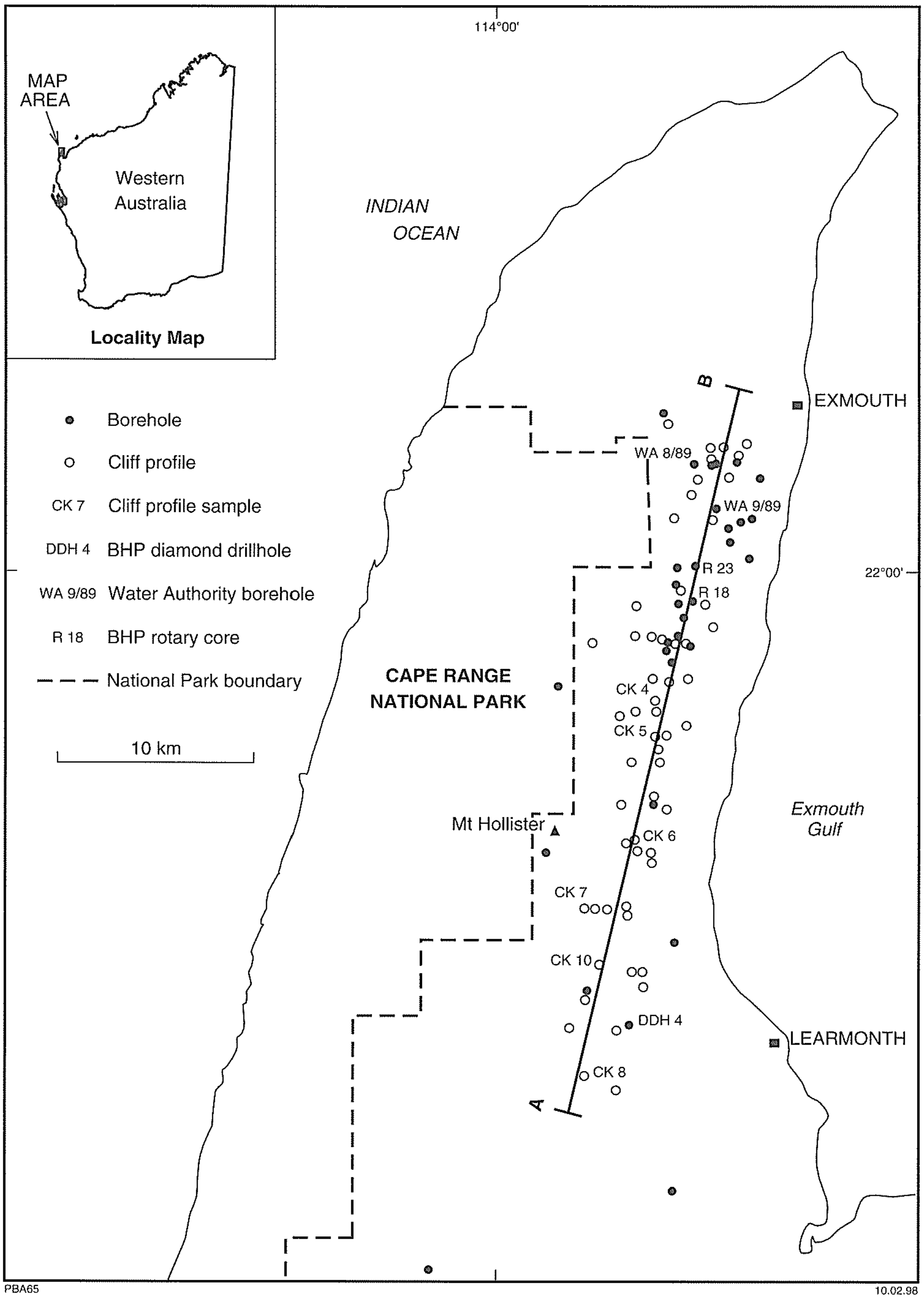


Figure 26. Borehole and cliff sample locations in the Cape Range (after Kojan et al., 1995)

high as 95%, indicating the suitability of this limestone for the production of lime.

Other areas in the Cape Range region that contain high-quality limestone are as follows:

(a) Extensions of the Trealla and Tulki Limestones — these limestones extend in a north–south direction for about 200 km. However, the presence of the protected Ningaloo Reef on the western and northern sides of the Cape Range peninsula, and the current requirement that any economically viable mining operation be within 20 km of a deep-water port, leave the area closest to Exmouth Gulf as the most favourable option for the development of any mining operation. However, according to Kojan et al. (1995) there are possible port sites on the eastern coast of North West Cape, as far south as Learmonth. A 20 km radius from these sites includes a significant area of limestone outcrop, both within and outside areas identified as possible conservation reserves. Currently, there is very limited information on the quality of limestone in these areas.

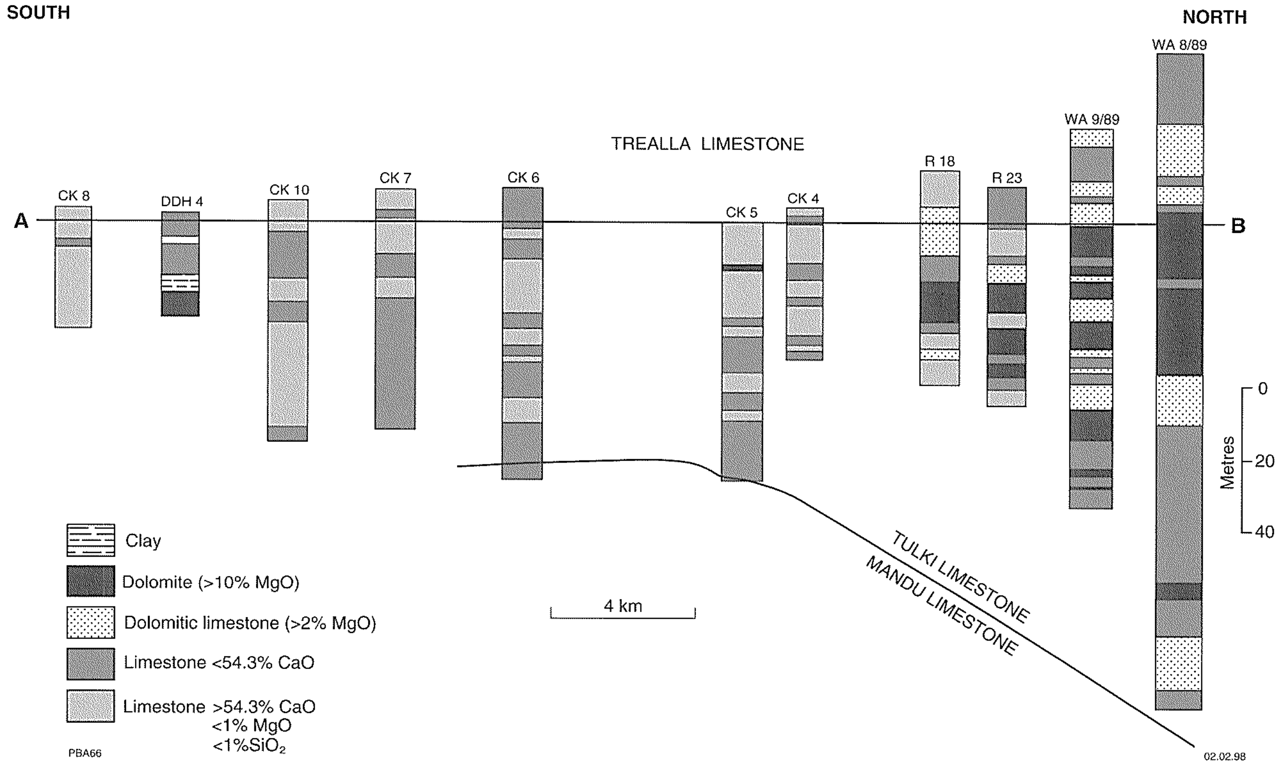


Figure 27. North–south cross section in the Cape Range (after Kojan et al., 1995)

(b) Rough Range — is located southeast of Cape Range (Fig. 25) within and outside the 20 km radius of port sites south of Learmonth. Kojan et al. (1995) suggested that although a limestone resource of approximately 400 Mt could be present in this area beneath cover, most of the area is greater than 20 km distance from deep-water port sites, and hence development of an economically viable operation is unlikely at this stage.

Cape Cuvier

BHP explored the Trealla Limestone in the Cape Cuvier (Fig. 28) area to assess its viability for a planned steel-making plant (McLaren, 1977). The Trealla Limestone is overlain by a calcarenite bed, the thickness of which was estimated by seismic methods and by two diamond drillholes. The first hole, which had a seismically interpreted overburden depth of 75 m, was terminated at 70 m in calcarenite overburden due to drilling difficulties. The second hole, which had a seismically interpreted overburden depth of 30 m, intersected limestone between 34 and 52 m.

The overburden depth was considered too high for commercial development of the limestone. In addition, it had a silica content considered to be excessive for use in the steel industry.

An assay of limestone in hole 2, between 34 and 52 m, found 54.0% CaO (96.4% $CaCO_3$), 0.3% MgO (0.6% $MgCO_3$), 2% SiO_2, and 0.2% Al_2O_3.

Calcrete in the Cape Cuvier area has been used in the construction of port works in the area, and as road gravel on the Quobba ridge.

Lake MacLeod–Miniliya

Exploration for limestone, carried out in an area north of Minilya and at the northeast end of Lake MacLeod, has indicated that subhorizontal, easterly dipping Trealla Limestone, 9 to 15 m thick, occurs within an open anticlinal structure (Fig. 29) (Dalby, 1975). The limestone is hard, dense, fresh, cream to white in colour, and fossiliferous. Assays of six surface samples indicated 53.4 to 55.3% CaO plus MgO, and 0.2 to 1.2% SiO_2.

The Trealla Limestone and locally sourced calcrete are used in the area for road construction. Hocking et al. (1985a) noted that in coastal areas the Trealla Limestone is the only good source of aggregate for road construction.

Kalbarri–Pillawarra Hill

Toolonga Calcilutite and other limestone units in the Pillawarra Hill and Long Thicket Bore areas (Fig. 30) have been investigated intermittently by a number of companies.

Initial exploration work by Menchetti Corporation in 1986, involving vacuum drilling of 38 holes to depths varying from 3 to 19 m (200 m total), indicated zones

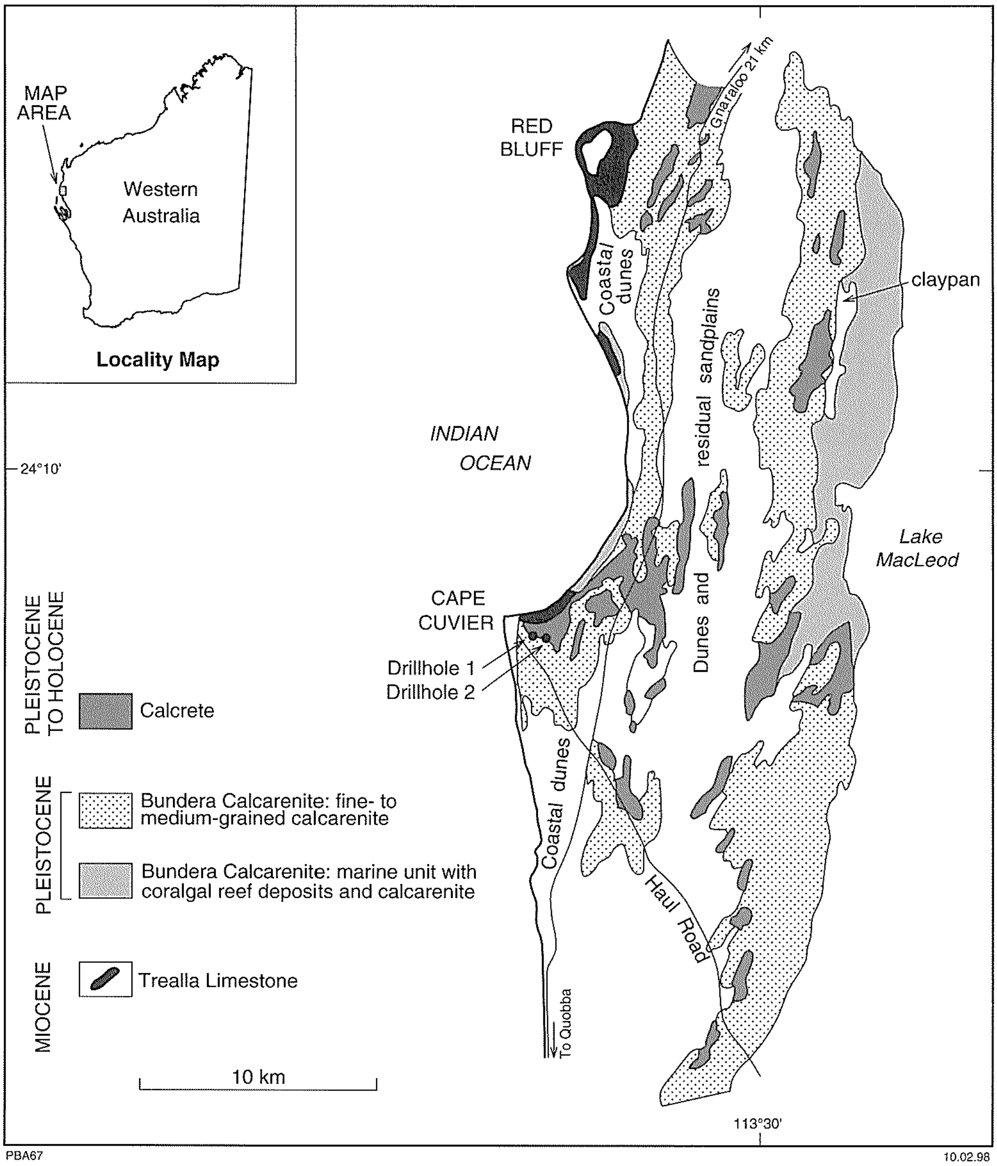


Figure 28. Distribution of limestone, calcrete, and calcarenite units around Cape Cuvier (after Denman and van de Graaff, 1982)

having greater than 70% and less than 90% $CaCO_3$, and chalky horizons. Based on this drilling, a limestone resource of over 1500 Mt was estimated (Johnston & Associates, 1986), but more drilling was recommended to confirm the resource estimate. Critical assumptions in the estimate were uniform grade and overburden depths, but subsequent drilling in the area has indicated significant variations in these parameters. However, continuing exploration activities by Conlan Management Pty Ltd and Australian Chalk and Minerals NL have identified substantial, unpublished resources of high-grade limestone in the area.

Kalbarri

Limestone and limesand of undetermined quality are available from the Tamala Limestone and the mobile sandbelt south of Kalbarri (Fig. 23) (Hocking et al., 1982). The limesand has been partly derived from Tamala Limestone, and correlates with the Safety Bay Sand of the central Perth Basin.

Shark Bay

The Hamelin Coquina in the Shark Bay area forms beach ridges composed of small shells of *Fragum erugatum* bivalves. Hypersaline waters in L'Haridon Bight and Hamelin Pool (Fig. 31) have restricted the size of the normally much larger bivalve to one third of its usual size. Extensive deposits up to 6 m thick, 1 km wide, and 40 km long occur on shorelines (Townsend, 1996).

There are two coquina mining areas on the eastern shore of L'Haridon Bight, both operated by L'Haridon

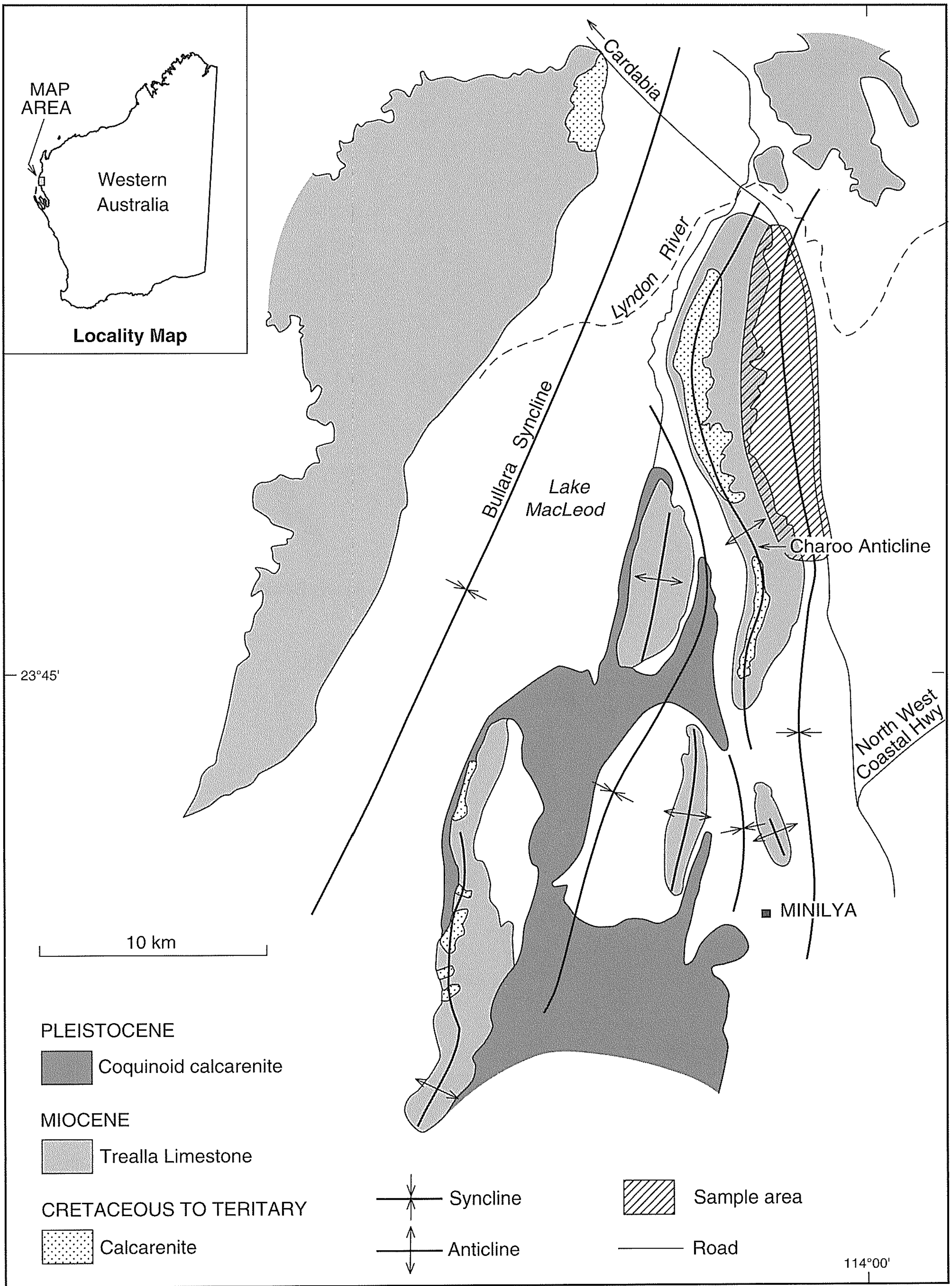


Figure 29. Distribution of limestone units north and northwest of Minilya (after Hocking et al., 1985a)

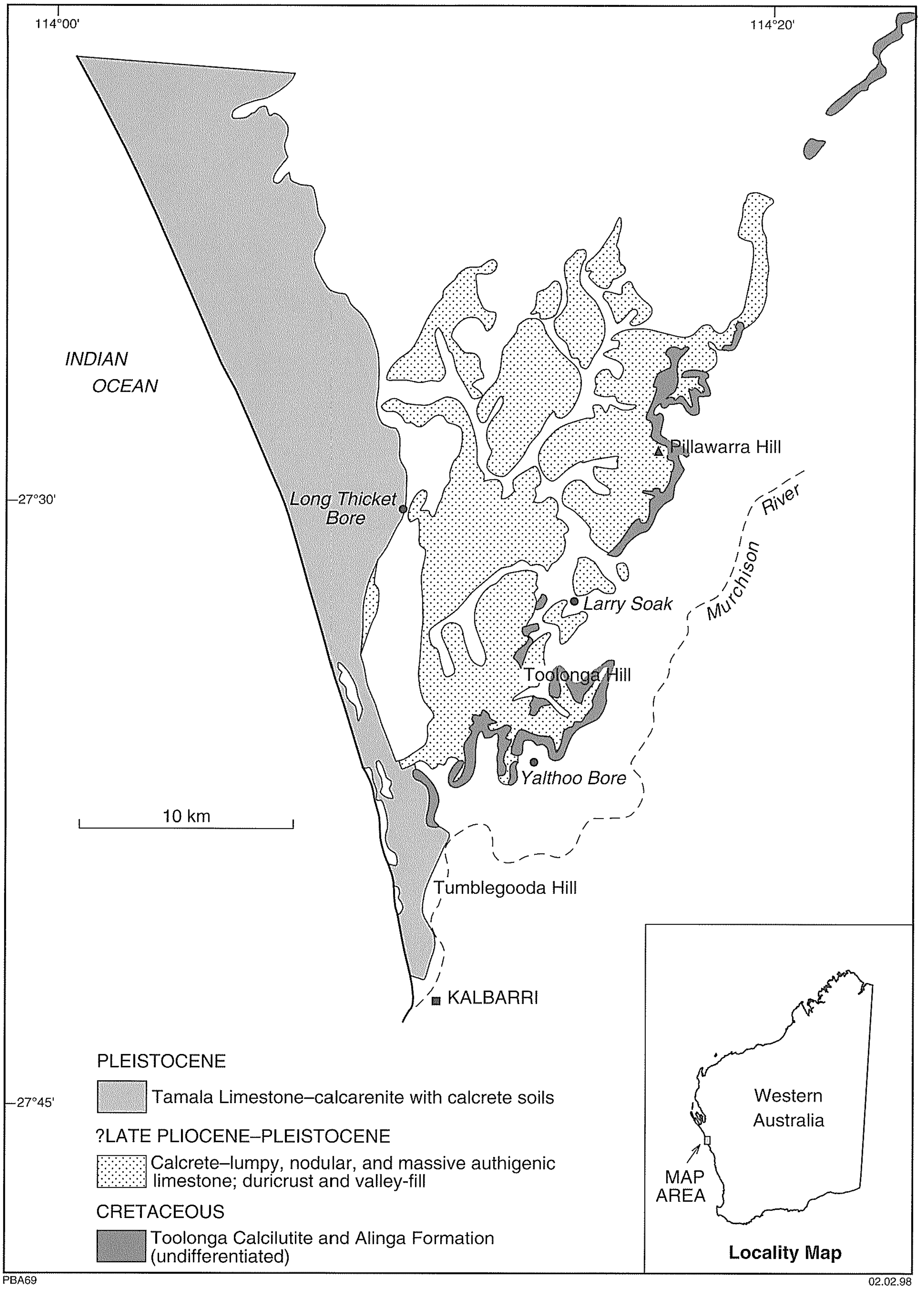


Figure 30. Major limestone units in the area north of Kalbarri (after Hocking et al., 1982)

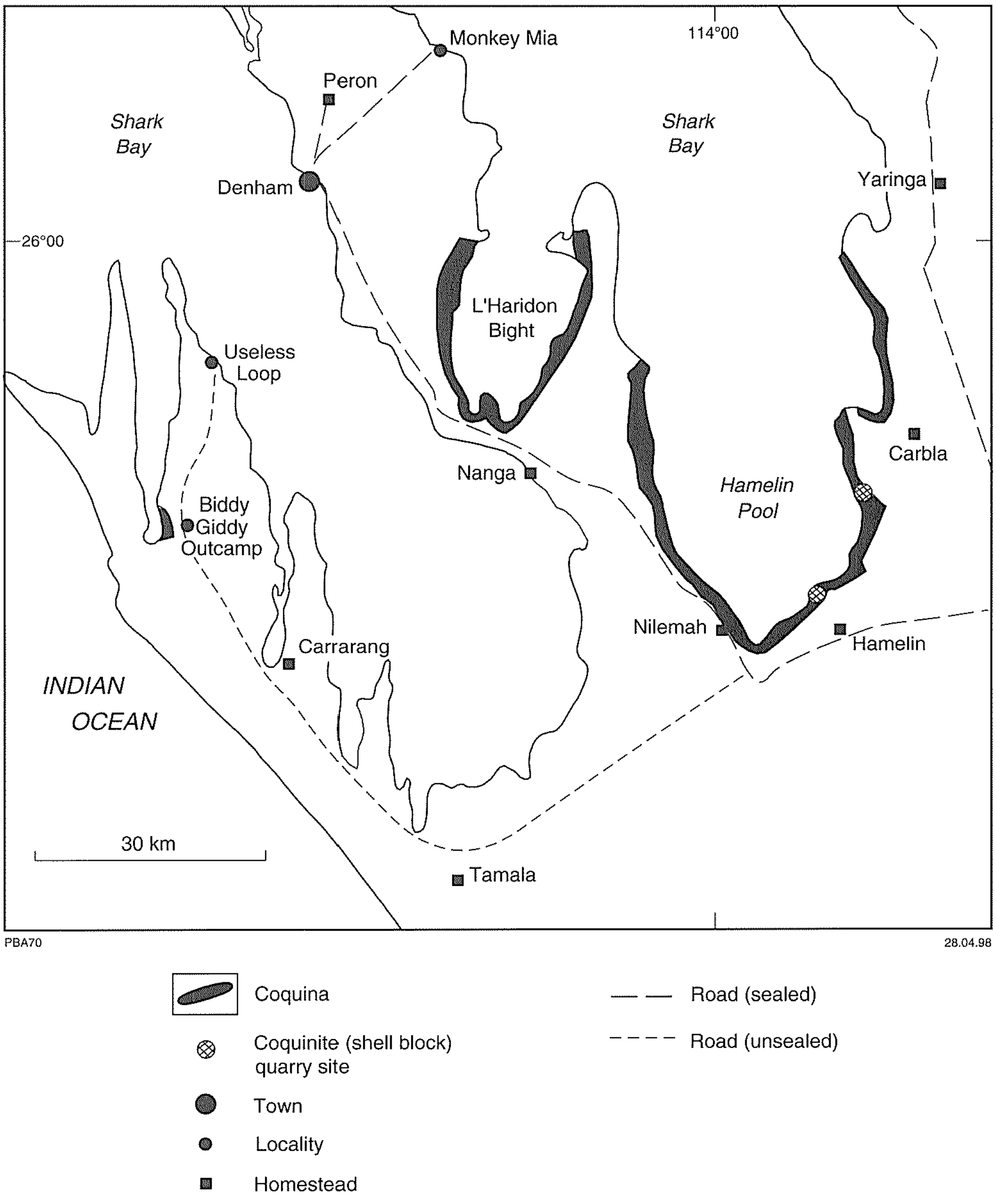


Figure 31. Distribution of Hamelin Coquina beach ridges at Shark Bay (after Townsend, 1996)

Mining Pty Ltd, with reported 1994–95 production of 1552 t. The material mined is used for concrete aggregate and sand, landscaping supplies, roadbase, and as shell grit for poultry. Other than as poultry shell grit, which is bagged and shipped to markets outside the region, the coquina is only being used locally for landscaping (Fig. 32), due to lack of other suitable raw materials.

Assuming similar quantities of coquina per kilometre as found in the mining areas, Townsend (1996) estimated that there is approximately 0.7 Mt of coquina in the beach ridges of the eastern margin of L'Haridon Bight.

Coquina is also quarried near Biddy Giddy Outcamp for landscaping at Useless Loop. *Ad hoc* mining of coquinite also occurs near the telegraph station at the southern end of Hamelin Pool (Fig. 31) (Townsend, 1996). Van de Graaff et al. (1983) reported quarrying of coquinite for building stone near the telegraph station and at Carbla Point. Unconsolidated Bibra Limestone from the area has also been used for road construction.

The extraction of raw materials in the Shark Bay area was essentially uncontrolled until the mid-1980s and many old pits remain open and unrehabilitated. However, adoption of the Western Australian Environmental Protection Act, 1986 and World Heritage listing has made operators in the area aware of their responsibilities in relation to environmental protection and rehabilitation of mine and quarry sites.

A grab sample of loose shell material from a location 1 km northwest of the Hamelin Pool telegraph station contained 53.6% CaO (95.7% $CaCO_3$), 0.3% MgO (0.6% $MgCO_3$), and 0.14% total iron oxide. Another sample from a large mass of dune material on the western shoreline of Hamelin Pool, about 1 km southeast of the abandoned Nilemah Homestead, contained 42.8% CaO

Figure 32. Photograph of coquinite blocks used in the construction and repair of historic buildings in Denham (after Townsend, 1996)

(76.4% $CaCO_3$), 0.8% MgO (1.7% $MgCO_3$), and 0.12% total iron. Simpson (1948) analysed a typical specimen of shell material that contained 55.9% CaO (99.8% $CaCO_3$), 0.1% MgO (0.2% $MgCO_3$), and 0.3% Al_2O_3 plus Fe_2O_3.

Onslow coast

Although large deposits of promising high-grade limesand were discovered off the Onslow coast by Ocean Mining A.G. in 1967, the project was abandoned due to the high cost of mining and an inability to compete with other sources (van de Graaff et al., 1982). A typical analysis of the sand was 47.5% CaO (84.8% $CaCO_3$) and 87.8% (Ca, Fe, Mg)CO_3. The highest quality recorded was 50.5% CaO (90.2% $CaCO_3$), 93.6% (Ca, Fe, Mg)CO_3, and 89.9% $CaCO_3$.

Kennedy Range

Trealla Limestone, Toolonga Calcilutite, and calcrete have been quarried for road aggregate in a number of locations on KENNEDY RANGE (Hocking et al., 1985b).

Eucla Basin

The Eucla Basin is located on the southern coast of the Australian continent, extending from near Israelite Bay in Western Australia to Fowlers Bay in South Australia. The onshore part of the basin is bounded by the Albany–Fraser Orogen to the west, the Officer Basin to the north, and the Gawler Craton to the east. The Eucla Basin consists of a number of major physiographic units (Lowry, 1970a) that are delineated in Figure 33.

Regional geology

Sediments in the Eucla Basin range in age from Jurassic to Holocene. The lower part of the basin consists of Loongana Sandstone and an unnamed sequence of siltstone and shale, interbedded with fine-grained sandstone of Jurassic to Early Cretaceous age. Overlying these are Cretaceous rocks belonging to the Madura, Toondi, and Nurina Formations (Hocking, 1990).

Both the Madura Formation and the disconformably overlying Toondi Formation consist of fine-grained siliciclastic, generally monotonous sequences that extend throughout the Eucla Basin. The Nurina Formation, which appears to be restricted to the central portion of the Eucla Basin and disconformably overlies the Toondi Formation, consists of glauconitic sandstone and greensand, with glauconitic sandy siltstone.

The Early Eocene Hampton Sandstone, which disconformably overlies the Toondi Formation, consists of limonite-stained sandstone and minor conglomerate. Rocks overlying the Hampton Sandstone consist of

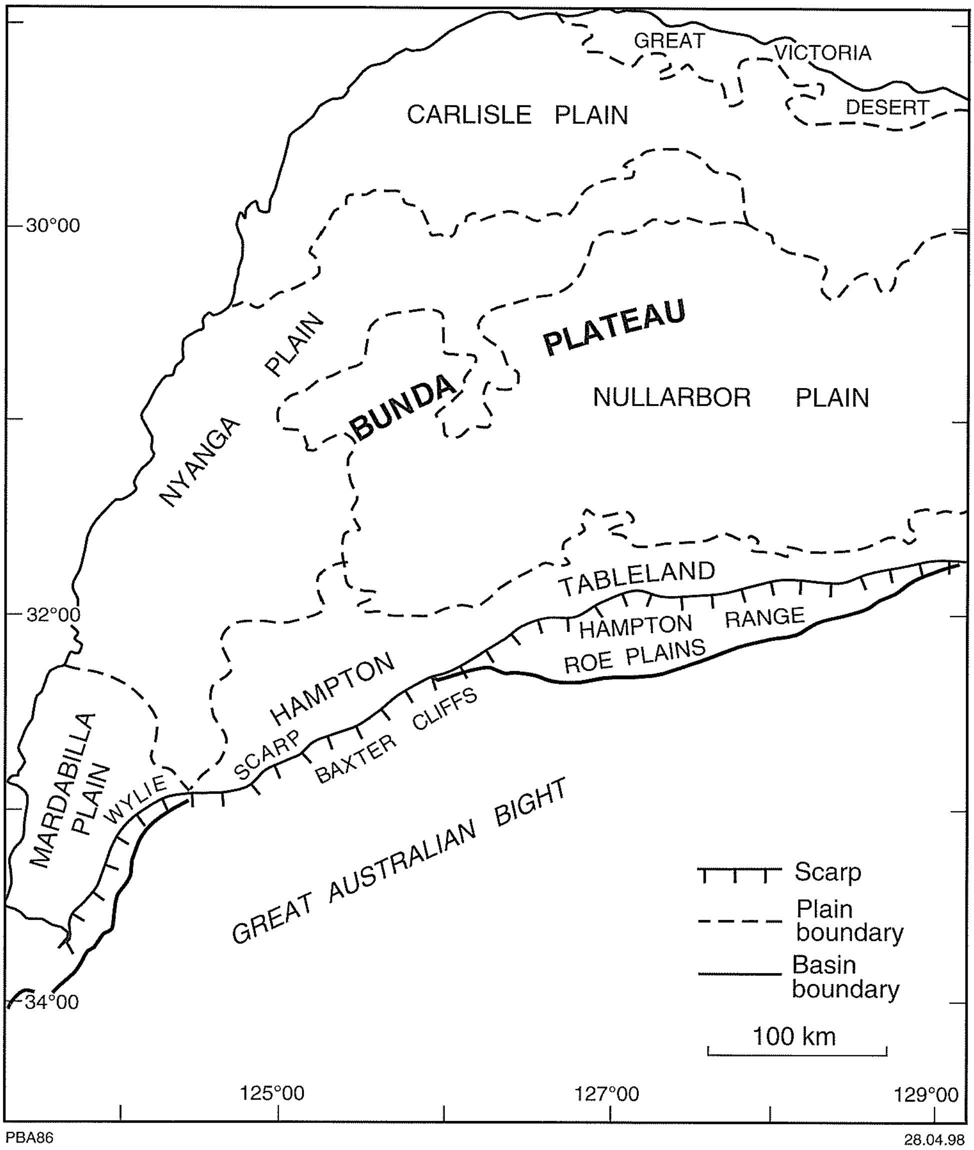


Figure 33. Major physiographic units of the Eucla Basin (after Lowry, 1970a)

mostly limestone, calcarenite, and minor sandstone and siltstone.

Limestone formations

The major limestone formations of the Eucla Basin (Fig. 34) are as follows:

Age	*Unit*
Quaternary	Roe Calcarenite
Late Tertiary and Quaternary	Recrystallized Nullarbor Limestone Kankar
Miocene	Nullarbor Limestone Mullamulang Limestone Member Abrakurrie Limestone
Eocene	Toolinna Limestone Wilson Bluff Limestone

Wilson Bluff Limestone

The Wilson Bluff Limestone disconformably overlies the Madura Formation. It also overlies, and locally grades laterally into, the Early Eocene Hampton Sandstone. In the Madura area, the Wilson Bluff Limestone is overlain disconformably by the Abrakurrie Limestone, and by the Nullarbor Limestone towards the basin margin. In some localities, the upper parts of the Wilson Bluff Limestone grade into the Toolinna Limestone.

The limestone, consisting mainly of bryozoan calcarenite with a lime-mud matrix, also contains intercalations of clay, silt and fine-grained sand, marl, and chert nodules. Ludbrook (1960, 1963) inferred an age of Middle to Late Eocene for the unit, based on foraminiferal evidence. The upper parts of the formation contain Late Eocene echinoids, brachiopods, and pelecypods (Lowry, 1970a), and Middle Eocene

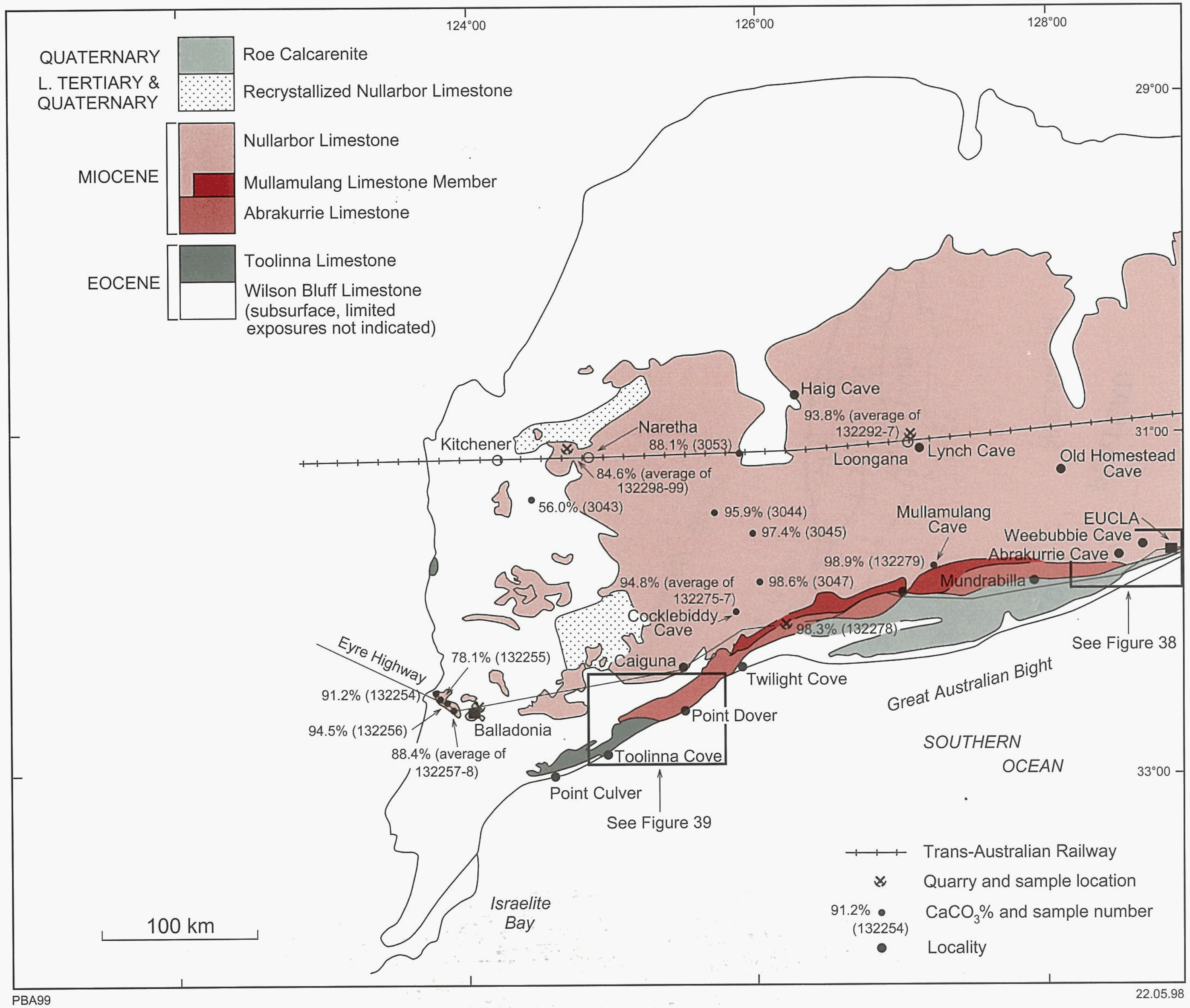


Figure 34. Major limestone units in the Eucla Basin

foraminiferids have been recovered from limestone in the southern part of the basin (Ludbrook, 1963).

The type section for the unit is at the eastern end of Wilson Bluff in South Australia (Lat. 31°41'S, Long. 129°02'E), and the unit reaches a maximum thickness of about 300 m at a location south of Madura. The Wilson Bluff Limestone, as indicated by a number of boreholes, extends widely beneath the surface in most parts of the basin, but it is poorly exposed. Outcrops are found near sea level in the coastal cliffs at Wilson Bluff and between Point Culver and Point Dover, and on the southwestern part of the Baxter Cliffs (Lowry, 1970b). The unit is also exposed on the walls of Cocklebiddy Cave (Lowry, 1968; Lowry, 1970c), Haig Cave (Lowry, 1970d), Weebubbie Cave, Abrakurrie Cave, and Winbirra Cave (Lowry, 1971).

The Wilson Bluff Limestone was deposited on a wide continental shelf under conditions of normal marine salinity (Lowry, 1970a).

Toolinna Limestone

The Toolinna Limestone, which overlies and grades into the Wilson Bluff Limestone, occurs in the southwestern part of the Eucla Basin (Fig. 34). It is of the same age as the upper part of the Wilson Bluff Limestone, but is distinguished from the latter by larger grain size and better sorting. At the western margin of the basin, Toolinna Limestone unconformably overlies Proterozoic rocks.

Commonly cross-bedded, well sorted, and porous to indurated, the Toolinna Limestone consists of calcarenite and calcirudite. The unit is bryozoan rich, with an abundant shelly fauna consisting of echinoids, brachiopods, and pelecypods. Overall, the fossil assemblages are similar to those in the upper part of the Wilson Bluff Limestone (Lowry, 1970a).

In its type section at Toolinna Cove, the Toolina Limestone is 55 m thick, which is typical of the 55–70 m thickness of the unit. The limestone is exposed in the Baxter Cliffs along the seaward part of the Bunda Plateau southwest of Point Dover, and is also present in the spoil of wells and dams at Booanya Rock, North Rocks, Kullingobinya No. 2 Dam, and New Pioneer tank. A weathered outcrop occurs in a salt lake approximately 14 km southwest of Booanya Rock (Doepel and Lowry, 1970a, b).

The Toolinna Limestone was deposited along the inner part of a wide continental shelf with strong bottom currents (Lowry, 1970a).

Abrakurrie Limestone

The Abrakurrie Limestone disconformably overlies the Toolinna Limestone in the vicinity of Point Dover, and the Wilson Bluff Limestone in other areas. In most areas, the Mullamulang Limestone Member of the Nullarbor Limestone disconformably overlies the Abrakurrie Limestone.

The Abrakurrie Limestone is generally a coarse-grained calcarenite, but ranges from a granular calcirudite to a micritic fine-grained calcarenite. In outcrop, the unit is generally porous, yellowish, bryozoan-rich, medium- to coarse-grained, and commonly cross-bedded. Brachiopods and pelecypods are common throughout the formation, and rod-shaped segments of bryozoan zoaria are the chief skeletal components. A rich echinoid fauna indicates an Early Miocene or Oligocene age, but the absence of distinctive Oligocene fossils suggests an Early Miocene age (Lowry, 1970a,c).

The unit, best developed in the central part of the basin, is exposed in numerous caves, on parts of the Hampton Tableland, in the Hampton Range and Baxter Cliffs, as low coastal cliffs at Scorpion Bight and east of Twilight Cove, and as reefs along the coast. Onshore, it is restricted to an arcuate area extending from Toolinna Cove, through Loongana, to Eucla (Hocking, 1990). The maximum thickness of the limestone is over 90 m near Madura, and the type section is on the west wall of Abrakurrie Cave (Lat. 31°39'20"S, Long. 128°29'20"E).

The Abrakurrie Limestone was deposited in a shallow open-shelf environment with normal marine salinity and strong bottom currents (Lowry, 1970a).

Nullarbor Limestone

The Nullarbor Limestone, disconformably overlying the Abrakurrie Limestone, is the youngest Tertiary marine limestone in the Eucla Basin. The Mullamulang Limestone Member that occurs at the base of the Nullarbor Limestone Formation overlies the Abrakurrie Limestone over most of the basin. However, in the western and southwestern parts of the basin the Nullarbor Limestone disconformably overlies the Toolinna Limestone, and further north grades laterally into the Colville Sandstone. The Nullarbor Limestone is overlain by a variety of soils, dunes, and other Quaternary deposits.

The Nullarbor Limestone is generally a hard, grey or yellow, micritic, fine- to medium-grained calcarenite, with rare cross-bedding. Foraminiferids and coralline algae form the principal skeletal components of the limestone, while bryozoans and echinoid fragments are minor components. Pelecypods and gastropods are locally abundant. A medium- to coarse-grained foraminiferal calcarenite variety of the Nullarbor Limestone, with interclasts as a major component, occurs mostly in the northern part of the Nullarbor Plain. The interclasts are formed of fine- to coarse-grained foraminiferal calcarenite similar to that found elsewhere in the formation. Another facies variation of the Nullarbor Limestone, developed largely in the southern part of the plateau, is a medium- to coarse-grained poorly sorted calcarenite.

The Nullarbor Limestone outcrops over large areas of the Bunda Plateau, but the formation is altogether absent over much of the southern edge of the plateau. The thinning or absence of the formation, southwards towards the coast, is primarily due to the increased erosion caused by higher rainfall in this region. The unit is 14 m thick at its type section approximately 2 km east of the Wilson Bluff trigonometrical station (Lowry, 1968), but in Old Homestead and Cocklebiddy Caves the Nullarbor Limestone reaches its maximum thickness of approximately 30 m (Lowry, 1970c).

The Nullarbor Limestone was deposited in a shallow sea of normal salinity under conditions of weak bottom currents.

Mullamulang Limestone Member

The Mullamulang Limestone Member is an algal limestone developed at the base of the Nullarbor Limestone. This unit is present in the central portion of the Eucla Basin, and outcrops over parts of the Hampton Tableland and on the Hampton Range. It is well exposed on the walls of many of the large collapse dolines. Fossil algae are used to distinguish this unit, which contains nodular red forms, from the Nullarbor Limestone that contains mainly articulated red forms.

The type section at Mullamulang Cave (Lat. 31°43'S, Long. 127°14'E) is about 6m thick, but the unit reaches 15 m in thickness in the Madura area (Lowry, 1972).

Kankar

Kankar occurs as a hard, cemented deposit of calcium carbonate that forms part of the soil profile in the Eucla Basin. The stratigraphic relationships of kankar suggest that its age ranges from Pliocene or Pleistocene to Recent. Lowry (1970a) described six types of kankar, depending on its lithological association. These are as follows:

(a) Kankar in the residual clay of the Nyanga Plain — occurs both as sheet kankar and 'glaebules' of kankar within alternating layers of clay and rubbly clay about 4.5 m thick, underlying the Nyanga Plain. In most areas, the upper parts of kankar horizons consist of hard tabular horizontal slabs grading downwards into rubbly cobble- to granule-sized 'glaebules' of kankar set in clay. The term 'glaebule' was used by Brewer and Sleeman (1964) for discrete, approximately equidimensional carbonate bodies set in a clay, regardless of their internal structure. The kankar consists of a mosaic of calcite crystals, mostly 1 to 3 mm in size, with a scattering of crystals up to 10 mm.

(b) Kankar developed in dune sand — is developed close to the surface of many coastal dunes, usually in the form of sandy, grey to yellow-brown, cobble- to pebble-sized 'glaebules' concentrated in a layer less than a metre thick.

(c) Kankar developed over Toolinna Limestone on the Mardabilla Plain — occurs with clay in a layer up to 3 m thick in many parts of the southwest of the Eucla Basin. The kankar is usually in the form of brown to grey 'glaebules' up to 15 cm across, with concentric laminae or a crude oolitic texture.

(d) Kankar in residual sand and clay on the Carlisle Plain and Hampton Tableland — is generally covered by clayey sand and soil less than a metre in thickness, and is developed in residual sand and clay over the Nullarbor Limestone and other rocks of the Carlisle Plain and Hampton Tableland. In northeastern parts of NARETHA, the northern part of BALLADONIA, and the northwestern part of MADURA-BURNABBIE, the Nullarbor Limestone is overlain by a layer of residual calcareous clay containing a kankar layer about 2 m thick. Kankar of this type also occurs on the northern and western parts of LOONGANA, in areas on the southern part of JUBILEE, on the northern part of ZANTHUS, and on the southwestern part of MASON. In all these areas, kankar occurs as slabs and cobbles, with a complex internal structure that is characteristically oolitic or pisolitic (Doepel and Lowry, 1970a,b; Lowry, 1970a–e, 1972; van de Graaff, 1974a).

(e) Kankar developed in colluvial clay — occurs as 'glaebules' 2 to 20 mm in diameter that are common in many flats of colluvial clay on the Nullarbor Plain and Hampton Tableland. The kankar is reddish-brown, with hard 'glaebules' in the upper part and soft plates in the lower section.

(f) Kankar in veins in Tertiary limestone — is developed along fractures in the limestone on the Bunda Plateau. The veins contain variably lithified material, ranging from soft clay to hard kankar.

Recrystallized Nullarbor Limestone

The Nullarbor Limestone, where it has been recrystallized in some areas near the surface of the Bunda Plateau, probably during the Late Tertiary, consists of microcrystalline limestone with little or no trace of the original texture. In other localities, recrystallized limestone varies from pale, porous, and friable, to hard and compact, occurring as featureless limestone, limestone with irregular light and dark-brown patches, and limestone with a texture resembling well-rounded calcarenite (Lowry, 1970c; Bunting and van de Graaff, 1977).

Roe Calcarenite

The Roe Calcarenite (Lowry, 1971), a shelly calcarenite developed at or near the surface of the Roe Plains, overlies the Abrakurrie Limestone beneath the central and western parts of the Roe Plains, and the Wilson Bluff Limestone beneath the eastern part. Coastal sand dunes overlie the calcarenite at the western end of the plain and around the coast, while at the foot of the Hampton Range, and in many other areas, the unit is covered with clayey soil containing kankar nodules.

The Roe Calcarenite is largely composed of fragmented algae, foraminiferids, mollusca, and echinoids. Ludbrook (1958a,b) suggested that the age of the calcarenite was early or middle Pleistocene because of the presence of living as well as extinct species of molluscs.

While rarely exposed at the surface, the Roe Calcarenite underlies most of the Roe Plain. Where it is not exposed, subsurface presence of the unit is generally inferred by the occurrence of marine molluscs, either loose in the soil or cemented in kankar. It is best exposed in shallow excavation pits for road-building material, along the Eyre Highway. The type section, 1.4 m thick, is an exposure in the doline of Nurina Cave (Lat. 32°01'S, Long. 127°00'E), about 13 km south of Madura. In Transcontinental Railway No. 1 Bore (Ludbrook, 1958a), the unit reaches its maximum thickness of about 7 m.

Limestone deposits

Limestone resources in the Eucla Basin, easily exceeding several billion tonnes of high-grade material, can be considered as the largest in Western Australia. However, the only major mining operation is limestone quarried for production of lime at Loongana, although in the past Nullarbor Limestone has also been crushed for rail ballast in these quarries (Lowry, 1970d) and near Reid (Lowry, 1970f).

The other economic usage of the limestone is as roadbase material. Loam that contains kankar has been excavated at numerous locations for roadbase material, and crushed limestone has been used as road metal to surface the Eyre Highway (Doepel and Lowry, 1970a). Hardened Abrakurrie Limestone, from near the surface of the plateau and on top of the Hampton Range at Kuthala Pass, has been quarried for road metal (Lowry, 1971, 1972).

Very little information exists on the quality and quantity of limestone in the Eucla Basin, although limestone is widespread within a large surface area of nearly 425 km × 200 km (Fig. 34). Exploration activities are limited to those carried out in the Kitchener area in 1979 by Lenkane Exploration Pty Ltd, exploration of the coastal region between Israelite Bay and Point Culver, and between Twilight Cove and Eucla, by BHP Minerals Ltd in the early 1960s, and the ongoing exploration activities by Loongana Lime Pty Ltd.

Samples analysed by the author from a number of quarries along the Eyre Highway, and from caves, outcrops, and rockholes in the Eucla Basin, suggest that high-grade limestones are widespread within the Nullarbor, Abrakurrie, and Toolinna units. In many localities, the limestones in these units are fresh and occur beneath a thin soil cover, often less than a metre thick.

Recrystallized Nullarbor Limestone is unsuitable for lime production because it tends to disintegrate during burning and choke the fire (Lowry, 1970a).

Loongana

History

The limestone quarry currently in operation at Loongana, 540 km east of Kalgoorlie (Fig. 34), was originally opened as a railway-ballast quarry. However, with the introduction of concrete sleepers the quarry was abandoned because more abrasion-resistant material, such as granite, was preferred.

In December 1989, the quarry was reopened by Loongana Lime Pty Ltd to mine limestone for the manufacture of quicklime. In 1991, this company was sold to Melcann Pty Ltd, a subsidiary of Australian Cement Limited, and in March of the same year the new company sought assistance from David Mitchell Limited (which had limestone operations in Victoria and other states) to improve kiln design and quarrying operations. Later developments resulted in David Mitchell Limited controlling Loongana Lime Pty Ltd.

Mining

Open-cut mining has proceeded northwards from the old quarry located by the railway, as the material in the old quarry was found to be of lower grade. Mining depth is generally restricted to about 7 m because of the lower quality of the material below. Loamy material, forming overburden, is generally less than 1.5 m thick.

Limestone quality

The area consists of fine- to medium-grained, micritic Nullarbor Limestone, with grains composed of foraminiferids and calcareous algae. Locally, the limestone is highly fossiliferous, fine to medium grained, creamy brown to pinkish, hard, and massive.

Pockets of ferruginous clay, associated with limestone within quarry faces, are generally avoided during mining. Massive high-quality limestone below the overburden generally extends to a depth of about 7 m, below which is a layer of generally cavernous, clayey, and highly fossiliferous material (Fig. 35) considered unsuitable for mining. Ferruginous clayey pockets also occur locally within the high-grade material (Fig. 36).

Nine samples collected from the mine area contained 87.25 to 96.62% $CaCO_3$ (48.86 to 54.11% CaO), with an average of 93.78%. $MgCO_3$ ranged from 1.51 to 2.36%, averaging 1.93% (Table 34).

Thomas (1993) noted that improved quarrying methods have enabled the company to upgrade the CaO content of their burnt lime from 78–80% to 83–85% available CaO.

Lime manufacture

Quicklime at Loongana is produced from a vertical-shaft mixed-feed kiln (Fig. 36) capable of producing around 30 000 t per annum. The limestone, after blending with coke fuel at a rate of 83 kg of coke per tonne of limestone, is fed by a conveyor into a charging hopper at the top of the kiln. The calcination temperature is around 1100°C. Quicklime is discharged through a set of 1100 mm-aperture clam gates at the end of the kiln. After an initial quality inspection, the lime is ground to a 100% passing 2.36 mm to yield the final product. The

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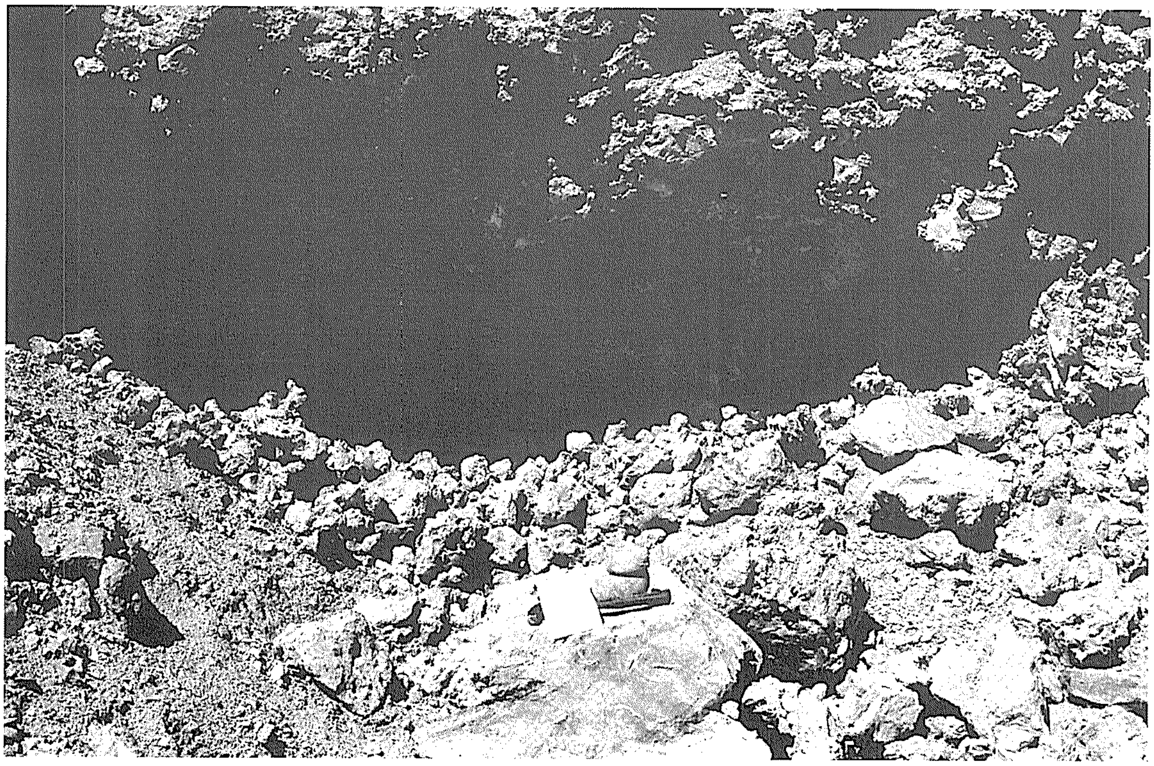

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Figure 35. Photographs of limestone in a quarry face at the Loongana mine
Top: High-quality limestone
Lower: Cavernous and fossiliferous layer below high-quality limestone

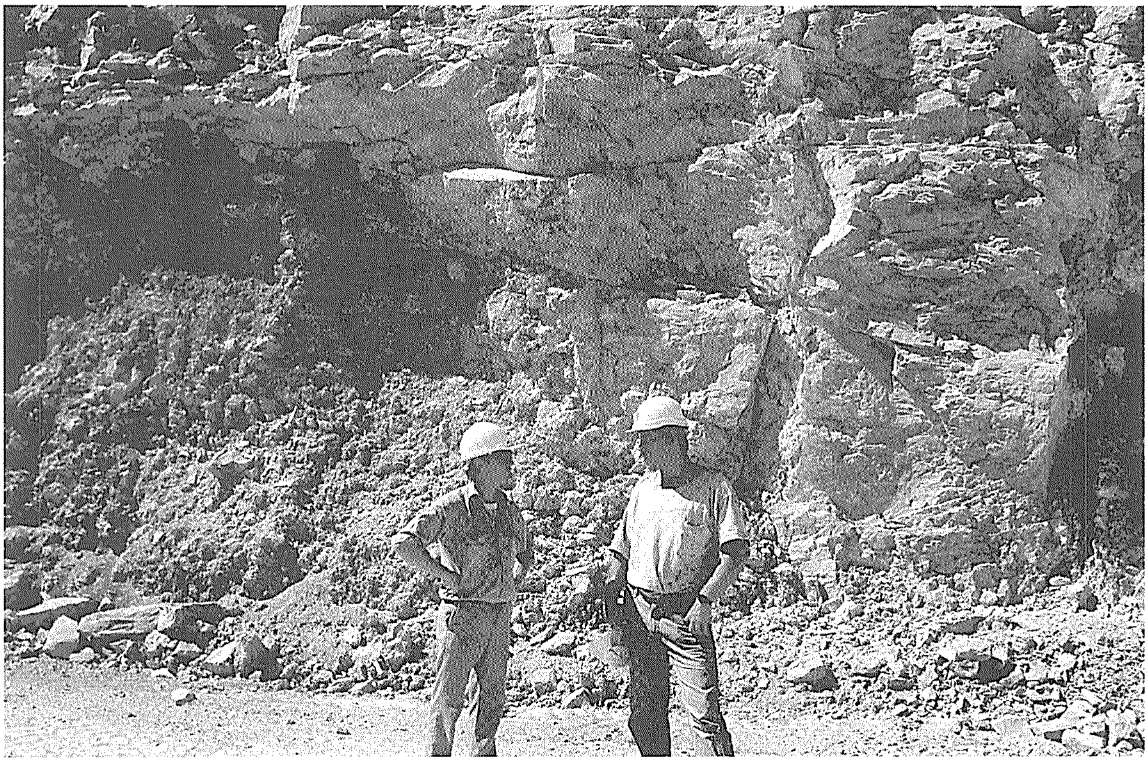

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Figure 36. Photographs of the Loongana mine
Top: Pockets of clay within high-quality limestone on the quarry face
Lower: Verticle lime kiln

Table 34. Chemical analyses of limestone from the Loongana mine

Sample no.	*132292*	*132293*	*132294*	*132295*	*132296*	*132297*
			Percentage			
SiO_2	0.41	5.24	1.60	2.00	0.42	0.40
TiO_2	0.01	0.07	0.03	0.03	<0.01	0.01
Al_2O_3	0.15	1.48	0.43	0.53	0.07	0.16
Fe_2O_3	0.12	0.53	0.19	0.21	0.04	0.09
MnO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
MgO	0.72	1.13	1.13	0.97	0.83	0.76
CaO	54.02	48.86	52.31	51.84	54.11	53.98
Na_2O	0.06	0.09	0.05	0.07	0.04	0.05
K_2O	0.02	0.18	0.04	0.06	<0.01	0.03
P_2O_5	0.01	0.01	0.01	0.02	0.01	0.01
LOI	43.47	41.33	43.49	42.88	43.23	43.60
Total	**98.99**	**98.92**	**99.28**	**98.61**	**98.75**	**99.09**
CO_2	40.40	36.40	41.90	40.70	42.00	40.80
			Parts per million			
As	<0.5	12	8.4	2.7	2.7	5.5
Ba	5	21	14	28	<5	<5
Be	0.3	0.5	<0.2	0.3	0.3	0.6
Ce	1.47	4.7	1.91	2.6	1.04	1.24
Cr	9	13	7	8	6	3
Ga	0.52	2.4	0.75	0.91	0.33	0.39
La	1.85	6.8	3.5	3.6	1.31	2.1
Nb	0.6	1.8	0.6	0.7	<0.5	<0.5
Rb	1.06	4.7	1.84	1.96	0.38	0.81
S	0.01	0.01	0.01	0.02	0.01	0.01
Sn	0.2	0.4	0.2	0.3	0.1	0.2
Sr	831	504	800	761	784	789
Th	0.43	1.83	0.75	0.96	0.28	0.45
U	1.71	1.4	1.51	2.2	1.12	1.65
V	26	15	6	10	<2	<2
W	0.2	1.2	0.3	0.3	0.2	0.2

NOTE: 132292 Loongana mine, Lat. 30°56'20"S, Long. 127°02'24"E, high-quality limestone, mill feed from stockpiles
132293 Loongana mine, Lat. 30°56'20"S, Long. 127°02'24"E, impure limestone mixed with mill feed from stockpiles
132294 Loongana mine, Lat. 30°56'20"S, Long. 127°02'24"E, high-grade limestone (-4 mm fraction)
132296 Loongana quarry, Lat. 30°56'20"S, Long. 127°02'24"E, high-grade limestone
132297 Loongana quarry, Lat. 30°56'15"S, Long. 127°02'24"E, high-grade limestone

company intends to introduce a bottom discharge fluidized-bed calciner, involving a kiln design unique to the lime industry, which is expected to increase the production of lime to about 65 000 t per annum (Louthean, 1995).

Markets

Rail is used to transport the lime to market. Clients using Loongana lime include Western Mining Corporation Holdings Limited, Coolgardie Gold NL, and Great Central Mines NL.

Kitchener

In 1979, Lenkane Exploration Pty Ltd explored for high-grade limestone in an area approximately 20 km southeast of Kitchener (Fig. 34). The exploration program involved the drilling of 20 widely spaced holes, averaging 2.4 m in depth, six of which bottomed in bryozoan limesand, three in kankar, and three in probable Nullarbor Limestone. Another 13 holes, drilled in the same area, penetrated the limestone sequence of Nullarbor, Toolinna, and Wilson Bluff Limestones. Further exploration involving costeaning indicated that the grade of the Toolinna Limestone is variable, having an average insoluble content of about 20%, with 90 to 95% of this material being in the minus 0.25 mm fraction. However, simple scrubbing and screening could upgrade the material to greater than 94% $CaCO_3$.

Another program of drilling and sampling, carried out in 1980, indicated that the Toolinna Limestone which occurred below an overburden depth of 2–5 m was more than 2 m thick and averaged about 90% $CaCO_3$. In 1992, Loongana Lime Pty Ltd drilled 50 holes to 10 m depth. The inferred resource from the area explored was around 550 000 t, with an average thickness of 3.8 m. The overburden volume was estimated at 210 000 m^3 (Trask, 1980; Cochrane, 1992).

Southern coastal region of the Eucla Basin

In 1962, BHP Minerals explored the coastal region between Israelite Bay and Point Culver, and also between

Table 35. Calcium contents of Eucla Basin limestones

Limestone unit	*No. of samples*	*%CaO (range)*	*%CaO (average)*	*%$CaCO_3$ (average)*
Nullarbor	20	43.73–55.37	51.54	92.03
Abrakurrie	10	50.46–54.91	54.08	96.57
Toolinna	5	52.02–55.58	53.90	96.24
Wilson Bluff	4	51.11–54.61	53.33	95.23

Twilight Cove and Eucla, to identify limestone for the steelmaking industry (BHP Minerals Ltd, 1963).

Preliminary surveys indicated the presence of high-grade limestone, suitable for use in the steel industry, along the western coast of the Great Australian Bight. Assays indicated that the Nullarbor Limestone was of high quality throughout, but tests for stability after calcination indicated a wider variation in grade than anticipated. The Wilson Bluff Limestone from Point Culver yielded unexpectedly high silica assays, but it was not certain whether this was due to inherent silica or contamination from overlying sands. Assays of limesand indicated that there were no areas of high-grade limesand along the coast.

Further work showed that Nullarbor Limestone from Point Culver had an average composition of around 54.2% CaO, 0.5% MgO, and 0.5% SiO_2, and that from Point Dover was around 54.2% CaO, 0.4% MgO, and 0.4% SiO_2. Nullarbor Limestone samples from Twilight Cove contained 54.2% CaO, 0.3% MgO, and 0.4% SiO_2, while Wilson Bluff Limestone from the same location contained 54.6% CaO, 0.3% MgO, and 0.2% SiO_2.

Resources of high-grade limestone from the Nullarbor Limestone are enormous, as the unit extends over thousands of square kilometres. On the assumption of an average 15 m thickness, resources of limestone were estimated to be around 40 Mt/km^2. Resources from the Wilson Bluff Limestone, calculated on the basis of an average mineable thickness of 30 m, were 65 Mt/km^2.

The conclusions at the end of the BHP Minerals exploration program were:

1. Limesand deposits of sufficient purity to be of economic value were not found;
2. The Nullarbor Limestone is of high grade throughout the area surveyed;
3. The physical properties of the Nullarbor Limestone appear to vary between centres sampled, with Point Culver offering the most suitable for steel industry requirements;
4. The Wilson Bluff Limestone, the thickest limestone unit, is a high-grade soft limestone that could possibly be used as a sinter additive, or in the manufacture of cement;
5. It is desirable to confirm the grade and thickness of the Nullarbor and Wilson Bluff Limestones at Point Culver by drilling.

Reconnaissance sampling in the Eucla Basin

Reconnaissance sampling carried out in parts of the Eucla Basin indicates the presence of high-quality Nullarbor, Abrakurrie, Toolinna, and Wilson Bluff Limestones suitable for lime and cement manufacture. A summary of CaO abundances within these limestone units is given in Table 35.

Chemical analyses for major elements were determined for samples collected from Kuthala Pass, Chowilla Doline, Naliwoodin Rockhole, Baxter Memorial, and Abrakurrie, Cocklebiddy, Mullamulang, and Weebubbie Caves (Figs 34, 37–39). These analyses are given in Table 36.

A number of samples were analysed for major and also trace elements. These were collected from Balladonia, Naretha, Caiguna, Toolinna Cove, and from around Eucla. These analyses are given in Table 37.

Analyses of five samples of 'Eucla Limestone' (?Nullarbor Limestone), collected by Maitland (1919) from a number of locations between Haig and Cocklebiddy Caves (Fig. 34), are given in Table 38.

Brief descriptions of the more important localities from which samples were collected are given below.

Balladonia

Scattered, small outcrops of Nullarbor Limestone occur east of the Balladonia roadhouse (Fig. 34). Some outcrops appear to be partly weathered, whereas in others there is minor development of kankar. Limestone from a quarry located south of the highway (sample locations 132257–58) is used as roadbase material.

Caiguna

Nullarbor Limestone from a quarry located approximately 42 km west of Caiguna (sample locations 132259–60 shown on Figure 39) is used as roadbase material. The limestone is fine grained, massive, fossiliferous, and exhibits vertical and horizontal fractures.

Baxter Memorial

The Abrakurrie Limestone is widespread in the coastal belt around the Baxter Memorial, located at the top of the coastal cliff approximately 30 km south of Caiguna. At Baxter Memorial, the Abrakurrie Limestone is fine to medium grained (occasionally coarse grained), massive, fossiliferous, pinkish to salmon-coloured, and generally fresh. There are extensive outcrops of limestone along the track from the Baxter Memorial to Toolinna Cove.

Table 36. Major-element analyses of limestones from the Eucla Basin

Sample no.	*Latitude (S)*	*Longitude (E)*	*Description*	*SiO_2*	*TiO_2*	*Al_2O_3*	*Fe_2O_3*	*MnO*	*MgO*	*CaO*	*Na_2O*	*K_2O*	*P_2O_5*	*LOI*	***Total***	*CO_2*
										Percentage						
Abrakurrie Cave																
132289	31°39'27"	128°29'19"	Fine-grained, micritic, cream to salmon-coloured fossiliferous ?Wilson Bluff Limestone	0.77	0.01	0.11	0.07	<0.01	0.37	54.61	0.11	0.07	0.16	43.13	**99.41**	31.00
132290	31°39'27"	128°29'19"	Fine-grained, cream to greyish Abrakurrie Limestone	0.36	0.01	0.04	<0.01	<0.01	0.74	54.43	0.10	0.04	0.05	43.83	**99.60**	38.50
Kuthala Pass																
132291	31°48'28"	128°13'06"	Cream to grey, medium-grained, fossiliferous, massive Abrakurrie Limestone from a quarry	0.15	0.01	0.01	0.06	0.01	0.33	54.91	0.02	<0.01	0.03	43.47	**99.00**	42.00
Cocklebiddy Cave and east of Cocklebiddy roadhouse																
132275	31°58'01"	125°54'51"	Medium-grained, pinkish to cream, massive ?Nullarbor Limestone (from boulders at the lower level of the cave)	1.62	0.01	0.07	0.03	<0.01	0.46	54.09	0.07	0.03	0.05	43.06	**99.49**	41.20
132276	31°58'01"	125°54'51"	Medium-grained, pinkish to cream, massive Nullarbor Limestone (from boulders at the middle level of the cave)	0.57	0.01	0.06	0.02	<0.01	2.87	51.91	0.10	0.05	0.03	44.00	**99.62**	43.90
132277	31°58'01"	125°54'51"	Medium-grained, pinkish to cream, massive Nullarbor Limestone from an outcrop at the surface, near the entrance of the cave	1.83	<0.01	0.05	<0.01	<0.01	0.89	53.30	0.08	0.03	0.03	42.91	**99.12**	43.70
132278	32°01'32"	126°11'07"	Medium-grained, pinkish to cream, fossiliferous, fresh Nullarbor Limestone	0.35	<0.01	0.02	0.09	<0.01	0.39	55.04	0.01	0.02	0.03	43.27	**99.22**	39.20
Mullamulang Cave																
132279	31°43'31"	127°13'43"	Pinkish to salmon-coloured, fine- to medium-grained, fossiliferous Nullarbor Limestone (?Mullamulang Limestone Member)	0.21	<0.01	0.01	0.05	<0.01	0.35	55.37	0.02	0.02	0.04	42.78	**98.85**	42.00
Chowilla Doline																
132288	31°38'39"	128°29'01"	Medium-grained, pinkish to salmon-coloured, massive Nullarbor Limestone	2.11	0.01	0.01	<0.01	<0.01	1.39	52.47	0.07	0.03	0.04	42.75	**98.88**	39.00
Weebubbie Cave																
132280	31°39'21"	128°46'26"	Fine- to medium-grained Wilson Bluff Limestone from the lower level of the cave	0.50	<0.01	<0.01	0.01	<0.01	0.32	51.11	0.24	0.04	0.06	36.21	**88.49**	33.00
132281	31°39'21"	128°46'26"	Fine- to medium-grained Wilson Bluff Limestone from the middle level of the cave	0.66	0.01	0.07	0.05	0.01	0.37	54.55	0.33	0.06	0.15	43.40	**99.66**	34.10

Table 36. (continued)

Sample no.	*Latitude (S)*	*Longitude (E)*	*Description*	SiO_2	TiO_2	Al_2O_3	Fe_2O_3	*MnO*	*MgO*	*CaO*	Na_2O	K_2O	P_2O_5	*LOI*	***Total***	CO_2
									Percentage							
Weebubbie Cave (cont.)																
132282	31°39'21"	128°46'26"	Fine-grained Nullarbor Limestone from a surface outcrop near the entrance of the cave	0.96	0.02	0.20	0.06	<0.01	0.56	54.16	0.09	0.07	0.03	43.25	**99.40**	42.50
Naliwoodin Rockhole																
132284	31°34'50"	128°52'24"	Cream to greyish, medium-grained, fresh, fossiliferous Nullarbor Limestone	0.05	<0.01	0.01	0.01	<0.01	0.54	54.74	0.04	0.04	0.03	43.23	**98.69**	38.50
Baxter Memorial, northeast of Point Dover																
132261	32°24'25"	125°29'30"	Soft, greyish kankar with lenses of greyish to pinkish, fine-grained, massive Nullarbor Limestone	0.95	0.01	0.17	0.12	<0.01	0.54	53.63	0.08	0.05	0.03	43.60	**99.18**	42.20
132262	32°27'19"	125°31'12"	Pink to salmon-coloured, fossiliferous, fresh Abrakurrie Limestone	0.33	0.01	0.03	<0.01	0.02	0.46	54.70	0.03	0.03	0.04	42.99	**98.64**	41.10
132263	32°27'38"	125°31'46"	Pink to salmon-coloured, fossiliferous, fine- to medium-grained, massive, relatively fresh Abrakurrie Limestone	0.37	0.01	0.02	<0.01	0.01	0.55	54.54	0.12	0.04	0.04	43.36	**99.06**	43.30
132264	32°28'38"	125°38'23"	Medium-grained, greyish to pinkish, fossiliferous Abrakurrie Limestone	0.71	0.01	0.08	0.01	0.01	0.58	54.40	0.09	0.07	0.04	43.54	**99.54**	42.20
132265	32°28'14"	125°38'49"	Moderately weathered, medium- to coarse-grained, greyish-brown, fossiliferous Abrakurrie Limestone	3.94	0.03	0.33	0.15	<0.01	0.93	50.46	0.14	0.10	0.03	42.87	**98.98**	42.20
132266	32°28'13"	125°38'04"	Greyish-white to salmon-coloured, fine- to medium-grained Abrakurrie Limestone with occasional micritic material	0.99	0.01	0.05	0.01	<0.01	0.47	54.15	0.07	0.04	0.02	43.52	**99.33**	43.60
132267	32°28'20"	125°36'55"	Relatively fresh, pinkish to salmon to off-white, medium-grained Abrakurrie Limestone	0.22	0.01	0.07	0.02	0.01	0.44	54.77	0.01	0.02	0.04	43.29	**98.90**	42.90
132268	32°29'50"	125°23'32"	Medium-grained, pinkish to salmon-coloured, moderately fresh, fossiliferous Abrakurrie Limestone	0.22	0.01	0.01	0.02	0.01	0.60	54.08	0.13	0.04	0.03	43.65	**98.80**	42.20
132269	32°32'38"	125°18'50"	Medium-grained, pinkish to salmon-coloured, moderately fresh, fossiliferous Abrakurrie Limestone	0.39	0.01	<0.01	<0.01	<0.01	0.26	54.38	0.02	0.01	0.04	42.90	**98.01**	39.69

Table 37. Major- and trace-element analyses of limestones from the Eucla Basin

	Naretha		*Localities around Eucla*			
Sample no.	*132298*	*132299*	*132283*	*132285*	*132286*	*132287*
Latitude (S)	*30°59'48"*	*30°59'48"*	*31°37'10"*	*31°42'52"*	*31°41'01"*	*31°40'58"*
Longitude (E)	*124°49'31"*	*124°49'31"*	*128°50'26"*	*128°53'08"*	*128°57'55"*	*128°53'24"*
Description	*Fine-grained, grey, slightly weathered Nullarbor Limestone*	*Fine-grained, moderately fresh, creamy grey Nullarbor Limestone*	*Fine- to medium-grained Nullarbor Limestone from a quarry approximately 8 km north-northwest of Eucla*	*Limesand from Eucla beach, old town site*	*Fine- to medium-grained ?Wilson Bluff Limestone, approximately 8 km east of Eucla*	*Nullarbor Limestone with minor kankar development, from Eucla Pass at the eastern end of Eucla*
			Percentage			
SiO_2	1.11	1.47	0.14	45.30	0.69	4.36
TiO_2	0.01	0.02	0.01	0.04	0.01	0.01
Al_2O_3	0.28	0.39	0.05	0.36	0.01	0.18
Fe_2O_3	0.11	0.21	0.03	0.13	<0.01	0.08
MnO	<0.01	<0.01	<0.01	0.02	<0.01	0.01
MgO	9.18	2.79	0.58	3.09	1.00	5.24
CaO	43.79	50.99	54.13	25.78	53.05	45.39
Na_2O	0.11	0.06	0.05	0.18	0.09	0.23
K_2O	0.04	0.06	0.01	0.13	0.02	0.08
P_2O_5	0.01	<0.01	0.02	0.06	0.03	0.04
LOI	44.99	43.42	43.58	23.97	43.60	42.98
Total	**99.63**	**99.41**	**98.60**	**99.06**	**98.50**	**98.60**
CO_2	42.2	42.2	36.60	23.50	42.70	41.70
			Parts per million			
As	2.9	2.8	2.2	–	–	–
Ba	<5	9	6	–	–	–
Be	0.4	0.6	0.4	–	–	–
Ce	1.71	3.4	0.97	–	–	–
Cr	3	8	9	–	–	–
Ga	0.43	0.59	0.35	–	–	–
La	2.8	5.9	1.99	–	–	–
Nb	<0.5	<0.5	2.2	–	–	–
Rb	2.3	2.3	0.67	–	–	–
S	0.02	0.09	0.01	–	–	–
Sn	0.2	0.2	0.2	–	–	–
Sr	586	594	527	–	–	–
Th	0.5	0.74	0.14	–	–	–
U	1.09	1.31	0.7	–	–	–
V	2	4	<2	–	–	–
W	0.2	0.2	0.3	–	–	–

Table 37. (continued)

	Balladonia					*Caiguna*	
Sample no.	*132254*	*132255*	*132256*	*132257*	*132258*	*132259*	*132260*
Latitude (S)	*32°22'57"*	*32°23'48"*	*32°27'09"*	*32°28'12"*	*32°28'12"*	*32°19'30"*	*32°19'30"*
Longitude (E)	*123°45'23"*	*123°45'30"*	*123°48'14"*	*123°56'34"*	*123°56'34"*	*125°02'46"*	*125°02'46"*
Description	*Fine- to medium-grained,yellowish-brown to pale-white Nullarbor Limestone*	*Fine-grained massive, greyish-brown to yellowish Nullarbor Limestone (dolomitic)*	*Micritic fine-grained, yellowish-brown Nullarbor Limestone associated with kankar*	*Greyish-white to pale-brown to salmon-pink, fine-grained to micritic Nullarbor Limestone from a quarry on south side of the Eyre Highway*	*Greyish-white to pale-brown to salmon-pink, fine-grained to micritic Nullarbor Limestone from a quarry on south side of the Eyre Highway*	*Fine-grained, greyish, massive, fossiliferous ?Nullarbor ?Abrakurrie Limestone from a quarry 42 km west of Caiguna*	*Fine-grained, greyish, massive, fossiliferous ?Nullarbor ?Abrakurrie Limestone from a quarry 42 km west of Caiguna*
				Percentage			
SiO_2	1.47	1.85	0.68	2.35	1.80	1.72	1.92
TiO_2	0.01	0.02	0.01	0.03	0.03	0.01	0.01
Al_2O_3	0.16	0.21	0.09	0.38	0.43	0.26	0.27
Fe_2O_3	0.21	0.11	0.01	0.17	0.19	0.15	0.12
MnO	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
MgO	2.79	8.83	1.42	3.44	2.60	1.11	1.17
CaO	51.06	43.73	52.93	49.02	50.00	52.35	52.67
Na_2O	0.03	0.09	0.09	0.12	0.16	0.16	0.11
K_2O	0.01	0.07	0.05	0.07	0.06	0.06	0.07
P_2O_5	0.03	0.03	0.03	0.03	0.01	0.01	0.03
LOI	43.70	44.54	43.96	43.49	43.67	43.20	43.26
Total	**99.47**	**99.48**	**99.27**	**99.10**	**98.95**	**99.03**	**99.63**
CO_2	41.50	43.90	43.00	40.80	41.30	42.30	42.90
				Parts per million			
As	–	–	–	–	2.6	1.1	–
Ba	–	–	–	–	30	26	–
Be	–	–	–	–	<0.2	0.4	–
Ce	–	–	–	–	1.96	2.5	–
Cr	–	–	–	–	6	8	–
Ga	–	–	–	–	1.04	0.79	–
La	–	–	–	–	1.99	3.4	–
Nb	–	–	–	–	4.5	1	–
Rb	–	–	–	–	1.77	1.78	–
S	–	–	–	–	0.01	0.01	–
Sn	–	–	–	–	0.4	0.3	–
Sr	–	–	–	–	788	714	–
Th	–	–	–	–	1.09	0.97	–
U	–	–	–	–	0.88	2.6	–
V	–	–	–	–	4	17	–
W	–	–	–	–	0.4	0.2	–

Table 37. (continued)

	Toolinna Cove				
Sample no.	*132270*	*132271*	*132272*	*132273*	*132274*
Latitude (S)	*32°35'09"*	*32°38'32"*	*32°43'52"*	*32°43'52"*	*32°44'22"*
Longitude (E)	*125°13'23"*	*125°08'33"*	*125°01'23"*	*125°01'23"*	*125°00'20"*
Description	*Fine-grained, massive, pinkish to salmon-coloured, moderately fresh Toolinna Limestone*	*Pale-brown to off-white, medium- to coarse-grained, fresh, fossiliferous Toolinna Limestone*	*Pinkish to salmon-coloured, fine- to coarse-grained, layered, weathered Toolinna Limestone*	*Pinkish , fine-grained, massive, fossiliferous, fresh Toolinna Limestone*	*Pale-brown, fine-grained, moderately fresh (weathered in parts) Toolinna Limestone*
			Percentage		
SiO_2	0.35	1.22	0.52	0.33	1.03
TiO_2	0.01	0.01	0.01	0.01	0.02
Al_2O_3	0.05	0.24	0.22	0.05	0.20
Fe_2O_3	0.05	0.30	0.10	0.01	0.07
MnO	<0.01	0.01	<0.01	<0.01	0.01
MgO	0.34	1.02	0.86	0.24	0.33
CaO	54.60	52.72	52.02	55.58	54.77
Na_2O	0.02	0.06	0.13	0.04	0.06
K_2O	0.01	0.04	0.03	0.03	0.06
P_2O_5	0.04	0.02	0.02	<0.01	0.04
LOI	43.02	43.51	44.12	42.82	42.82
Total	**98.49**	**99.15**	**98.03**	**99.11**	**99.41**
CO_2	41.20	40.80	42.10	42.70	42.40
			Parts per million		
As	–	7.9	2.2	–	–
Ba	–	26	31	–	–
Be	–	<0.2	<0.2	–	–
Ce	–	1.75	2	–	–
Cr	–	<2	<2	–	–
Ga	–	0.65	0.91	–	–
La	–	2.2	6	–	–
Nb	–	1.1	0.7	–	–
Rb	–	1.23	1.05	–	–
S	–	0.01	<0.01	–	–
Sn	–	0.2	0.2	–	–
Sr	–	320	355	–	–
Th	–	0.75	0.67	–	–
U	–	0.43	0.43	–	–
V	–	6	<2	–	–
W	–	0.3	0.2	–	–

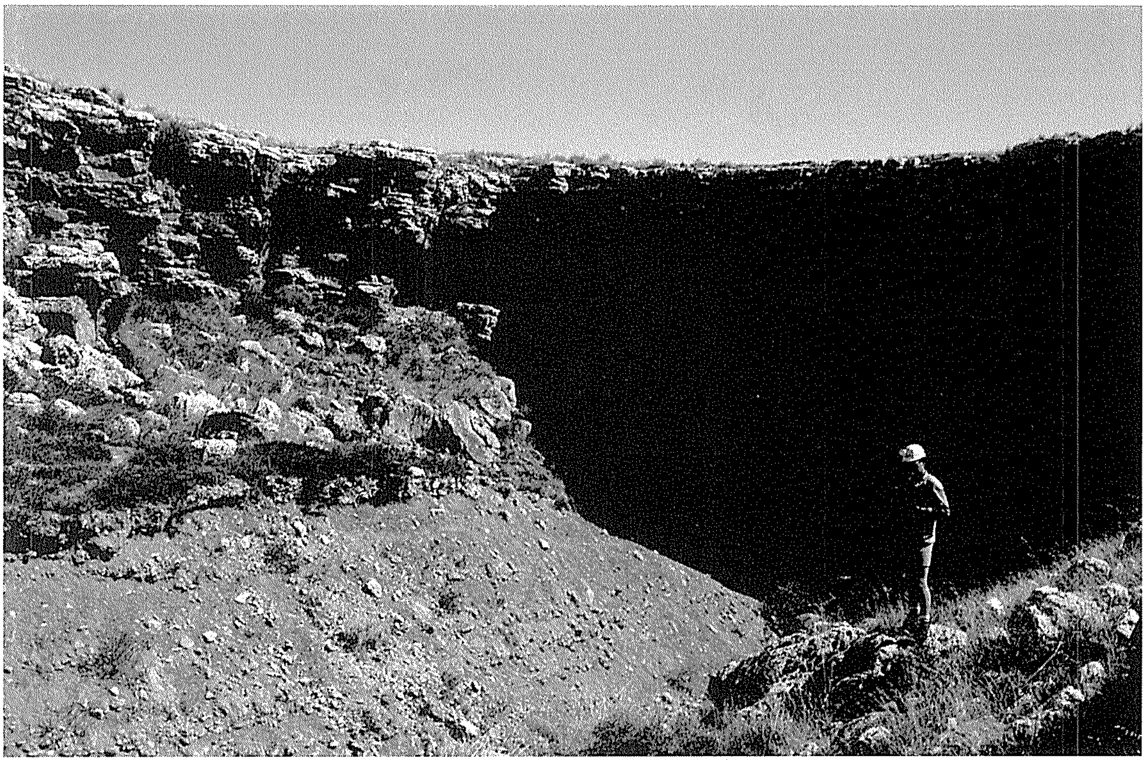
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Figure 37. Photograph of horizontally-bedded limestone near the entrance of Cocklebiddy Cave

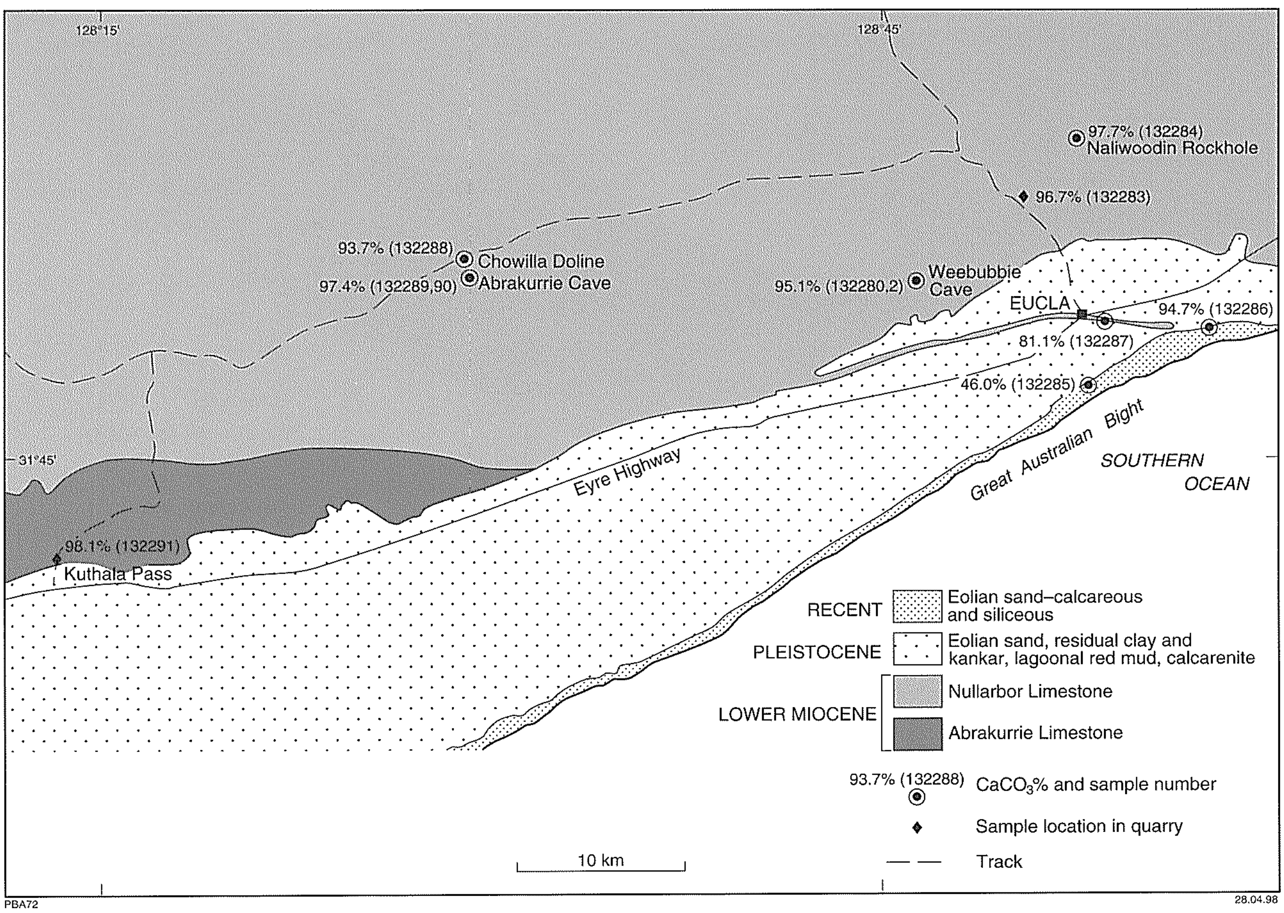

Figure 38. Sample locations and assays of limestone around Eucla (geology after Lowry, 1971)

Table 38. Partial chemical analyses of 'Eucla Limestone' (?Nullarbor Limestone)

Sample no.	*3043*	*3044*	*3045*	*3047*	*3053*
Specific gravity	2.69	–	–	2.57	2.58
			Percentage		
CaO	31.36	53.73	54.52	55.23	49.34
MgO	16.40	0.68	1.20	0.67	1.40
FeO	1.48	0.56	–	–	1.47
Fe_2O_3	1.02	tr	(a)0.65	(a)0.38	(a)3.41
Al_2O_3	2.43	0.24	–	–	–
SiO_2	2.38	0.70	0.45	0.36	5.49
CO_2	44.93	44.09	43.18	43.36	38.89

NOTE: after Maitland (1919)
(a) $Fe_2O_3 + Al_2O_3$
tr trace

Sample 3043 Lat. 31°17'S, Long. 124°30'E
Sample 3044 Lat. 31°22'S, Long. 125°45'E
Sample 3045 Lat. 31°30'S, Long. 126°00'E
Sample 3047 Near Yayoudle Rockhole
Sample 3053 Lat 31°00'S, Long. 126°00'E

Naretha

Limestone near Naretha has been used in the production of calcium hydroxide for use in the gold industry since about 1929 (Lowry, 1970a). Production reached a maximum of around 100 t per week, but later dwindled and finally ceased in 1966. Surface slabs of Nullarbor Limestone, hand-picked and burnt with myall (*Acacia* species), resulted in a high-purity product reputedly reaching 98.8% $Ca(OH)_2$.

An abandoned limestone quarry located at Lat. 30°59'48"S and Long. 124°49'31"E, has been excavated to a depth of approximately 8 m, a length of approximately 250 m, and a width of 75 m. The horizontally bedded limestone is micritic to fine grained, and grey to cream-grey in colour. Lenses of ferruginous clayey material, and local weathered zones, are not uncommon. Samples 132298 and 132299 in Table 37 were collected from this location (Fig. 34).

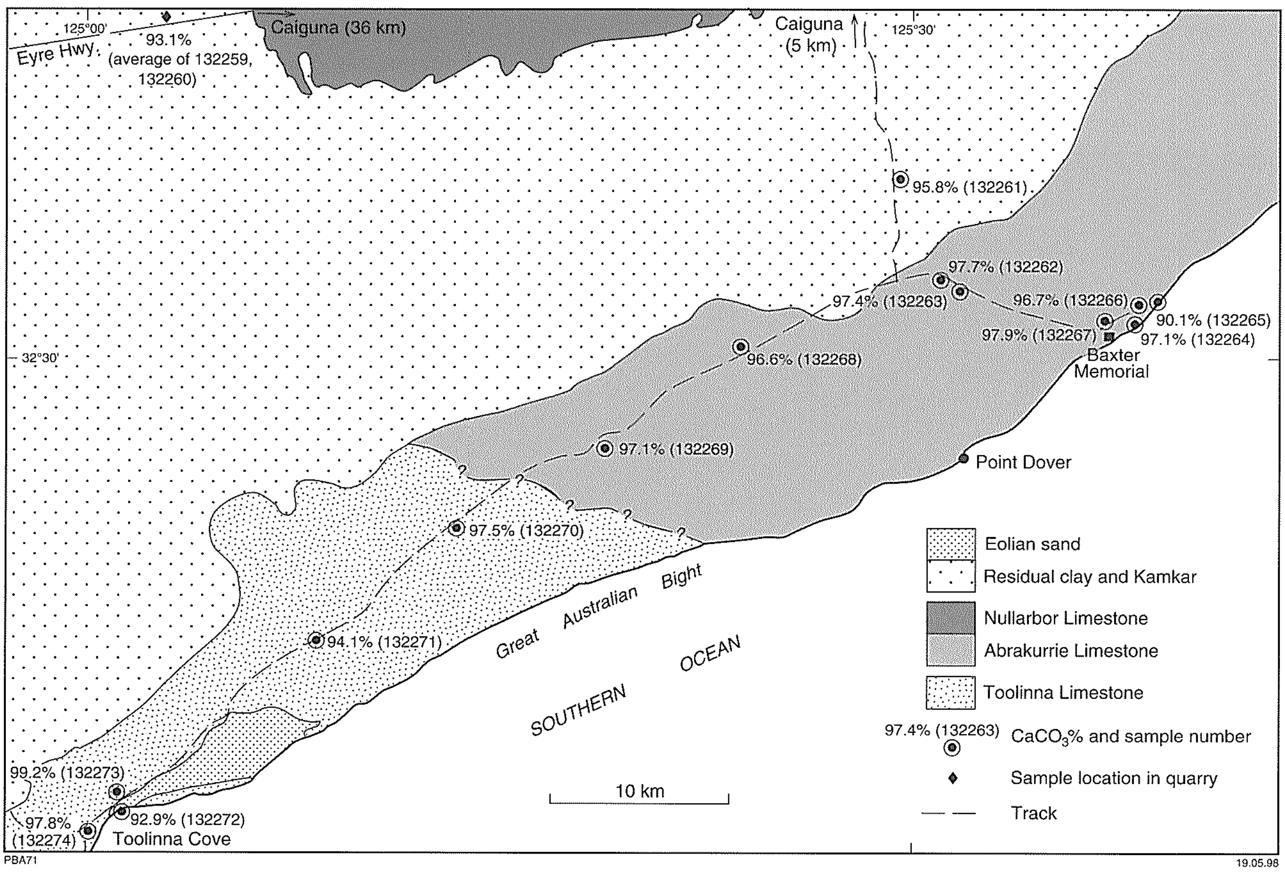

Figure 39. Sample locations and assays of limestone around Baxter Memorial and Toolinna Cove in the Eucla Basin (geology after Lowry, 1970b)

Pilbara Craton

The most important limestone and limesand deposits of the Pilbara Craton occur in the Dampier Archipelago, north of Karratha (Fig. 40). These are Pleistocene to Holocene deposits, and are mainly restricted to islands, beaches, and the coastal stretches on islands and the adjoining mainland.

Large deposits of calcrete occur in the Oakover Formation within the Hamersley Basin (Fig. 41). Other potential sources of calcium carbonate in the Pilbara Craton include the Bossut Formation, the Meentheena Carbonate Member of the Tumbiana Formation, the Carawine Dolomite, the Warrie Member of the Jeerinah Formation, and Quaternary kankar (Ryan, 1966; Hickman, 1983).

Dampier Archipelago

The Dampier Archipelago consists of 40 islands, islets, and rock groupings, which range in size from rock islets of less than one hectare to large islands of up to 3290 ha. Many of the islands are steep and rugged, with coastal cliffs and large exposures of volcanic and other igneous rocks separated by valleys, beaches, and coastal plains.

Many islands in the northern part of the archipelago have limestone cliffs adjacent to beaches. Large resources of limestone and limesand of this type occur on Legendre and Hauy Islands, Collier Rocks, Cohen, Keast, and Delambre Islands, and in many locations on the Burrup Peninsula. Limesand has been extracted from deposits on the mainland at Hearson Cove (Fig. 40) and Cleaverville (Fig. 41).

Geology

The islands of the Dampier Archipelago consist predominantly of Early Archaean basalt and intrusive igneous rocks such as dolerite, gabbro, and granophyre (Figs 40 and 42). The early Archaean basalt and sandstone of the Fortescue Group have given rise to the rugged topography of the Burrup Peninsula and other major islands in the area. These rocks are unconformably underlain by Archaean granite and gneiss that is exposed on the mainland. The basalt and sandstone of the Fortescue Group date from about 2.8 to 2.7 Ga. The granophyre, gabbro, and dolerite, which intrude the Fortescue Group, range in age from 2.7 to 2.4 Ga.

Limestone occurs on a number of islands in the northern part of the archipelago, while scattered deposits of limesand occur throughout the islands of the archipelago and in coastal areas of the mainland. Pleistocene limestone and gravel deposits date from approximately 2 Ma, and the Holocene limesand deposits, mud, and silt have an age of around 0.01 Ma.

Limestone and limesand resources

Onshore resources

Biggs and Denman (1981) investigated 97 separate onshore limesand and limestone occurrences within the Dampier Archipelago (Fig. 40). During the investigation, representative limesand samples of approximately 200 g were collected from near-surface depths (100 mm to 200 mm), and limestone samples were collected from cliff faces at vertical intervals of about one metre. Information on geology, bedrock features, and topography, which was relevant to the quality or quantity of the limestone and limesand resources, was also gathered during the investigation. Based on these observations, deposits were categorized as belonging to one or more of three types, based on 'floor features'; those with a platform-type floor, those with an irregular basement floor, and and those with a 'high water mark' base (those limesand or limestone deposits that extend below the high water mark).

Of the 97 occurrences investigated by Biggs and Denman (1981), the 47 identified as potentially economic deposits of limesand had a total approximate resource of 190 Mt (Tables 39 and 40). Limestone underlies most of the archipelago sea floor, but onshore outcrops of this limestone are largely confined to Legendre, Hauy, and Delambre Islands, and the adjacent Collier Rocks. According to estimates by Biggs and Denman (1981), the limestone resources within these islands amount to approximately 300 Mt (Tables 41 and 42). They considered that at least half of this resource could be extracted economically.

Most limestone and limesand resources in the Dampier Archipelago are within nature and conservation reserves, and also within a proposed national park. Kojan (1994) noted that a limesand resource of 166.5 Mt, with a weighted mean grade of 89.58% $CaCO_3$ (reported from 36 locations by Biggs and Denman (1981)), was contained within the proposed national park (Table 39). The limesand resource outside the proposed national park is 22.4 Mt, with a weighted mean average of 83.51% $CaCO_3$ (Table 40). Kojan (1994) also estimated that 32.2 Mt of limestone resources, with a weighted mean average of 85.20% $CaCO_3$, occur on Delambre and Hauy Islands, and Collier Rocks, which are all within the proposed national park (Table 41). Legendre Island, currently set aside for industrial development, has an approximate limestone resource of 264 Mt, with a mean grade of 84.80% $CaCO_3$ (Table 42).

Offshore resources

On the basis of drilling and sampling data from Woodside Petroleum Ltd, Kojan (1994) noted that extensive deposits of limesand underlie the archipelago sea floor. However, information on the grade and thickness of this material is poor.

Potential uses

The large resource of moderate- to high-quality limesand and limestone on the Dampier Archipelago that occurs

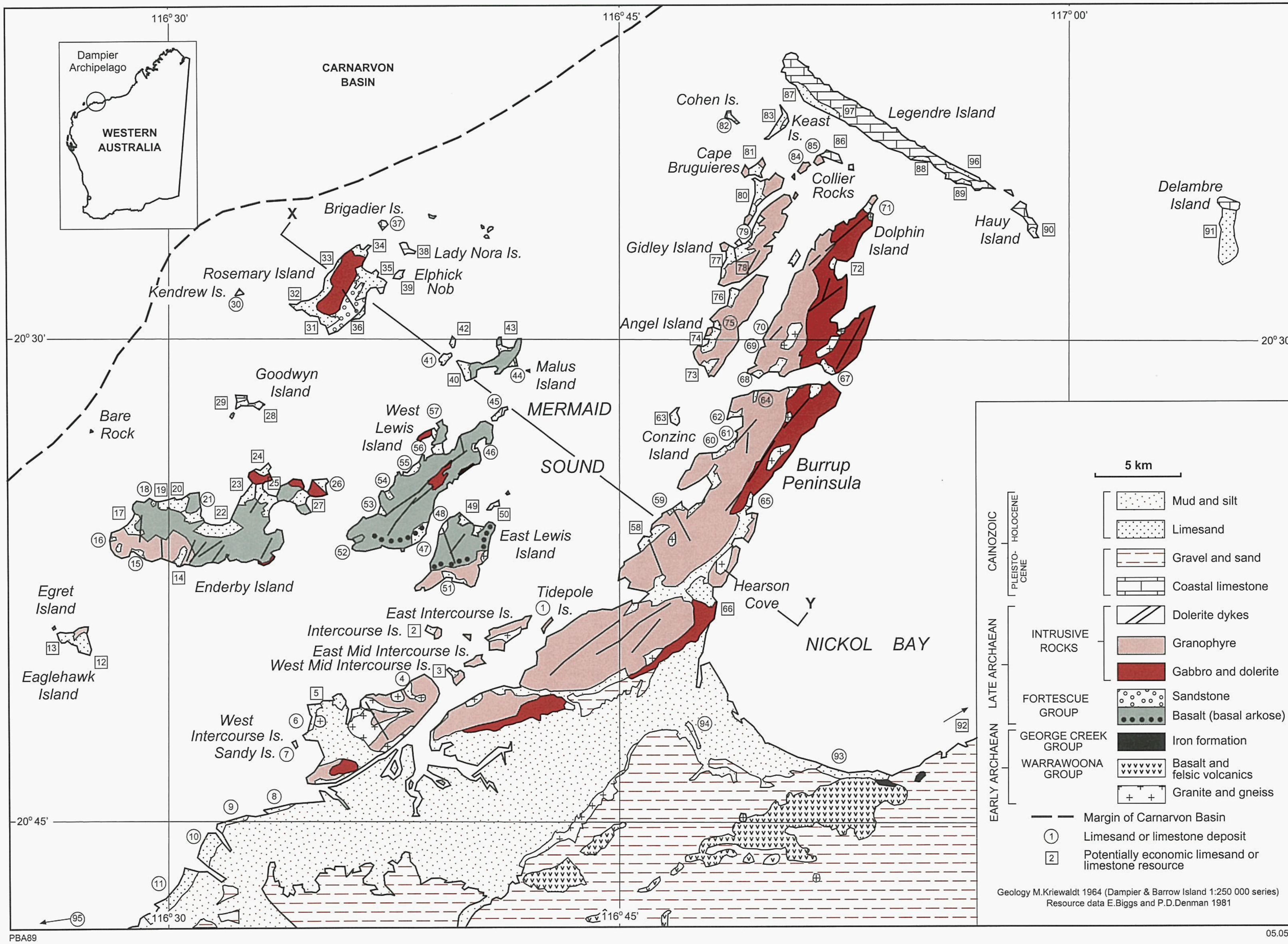

Figure 40. Limestone and limesand deposits and geology of the Dampier Archipelago (after Kojan, 1994) (Section X–Y shown on Fig. 42)

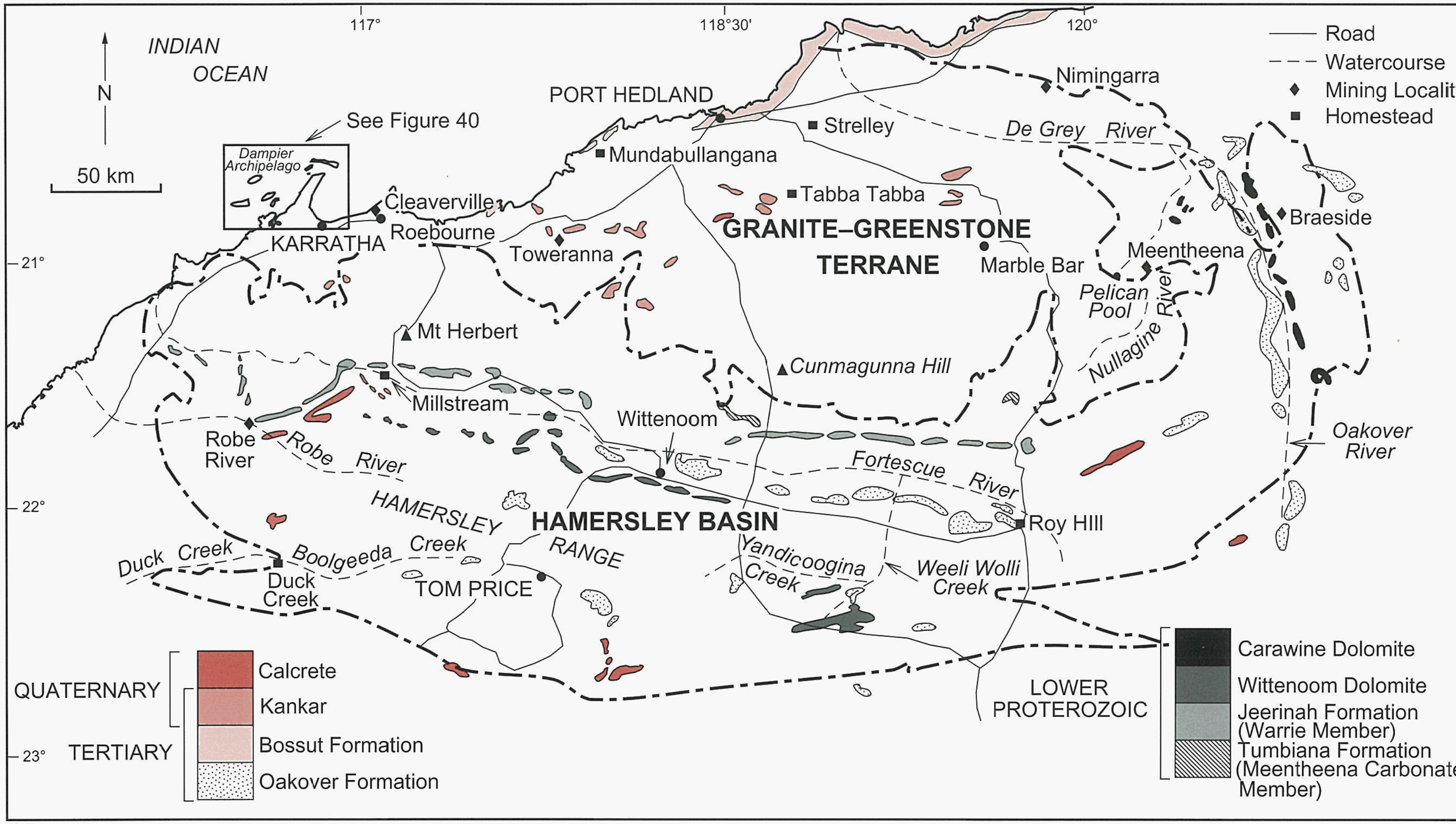

Figure 41. **Distribution of calcrete, kankar, and other calcium-carbonate bearing formations in the Hamersley Basin and granite–greenstone terrane of the Pilbara Craton (after Williams et al., 1972; Ryan et al., 1965; Kriewaldt and Ryan, 1967; Blight et al., 1986; Thorne et al., 1991; Thorne et al., 1996; Hickman and Gibson, 1982; Hickman and Lipple, 1978)**

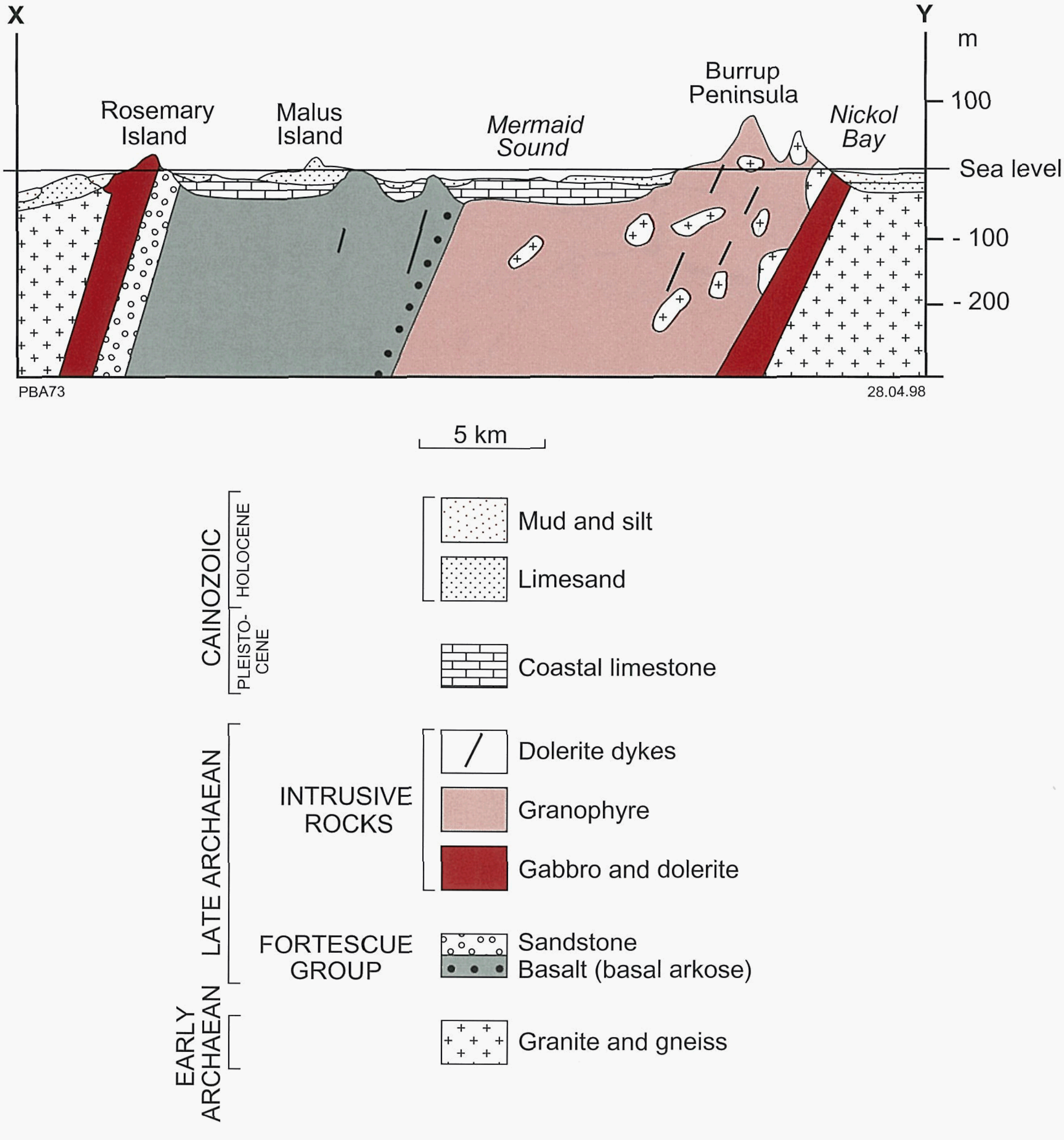

Figure 42. Geological cross section of the Dampier Archipelago (X and Y as shown on Figure 40) (after Kojan, 1994)

outside the proposed national park, provides an important source of raw material for any future cement- and lime-manufacturing industries in the rapidly developing Dampier and Karratha regions. The material may also be useful in proposed iron-ore processing and steelmaking industries within the region.

Mining activities

Hamersley Iron Pty Ltd extracted 379 000 t of limesand, with an average grade of approximately 80% $CaCO_3$, from three mining leases located at Hearson Cove (deposit no. 66 on Fig. 40). This was used to supply an iron-ore pelletizing plant located at Dampier. Extraction of limesand began in 1968 and continued until closure of the plant in 1980.

Specified Services Pty Ltd, a subsidiary of Pioneer Concrete, extracted limesand from a deposit at Cleaverville on the mainland, northeast of Karratha. Mining of this deposit commenced in 1974 and continued until 1992, with a total production of 173 000 t. Of this amount, 94 000 t of material containing 75% $CaCO_3$, produced during 1974 to 1976, was used by the Cliffs International Cape Lambert iron-ore pellet plant. Since 1976, the deposit has only been used for cement manufacture (Kojan, 1994).

Other potential sources of limestone

Oakover Formation

Extensive deposits of partly or entirely silicified calcrete occur in the valleys of the Oakover and Fortescue Rivers (Fig. 41). There are also isolated occurrences at Tabba Tabba, Cunmagunna Hill, Yarrie, 17 km southwest

Table 39. Limesand resources of islands for inclusion in the Dampier Archipelago National Park

Island	*Current purpose*	*Map locality*[(a)]	*Limesand (Mt)*	*Grade $CaCO_3$(%)*
Enderby Island	A Nature Reserve	14	2.4	89.00
		17	1.4	90.20
		19/20	3.2	93.60
		22	9.2	90.70
		23	2.3	93.90
		24	3.0	93.40
		25	4.7	89.50
		27	2.3	92.30
		Subtotal	**28.5**	**WM 91.34**
Rosemary Island	A Nature Reserve	31	5.7	89.70
		32	14.4	90.40
		33	3.0	90.20
		34	2.1	89.50
		35	8.4	90.00
		36	4.5	92.30
		Subtotal	**38.1**	**WM 90.37**
Eaglehawk Island	C Nature Reserve	12	7.4	81.40
		13	3.9	84.10
		Subtotal	**11.3**	**WM 82.34**
Goodwyn Island	C Nature Reserve	28	2.5	89.10
		29	2.0	87.60
		Subtotal	**4.4**	**WM 88.44**
Malus Island	C Nature Reserve	40	4.9	92.50
		42	1.1	94.50
		43	1.5	92.50
		Subtotal	**7.4**	**WM 92.78**
Angel Island	C Nature Reserve	73	2.1	88.20
		74	4.0	88.80
		76	2.6	94.50
		Subtotal	**8.7**	**WM 90.38**
Gidley Island	C Nature Reserve	77	7.7	89.80
		78	1.4	88.80
		Subtotal	**9.1**	**WM 89.65**
Dolphin Island	B Nature Reserve	72	1.5	87.10
Lady Nora Island	C Nature Reserve	38	2.0	90.20
Elphick Nob	C Nature Reserve	39	1.4	90.20
Conzinc Island	C Nature Reserve	63	1.1	88.00
North Gidley Island	C Nature Reserve	80	9.0	88.20
Cape Bruguieres	C Nature Reserve	81	3.8	86.10
Keast Island	C Nature Reserve	83	1.7	88.90
Hauy Island	C Nature Reserve	90	2.2	91.80
Delambre Island	C Nature Reserve	91	36.5	89.60
		Subtotal	**59.1**	**WM 89.17**
		Grand total limesand	**166.5**	**WM 89.58**

NOTE: after Kojan (1994)
WM weighted mean
(a) see Figure 40 for localities

of Nimingarra, and 10 km southeast of Strelley Homestead. Noldart and Wyatt (1962) named this unit the Oakover Formation and assigned it a Tertiary age (Hickman and Gibson, 1982; Hickman, 1983). In this area, the Oakover Formation has a thickness of 5–30 m and unconformably overlies the Paterson Formation. It is locally overlain by laterite. Oakover Formation calcrete also occurs at Weeli Wolli Creek and in the western branch of Yandicoogina Creek (MacLeod and de la Hunty, 1966). The calcrete occurs as white limestone, with a considerable amount of magnesia and opaline silica. South of Weeli Wolli Spring the formation covers an area of 75 km^2 and has a thickness of about 25 m.

Table 40. Limesand resources of islands or areas excluded from the Dampier Archipelago National Park

Island or adjacent area	*Current purpose*	*Map locality[(a)]*	*Limesand (Mt)*	*Grade $CaCO_3$ (%)*
East Lewis Island	C Recreation Reserve	49	1.4	90.50
		50	1.3	88.80
		Subtotal	**2.7**	**WM 89.70**
Legendre Island	Industrial development	87	1.4	83.00
		88	0.8	89.10
		89	1.4	88.20
		96	3.2	90.80
		Subtotal	**6.7**	**88.49**
Hearson Cove	Crown Land	66	4.5	78.20
Dampier Promontory	Crown Land	58	1.1	84.60
Cleaverville	Crown Land	92	4.1	75.60
Intercourse Island	Crown land	2	0.6	87.30
West Mid Intercourse	Crown Land	3	0.9	85.40
West Intercourse	Crown Land	5	1.8	84.30
		Subtotal	**13.1**	**WM 79.69**
		Grand total limesand	**22.4**	**WM 83.51**

NOTE: after Kojan (1994)
WM weighted mean
(a) see Figure 40 for localities

Table 41. Limestone resources of islands for inclusion in the Dampier Archipelago National Park

Island area	*Current purpose*	*Map locality[(a)]*	*Limesand (Mt)*	*Grade $CaCO_3$ (%)*
Collier Rocks	C Nature Reserve	86	7.7	88.00
Hauy Island	C Nature Reserve	90	15.6	82.00
Delambre Island	C Nature Reserve	91	8.9	88.40
		Grand total limestone	**32.2**	**WM 85.20**

NOTE: after Kojan (1994)
WM weighted mean
(a) see Figure 40 for localities

Table 42. Limestone resources of islands for exclusion from the Dampier Archipelago National Park

Island area	*Current purpose*	*Map locality[(a)]*	*Limesand (Mt)*	*Grade $CaCO_3$ (%)*
Legendre Island	Industrial development	97	264.0	88.80 84.80 80.80
		Grand total limestone	**264.0**	**Mean 84.80**

NOTE: after Kojan (1994)
WM weighted mean
(a) see Figure 40 for localities

In the Hamersley Range, calcrete is best developed on the Wittenoom Dolomite, particularly where the drainage from the dolomite is restricted by weathering-resistant formations. Calcrete of the Oakover Formation has also been found in the valleys of Duck and Boolgeeda Creeks (de la Hunty, 1965). Williams (1968) described an impure earthy limestone or calcrete, containing bands of porcelanite, which outcrops along the valley of the Robe River, a few kilometres west of Millstream. This calcrete is considered to be similar to that of the Oakover Formation, and appears to have formed in areas with internal drainage.

Two samples of calcrete, collected from Lat. 22°58'S, Long. 119°14'E and Lat. 22°40'S, Long. 119°57'E, assayed 53.0 and 73.0% $CaCO_3$, 19.7 and 5.8% MgO, and 1.0 and 7.9% SiO_2 respectively (Baxter, 1972).

Bossut Formation

The Bossut Formation consists of sandy calcarenite, oolite, and calcilutite, and is considered to be equivalent to the Tamala Limestone. The formation is discontinuously exposed near the coast as dune, beach-ridge, beach, and offshore-bar deposits, which attain a maximum thickness of 33 m (Low, 1965; Hickman and Gibson, 1982; Hickman, 1983). Ryan (1966) observed that the formation, in which old dune lines may be distinguished, is extensively exposed northeast of Mundabullangana Homestead.

Analyses of samples of the Bossut Formation (Table 43) indicate that the $CaCO_3$ range is 43.6 to 87.5% (24.4 to 49.0% CaO), and SiO_2 is 5.7 to 43.2% (Baxter, 1972).

Meentheena Carbonate Member (Tumbiana Formation)

The Meentheena Carbonate Member of the Tumbiana Formation (Hickman and Lipple, 1975) consists of ripple-bedded siliceous limestone and thin beds of tuff and shale. Exposures on the banks of the Nullagine River, between Pelican Pool and Meentheena, reveal excellent exposures of stromatolites. Other fossil localities are located on the northern scarp of the Chichester Range at Mount Herbert on the Port Hedland–Wittenoom Road.

Wittenoom and Carawine Dolomites

Baxter (1972) noted that although the Wittenoom Dolomite is principally dolomite, it also contains some limestone. The unit is exposed in the Hamersley Range, where it unconformably overlies the Marra Mamba Iron Formation, and attains a maximum thickness of 150 m on the southern limb of the Jeerinah anticline. The Wittenoom Dolomite is subdivided into two units; a lower unit consisting of thin- to medium-bedded dolomite intercalated with thin beds of chert and mudstone, and an upper unit consisting of thin-bedded, parallel-laminated dolomite with small slump folds. It is generally poorly exposed, occupying valleys between the Marra Mamba Iron and Brockman Iron Formations.

Carbonate rock samples analysed by Baxter (1972) (Table 44) contained 41.4–88.2% $CaCO_3$, 1.4–20.0% MgO, and 20.8–39.6% SiO_2, indicating that both dolomite and limestone are found in the Wittenoom Dolomite. Kriewaldt and Ryan (1967) found that one specimen assayed 99% $CaCO_3$, although this was considered to be unusual.

The Carawine Dolomite is the stratigraphic equivalent of the Wittenoom Dolomite in the Hamersley Range and west Pilbara areas. It conformably overlies the Lewin Shale in the east Pilbara and the Marra Mamba Iron Formation in the west. The unit, which reaches 200 m in thickness, consists of brown-weathered, well-bedded grey dolomite, with minor chert beds and veins generally less than 100 mm thick. Unweathered portions of the dolomite are finely crystalline and grey-pink, with faint colour banding. A wide range of banded structures, ranging from stratiform laminations (stromatolitic or microbial mats) to large-scale bedding, are present. The presence of stromatolites, and other features of the Carawine Dolomite that are absent from the Wittenoom Dolomite, suggest that the Carawine Dolomite was deposited in a more varied palaeoenvironment (Williams, 1989; Hickman, 1983)

Jeerinah Formation

Carbonate rocks within the Jeerinah Formation, a marine sequence that grades upwards into the Marra Mamba Iron Formation, are mainly confined to the Warrie Member (MacLeod et al., 1963). Baxter (1972) assayed two carbonate rock samples that contained 50.9–70.0% $CaCO_3$, 0.9–4.6% MgO, and 14.1–18.3% SiO_2. The samples were collected on ROY HILL at Lat. 22°20'S, Long. 119°57'E and Lat. 22°23'S, Long. 119°58'E.

Kankar

Impure, earthy white limestone and magnesite underlies Quaternary colluvium and poorly consolidated gravel deposits in some areas of the Pilbara Craton (Fig. 41). Ryan (1966) noted that widespread deposits of impure calcareous concretionary material form dissected plains between Toweranna and the eastern margin of ROEBOURNE. Kriewaldt and Ryan (1967) identified two types of kankar deposits; incrustations formed on Precambrian rocks, and sheets formed within alluvium and exposed by erosion. Kankar with porcelanite, which occurs at Millstream, continues westerly from PYRAMID to YARRALOOLA. Similar deposits, that in part are correlated with the Oakover Formation, are recognized on the adjoining ROY HILL and MOUNT BRUCE sheets.

Albany–Fraser Orogen

Limestone deposits of the Albany–Fraser Orogen, probably equivalent to the Pleistocene Tamala Limestone,

Table 43. Partial chemical analyses of limestone from the Bossut Formation

Sample no.	*28522*	*28523*	*28518*	*28519*	*28520*	*22240*	*22241*	*22242*	*22243*	*22244*	*22249*	*22253*
1:250 000 sheet	*ROEBOURNE*	*ROEBOURNE*	*ROEBOURNE*	*ROEBOURNE*	*ROEBOURNE*	*BEDOUT ISLAND*	*BEDOUT ISLAND*	*BEDOUT ISLAND*	*BEDOUT ISLAND*	*BEDOUT ISLAND*	*BEDOUT ISLAND*	*BEDOUT ISLAND*
						Percentage						
Fe_2O_3	3.43	1.43	1.72	1.43	1.43	0.37	0.47	0.31	0.31	0.26	0.52	0.77
Al_2O_3	3.06	2.49	3.36	2.95	2.91	0.27	0.19	0.21	0.27	0.25	0.40	0.60
CaO	24.4	40.6	26.6	28.8	33.9	42.0	33.6	43.7	49.0	43.7	42.0	30.8
MgO	0.99	0.93	1.82	1.69	1.33	1.22	0.75	3.12	0.88	0.75	1.13	0.27
SiO_2	43.2	17.1	36.1	34.8	29.3	16.0	34.0	5.68	8.33	9.28	13.6	40.9
MnO	0.03	0.02	0.03	0.02	0.02	0.005	0.005	0.004	0.007	0.005	0.013	0.011
P_2O_5	<0.01	0.02	0.03	0.03	0.02	0.06	0.03	0.04	0.04	0.04	0.03	0.11
S	–	–	–	–	–	0.05	0.01	0.31	0.20	0.06	0.21	0.01

NOTE: after Baxter (1972)

28522	Lat. 20°25'S, Long. 118°03'E
28523	Lat. 20°24'S, Long. 118°03'E
28518	Lat. 20°20'S, Long. 118°29'E
28519–20	Lat. 20°21'S, Long. 118°28'E
22240–44	Lat. 19°57'S, Long. 119°46'E
22249	Lat. 20°00'S, Long. 119°42'E
22253	Lat. 20°05'S, Long. 119°37'E

Table 44. Partial chemical analyses of the Wittenoom Dolomite

Sample no.	*1:250 000 sheet*	Fe_2O_3	Al_2O_3	*CaO*	*MgO*	SiO_2	*MnO*	P_2O_5
					Percentage			
22217	NEWMAN	1.06	0.16	24.8	17.4	18.2	0.19	0.01
22218	NEWMAN	1.65	0.69	28.7	20.0	2.95	0.38	0.01
22219	NEWMAN	1.89	0.6	28.7	19.5	3.18	0.41	0.02
22220	NEWMAN	1.21	0.13	27.9	19.4	7.27	0.34	0.01
22221	NEWMAN	1.27	0.18	31.4	19.3	2.01	0.36	0.01
22222	NEWMAN	1.52	0.26	31.9	18.3	1.02	0.41	0.01
22223	NEWMAN	2.2	1.4	28.1	18.8	5.59	0.48	0.02
22224	NEWMAN	1.9	0.78	49.4	3.1	1.64	0.4	0.02
22225	NEWMAN	1.66	0.13	32.1	19.1	0.71	0.44	0.02
22226	NEWMAN	2.07	2.18	23.6	14.2	19.9	0.43	0.02
28548	YARRALOOLA	2.74	3.2	31.6	2.11	31.5	0.26	0.04
28549	YARRALOOLA	3.43	3.89	33.6	1.66	19.6	0.34	0.04
28550	YARRALOOLA	8.86	2.15	24.4	1.43	39.6	0.59	0.16
28551	Yarraloola	2.0	0.08	28.8	19.7	0.78	0.54	0.02
28552	PYRAMID	3.15	0.57	28.8	17.9	1.6	0.71	0.06
28553	PYRAMID	2.57	1.59	27.4	17.4	6.82	0.72	0.05
28554	PYRAMID	2.86	3.36	23.2	14.6	16.1	0.66	0.04
28555	PYRAMID	5.43	3.29	41.1	2.65	8.25	0.19	0.07
28556	MOUNT BRUCE	4.29	5.1	24.6	8.62	22.3	0.44	0.08
28557	MOUNT BRUCE	2.86	3.78	29.4	10.9	12.8	0.31	0.04
28558	MOUNT BRUCE	3.43	2.8	28.5	13.4	10.3	0.59	0.02

NOTE: after Baxter (1972)
22217–26 Lat. 23°50'S, Long. 119°09'E
28548–50 Lat. 21°51'S, Long. 116°24'E
28551 Lat. 21°50'S, Long. 116°30'E
28552–55 Lat. 21°50'S, Long. 117°36'E
28556–57 Lat. 22°07'S, Long. 117°39'E
28558 Lat. 22°43'S, Long. 117°45'E

are located mainly along the coastal belt extending from Point D'Entrecasteaux to Esperance, and range from calcarenite to pure limestone. They form a complex system of ridges along the coastal region, some of which are associated with extensive deposits of limesand. Major limestone and limesand deposits along the coastal belt are found at Point D'Entrecasteaux, Elleker, Torbay, Herald Point, south of Princess Royal Harbour, on the western side of the mouth of Wilson Inlet, at Parry Inlet, and Hopetoun.

Limestone and limesand production has been reported to the Department of Minerals and Energy from Point D'Entrecasteaux, Bornholm, south of Gledhow, Mount Manypeaks, Parry Inlet, and Boyadup Swamp (approximately 35 km east of Esperance).

Albany region

Wyatt (1961) investigated limestone occurrences within a 25 km radius of Albany in an attempt to identify commercially viable deposits. He noted that all limestone and limesand deposits in the area were restricted to a narrow coastal strip extending approximately 5 km inland.

Near the coast, sandy limestone, sandstone, and siliceous or calcareous sand dunes overlie the Precambrian basement rocks that consist of granite and granite gneiss. Further inland, siliceous sand overlies pisolitic laterite, and isolated outcrops of granite and gneiss occur as hills.

The generally cross-bedded limestone, overlying the Precambrian basement, varies in thickness from a few metres to about 60 m, generally striking in an east–west direction, with a gentle northerly dip.

Wyatt (1961) collected samples from a number of localities in the Albany region, and concluded that the following areas warranted further investigation:

(a) South and southwest of Princess Royal Harbour (Fig. 43);

(b) Elleker area — south of Lake Powell (Fig. 43);

(c) Torbay area — southwestern area along the coastal region (Fig. 44);

(d) Immediate vicinity of Herald Point (Fig. 45).

Gozzard (1987d) provided chemical analyses of limestone and limesand samples collected from a number of locations in the area around Albany.

Princess Royal Harbour

Partial analyses of 14 surface samples, from west of Princess Royal Harbour and south of Gledhow (Wyatt, 1961), showed CaO contents varying from 5.7 to 53.0%

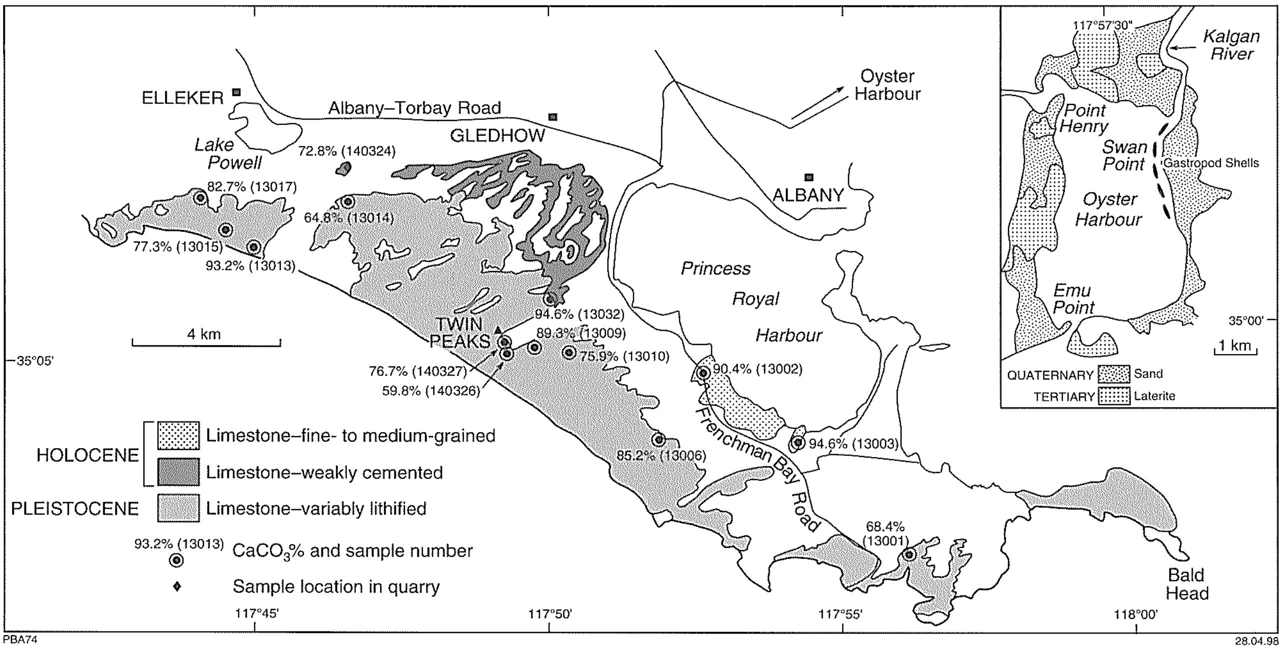

Figure 43. Distribution of limestone in the areas around Princess Royal and Oyster Harbours and Elleker in the Albany region (after Gozzard, 1989a,b)

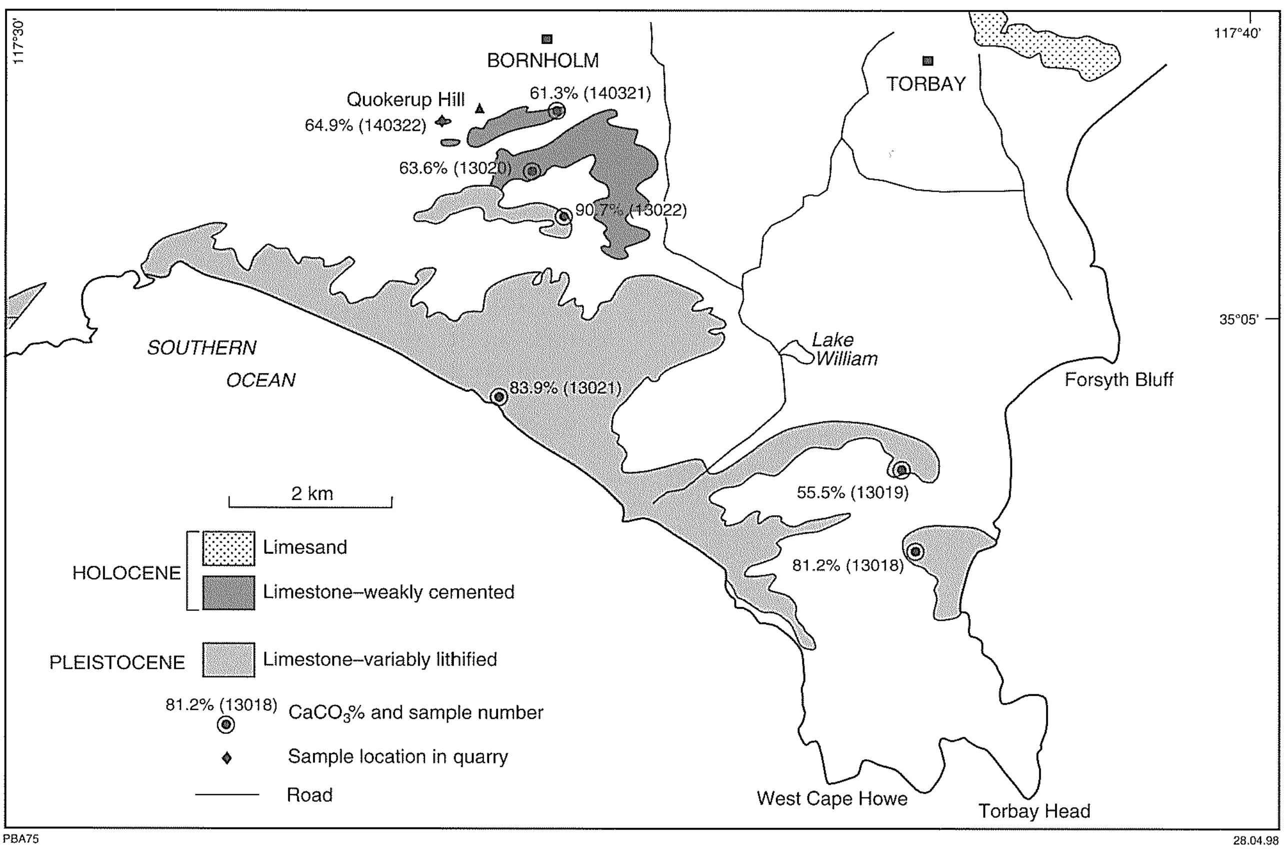

Figure 44. Distribution of limestone south and east of Torbay (after Gozzard, 1989b)

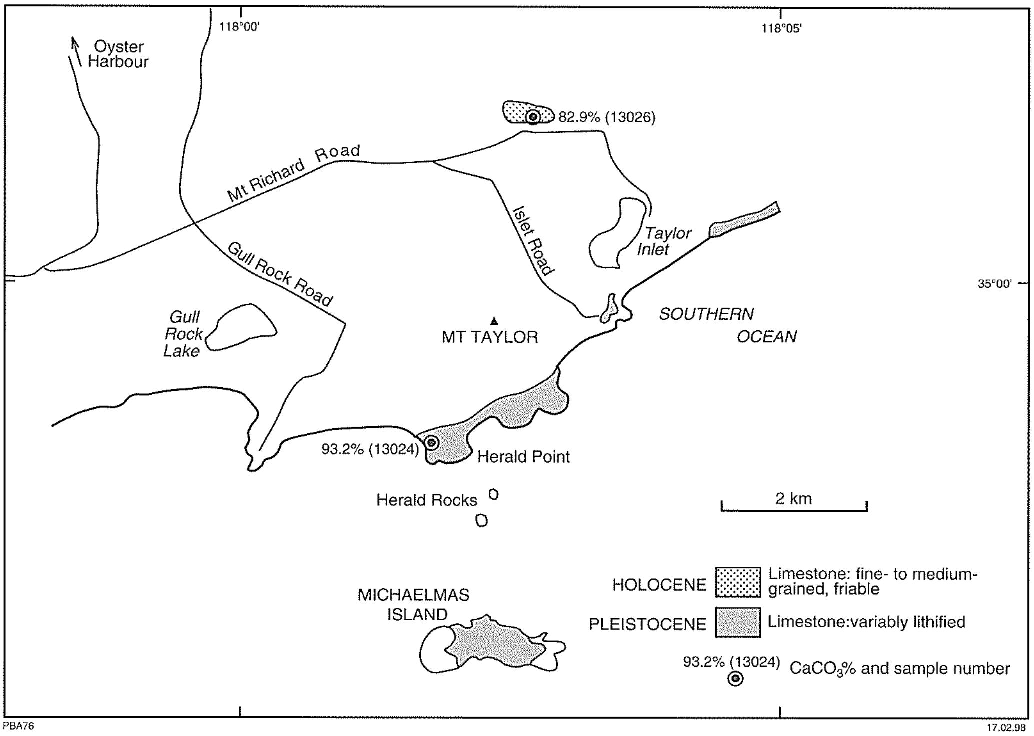

Figure 45. Distribution of limestone around Herald Point (after Gozzard, 1989a)

(10.2 to 94.6% $CaCO_3$), with an average of 33.0% (58.9% $CaCO_3$) (Table 45; Fig. 43). Two samples (140326–27) of impure, white to creamy-brown, medium- to coarse-grained cavernous limestone, collected by the author from a cliff south of Twin Peaks, contained 59.82 and 76.75% $CaCO_3$ (33.50 and 42.98% CaO), and 0.75 and 1.28% $MgCO_3$ (0.36 and 0.61% MgO) respectively (Table 46). There was reported production of 58 t from the area during 1967.

Elleker

Partial chemical analyses of four samples (Fig. 43), from the area south of Elleker and Lake Powell (Wyatt, 1961), indicated CaO contents of 36.3 to 52.2% (64.8 to 93.2% $CaCO_3$) with an average of 44.5% (79.5% $CaCO_3$) (Table 45). A sample (140324) of medium- to coarse-grained, yellowish-brown limestone, collected by the author from a quarry at Bindarrie Road (southeast of Lake Powell), contained 72.77% $CaCO_3$ (40.75% CaO) and 2.45% $MgCO_3$ (1.17% MgO) (Table 46). Limestone in the area is generally sandy and impure.

Torbay–Bornholm

Five samples from Bornholm and south of Torbay (Fig. 44; Table 45) gave assays of 31.1 to 50.8% CaO (55.5 to 90.7% $CaCO_3$), with an average of 42.0 % CaO (75.0% $CaCO_3$) (Wyatt, 1961). Two samples (140321–22) of cavernous, impure, medium- to coarse-grained, yellowish-brown limestone collected by the author from a road cutting and a quarry (close to Quokerup Hill at Bornholm) assayed 61.30 to 64.91% $CaCO_3$ (34.33 to 36.35% CaO) and 1.97 to 1.99% $MgCO_3$ (0.94 to 0.95% MgO) respectively (Table 46). During 1979 to 1983, 2421 t of limestone was produced in the Bornholm area.

Herald Point

Partial analysis of one sample from Herald Point (Fig. 45) gave an assay of 52.2% CaO (93.2% $CaCO_3$), 1.4% MgO (2.9% $MgCO_3$), and 0.77% insolubles. Another sample, from northwest of Taylor Inlet, contained 46.4% CaO (82.9% $CaCO_3$), 1.1% MgO (2.3% $MgCO_3$), and 12.0% insolubles.

Oyster Harbour

The eastern shore of Oyster Harbour (Fig. 43) contains gastropod shells, stretching for a distance of approximately 3 km to the south from the mouth of the Kalgan River. The average width of the shell bed is approximately 30 m, with a 60 cm layer of clean shells beneath a layer of about 15 cm of soil-contaminated shells. Adjoining this area is another shell deposit of around the same width, but of lower grade and covered with soil and scrub. The clean shells are underlain by sandy 'cockle beds' of lower grade (Simpson, 1948).

Samples collected from low- and high-grade zones of the deposit indicate that $CaCO_3$ values vary from 37.21 to 95.51% (20.84 to 53.49% CaO) (Table 47).

Table 45. Partial chemical analyses of limestones from Princess Royal Harbour, Elleker, and the Torbay area

Sample no.	*CaO*	*MgO*	*Acid insoluble*
		Percentage	
Princess Royal Harbour			
13001[a]	38.3	0.80	27.3
13002[a]	50.6	0.60	6.44
13003[a]	53.0	0.37	2.35
13004	46.0	1.09	12.9
13005	42.4	0.56	20.6
13006[a]	47.7	0.86	10.3
13007	8.59	0.75	82.1
13008	5.47	0.27	87.7
13009[a]	50.0	0.74	5.33
13010[a]	42.5	0.92	19.0
13011	12.7	0.07	74.7
13012	5.65	0.09	88.3
13031	6.34	0.54	86.3
13032[a]	53.0	0.54	1.42
Elleker			
13013[a]	52.2	0.68	1.72
13014[a]	36.3	0.04	33.90
13015[a]	43.3	1.30	16.50
13017[a]	46.3	1.10	12.4
Torbay area			
13018	45.5	0.91	13.8
13019	31.1	0.52	41.3
13020	35.6	1.73	30.8
13021	47.0	2.26	9.58
13022	50.8	1.11	3.85

NOTE: after Wyatt (1961)
(a) locations on Figure 43

Table 46. Whole-rock chemical analyses of limestones from Princess Royal Harbour, Elleker, and the Torbay area

	Princess Royal Harbour		*Elleker*	*Torbay area*	
Sample no.	*140326*	*140327*	*140324*	*140321*	*140322*
			Percentage		
SiO_2	38.42	18.89	21.32	36.00	31.44
TiO_2	0.06	0.03	0.06	0.03	0.02
Al_2O_3	0.23	0.12	0.06	0.32	0.17
Fe_2O_3	0.14	0.08	0.05	0.35	0.09
MnO	<0.01	<0.01	<0.01	<0.01	<0.01
MgO	0.36	0.61	1.17	0.94	0.95
CaO	33.50	42.98	40.75	34.33	36.35
Na_2O	0.12	0.11	0.14	0.12	0.16
K_2O	0.12	0.09	0.04	0.17	0.08
P_2O_5	0.08	0.05	0.07	0.06	0.09
LOI	26.74	36.88	35.95	27.40	30.28
Total	**99.77**	**99.84**	**99.61**	**99.72**	**99.63**
CO_2	26.40	35.60	34.30	26.80	28.50

NOTE:
140326 Twin Peaks, Lat. 35°04'06"S, Long. 117°47'52"E, impure limestone
140327 Twin Peaks, Lat. 35°04'05"S, Long. 117°47'59"E, limestone
140324 Southeast of Lake Powell, Bindarrie Road, quarry, Lat. 35°01'46"S, Long. 117°46'06"E, limestone
140321 Bornholm, Lat. 35°03'35"S, Long. 117°34'30"E, impure limestone
140322 Bornholm, quarry, Lat. 35°03'37"S, Long. 117°33'43"E, impure limestone

Localities west of Albany

Point D'Entrecasteaux

Point D'Entrecasteaux is located approximately 1 km west of Windy Harbour (Fig. 46). In 1960, a reconnaissance survey was conducted along the coastal fringe, between Point D'Entrecasteaux and the mouth of the Gardner River, to determine the availability of lime for agricultural uses (Connolly and Wyatt, 1960).

At Point D'Entrecasteaux, the only locality where limestone occurs along the coast, limestone forms prominent cliffs approximately 20 m high (Fig. 47). The limestone is medium grained, compact, and is composed almost entirely of well-rounded shell fragments.

Analysis of a grab sample of limestone indicated 93.5% total carbonates. Connolly and Wyatt (1960) were of the view that at least 25 Mt of limestone assaying 90.0% $CaCO_3$ (50.4% CaO) would be available from this locality, and they considered that this deposit would be a good source for large-scale production, but not satisfactory for the small and intermittent demand that prevailed at the time. The area is now within the Point D'Entrecasteaux National Park.

There is recorded production of 2924 t of limestone during 1968 and 1969, and another 15099 t from 1988 to 1994. Connolly and Wyatt (1960) noted that small pits have been opened up 1.5 km northwest of Windy Harbour to supply material for roadbase.

Wilde and Walker (1984) suggested that considerable quantities of Tamala Limestone may be present beneath sand northwest of Point D'Entrecasteaux, where the coastal belt is wide.

Wilson Inlet–Denmark

A limestone ridge occurs on the western side of the mouth of Wilson Inlet, approximately 10 km south-southwest of Denmark (Fig. 48). Woodward (1915b) described the limestone as ‘false-bedded’, with a fairly thick caprock of relatively high but variable grade overlying material of lower grade. Partial analyses of three samples of higher grade material, given by Woodward (1915b), had an average of 74.90% $CaCO_3$ (41.94% Ca) (Table 48). Further sampling of caprock in the area, in 1923, indicated an average of 88.74% $CaCO_3$ (49.69% CaO), 2.07% $MgCO_3$ (0.99% MgO), 6.41% insolubles, and 0.52% Fe_2O_3 plus Al_2O_3 (Simpson, 1948).

Two samples (140319–20) of friable, soft, light-brown, medium- to coarse-grained limestone, collected from a quarry located on the cliff on the western side of Wilson Inlet, contained 92.75 and 89.71% $CaCO_3$ (51.94 and 50.24% CaO), and 1.86 and 1.76% $MgCO_3$ (0.89 and 0.84% MgO) respectively (Table 49). The samples were representative of the friable limestone found in the quarry. The surrounding hill appears to contain material of similar grade in significant quantities.

Table 47. Partial chemical analyses of shells from Oyster Harbour

	$CaCO_3$	Insolubles	NaCl	MgO	$Fe_2O_3 + Al_2O_3$
			Percentage		
Clean shells	95.51	trace	trace	trace	0.45
Shells — most contamination	–	55.13	38.32	0.18	trace
Shells — average contamination	–	68.84	25.85	0.10	–
Lake marl	54.91	21.86	4.63	–	–
Cockle bed	37.21	60.60	0.04	–	–

NOTE: after Simpson (1948)

Another sample (140318) of impure, soft, medium- to coarse-grained, yellowish-brown limestone collected from a cutting on Ocean Drive, west of Wilson Inlet, assayed 75.82% $CaCO_3$ (42.46% CaO) and 1.80% $MgCO_3$ (0.86% MgO) (Table 49).

High-grade limestone from an outcrop on the western side of Wilson Inlet has been used in the past for the production of lime.

Parry Inlet

During 1961 to 1970, 2209 t of limestone was produced from Parry Inlet. No information is available on the quality and quantity of limestone exposed along the coastal belt extending to the west from William Bay (Fig. 48).

Lake Muir

Ellis (1948) described a minor limestone occurrence at Lake Muir, approximately 75 km east-southeast of Manjimup (Lat. 34°28'S, Long. 116°39'E), which he considered to be of no commercial significance. A sample from this locality assayed 36.77% CaO (65.66% $CaCO_3$), 0.51% MgO (1.07% $MgCO_3$), and 31.60% insolubles.

Localities east of Albany

Nanarup

The Nanarup Limestone Member is a highly fossiliferous limestone subunit of the Tertiary Werillup Formation. It is exposed in the Nanarup (Lat. 35°00'S, Long. 118°04'E) lime quarry, where it is known to be at least 4.6 m thick

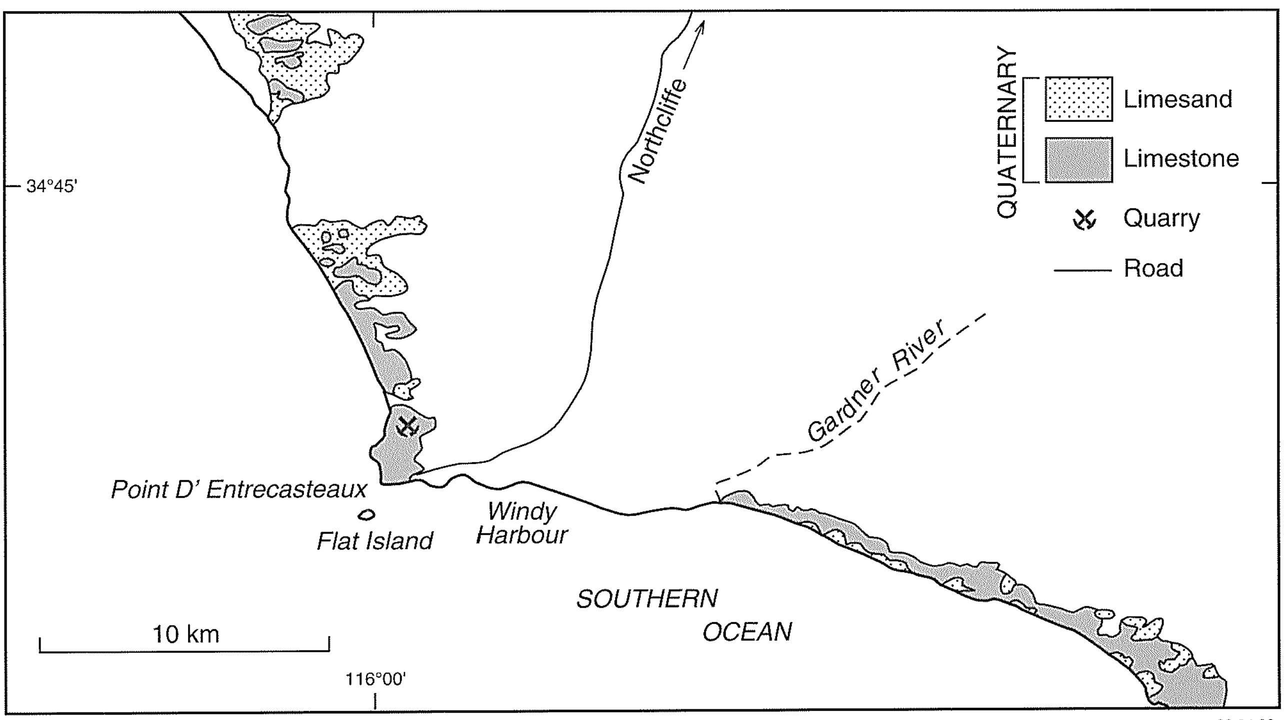

Figure 46. Limestone occurrences around Point D'Entrecasteaux (after Wilde and Walker, 1984b)

Figure 47. Photograph of a coastal cliff of cavernous limestone at Point D'Entrecasteaux

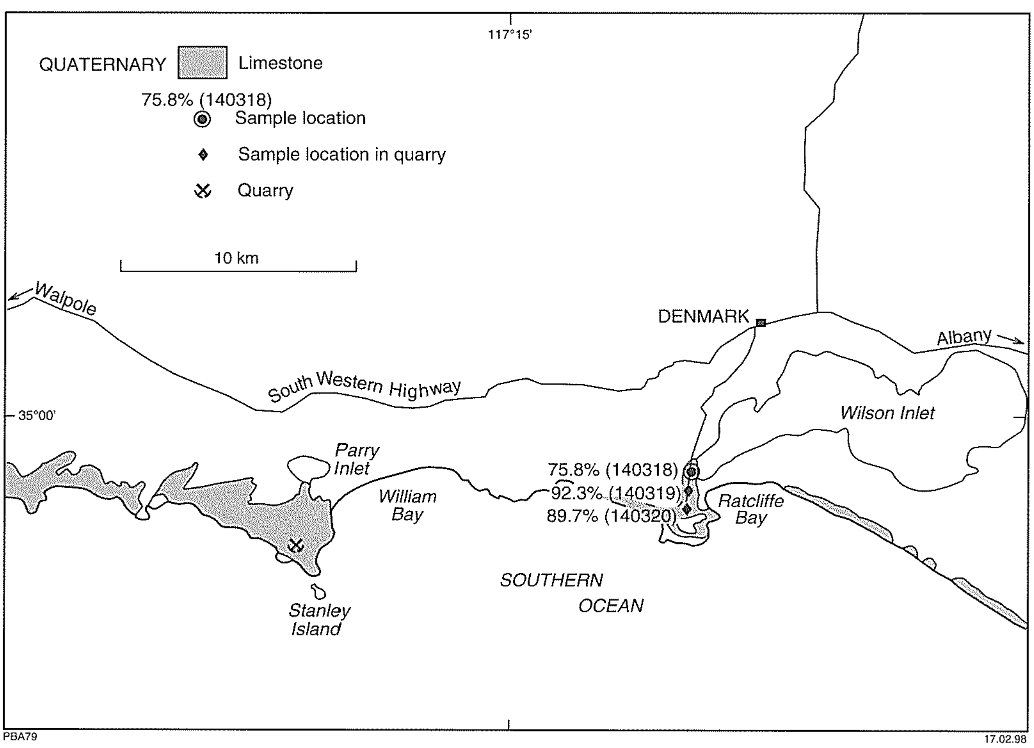

Figure 48. Distribution of limestone around Parry and Wilson Inlets (geology after Muhling et al., 1984)

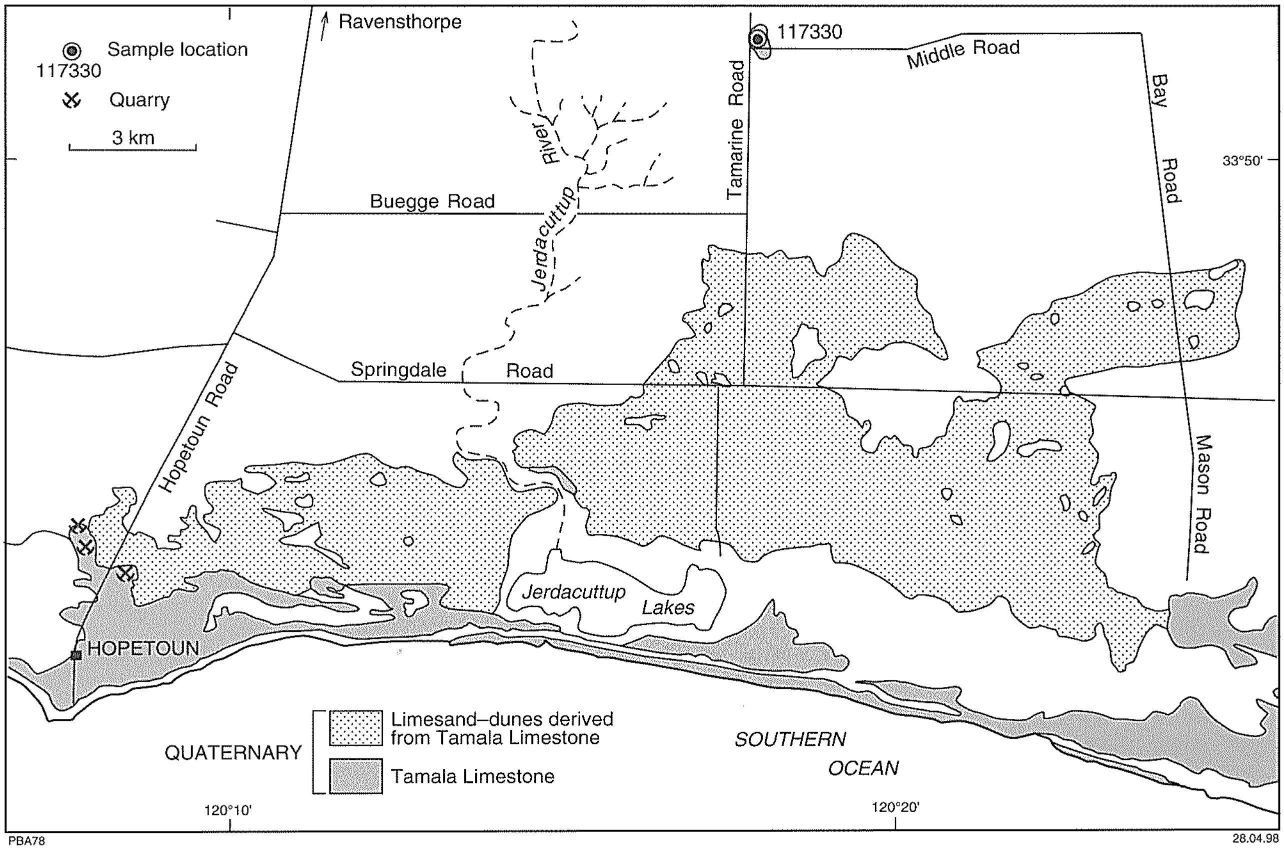

Figure 49. Distribution of Tamala Limestone and sand dunes derived from Tamala Limestone in the Hopetoun area (after Witt, 1996)

(Muhling and Brakel, 1985). The fossils present in this unit include foraminiferids, echinoids, bryozoans, brachiopods, and molluscs.

Mount Manypeaks

From 1966 to 1975, 14 982 t of limestone was produced from a location a few kilometres west of Mount Manypeaks (Lat. 34°49'20"S, Long. 118°12'30"E) (Fig. 7). As the location is within the Werillup Formation, the mined material was possibly the Nanarup Limestone Member.

Hopetoun

The Tamala Limestone and derived sand regolith are widespread along the coastal belt in the Hopetoun area (Fig. 49). One sample (117330) of limestone, collected along Tamarine Road, contained 88.6% $CaCO_3$ (49.6% CaO) and 3.4% $MgCO_3$ (1.63% MgO).

Several quarries near Hopetoun have produced aggregate for road building. During the operation of the copper smelter at Cordingup, limestone from the area was used as a flux (Thom et al., 1977). However, no production from the area has been reported to the DME.

Esperance

Carbonate-rich eolianite of Pleistocene age, possibly equivalent to the Tamala Limestone, occurs between coastal hills around Esperance (Morgan and Peers, 1973).

The only limestone production reported to the DME from the Esperance area is from a location (Lat. 33°51'55"S, Long. 122°16'55"E) approximately 35 km east of Esperance and 7 km south-southwest of Boyadup Swamp. Total production from this location was 7538 t during the period 1961 to 1982. The material mined was probably limesand, which was used as a source of agricultural lime.

Canning Basin

The major limestone deposits of the Canning Basin occur in Devonian reef complexes that form part of the Lennard Shelf. Limestone resources are also associated with calcrete deposits occurring in a number areas in the northeastern and southeastern parts of the central Canning Basin (Fig. 7).

Table 48. Partial chemical analyses of limestone from Wilson Inlet

Sample no.	*A*	*B*	*C*
		Percentage	
$CaCO_3$	81.88	65.68	77.14
$MgCO_3$	2.32	1.46	1.55
Acid insolubles	11.68	29.42	17.60
$Fe_2O_3 + Al_2O_3$	0.62	0.76	1.28
Organic matter, moisture etc.	3.50	2.68	2.43

NOTE: after Woodward (1915b)

Devonian reef complexes of the Lennard Shelf

The Devonian reef complexes of the Lennard Shelf consist of extensive, highly fossiliferous limestone formations interbedded with sandstone, siltstone, and other sediments. Information on the quality of these limestone formations for industrial uses is scarce as the main emphasis of geological studies in the area has been to assess prospectivity for petroleum and for Mississippi Valley-type base-metal deposits. The remoteness of the Lennard Shelf from potential markets for limestone products is another factor responsible for the paucity of investigations into limestone quality.

However, according to the geologists who have worked in the area, there are large areas of limestone that appear to be suitable for limestone-based industries. For example, Roberts et al. (1968) noted that deposits of limestone, presumed to be of high quality, are plentiful in the Devonian reef complex on the western part of MOUNT RAMSAY, and Derrick and Playford (1973) suggested that limestones in some areas of LENNARD RIVER could be used as building stone, marble, and as a source of lime for cement manufacture. Gellatly and Derrick (1967) commented on the possibility of obtaining adequate supplies of limestone for agricultural purposes from the Devonian rocks of the Lennard Shelf.

A series of Devonian reef complexes, forming a northwesterly trending belt approximately 300 km long and 50 km wide, occurs on the Lennard Shelf at the northern margin of the Canning Basin (Fig. 50). These complexes are bounded by the Precambrian rocks of the King Leopold Orogen in the north, and Permian and Late Carboniferous sediments of the Fitzroy Trough to the south. The reef complexes are underlain directly by Precambrian granite, gneiss, schist, and metasediments, except in the Emanuel Range area where they rest on Ordovician sediments. Detailed descriptions of the reef complexes in the Lennard Shelf area are given by Playford and Lowry (1966), Playford et al. (1976b, 1989), Playford (1980, 1981, 1984), Towner and Gibson (1983), Cockbain (1984), Purcell (1984), Kerans (1985), Buchhorn (1986), Hurley (1986), Kerans et al. (1986), Rigby (1986), Hurley and Van der Voo (1987, 1990), Wallace (1987), Hurley and Lohman (1989), and Griffin et al. (1993).

Table 49. Whole-rock chemical analyses of limestone from Wilson Inlet

Sample no.	*140318*	*140319*	*140320*
		Percentage	
SiO_2	19.07	6.03	6.52
TiO_2	0.04	0.03	0.02
Al_2O_3	0.38	0.41	0.25
Fe_2O_3	0.17	0.20	0.05
MnO	<0.01	<0.01	<0.01
MgO	0.86	0.89	0.84
CaO	42.46	51.94	50.24
Na_2O	0.26	0.15	0.23
K_2O	0.15	0.10	0.09
P_2O_5	0.07	0.10	0.08
LOI	36.03	41.09	40.93
Total	**99.49**	**100.94**	**99.25**
CO_2	33.10	38.90	39.10
		Parts per million	
As	–	1.6	–
Ba	–	28	–
Be	–	<0.2	–
Ce	–	5.1	–
Cr	–	16	–
Ga	–	1.09	–
La	–	5.6	–
Nb	–	0.8	–
Rb	–	3.4	–
S	–	<0.01	–
Sn	–	0.7	–
Sr	–	1 353	–
Th	–	0.75	–
U	–	0.61	–
V	–	<2	–
W	–	<0.1	–

NOTE: 140318 Wilson Inlet (western side, road cutting), Lat. 35°01'40"S, Long. 117°19'33"E, limestone
140319 Quarry at Lat. 35°01'58"S, Long. 117°19'23"E, Wilson Inlet (western side), limestone
140320 Quarry at Lat. 35°01'58"S, Long. 117°19'23"E, Wilson Inlet (western side), limestone

The Lennard Shelf reef complexes range in age from Middle to Late Devonian. The exposed rocks are predominantly limestone, although terrigenous sediments occur in some parts of the sequence. The limestones form a rough karst topography, generally 30 to 90 m above the surface of the plains, with some areas almost impassible on foot due to their extreme roughness. Deep gullies, controlled by major joints, locally dissect the reef complex, and small-scale karst features including vertical fluting, razor-sharp ridges, and solution pans are conspicuous, especially in the more massive limestone.

Three basic facies are recognized in the reef complexes: platform, marginal-slope, and basin facies (Fig. 51) (Griffin et al., 1993). The platform facies is subdivided into reef-margin, reef-flat, back-reef, and bank subfacies, and the marginal-slope facies into reefal-slope, fore-reef, and fore-bank subfacies. The fracturing of limestones around the platform margins and upper marginal slopes has resulted in periodic submarine landsliding of large sections of reef, causing massive debris flows and accumulations of large allochthonous reef blocks in the marginal-slope deposits, and turbidites in the basin deposits. This phenomenon is well displayed in the Dingo Gap area of the Napier Range (Fig. 52). In some parts of the Napier and Oscar Ranges, discrete marginal-slope beds with abundant debris flows and allochthonous beds can be traced for many kilometres.

In the evolution of the Oscar Range and Napier Range reef complexes, two types of platform development are recognized; the Frasnian (early Late Devonian) Pillara cycle and the Famennian (Late Devonian) Nullara cycle. The Pillara cycle is characterized by vertical platform growth followed by widespread drowning and back-stepping, whereas the Nullara cycle is characterized by strongly advancing platforms. However, in other parts of the Lennard Shelf the Pillara cycle can be shown to have begun in the Middle Devonian (Givetian). The total maximum thickness of platform deposits of the two cycles on the Lennard Shelf is about 2000 m, while seismic data suggest that contemporary basinal facies, largely comprising terrigenous clastics and turbidites, are up to 2500 m thick (Playford and Lowry, 1966; Griffin et al., 1993).

Limestone formations

Limestone formations in the reef complexes are shown on Figure 53 and are discussed below.

Gogo Formation

The Gogo Formation was originally the name proposed by Guppy et al. (1958) for a sequence of siltstone with thin beds of limestone, containing characteristic limestone concretions, which was believed to underlie the Virgin Hills Formation and to overlie and intertongue with the Sadler Limestone. Subsequently, Playford and Lowry (1966) recognized that the Gogo Formation is the basin-facies equivalent of the Sadler Limestone. The age of the Gogo Formation is believed to extend from Givetian to early Frasnian.

The formation, generally poorly exposed, outcrops in Bugle Gap, Emanuel Range, and the Pillara Range (Fig. 50), where it consists of mainly shale and siltstone with thin lenticular beds of limestone, and layers containing abundant calcareous nodules (Playford and Lowry, 1966). The thin limestone bands in the formation are fine to very fine grained, intraclastic, sparry to micritic calcarenites, grading into calcilutites.

Sadler Limestone

The name Sadler Limestone was proposed by Playford and Lowry (1966) for the Sadler Formation, which was the name originally applied by Guppy et al. (1958) to the late Givetian to early Frasnian marginal-slope sequence of calcarenite and reef limestone exposed at Sadler Ridge, along the northeast side of the Emanuel Range. The new name was suggested because of the abundance of limestone in the unit. The Sadler Limestone interfingers with the Gogo Formation and Pillara Limestone.

The Sadler Limestone is commonly thinly bedded, sparry to micritic, medium to fine grained, yellow-grey in colour, and contains relatively thin beds of soft sediments. A characteristic feature on weathered surfaces is the occurrence of silicified fossils such as brachiopods and corals. Exposures of Sadler Limestone in some areas are marked by the presence of numerous small, dark-brown, limonitic nodules scattered over the ground.

The Sadler Limestone is well exposed along the northern sides of the Pillara and Emanuel Ranges, and north of Outcamp Hill.

Virgin Hills Formation

Guppy et al. (1958) gave the name Virgin Hills Formation to the sequence of red limestone and calcareous siltstone and sandstone overlying the Sadler Limestone. It includes sediments of both marginal-slope and basin facies. The age of the formation is considered to be middle Frasnian to middle Famennian.

The formation is characterized by its bright-red colour, which is particularly prominent in the inter-reef facies, the lithology of which consists of interbedded limestone and calcareous siltstone, shale, and sandstone. However, some parts of the formation are white, yellow-grey, and grey-green. The limestone in the formation is mainly calcilutite and fine to very fine grained, intraclastic, micritic calcarenite, with lesser amounts of intraformational calcirudite.

The Virgin Hills Formation occurs in the Horse Spring Range, Virgin Hills, Bugle Gap, and Old Bohemia areas (Fig. 50) (Playford and Lowry, 1966).

Bugle Gap Limestone

Guppy et al. (1958) introduced the name Bugle Gap Limestone for the sequence of limestone overlying the Virgin Hills Formation in the Bugle Gap and Old Bohemia areas (Fig. 50). The limestone is interpreted as being a marginal-slope facies. The age of the Bugle Gap Limestone is early to middle Famennian.

The Bugle Gap Limestone is white to pink and consists of medium- to thick-bedded, intraclastic, sparry, fine to very coarse grained calcarenite, grading to calcirudite. It is known only in the area around the southern end of Bugle Gap, extending east into the Old Bohemia area (Playford and Lowry, 1966).

Piker Hills Formation

Playford and Lowry (1966) applied the name Piker Hills Formation to the Famennian sequence of limestone, shale, and siltstone that overlies the Virgin Hills Formation in the Mount Pierre – Piker Hills area. The formation is part of the marginal-slope and basin facies

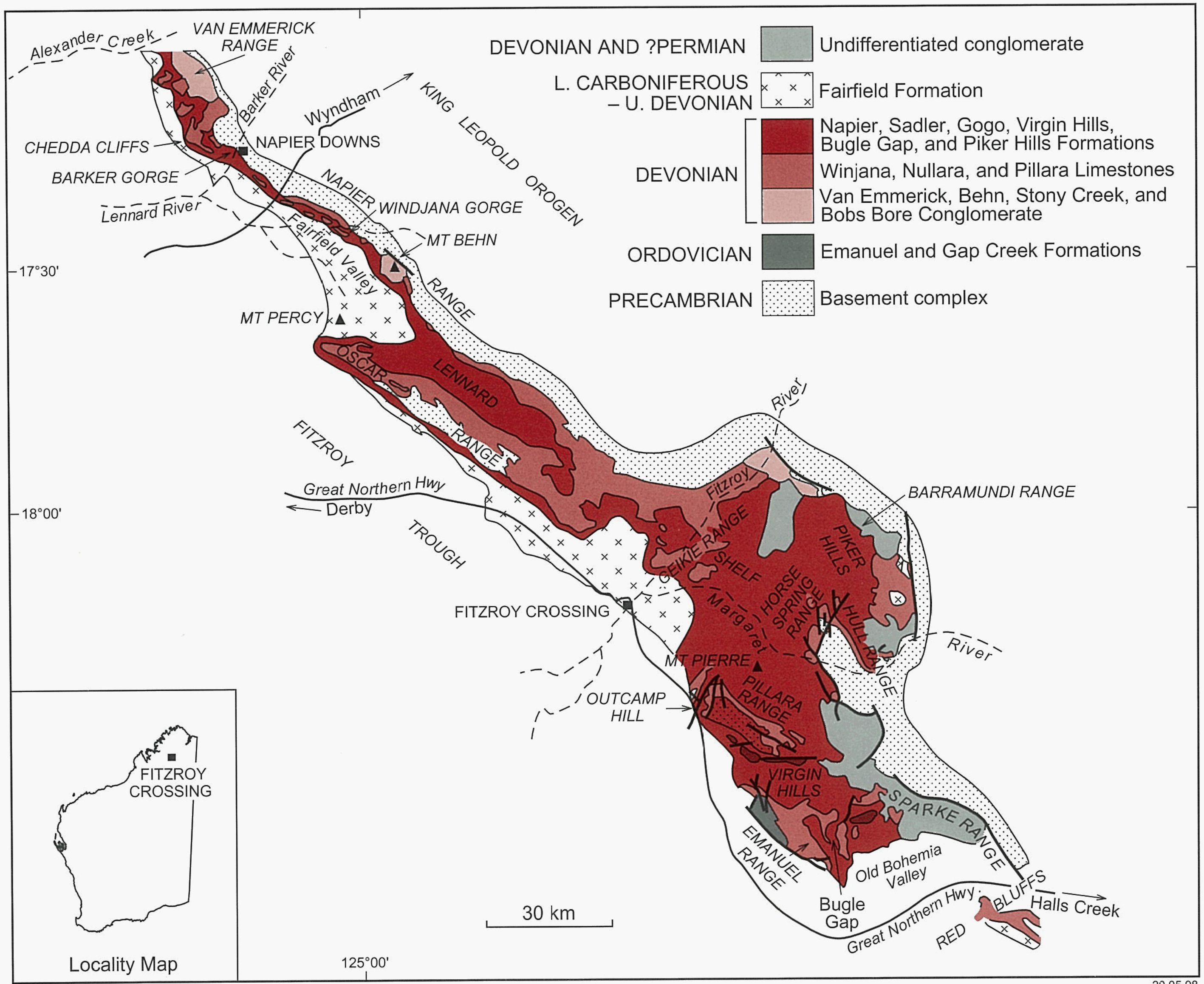

Figure 50. Limestone formations in the Fitzroy Crossing to Alexander Creek areas of the Lennard Shelf (after Playford and Lowry, 1966)

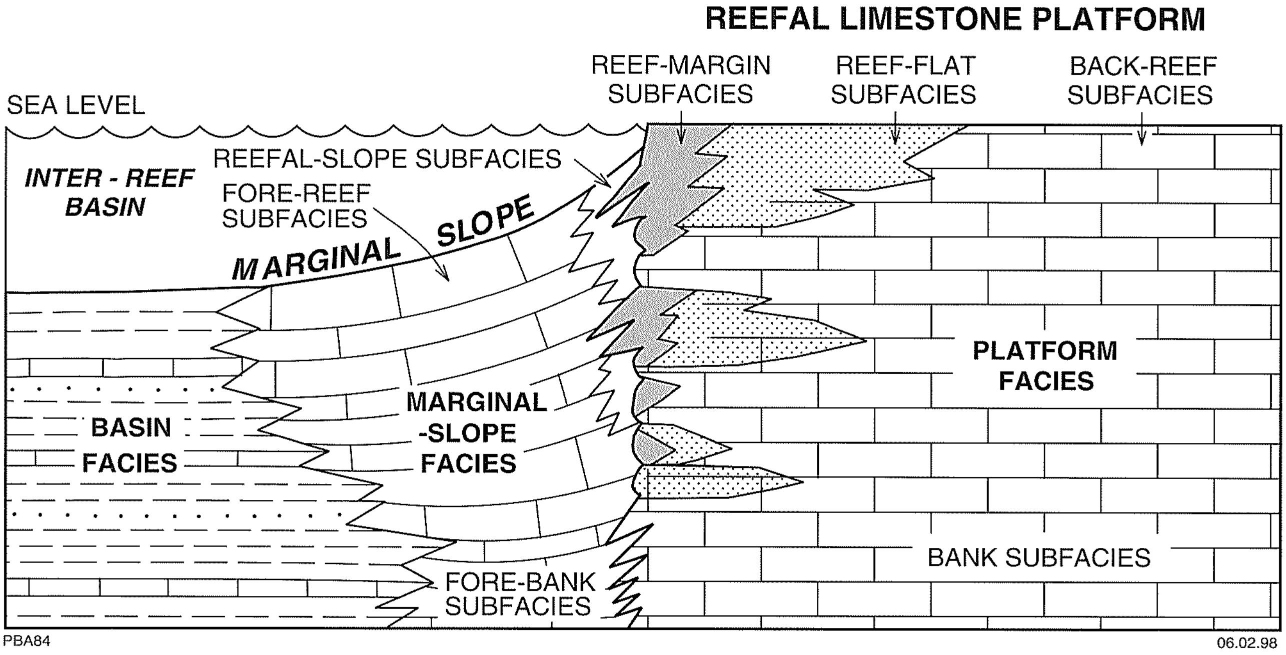

Figure 51. Facies and subfacies morphology of Devonian Reef complexes of the Lennard Shelf (after Playford, 1984)

of the reef complexes developed in the southeastern part of the Lennard Shelf

The basin facies of the Piker Hills Formation is a generally poorly exposed sequence of interbedded shale, siltstone, and limestone. Limestones in this facies are commonly thinly bedded and characteristically form slabby exposures. The marginal-slope facies deposits of this formation are mainly limestones with minor interbedded shales and siltstones. The limestones in this facies are white to yellow-grey, intraclastic, sparry calcarenites and calcirudites, with many blocks of reef limestone in some horizons.

Exposures of the Piker Hills Formation are restricted to an area between the western end of the Pillara Range and the Barramundi Range (Fig. 50).

Pillara Limestone

The mid-Givetian to late-Frasnian Pillara Limestone constitutes that part of the platform facies of the reef complexes originally named as the Pillara Formation (Guppy et al., 1958). Playford and Lowry (1966) changed the name to Pillara Limestone as limestone is the dominant rock type in the unit. The type section, at Menyous Gap in the Pillara Range (Lat. 18°23'20"S, Long. 125°50'00"E), is about 410 m thick. The formation unconformably overlies Ordovician sediments in the Emanuel Range area, and Precambrian metamorphic rocks in other areas.

Lithology

The Pillara Limestone consists of generally dolomitized, well-bedded back-reef deposits made up of stromatoporoid biostromes, fenestral limestone, oolite, and peloidal limestone. Sandstone, siltstone, and lesser amounts of conglomerate are present, especially in the basal section and in areas adjacent to Precambrian and Devonian rocks. The limestone is typically yellow, yellow-grey, or pink, while the dolomite is usually yellow in colour.

Playford and Lowry (1966) subdivided the back-reef facies into five subfacies on the basis of lithology. These are stromatoporoid, birdseye limestone, oolite, coral, and oncolite subfacies.

The stromatoporoid subfacies, which is the most distinctive and probably the most common subfacies, consists of locally extensively dolomitized biostromal beds from a few centimetres to about a metre thick. Stromatoporoid biostromes are commonly separated by beds of calcarenite or calcilutite, and bedding planes may be marked by a thin film of clay or silt. Flocculent micrite to micritic or sparry calcarenite, locally replaced by fibrous calcite, forms the matrix of the stromatoporoid limestone.

The birdseye limestone subfacies is medium bedded and is characterized by the presence of small (1–10 mm) patches of sparry calcite in a groundmass of calcilutite or calcarenite. This subfacies, probably laid down as algal-mat deposits, is locally dolomitized.

The oolite subfacies is not as extensive as either of the above subfacies, but it still covers large areas. Oolites are typically coarse to fine grained with a sparry cement. Although the subfacies is virtually devoid of fossils, large pelecypods, gastropods, and oncolites have been noted at some localities.

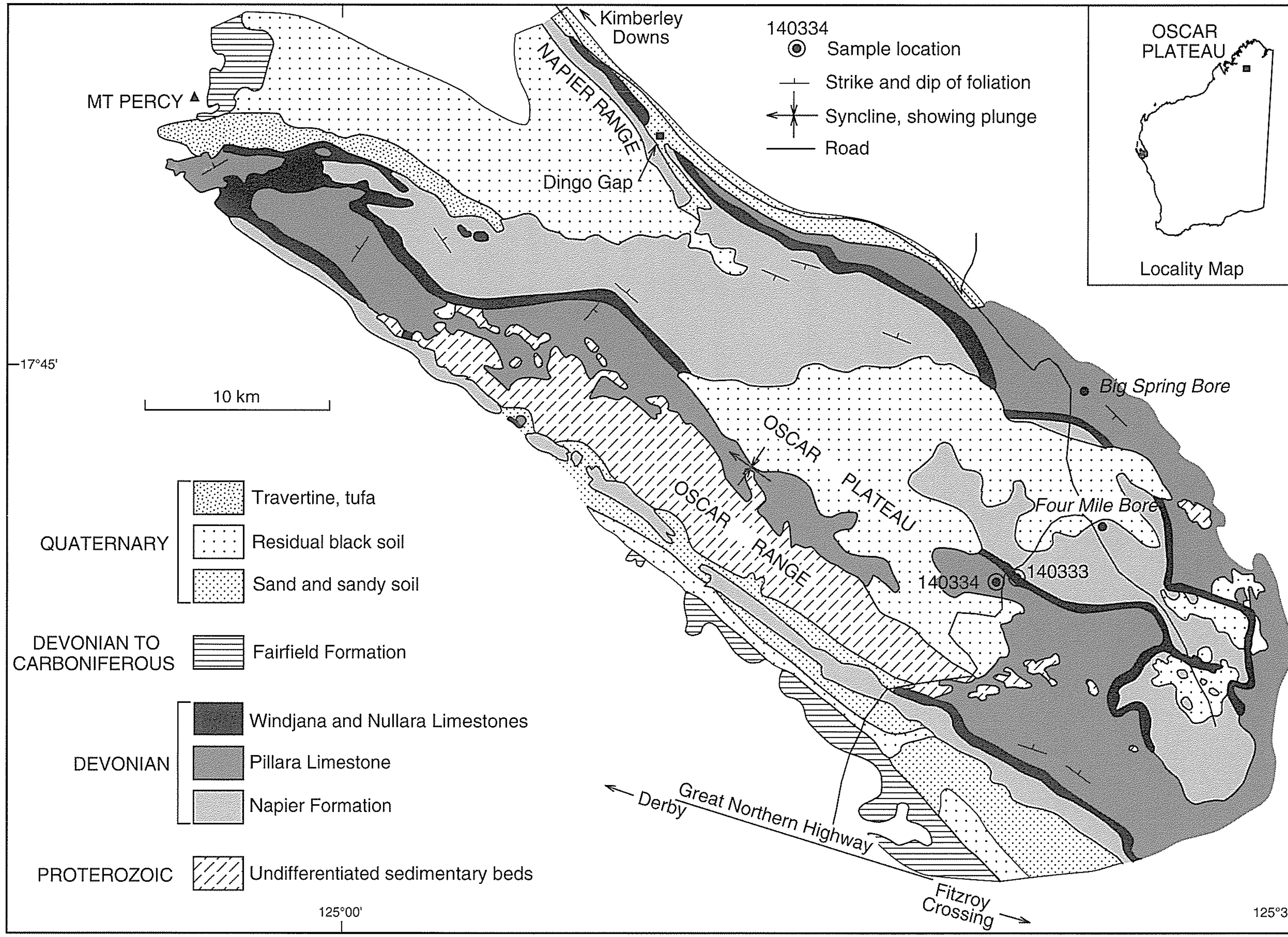

Figure 52. Distribution of limestone formations in the Oscar Plateau area (after Griffin et al., 1993)

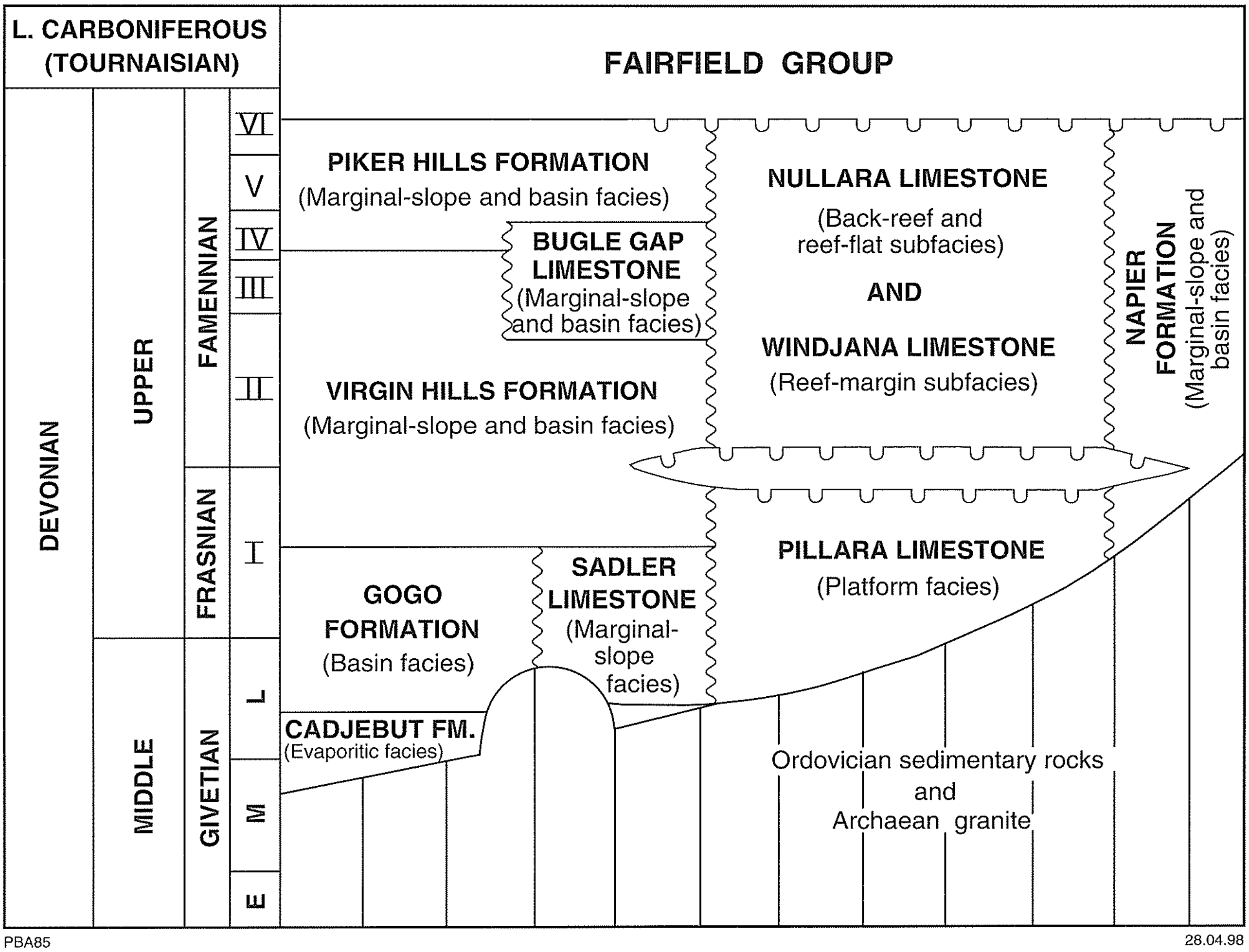

Figure 53. Stratigraphic relationships of rock units in Devonian Reef complexes of the Lennard Shelf (after Copp, in prep.)

The coral subfacies is not widely distributed and appears to be restricted to the Givetian and early Frasnian parts of the reef complexes. Corals are embedded in a matrix of turbid micrite or in a fine- to coarse-grained calcarenite. Silicification of the corals, leaving the matrix unaltered, is common.

The oncolite subfacies, characterized by beds of oolite or sparry, intraclastic calcarenite containing abundant algal nodules or oncolites, is less widespread than the other subfacies.

Distribution

The Pillara Limestone occurs throughout the reef complexes of the Lennard Shelf from Alexander Creek in the northwest to Red Bluffs in the southeast (Figs 50 and 52).

Napier Formation

The name Napier Formation was originally proposed by Guppy et al. (1958) for the sequence of limestone and terrigenous clastic sediments exposed in the Napier Range and on the northern side of the Oscar Range, but was later modified by Playford and Lowry (1966) to include the Oscar, Brooking, Geikie, Copley, and Fossil Downs Formations of Guppy et al. (1958). The reef limestones included by Guppy et al. (1958) in his Napier Formation are now included in the Windjana Limestone. The type section of the early Frasnian to late Famennian Napier Formation is located at Barker Gorge (Playford and Lowry, 1966).

Lithology

The Napier Formation constitutes the marginal-slope and basin facies of the Napier Range and Oscar Range reef complexes. It consists of crudely bedded to well-bedded limestone and some dolomite, as well as substantial thicknesses of calcareous sandstone and siltstone, with minor shale and conglomerate (Playford and Lowry, 1966; Griffin et al., 1993). The limestones in the formation vary from intraclastic and biogenic calcarenites and calcirudites to megabreccias.

The fore-reef subfacies of the marginal-slope facies consists of debris derived by erosion of the Pillara platforms during the Frasnian, and the Windjana–Nullara platforms during the Famennian. It includes large reef-block megabreccia, massive debris-flow deposits, and early lithified parts of the marginal-slope limestone (Playford, 1981; Playford et al., 1989; Griffin et al., 1993).

The reefal-slope subfacies was deposited at the top of the marginal slopes, immediately adjoining the limestone platforms. It consists of layers of cyanobacteria and sponges, which formed the reefal frameworks and trapped and bound platform-derived sediments. Cyanobacteria and sponges in some places built up large biohermal mounds on the marginal slopes or on top of drowned Frasnian pinnacle reefs.

Distribution

The Napier Formation extends from near Alexander Creek at the northwestern end of the Napier Range to as far southeast as Geike Range (Figs 50 and 52).

Windjana Limestone

Playford and Lowry (1966) proposed the name Windjana Limestone for the limestone unit with lesser amounts of dolomite that forms the reef-margin subfacies of the Kimberley reef complexes. The western end of Windjana Gorge (Fig. 50) in the Napier Range is the type locality. Here the unit it is well exposed in cliffs up to 70 m high. Playford (1980) assigned a Famennian age to the limestone.

Lithology

The Windjana Limestone consists of massive to crudely bedded reef limestone and minor dolomite. The reefs were built mostly by cyanobacteria, commonly *Renalcis* and *Sphaerocodium*, with only minor contribution from stromatoporoids. Some of the reef limestones are wholly or partly recrystallized or replaced by microcrystalline calcite. The limestone is typically white, light grey, yellow or red in colour, while the dolomites are usually yellow. Patches of calcarenite and oolite occur in some parts of the reef where they apparently filled potholes and channels in the reef surface. Locally, calcarenite, oolite, or calcareous sandstone occur in irregular joints cutting the reef limestone. Dolomitization occurs in discontinuous patches along the reef, but is locally extensive.

Distribution

The Windjana Limestone is exposed discontinuously around the rims of limestone platforms between Alexander Creek and Bugle Gap (Figs 50 and 52).

Nullara Limestone

The Famennian Nullara Limestone, the back-reef and bank subfacies equivalent of the Windjana Limestone, consists of fenestral limestone and oolite, and is partly dolomitized in some areas.

The type section for the Nullara Limestone is at the northwestern end of the Oscar Range (Fig. 52). It is also exposed along the Napier Range, notably behind Chedda Cliffs (Fig. 50). However, the unit has been removed by erosion over most of the range.

Fairfield Group

The Fairfield Group is a poorly exposed unit of late Famennian to Tournaisian age consisting of an interbedded sequence of limestone, shale, siltstone, and sandstone. The name Fairfield Group was introduced by Druce and Radke (1979) for the Fairfield Formation of Playford and Lowry (1966) that included the Carboniferous Laurel Formation of Thomas (1959) and the Devonian 'Fairfields Beds' of Guppy et al. (1958).

The Fairfield Group has been interpreted as a shallow-water unit deposited conformably on the Devonian reef complexes (Griffin et al., 1993).

Limestone quality

There is little information on the quality of the limestone in the Lennard Shelf area. Two samples of limestone collected from the area east of the Oscar Plateau (Fig. 52) are of very high quality (Table 50). Sample 140333 from the Windjana Limestone contained 53.4% CaO (95.4% $CaCO_3$), 0.73% MgO, and 1.85% SiO_2, while sample 140334 from the Pillara Limestone assayed 55.1% CaO (98.4% $CaCO_3$), 0.61% MgO, and 0.54% SiO_2. Vast areas of limestone of similar appearance occur in the east Oscar Plateau area (White, S., 1997, pers. comm.), suggesting that the Lennard Shelf area could contain a large resource of high-grade limestone.

Other areas in the Canning Basin

Table 51 summarizes the extensive calcrete deposits that occur in many areas of the Canning Basin.

Bonaparte and Ord Basins

The Bonaparte and Ord Basins straddle the border between Western Australia and the Northern Territory of Australia (Fig. 54).

The Bonaparte Basin covers a total area of approximately 270 000 km^2, most of which is offshore. Only about 8000 km^2 fall within onshore Western Australia. The Ord Basin is located immediately south of the Bonaparte Basin and covers an area of about 40 000 km^2, of which 16 000 km^2 lie within Western Australia.

The Bonaparte Basin consists of an 18 km thickness of sedimentary and volcanic rocks, ranging in age from Cambrian through to Cainozoic, although the presence of Silurian sediments has not been confirmed. The Ord Basin contains up to 2.5 km of Cambrian and Late Devonian volcanics and sediments, and minor amounts

Table 50. Chemical analyses of limestones from the Lennard Shelf

Sample no.	*140333*	*140334*
	Percentage	
SiO_2	1.85	0.54
TiO_2	0.04	<0.01
Al_2O_3	0.64	0.10
Fe_2O_3	0.05	0.19
MnO	0.02	<0.01
MgO	0.73	0.61
CaO	53.42	55.07
Na_2O	0.04	0.04
K_2O	0.32	0.09
P_2O_5	0.04	0.05
LOI	42.66	43.59
Total	**99.81**	**100.28**
CO_2	41.80	42.20
	Parts per million	
As	151	277
Ba	106	8
Be	0.8	0.5
Ce	11	2.2
Cr	4	<2
Ga	4.3	1.12
La	12	3.6
Nb	1.3	<0.5
Rb	20	4.0
S	<0.01	<0.01
Sn	0.3	0.1
Sr	245	301
Th	1.15	0.16
U	0.26	0.38
V	6	<2
W	<0.1	<0.1

NOTE: 140333 Windjana Limestone, Lat. 17°51'12"S, Long. 125°21'18"E
140334 Pillara Limestone, Lat. 17°51'33"S, Long. 125°20'06"E

of Cainozoic sediments. In both basins, the base of the Cambrian is dominated by tholeiitic basalts (Antrim Plateau Volcanics).

Further information on both basins can be obtained from Laws (1981), Mory and Beere (1988), and Mory (1990).

Limestone units

The main limestone units in the Bonaparte and Ord Basins can be summarized as follows:

Bonaparte Basin
Ningbing Group (Late Devonian (Famennian))
- Garimala Limestone
- Wungabal Limestone
- Kamilili Formation
- Djilirri Limestone

Cockatoo Group (Late Devonian (Frasnian))
- Hargreaves Formation
  - Westwood Member

Ord Basin
Goose Hole Group (Middle Cambrian)
- Negri Subgroup
  - Panton Formation
    - Corby Limestone Member
    - Shady Camp Limestone Member
  - Linnekar Limestone
  - Headleys Limestone

Ord Basin

Negri Subgroup

Headleys Limestone

The Headleys Limestone consists of grey, laminated or massive micrite with chert nodules. The unit's type section is in the vicinity of Headleys Knob (Northern Territory) from Lat. 17°30'25"S, Long. 129°01'25"E (base) to Lat. 17°27'25"S, Long. 129°00'25"E (top) (Traves, 1955).

The thickness of the the Headleys Limestone, the basal unit of the Negri Subgroup, varies from 35 to 50 m. It is widespread south of the Hardman Syncline and extends in a northeasterly direction from north of the Great Antrim Plateau to the Northern Territory border (Fig. 55). The unit is also present around the Rosewood Syncline and extends east-northeast from Lissadell Homestead into the Northern Territory (Fig. 56).

Based on its stratigraphic position, the age of the Headleys Limestone is considered to be late Early or early Middle Cambrian. The only fossils recovered from the unit are simple non-branching stromatolites.

Linnekar Limestone

The type section for the Linnekar Limestone is found near the junction of Linnekar and Brook Creeks at Lat. 17°32'50"S, Long. 128°42'35"E (Traves, 1955). The unit, consisting of fossiliferous limestone and shale, is conformable between the underlying Nelson Shale and the overlying Panton Formation.

The Linnekar Limestone occurs in the Hardman, Rosewood, and Argyle Synclines (located in Lake Argyle, north of the Rosewood Syncline) and has a thickness varying between 8 and 24 m (Figs 55 and 56).

An early Middle Cambrian age has been assigned to the unit based on the presence of the trilobite *Redlichia forresti* (Opik, 1967).

Panton Formation

The Panton Formation includes the Panton Shale, Shady Camp Limestone, Negri River Shale, Corby Limestone, and Hudson Shale (Mory and Beere, 1985). The type section is at Mount Panton in the Northern Territory at Lat. 17°16'15"S, Long. 129°12'40"E (Playford et al., 1975).

Table 51. Calcrete and limestone occurrences in the Canning Basin

Geology sheet (1:250 000)	*Location (approximate)*	*Description*
TABLETOP	Lake Auld, south of Lake Winifred, southwest of Lake Blanche, and east and west of Lake Dora	Extensive calcrete deposits
URAL	Southern and southwestern parts of the sheet	Fluviolacustrine calcrete deposits outcropping as low rises of rubble of pale-grey limestone with minor hard, vuggy chalcedony in the ancient drainage channels
PERCIVAL and SAHARA	Lake Tobin, Percival Lakes	Calcrete deposits are exposed as hard, vuggy, chalcedonic limestone within the valleys and around the margins of playa lakes
CROSSLAND, MOUNT BANNERMAN, and MCLARTY HILLS	Near Christmas Creek, and southern part of of CROSSLAND (e.g. Clapp Ridge) extending to MOUNT BANNERMAN and MCLARTY HILLS	Limestone in Noonkanbah Formation (Towner, 1977). Extensive calcrete deposits overlying the Noonkanbah Formation occur as pale-grey to white limestone associated with massive, vuggy chalcedony around margins of clay pans, in drainage depressions, and along ancient stream courses
MOUNT RAMSAY	Bohemia Downs	Limestone associated with calcareous siltstone
CORNISH	In many areas, notably in the eastern and southern parts of the sheet	Calcrete
WARRI	North of Lake Cohen	Calcrete
PATERSON RANGE	Lake Waukarlycarly	Extensive calcrete deposits which have similar patterns to those of Oakover Formation. Some samples contain up to 96% $CaCO_3$ (Wells, 1959)
BROWNE	Northern part of the sheet	Calcrete

NOTE: Capitalized names refer to standard 1:250 000 map sheets

Shady Camp Limestone Member

The Shady Camp Limestone Member consists of oncolitic fossiliferous limestone, with a type section at Mount Panton (Mory and Beere, 1985).

Corby Limestone Member

Above the Shady Camp Limestone Member is the Corby Limestone Member, which consists of laminated and massive micrite with chert nodules. The type section is in Hudson Creek at Lat. 17°15'35"S, Long. 128°57'20"E.

The Panton Formation is best exposed in the Hardman Syncline (Fig. 55), and also occurs in the Rosewood and Argyle Synclines (Fig. 56). The presence of *Redlichia* and *Xystridura* (trilobites) suggests a Middle Cambrian age for the unit (Opik, 1967; Jell, 1983).

Bonaparte Basin

Westwood Member (Hargreaves Formation)

The Westwood Member of the Hargreaves Formation was originally defined as the sequence of interbedded limestone or dolomite and fine to medium thin-bedded quartz sandstone in the Westwood Creek area (Veevers and Roberts, 1968), but the name was later restricted by Mory and Beere (1988) to massive limestone and minor interbedded sandstone near the base of the type section at Westwood Creek (Lat. 14°51'49"S, Long. 128°30'06"E).

The Westwood Member is 35 m thick and is exposed only at the type section, where a reef environment occurs in a restricted area. It consists of two interfingering facies of massive boundstone and crudely bedded fossiliferous limestone. The boundstone consists mainly of stromatoporoids, *Renalcis*, and stromatolites. Fossils in both facies include diverse shelly and microbial material. Large bivalves and oncolites are locally abundant in the bedded limestone.

Ningbing Group

Djilirri Limestone

The Djilirri Limestone is the basal unit of the Ningbing Group, and is named after Djilirri, a prominent hill 1 km southwest of Ningbing Homestead. The type section for the limestone is on the south side of The Gorge

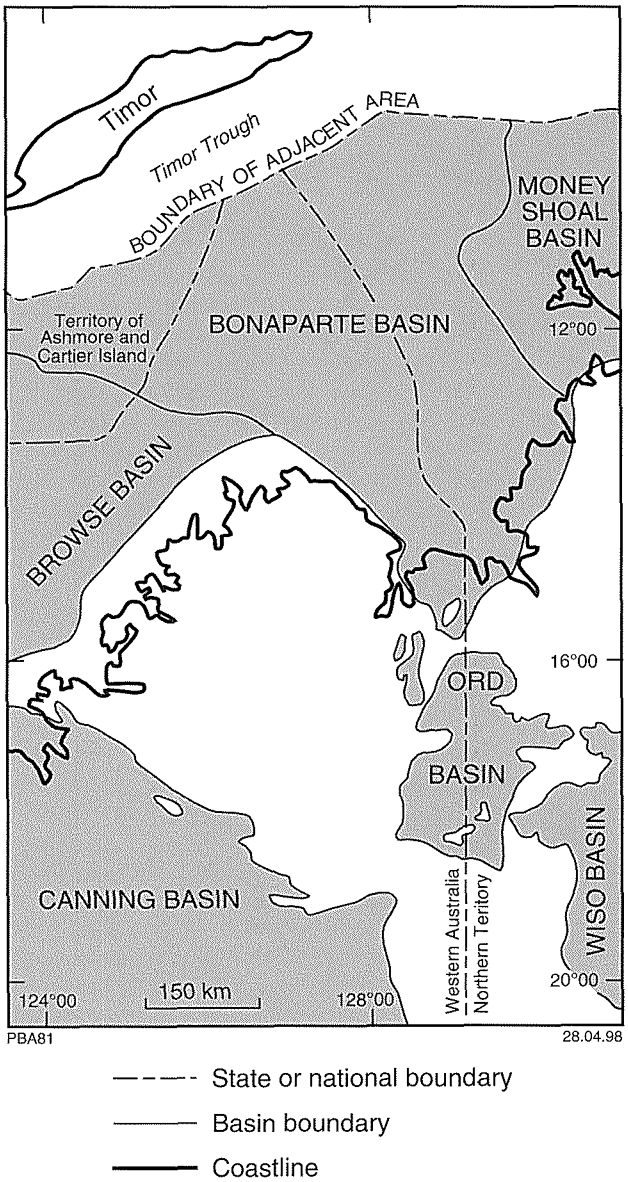

Figure 54. Location map showing the Bonaparte, Ord and surrounding Phanerozoic Basins (modified from Mory and Beere, 1988)

from Lat. 15°10'40"S, Long. 128°37'10"E (base) to Lat. 15°10'55"S, Long. 128°37'55"E (top). The unit encompasses both platform and marginal-slope facies of the early Famennian reef complex exposed in the Ningbing Range and Jeremiah Hills (Fig. 57). The back-reef subfacies of the Djilirri Limestone consists of skeletal, oolitic, oncolitic, and peloidal grainstone and packstone, with local interbeds of calcarenite and sandstone. The reef-margin and reef-flat subfacies of the Djilirri Limestone consist of massive and crudely bedded microbial boundstone respectively, in which *Sphaerocodium* and *Giravanella* are major constituents. The fore-reef subfacies of the marginal slope consists predominantly of crudely bedded limestone breccia with a silt-rich matrix, which is generally preferentially dolomitized.

The Djilirri Limestone conformably overlies the Hargeaves Formation and is unconformably overlain by the Kamilili Formation or Garimala Limestone. The unit is exposed in the Jeremiah Hills and along the western side of the Ningbing Range, although outcrop is discontinuous north of Surprise Creek. The conodont *Icriodus rectus*, found in the back-reef subfacies, indicates an age from Frasnian to middle Famennian.

Kamilili Formation

The Kamilili Formation consists of thin- to medium-bedded terrigenous and carbonate lithologies that disconformably overlie the Djilirri Limestone and are overlain by the Wungabal Limestone. Locally, the Kamilili Formation is unconformably overlain by the Garimala Limestone.

The Kamilili Formation is exposed in three main areas in the Ningbing Range; just north of Surprise Creek, between Tanmurra Bore and Tanmurra Creek, and near Knob Peak (Fig. 57).

Carbonates of the Kamilili Formation are of three types; very fine grained skeletal packstone and wackestone, limestone breccia, and stromatolitic boundstone. The wackestone and packstone exhibit cross-bedding and ripple cross-lamination, while the limestone breccia forms beds up to 1.5 m thick and is interbedded with the thinly bedded lithologies at most levels of the unit. The stromatolitic boundstone consists of beds of massive microbial boundstone, generally less than 0.5 m thick, interbedded with the flaggy skeletal packstone.

The Kamilili Formation is highly fossiliferous with abundant brachiopods, crinoids, corals, and the foraminiferid *Uralinella*. Also present are bryozoans, stromatolites, stromatoporoids, miospores, gastropods, and conodonts, as well as rare ammonoids and trilobites.

Wungabal Limestone

The Wungabal Limestone is named after Wungabal, which is located 14 km east-northeast of Knob Peak. This unit consists predominantly of bedded red mudstone with red skeletal wackestone, and mudstone with microbial laminations deposited in a marginal-slope facies (Mory and Beere, 1986). The Wungabal Limestone is disconformable between the Garimala Limestone (above) and the Kamilili Formation (below).

Distinctive red intraclast mudstone with white sparry calcite cement is predominant in the Wungabal Limestone. The clasts consist of red crinoidal boundstone with microbial laminations, quartz-silt wackestone, and peloidal packstone. Another distinctive lithology developed in this unit is dominated by large (up to 60 cm in diameter) spar balls found in neptunian dykes, similar to those described by Playford (1984) from the Canning Basin. The balls consist of alternating layers of fine-grained micritic spar, with some microbial laminations, coating angular fragments of the same composition in a matrix of calcareous mudstone of fine-grained dolomite (Mory and Beere, 1988).

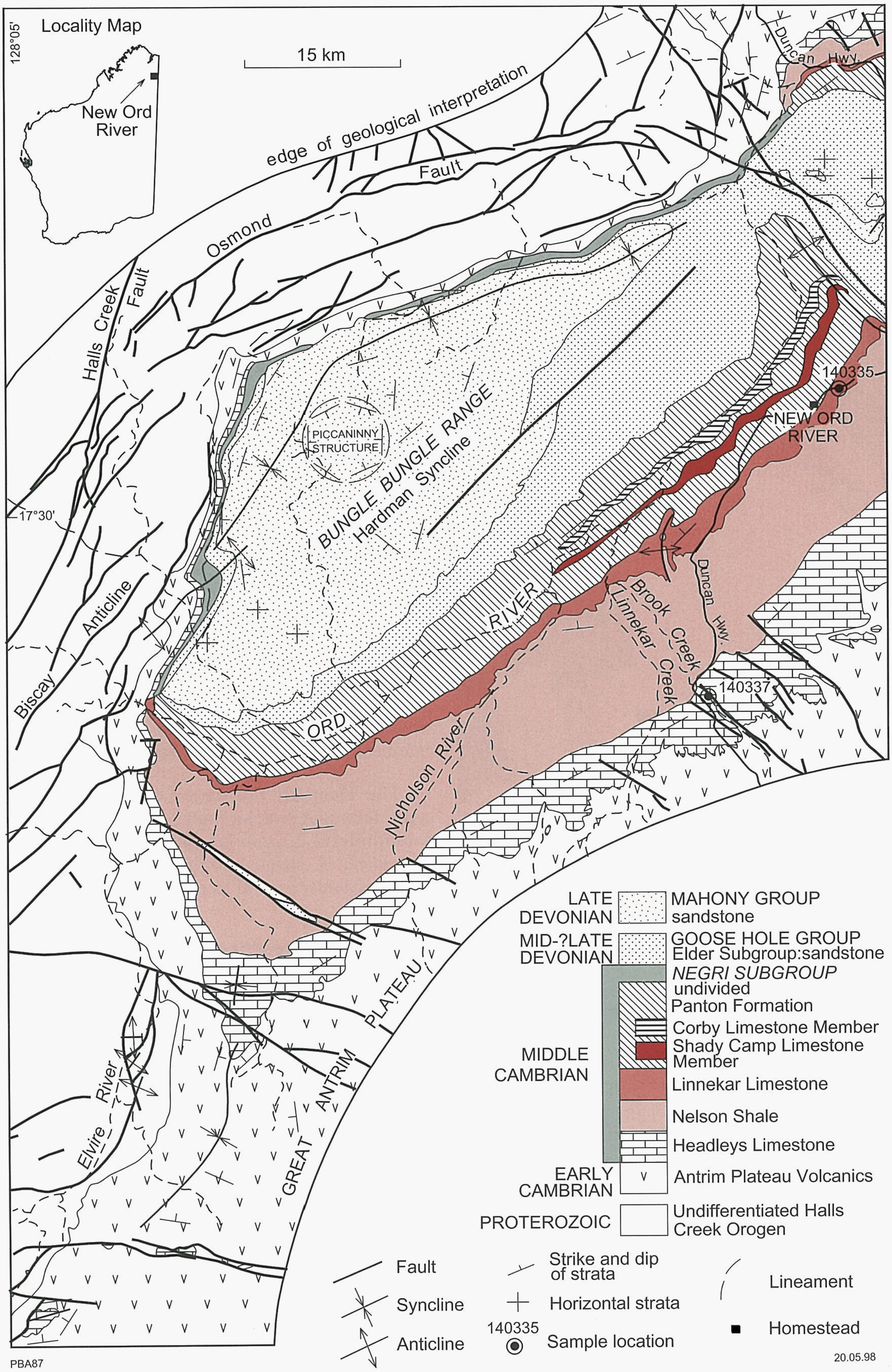

Figure 55. Distribution of limestones of the Negri Subgroup in the Hardman Syncline area of the Ord Basin (modified from Mory and Beere, 1988)

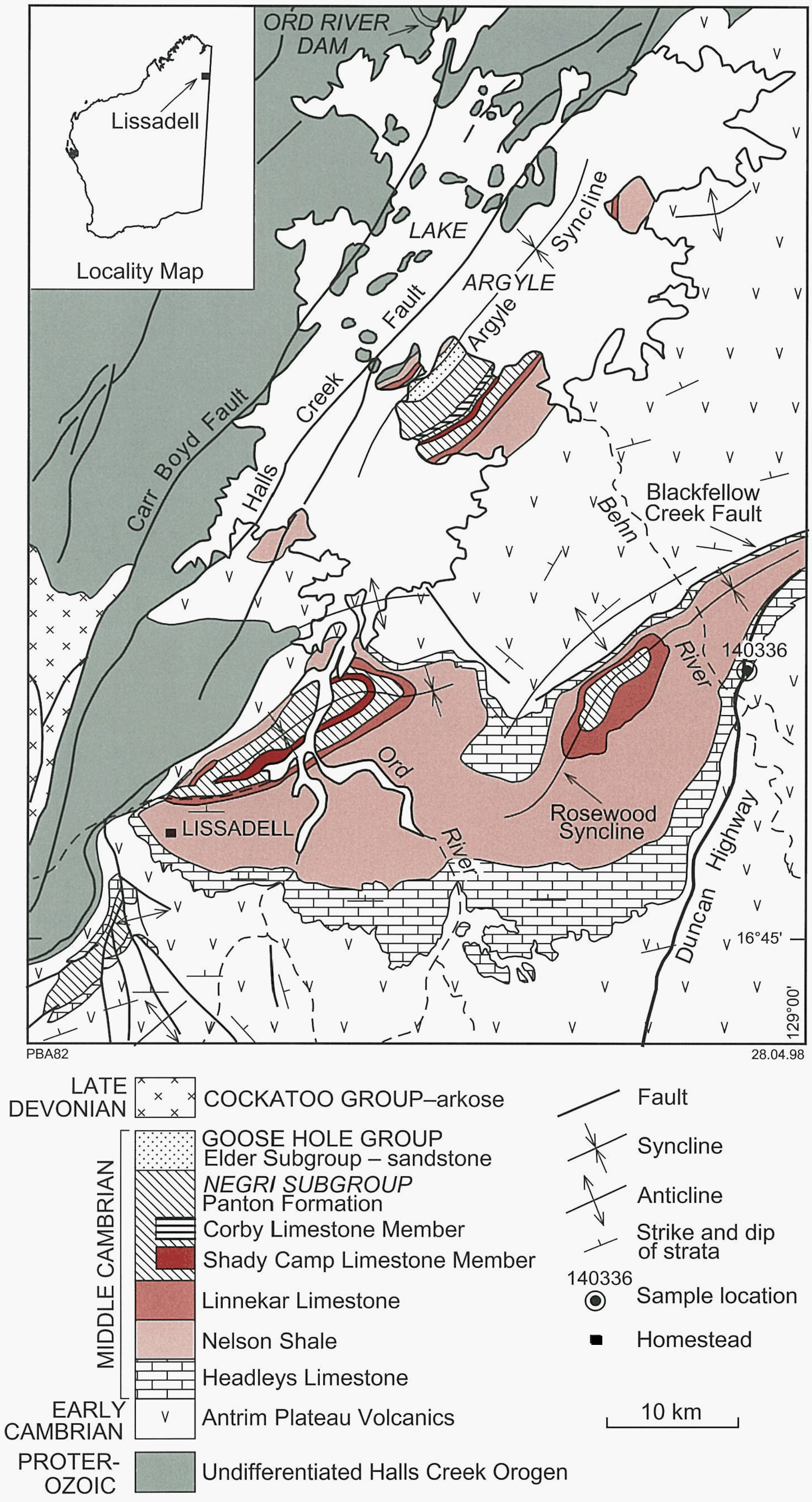

Figure 56. Distribution of limestones of the Negri Subgroup in the Rosewood and Argyle Synclines of the Ord Basin (modified from Mory and Beere, 1988)

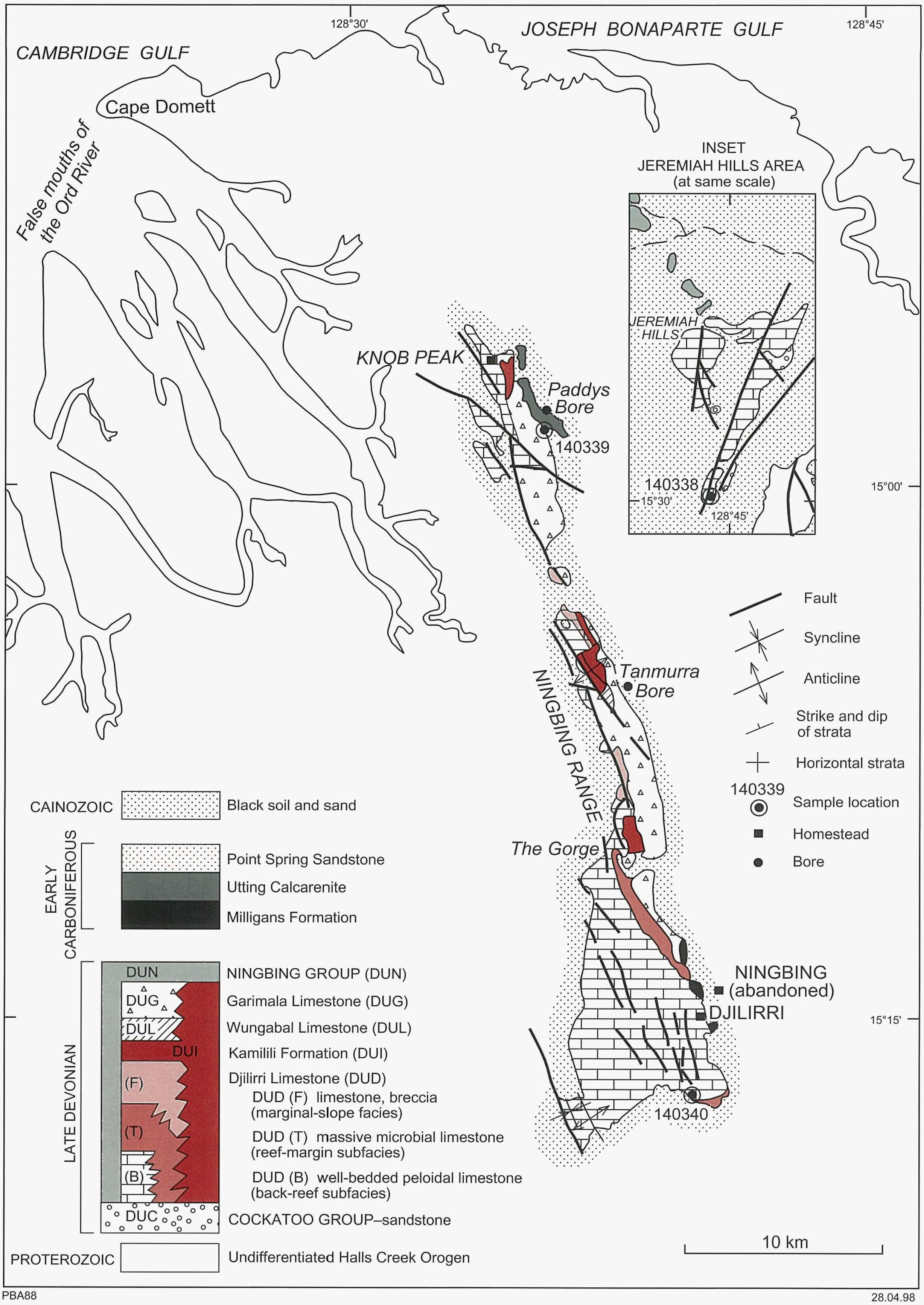

Figure 57. Distribution of limestones of the Ningbing Group in the Ningbing Range and Jeremiah Hills areas of the Bonaparte Basin (modified from Mory and Beere, 1988)

Exposure of the Wungabal Limestone is discontinuous and is mainly restricted to a 6 km-long belt on the eastern side of the Ningbing Range, west of the Tanmurra Bore area (Fig. 57). The type section is west of Tanmurra Bore from Lat. 15°05'40"S, Long. 128°37'45"E (base) to Lat. 15°05'45"S, Long. 128°37'35"E (top), where a 100 m thickness is exposed.

The age of the Wungabal Limestone is mid-Famennian (Mory and Beere, 1988). Stratiform stromatolites that produced much of the red carbonate are the most important fossils to be found in the unit. Other fossils present include crinoids, brachiopods, and rare bony-fish plates.

Garimala Limestone

The Garimala Limestone is named after Garimala, the spring on Surprise Creek in The Gorge. It is the uppermost unit of the Ningbing Group, and unconformably overlies the Djilirri Limestone, Kamilili Formation and Wungabal Limestone, and is disconformably overlain by the Carboniferous Milligans Formation and Utting Calcarenite.

The Garimala Limestone consists predominantly of limestone breccia that accumulated in a marginal-slope facies. The fore-reef subfacies is dominated by peloidal-lithoclast grainstone and limestone breccia, with a matrix usually consisting of skeletal peloidal mudstone. Some clasts of the limestone breccia are dolomitized, while the calcite cement is unaffected. Lithoclasts in the limestone breccias consist of peloidal grainstone of back-reef origin and microbial boundstone from reef-margin subfacies.

The Garimala Limestone is exposed in an almost continuous belt along the eastern side of the Ningbing Range, from Knob Peak to 2 km north of Ningbing Homestead (Fig. 57). The thickness of the unit varies from 150 m at the type section, to 340 m near Paddys Bore (Mory and Beere, 1988).

The age of Garimala Limestone, based on fossil evidence, is late Famennian (Mory and Beere, 1988).

Limestone quality

There is no record of any previous assessments of limestone quality within the Ord and Bonaparte Basins. However, samples (140335–40) taken from the Linnekar, Headleys, Djilirri, and Garimala Limestones, from six different locations within the basins, indicate the presence of very high quality limestone (Figs 55–57; Table 52).

Other areas

Known limestone resources in the central part of the State are relatively small in comparison to those in the western coastal region and the Eucla Basin, being restricted mainly to extensive calcrete deposits close to large lakes and along river drainages. Given below is a brief description of these resources.

Southwest Region of the Yilgarn Craton

Lime Lake

Simpson (1948) noted that Lime Lake (Lat. 33°25'S, Long. 117°22'E), located 12 km south-southeast of Wagin, is enclosed on two sides with low banks of limestone. On the southeastern side, a 'chalky limestone' underlies the lake bed, which is covered with marl that contains shells.

Limestone also occurs approximately 3 km north of Lime Lake. Woodward (1906, 1907) presented analyses of seven samples from the area that contained up to 52.3% $CaCO_3$. In the early 1900s, calcium carbonate was extracted from these shell deposits for the production of lime (Chin and Brakel, 1986). Analyses of three samples by Simpson (1948) showed 34.5 to 41.05% CaO and 2.51 to 4.92% MgO.

Other known deposits in the Southwest Region of the Yilgarn Craton are listed in Table 53.

Southern Cross Region of the Yilgarn Craton

Calcium carbonate resources in the Southern Cross Region occur mainly in calcrete deposits associated with lake deposits distributed within the following 1:250 000 geological sheet areas: SANDSTONE, YOUANMI, BARLEE, HYDEN, SOUTHERN CROSS, KELLERBERRIN, RAVENSTHORPE, and NEWDEGATE. Some of the more extensive calcrete deposits are described in Table 54.

Eastern Goldfields Region of the Yilgarn Craton

Norseman–Lake Cowan

The main limestone formation found in the Eastern Goldfields Region is the Norseman Limestone, which is exposed at the southern end of the Lake Cowan causeway. The outcrop consists of sandy fossiliferous limestone, fossiliferous fine-grained sandstone, and fossiliferous mudstone. The formation also outcrops approximately 11 km east of Buldania Rocks (Lat. 32°05'S, Long. 122°02'E). Fauna in the formation includes molluscs, bryozoans, foraminifers, echinoids, corals, and a crinoid columnal (Doepel, 1973).

In the 1970s, Western Mining Corporation explored the Lake Cowan area for limestone suitable for use as a flux in nickel smelting. Investigations showed that limestone occurs, together with clays and ferruginous silcrete, in the first 6 to 10 m below the surface. This material overlies coquina with a muddy matrix. Material in the first 20 m below the surface averaged 27% CaO (Fletcher and Hughes, 1976).

Table 52. Chemical analyses of limestones from the Ord and Bonaparte Basins

Sample no.	*140335*	*140336*	*140337*	*140338*	*140339*	*140340*
			Percentage			
SiO_2	3.77	1.49	2.52	4.21	1.58	3.34
TiO_2	0.03	0.03	0.06	0.05	0.02	0.03
Al_2O_3	0.49	0.32	0.52	0.64	0.17	0.39
Fe_2O_3	0.43	0.65	0.28	0.42	0.07	0.13
MnO	0.08	0.14	0.03	0.02	<0.01	<0.01
MgO	0.41	20.52	0.70	0.79	0.53	0.74
CaO	52.84	30.55	53.50	51.89	54.44	52.80
Na_2O	0.04	0.07	0.02	0.02	0.01	0.02
K_2O	0.18	0.13	0.21	0.23	0.11	0.23
P_2O_5	0.04	0.03	0.04	0.04	0.05	0.04
LOI	41.59	45.98	42.16	41.24	41.73	41.20
Total	**99.90**	**99.91**	**100.04**	**99.55**	**98.71**	**98.92**
CO_2	41.20	45.70	41.30	41.30	42.80	42.40
			Parts per million			
As	114	14	12	12	11	11
Ba	27	23	10	32	13	20
Be	0.4	0.4	0.4	0.3	0.3	0.2
Ce	14	1.60	4.5	8.5	2.5	8.1
Cr	14	12	8	16	6	5
Ga	1.40	1.00	1.00	1.90	0.80	1.30
La	10	1.40	3.6	7.0	2.5	6.0
Nb	0.8	0.5	0.7	1.0	<0.5	0.7
Rb	4.4	2.4	3.9	8.3	2.8	5.9
S	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sn	0.3	0.7	0.4	0.3	0.2	0.2
Sr	157	60	271	304	214	169
Th	0.70	0.40	0.60	1.60	0.50	1.20
U	0.40	0.40	1.10	1.00	0.90	1.50
V	9	10	5	11	<2	4
W	0.5	0.3	0.4	0.4	0.2	0.3

NOTE: Ord Basin

140335 Linnekar Limestone, Lat. 17°22'08"S, Long. 128°56'27"E, fine-grained, dark-grey limestone

140336 Headleys Limestone (dolomite), Lat. 16°34'53"S, Long. 128°57'02"E, massive, medium- to fine-grained, creamy brown to pinkish limestone

140337 Headleys Limestone, Lat. 17°40'59"S, Long. 128°48'40"E, fine-grained, layered, light-grey to light-brown, massive limestone

Bonaparte Basin

140338 Djilirri Limestone, Lat. 15°28'31"S, Long. 128°44'50"E, fine- to medium-grained, massive grey limestone

140339 Garimala Limestone, Lat. 14°58'09"S, Long. 128°35'46"E, fine-grained, creamy grey, massive limestone

140340 Djilirri Limestone, Lat. 15°17'37"S, Long. 128°40'12"E, fine- to medium-grained, fossiliferous, grey massive limestone

Table 53. Limestone resources in the Southwest Region of the Yilgarn Craton

Location	*Geological sheet 1:250 000*	*Description*	*Reference*
Kojonup	DUMBLEYUNG	Production of 436 t of limestone was reported from 1967 to 1972 on MC 1220	DME production statistics
Broomehill	DUMBLEYUNG	A sample of marl from the area contained 28.8% $CaCO_3$, 6.6% $MgCO_3$, and 42.6% insolubles	Chin and Brakel (1986)

Table 54. Limestone resources in the Southern Cross Region of the Yilgarn Craton

Location	*Geological sheet 1:250 000*	*Description*	*Reference*
Lake Magenta	NEWDEGATE	Calcrete in layers and nodules occurs adjacent to playa lakes	Thom et al. (1984)
Mount Desmond	RAVENSTHORPE	A considerable superficial deposit of 'travertine' occurs at this location. A representative sample contained 63.6% $CaCO_3$, 7.2% MgO, 2% Fe_2O_3, 1.1%Al_2O_3, and 12.2% SiO_2	Simpson (1948)
Mount Holland	HYDEN	Calcrete deposits occur adjacent to playa lakes approximately 15 km northeast of Mount Holland. Calcrete also occurs approximately 7 km north of Forrestania	Chin et al. (1984)
Marvel Loch	SOUTHERN CROSS	Approximately 6 km west of Marvel Loch is a large deposit of 'travertine' overlying dolerite. A typical sample contained 80.5% $CaCO_3$ and 0.22% MgO	Simpson (1948)
Southern Cross	SOUTHERN CROSS	An extensive deposit of impure limestone, mostly in the form of concretionary gravel, and partly in layers, occurs approximately 2 km south-southeast of Southern Cross	Simpson (1948)
Lake Mason	SANDSTONE	Massive nodular and sheet-valley calcrete with minor chalcedony occurs around Lake Mason. The deposits are locally dark coloured and some contain carnotite	Tingey (1985)
Kununoppin	KELLERBERRIN	A sample of calcareous hardpan from this location contained 60% $CaCO_3$ and 4.1% MgO	Simpson (1948)

Lake Raeside (Six-Ten Prospect)

Aurora Gold Ltd explored a calcrete prospect known as Six-Ten located 12 km west of Leonora, close to Lake Raeside. Three types of calcrete; highly weathered, indurated, and silicified, were found in the area. Exploratory drilling revealed that highly weathered portions of the deposit contain friable calcrete suitable for use in the Harbour Lights biological oxidation (BIOX) plant. Using an estimated average thickness of 1.5 m, the inferred resource in the weathered portion of the deposit was 200 000 t. However, calcrete would require crushing for use in the BIOX plant, and given the limited supply of sulfide ore, further development of the project was considered uneconomic (Aurora Gold Ltd, 1993).

Other limestone-related deposits in the Eastern Goldfields Region (Fig. 7) are confined mainly to the calcrete deposits occurring on the LEONORA, LAVERTON, SIR SAMUEL, DUKETON, THROSSELL, and WILUNA 1:250 000 geological sheet areas. Some of the more extensive deposits are described in Table 55.

Murchison Terrane of the Yilgarn Craton

Lake Austin

A calcrete deposit covering an area some 10 km (in a north–south direction) by 4 km, centred approximately 14 km southeast of Big Bell Mine and close to Lake Austin, was explored in 1994–95 to determine whether the material could supplement the lime required as a neutralizing agent in the mine-processing circuit. Exploration was restricted to two areas of reasonable access that were previously identified during waterbore drilling as having a reasonable thickness of calcrete. In the southern area, the average CaO% was 34.6 and that in the northern area was 34.4%. The SiO_2 contents were 14.8–24.8% and 16.3–26.4% respectively. Further work indicated that the deposit was uneconomic (Rankine, 1995).

Other limestone resources in the Murchison Terrane of the Yilgarn Craton (Fig. 7) are also restricted mainly

Table 55. Limestone resources in the Eastern Goldfields Region of the Yilgarn Craton

Location	*Geological sheet 1:250 000*	*Description*	*Reference*
Lake Way	WILUNA	Extensive beds of calcrete hosting uranium mineralization occur in the area. Carnotite in calcrete has been discovered in two channels of the saline palaeodrainage system	Elias and Bunting (1982)
Lake Miranda	SIR SAMUEL	An extensive but thin bed of calcrete	Simpson (1948)
Yeelirrie	SANDSTONE–SIR SAMUEL	Extensive deposits of valley calcrete in the area are well known for hosting uranium mineralization. The uranium mineral in the calcrete is carnotite	Tingey (1985)
Lake Wells	THROSSELL	Lake Wells and a north-trending valley south of this location contain extensive deposits of calcrete	Bunting et al. (1978)

to calcrete deposits formed in lake beds, and along river drainages and creeks. Most of these occur in the 1:250 000 geological sheet areas of NINGHAM, KIRKALOCKA, YALGOO, CUE, MURGOO, BELELE, and GLENGARRY. Some of the more extensive deposits are listed in Table 56.

Narryer Terrane of the Yilgarn Craton

Limestone resources in the Narryer Terrane are restricted to the calcrete deposits found in river drainages such as those of the Murchison and Gascoyne Rivers. A sample of impure calcrete, collected from a location 2 km east of Mount Taylor, contained 68.6% $CaCO_3$, 5.1% MgO, and 15.9% SiO_2. Analyses of two samples of calcrete from a quarry (Lat. 25°52'28"S, Long. 117°22'43"E) located 16 km towards Mount Gould from Moorarie Homestead indicated the material was dolomitic with 45.5–60.2% $CaCO_3$ and 9.5–11.4% MgO.

Officer Basin

The Officer Basin (Fig. 7) contains numerous extensive calcrete deposits of unknown quality and quantity, which are believed to have been formed by precipitation of carbonate from groundwater in alluvial and colluvial valley deposits (van de Graaff, 1974b). This basin now includes the area previously termed the Savory Basin. A summary of deposits occurring in the Officer Basin is given in Table 57.

Table 56. Limestone resources in the Murchison Terrane of the Yilgarn Craton

Location	*Geological sheet 1:250 000*	*Description*	*Reference*
Lake Annean	BELELE	There are large deposits of calcrete on the eastern side of this lake	Simpson (1948)
Moyagee	CUE	Calcrete material collected from Moyagee, located south of Lake Austin, has been used locally for making lime. A sample contained 65.9% $CaCO_3$	Simpson (1948)
Nallan	CUE	An extensive deposit of calcrete, covering an area of approximately 24 km by 5 km, occurs at this location. The calcrete body has been found to be a very good aquifer	Simpson (1948)
Hope River	BELELE	Extensive deposits of valley calcrete occupy the trunk drainages of the Hope and Yagar Rivers on the eastern part of BELELE. These deposits are prospective for Yeelirrie-type uranium mineralization	Elias (1982)

NOTE: Capitalized names refer to standard 1:250 000 map sheets

Table 57. Calcrete and limestone occurrences in the Officer Basin

Geological sheet 1:250 000	*Location (approximate)*	*Description*
BULLEN	West of Yanneri Lake	Calcrete deposits
GUNANYA	Along Savory Creek and on the western and southern parts of the sheet	Extensive calcrete deposits
HERBERT, ROBERT and YOWALGA	In large ancient drainage channels such as Herbert Wash and Lake Bremner and on the eastern part of ROBERT	Calcrete up to 30 m thick with dolomitic limestone (Kennewell, 1974). The deposits at Herbert Wash on HERBERT extend onto ROBERT and YOWALGA. Partial replacement of valley-fill material has produced extensive areas of cavernous sandy calcrete in the major depression on the eastern part of ROBERT (Jackson, 1978a)
MADLEY	Main localities are northeastern, eastern, and southern parts of the sheet (e.g. east of Mount Madley)	Relict drainage channels containing up to 30 m of calcrete consisting of dolomitic limestone with scattered quartz grains and siliceous concretions (Kennewell, 1975)
ROBERTSON	Along Savory Creek	Extensive calcrete deposits
RUDALL	Southwestern corner of the sheet	Calcrete deposits
THROSSELL	Major relict drainage systems such as Lake Throssell and Yeo Lake	Extensive calcrete deposits
WAIGEN	Major south-trending valleys on the western and eastern edges of WAIGEN (e.g. Waigen Lakes)	Calcrete formed by part replacement of valley-fill material (Jackson, 1978b)
WESTWOOD	Southern part of the sheet and east of Westwood Fault Zone	Calcrete consisting of dolomitic limestone (Kennewell, 1977)

NOTE: Capitalized names refer to standard 1:250 000 map sheets

Table 58. Limestone resources in some tectonic units in central, northern, and eastern Western Australia

Tectonic unit	*Description*
Amadeus Basin	Calcrete occurs on the southwestern part of WILSON
Bangemall Basin	Large deposits of calcrete occur along the Lyons River at localities north and northeast of Cobra, also in valleys close to Mount Egerton, and along drainages of the Ashburton River. Some calcrete deposits in Savory Creek in the Officer Basin extend into the Bangemall Basin. Other areas of calcrete include the northern part of STANLEY and drainage areas of the Gascoyne River south of Three Rivers
Birrindudu Basin	Calcrete deposits are widespread on the eastern half of LUCAS, and on the eastern part of STANSMORE
Gascoyne Complex	Calcrete deposits occur in the drainages of Lyons River (EDMUND) and Mount James Creek (MOUNT PHILLIPS)
Glengarry Basin	Calcrete deposits occur around Yandil and Killara on GLENGARRY, and along drainages of the Murchison River on ROBINSON RANGE
Gunbarrel Basin	Calcrete deposits occur around Linke Lakes on HERBERT and around Lake Wells and Lake Throssell on THROSSELL
Halls Creek Orogen	Limestone associated with calcareous siltstone and chalcedony occurs around Margaret River and One Tree Hill
Kimberley Basin	The Egan Formation in the O'Donnell Syncline on MOUNT RAMSAY is presumed to contain fairly high-quality limestone. The rocks in this formation consist of tillite, arkose, dolomite, sandstone, and shale (Roberts et al., 1968). Gellatly and Derrick (1967) stated that limestones of the Elgee Siltstone are partly dolomitic
Lucas Outlier	Extensive calcrete deposits occur around Lake Lucas on LUCAS
Nabberu Basin	Deposits of calcrete occur around Lake Gregory on PEAK HILL, and at Windidda and south of Lake Carnegie on KINGSTON. Other calcrete deposits are also known close to lakes in the basin. Kulele Limestone of Proterozoic age occurs north and south of Mount Throssell on the northeastern portion of KINGSTON and the southeastern portion of STANLEY. Kulele Limestone consists of limestone interbedded with pink or pale-grey mudstone
Paterson Orogen	Extensive deposits of calcrete occur around Lake Disappointment, located on GUNANYA and RUNTON. Massive calcrete and nodular vuggy limestone are widespread in the vicinity of salt lakes on PATERSON RANGE (e.g. north of Telfer). Calcrete deposits also occur along drainages of the Rudall River on RUDALL

NOTE: Excludes Officer Basin (see Table 57)
Capitalized names refer to standard 1:250 000 map sheets

Other regions

Known limestone resources in other areas of north, central, and eastern Western Australia are mainly restricted to calcrete deposits of unknown quality and quantity. A summary of these is given in Table 58.

Chapter 5

Development of limestone resources

The demand for limestone in the State will continue to increase with the expansion of industries such as iron ore and steel, heavy-mineral sands, alumina, gold, base metals, building blocks, and agriculture. In addition, future growth in the housing industry will require higher levels of cement production. Although large resources of limestone are available in the State, the development of many deposits is not feasible due to environmental restrictions and competing landuses. This chapter discusses the present status of the limestone industry in the State and directions for possible future development.

Cement and lime production

Perth Metropolitan Area

The past development of Western Australia has largely dictated a Perth metropolitan or at least a South West regional base for most cement and lime manufacture. The South West region is still the main source of demand for cement, and also lime for the alumina and ilmenite–titanium minerals processing industries.

The Western Australian cement industry requires limestone containing at least 80% $CaCO_3$, although grades above 85% are preferred. Lime manufacture usually requires more than 92% $CaCO_3$ content in the feedstock.

Most limestone exploration and mining activities in the State are concentrated in the Perth Metropolitan Area because of the relatively low transport costs allowable in associated commodity production. However, continued development of high-grade limestone resources within this region is under pressure from competing landuses and environmental constraints. With further urbanization, limestone resources outside the region will play an increasing role in satisfying the State's demand for limestone.

Cockburn Cement Ltd and Swan Portland Cement Ltd produce almost all the cement and lime manufactured in the State, at facilities in and around the Perth Metropolitan Area.

For some years, supplies of limestone and limesand for Cockburn Cement's operations have been sourced from Cockburn Sound and from the southern metropolitan area of Perth (Coogee at present). There is a large resource of high-grade limesand (>92% $CaCO_3$) in Cockburn Sound, but as dredging of this resource has come under increasing pressure because of the alleged environmental impact on seagrass banks, strict limitations have been placed on the company's dredging operations. Cockburn Cement has exploration licence applications over most of Cockburn Sound and offshore areas to the northwest and west, and has undertaken considerable evaluation of limesand resources in the area.

Cockburn Cement Limited has added an additional sixth kiln to existing facilities at Kwinana, increasing production of lime by a further 400 000 t per annum. At present, the production from all six kilns amounts to a total of 1.4 Mt per annum of cement clinker and lime.

Swan Portland Cement Limited sources its limestone supplies from the Wanneroo–Nowergup area in the northern Perth Metropolitan Region, and from Henderson (Kwinana) in the southern Perth Metropolitan Region. It also holds limestone resources under tenure in the Yanchep area (Parrot Ridge). However, these could be sterilized if the 1989 proposal to extend the Yanchep National Park is ratified by Parliament. Approval by the Minister for Mines is required before this can occur. Swan Portland Limited has plans to construct a clinker-grinding plant and a lime kiln at Kwinana, which will use limestone from the Cape Range area nearly 1300 km north of Perth. The company currently produces 40 000 t per annum of lime and 150 000 t per annum of cement clinker, and has approval to construct a lime–cement clinker plant in the Nowergup area, 13 km north of Wanneroo, with a production capacity of 460 000 t per annum of lime which would require 1 Mt of limestone feedstock (Landvision, 1996).

A large resource of limestone is likely to be present in the belt extending from Wilbinga Grove through Moore River to Seabird, but there is no information on available quantities, and information on quality is very limited. Assays for this material cover a wide range from 65.3 to 92% $CaCO_3$.

Although there are large deposits of limestone in the northern metropolitan area, the limestone is generally of relatively low grade (about 75% $CaCO_3$). The possibility of commercial utilization of this limestone would depend on either selective mining, or the economic viability of beneficiation techniques to produce a commodity of acceptable quality.

Other than Cockburn Sound, there are no identified resources of high-quality carbonates (>92% $CaCO_3$) in or near the Perth Metropolitan Area. Garden Island is being promoted as the site of a potential new project by

Precious Metals Australia Ltd. The quality of the material is reported to be quite high, but there are significant issues to be overcome in the area of environmental and other landuse constraints. Media reports (Sound Telegraph, 14 February, 1996, p. 1) indicate that the former Federal Labor Government rejected the application by Precious Metals Australia Ltd to mine on the island, and there is opposition from the Defence Department, based on security grounds. The island is not subject to the Western Australian Mining Act since it comes under Commonwealth jurisdiction.

North of the Perth Metropolitan Area

The closest limestone and limesand resources to Perth, north of the metropolitan area, are the extensive limesand deposits in coastal areas around Lancelin. Further evaluation of individual deposits would be required to determine whether appropriate quality limesand and limestone could be sourced from this coastal region. At present, producers between Lancelin and Dongara are supplying limesand and limestone mainly for agricultural purposes. However, individual deposits could be suitable for cement manufacture if magnesium contents of the limesand are within the required specifications.

The next closest high-quality limesand and limestone resource suitable for cement and lime manufacture occurs at Dongara, 320 km north of Perth. Westlime (WA) has plans to produce 120 000 t per annum of lime, with the commissioning of the plant scheduled towards the end of 1997. Cockburn Cement Limited has plans for a 100 000 t per annum facility in the same area, with production likely to begin around April–May 1998.

Conlan Management Pty Ltd and Australian Chalk and Minerals NL have examined the Toolonga Chalk (Kalbarri) deposit, which has the potential for supplying large quantities of lime to the Geraldton and Meekatharra regions.

Synthetic-rutile plants and the potential development of iron- and steel-manufacturing facilities in the Geraldton area will require local sources of limestone and limesand to meet the demand for lime production.

Pilbara region

This region, with its major iron-ore base, has naturally been seen as the major focus of iron- and steel-manufacturing projects. Limestone and limesand resources, often containing high-quality carbonate, have been identified in the Dampier Archipelago. However, the conservation value placed on islands in the archipelago may impact on development options. Outside of the proposed national park, Legendre Island has a large limestone resource, and quarrying at Hearson Cove has provided limesand for previous pelletizing operations in the Pilbara. Local supplies may also be available for use as lower specification feedstocks.

Cape Range

Limestones from the Cape Range Group, in the Exmouth region, have long been considered as a raw-material source suitable for use in high-quality metallurgical lime production for steelmaking. A number of mining groups, including BHP, Hancock and Wright, Alcoa, and currently Whitecrest Enterprises Pty Ltd, have attempted to prove-up sufficient limestone resources for long-term high-quality lime supplies. Swan Portland Cement Limited has plans to construct a clinker-grinding plant and a lime kiln at Kwinana that will use limestone from the Cape Range area. Development plans will need to contend with variations in limestone quality and proposals to extend the Cape Range National Park. The success of any development will be based on the ability of the project to supply a high-quality product conforming to strictly defined specifications. The product will need to be available at economically competitive rates when compared to imported metallurgical-grade material.

Loongana

Loongana Lime Pty Ltd uses limestone from Loongana for the production of lime destined for use in the gold industry in the Eastern Goldfields. At present, the Eastern Goldfields market is being shared by suppliers from Loongana and the Perth Metropolitan Region. The Eastern Goldfields area is likely to remain the main focus of gold activity for many years, although demand from other areas in the Yilgarn and from the Peak Hill district, north of Meekatharra, may increase slightly if the development of gold deposits continues in these areas. However, overall demand will not change significantly from present levels unless the pace of development accelerates markedly.

Agricultural lime production

Reported Western Australian production of agricultural lime in 1995 was 0.03Mt, with significant under-reporting likely. Agricultural lime requirements will undoubtedly continue to be dictated by close proximity of supply to demand centres. No significant problems are foreseen in supplying the projected demand for agricultural lime from existing limesand dune systems and limestone along the coastal and hinterland belts of the State.

Building blocks

In 1995, official figures suggested that approximately 0.08 Mt of limestone was used in the building industry in Western Australia. Based on available production figures, limestone demand for the building industry will total 2.2Mt over the next 20 years. The limestone building-block industry has grown significantly in the northern metropolitan region that includes Wanneroo, Nowergup, and Carabooda. At present, there do not appear to be significant alternative landuse pressures on existing supplies, but urbanization may eventually create problems in this region.

Concluding remarks

There is a strong demand for high-grade limestone within Western Australia. During 1995, the cement, alumina, gold, and heavy-mineral sands industries consumed 56% of the total limestone (both high and low grade) consumed in the State. At present, demand for limestone from the iron-ore and base-metal industries is very low (around 0.02% of the total used in 1995). Current annual demand for lime in the State is around 0.75–0.85 Mt, but will increase due to planned expansions of the iron-ore industry and continuing developments in the alumina, gold, and heavy-mineral sands industries. Possible discoveries of new base-metal deposits will also consume more lime in the future. Projected demand for high-grade limestone for the next two decades, as discussed in Chapter 3, is expected to be nearly 95 Mt. There is also a significant demand for low-grade limestone for use as a roadbase, in construction and building blocks, and for agricultural uses. These areas accounted for 44% of the total limestone used in 1995, and it is expected that the total tonnage required over the next 20 years could exceed 50 Mt.

Although Western Australia has vast resources of limestone and limesand, the State imports clinker (equivalent to about 500 000 t of high-grade limestone per year) from Japan and South Australia. With the vast resources of limestone and limesand available locally, the State could be an exporter of limestone-based products if issues such as infrastructure, transport costs, and land access were effectively addressed.

However, further development of limestone-based industries in the State seems likely as a number of companies have plans to increase their lime output. Indications are that annual production will increase to around 1.2 Mt. In addition, if the large limestone deposits located at Cape Range and in the Eucla Basin are developed, not only to serve local but also foreign markets, then a major expansion of the industry could occur. Deposits in the Dampier region could potentially supply the expanding iron-ore industry and other industries in the Pilbara region. Available information on the quality and quantity of limestone from the Lennard Shelf, and the Ord and Bonaparte Basins, suggests the presence of vast reserves of very high grade limestone. These deposits could be developed for use in the mineral and agricultural sectors (such as the sugar industry) in the Kimberley region, and also to supply rapidly expanding markets in the South-East Asian region.

References

ABARE, 1995, Limestone *in* Commodity Statistical Bulletin: Australian Bureau of Agricultural and Resource Economics, p. 303–305.

ADAMSON, A. N., 1970, Alumina production — principles and practice: The Chemical Engineer, June 1970, p. 156–164.

ALLEN, A. D., 1993, Outline of the geology and hydrogeology of Cape Range, Carnarvon Basin, Western Australia: Western Australian Museum Records Supplement, no. 45, p. 25–38.

ARCHER, R. H., BIGGS, E. R., and REXILIUS, J. P., 1977, Moore River–Cape Leschenault, W.A. Sheets 1935 II and 2035 III: Western Australia Geological Survey, 1:50 000 Urban Geology Series.

ASHWORTH, K. A., 1975, Limestone in the UK: Industrial Minerals, no. 90, March 1975, p. 15–27.

AURORA GOLD LTD, 1993, Relinquishment report, Six-Ten calcrete project: Western Australia Geological Survey, M-Series Open File, Item 7189 (unpublished).

BAXTER, J. L., 1972, Reconnaissance survey of the Pilbara region, W.A., for limestone, aggregate, and clay: Western Australian Geological Survey, Record 1972/3.

BAXTER, J. L., 1979, Ledge Point Power Station site — an inspection: Western Australia Geological Survey, Mineral Resources Report N. 124 (unpublished).

BAXTER, J. L., and REXILIUS, J. P., 1974, Lime resources between Lancelin and Mandurah, W.A.: Western Australia Geological Survey, Record 1974/24.

BHP MINERALS LTD, 1963, Nullarbor Limestone exploration: Western Australia Geological Survey, M-Series Open File, Item 46 (unpublished).

BIGGS, E. R., 1982, Harvey–Lake Preston, W.A. part of Sheets 2031 I and 2031 IV: Western Australia Geological Survey, 1:50 000 Urban Geology Series.

BIGGS, E. R., and DENMAN, P. D., 1981, Dampier Archipelago limesand and limestone: Western Australia Geological Survey, Record 1978/6.

BISSELL, H. J., and CHILINGAR, G. V., 1967, Classification of sedimentary carbonate rocks, *in* Developments in sedimentology — carbonate rocks, v. 9A *edited by* G. V. CHILINGAR, H. J. BISSELL, and R. W. FAIRBRIDGE: New York, Elsevier, p. 87–168.

BLATCHFORD, T. A., 1932, Report on the coastal limesands: Western Australia Geological Survey, Annual Report 1931, p. 37–39.

BLIGHT, D. F., SEYMOUR, D. B., and THORNE, A. M., 1986, Wyloo, W.A. Sheet SF 50-10: Western Australia Geological Survey, 1:250 000 Geological Series.

BREWER, R., and SLEEMAN, J. R., 1964, Glaebules — their definition, classification and interpretation: Journal of Soil Science, v. 15, p. 66–78.

BUCHHORN, I. J., 1986, Geology and mineralization of the Wagon Pass prospect, Napier Range, Lennard Shelf, Western Australia, *in* Geology and exploration *edited by* D. A. BERKMAN: Council of Mining and Metallurgical Institutions, 13th Congress, Publications, v. 2, p. 163–172.

BUNTING, J. A., JACKSON, M. J., and CHIN, R. J., 1978, Throssell, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 17p.

BUNTING, J. A., and van de GRAAFF, W. J. E., 1977, Cundeelee, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 27p.

BUTCHER, B. P., van de GRAAFF, W. J. E., and HOCKING, R. M., 1984, Shark Bay–Edel, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 21p.

CARR, D. D., and ROONEY, L. F., 1983, Limestone and dolomite, *in* Industrial minerals and rocks (5th edition) *edited by* S. J. LENFOND: New York, Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., p. 833–868.

CHAPRONIERE, G. C. H., 1975, Palaecology of Oligo–Miocene larger Foraminiferida, Australia: Alcheringa, v. 1, p. 37–58.

CHAPRONIERE, G. C. H., 1976, The Bullara Limestone, a new rock-stratigraphic unit from the Carnarvon Basin, Western Australia: Australia BMR, Journal of Australian Geology and Geophysics, v. 1, no. 2, p. 171–174.

CHAPRONIERE, G. C. H., 1984, Oligocene and Miocene larger Foraminiferida from Australia and New Zealand: Australia BMR, Bulletin 188.

CHIN, R. J., and BRAKEL, A. T., 1986, Dumbleyung, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 21p.

CHIN, R. J., HICKMAN, A. H., and THOM, R., 1984, Hyden, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 21p.

COCHRANE, G. W., 1992, Report on exploration of prospecting licence 28/739 Kitchener District, David Mitchell Limited: Western Australia Geological Survey, M-Series Open File, Item 6761 (unpublished).

COCKBAIN, A. E., 1984, Stromatoporoids from the Devonian reef complexes, Canning Basin, Western Australia: Western Australia Geological Survey, Bulletin 129, 108p.

CONDON, M. A., 1965, The geology of the Carnarvon Basin, Western Australia. Part 1 — Pre-Permian stratigraphy: Australia BMR, Bulletin 77.

CONNOLLY, R. R., and WYATT, J. D., 1960, Report on the availability of agricultural lime south of Northcliffe, S. W. Land Division: Western Australian Geological Survey, Bulletin 114, p. 180–182.

COPP, I. A., in prep., Subsurface facies analysis of the Devonian reef complex, Lennard Shelf, Canning Basin, Western Australia: Western Australia Geological Survey, Report.

DALBY, K. W., 1975, Final report, Temporary Reserve No. 5940H for limestone and limesand, Ashburton and Gascoyne Goldfields, August 1975: Western Australia Geological Survey, M-Series Open File, Item 91 (unpublished).

de la HUNTY, L. E., 1965, Mount Bruce, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 28p.

de la HUNTY, L. E., 1966, Details of limestone, bog limestone, and limesand samples taken during a geological survey of Perth and environs: Western Australian Geological Survey, Record 1966/12.

DENMAN, P. D., 1977, Report on the Boranup Limesand Deposit, Augusta Area, W.A. (Mineral Reserve No. 26493): Western Australia Geological Survey, Mineral Resources Report 102 (unpublished).

DENMAN, P. D., HOCKING, R. M., MOORE, P. S., WILLIAMS, I. R., and van de GRAAFF, W. J. E., 1985, Wooramel, W.A: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 23p.

DENMAN, P. D., and van de GRAAFF, W. J. E., 1982, Quobba, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 20p.

DEPARTMENT OF RESOURCES DEVELOPMENT, 1994, Lime consumption survey, Western Australia, 1992–93.

DERRICK, G. M., and PLAYFORD, P. E., 1973, Lennard River, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 49p.

DOEPEL, J. J. G., 1973, Norseman, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 40p.

DOEPEL, J. J. G., and LOWRY, D. C., 1970a, Balladonia, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 19p.

DOEPEL, J. J. G., and LOWRY, D. C., 1970b, Zanthus, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 19p.

DRUCE, E. C., and RADKE, B. M., 1979, The geology of the Fairfield Group, Canning Basin, Western Australia: Australia BMR, Bulletin 200.

DUNHAM, R. J., 1962, Classification of carbonate rocks according to depositional texture, *in* Classification of carbonate rocks *edited by* W. E. HAMM: American Association of Petroleum Geologists, Memoir 1, p. 108–121.

ELIAS, M., 1982, Belele, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 22p.

ELIAS, M., and BUNTING, J. A., 1982, Wiluna, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes. 20p.

ELLIS, H. A., 1948, Report on limestone deposit — Lake Muir: Western Australia Geological Survey, Annual Report 1946, p. 56.

FAIRBRIDGE, R. W., 1953, Australian stratigraphy: Perth, Western Australia, University of Western Australia Text Books Board, 516p.

FLETCHER, C. I., and HUGHES, W., 1976, Progress report, Binyarinyinna Mineral Claims, 1st July 1973 – 29th June 1976: Western Australia Geological Survey, M-Series Open File, Item 2185 (unpublished).

FOLK, R. L., 1959, Practical petrographic classification of limestones: American Association of Petroleum Geologists, Bulletin, v. 43, p. 1–38.

FOLK, R. L., 1962, Spectral subdivision of limestone types, *in* Classification of carbonate rocks *edited by* W. E. HAMM: American Association of Petroleum Geologists, Memoir 1, p. 62–84

GELLATLY, D. C., and DERRICK, G. M., 1967, Landsowne, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 28p.

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA, 1990, Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, 827p.

GLAUERT, L., 1910, The geological age and organic remains of the Gingin 'Chalk': Western Australia Geological Survey, Bulletin 36, p. 115–127.

GLAUERT, L., 1911, Further notes on the Gingin Chalk: Western Australia Geological Survey, Annual Report 1910, p. 29–30.

GLENISTER, B. F., HASSELL, C. W., and KNEEBONE, E. W. S., 1959, Geology of Rottnest Island: Royal Society of Western Australia, Journal, v. 42, p. 69–70.

GOZZARD, J. R., 1984, Muchea, W.A. Sheet 2034-I and part of Sheet 2134-IV: Western Australia Geological Survey, 1:50 000 Environmental Geology Series.

GOZZARD, J. R., 1985a, Yanchep, W.A. Sheet 2034-IV: Western Australia Geological Survey, 1:50 000 Environmental Geology Series.

GOZZARD, J. R., 1985b, Rockingham, W.A. part of Sheets 2033 II and 2033 III: Western Australia Geological Survey, 1:50 000 Environmental Geology Series.

GOZZARD, J. R., 1986a, Perth, W.A. Sheet 2034 II and part of Sheets 2034 III and 2134 III: Western Australia Geological Survey, 1:50 000 Environmental Geology Series.

GOZZARD, J. R., 1986b, Fremantle, W.A. part of Sheets 2033 I and 2033 IV: Western Australia Geological Survey, 1:50 000 Environmental Geology Series.

GOZZARD, J. R., 1987a, Limesand and limestone resources between Lancelin and Bunbury, Western Australia: Western Australia Geological Survey, Record 1987/5.

GOZZARD, J. R., 1987b, Information on industrial minerals — coastal plain between Lancelin and Fremantle: Western Australia Geological Survey, Record 1987/11.

GOZZARD, J. R., 1987c, Information on industrial minerals — coastal plain between Fremantle and Bunbury: Western Australia Geological Survey, Record 1987/9.

GOZZARD, J. R., 1987d, Information on industrial minerals — Albany area: Western Australia Geological Survey, Record 1987/14

GOZZARD, J. R., 1989a, Albany, W.A. part of Sheets 2427 I, 2428 II, 2527 IV, and 2528 III: Western Australia Geological Survey, 1:50 000 Environmental Geology Series.

GOZZARD, J. R., 1989b, Torbay, W.A. Sheet 2427 IV: Western Australia Geological Survey, 1:50 000 Environmental Geology Series.

GRIFFIN, T. J., TYLER, I. M., and PLAYFORD, P. E., 1993, Lennard River, W.A. (3rd edition): Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 56p.

GUPPY, D. J., LINDNER, A. W., RATTIGAN, J. H., and CASEY, J. N., 1958, The geology of the Fitzroy Basin, Western Australia: Australia BMR, Bulletin 36.

HARBEN, P. W., 1995, Carbonate rocks, *in* The industrial minerals handybook (2nd edition) : United Kingdom, Metal Bulletin Plc, Industrial Minerals Division.

HARBEN, P. W., and BATES, R. L., 1990, Carbonate rocks: *in* Industrial minerals — geology and world deposits: United Kingdom, Metal Bulletin Plc, Industrial Minerals Division, p. 41–47.

HICKMAN, A. H., 1983, Geology of the Pilbara Block and its environs: Western Australia Geological Survey, Bulletin 127.

HICKMAN, A. H., and GIBSON, D. L., 1982, Port Hedland – Bedout Island, W.A. (2nd edition): Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 28p.

HICKMAN, A. H., and LIPPLE, S. L., 1975, Explanatory notes on the Marble Bar 1:250 000 geological sheet, W.A.: Western Australia Geological Survey, Record 1974/20.

HICKMAN, A. H., and LIPPLE, S. L., 1978, Marble Bar, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 24p.

HOBSON, R. A., 1948, Chalk and marl samples from Gingin, Muchea and Bullsbrook: Western Australia Geological Survey, Annual Report 1945.

HOCKING, R. M., 1990, Eucla Basin *in* Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 548–561.

HOCKING, R. M., MOORS, H. T., and van de GRAAFF, W. J. E., 1987, Geology of the Carnarvon Basin, Western Australia: Western Australia Geological Survey, Bulletin 133.

HOCKING, R. M., van de GRAAFF, W. J. E., BLOCKLEY, J. G., and BUTCHER, B. P., 1982, Ajana, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 27p.

HOCKING, R. M., WILLIAMS, S. J., LAVARING, I. H., and MOORE, P. S., 1985a, Winning Pool–Minilya, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 36p.

HOCKING, R. M., WILLIAMS, S. J., MOORE, P. S., DENMAN, P. D., LAVARING, I. H., and van de GRAAFF, W. J. E., 1985b, Kennedy Range, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 31p.

HURLEY, N. F., 1986, Geology of the Oscar Range Devonian reef complex, Canning Basin, Western Australia: University of Michigan, PhD thesis (unpublished).

HURLEY, N. F., and LOHMAN, K. C., 1989, Diagenesis of Devonian reefal carbonates in the Oscar Range, Canning Basin, Western Australia: Journal of Sedimentary Petrology, v. 59, p. 127–146.

HURLEY, N. F., and VAN der VOO, R., 1987, Palaeomagnetism of Upper Devonian reefal limestones, Canning Basin, Western Australia: Geological Society of America, Bulletin, v. 98, p. 138–146.

HURLEY, N. F., and VAN der VOO, R., 1990, Magnetostratigraphy, Late Devonian iridium anomaly, and impact hypotheses: Geology, v. 18, p. 291–294.

JACKSON, M. J., 1978a, Robert, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 20p.

JACKSON, M. J., 1978b, Waigen, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 16p.

JELL, P. A., 1983, The Early to Middle Cambrian boundary in Australia, *in* Abstracts No. 9: Geological Society of Australia, 6th Convention, Canberra, 1983, p. 236.

JOHNSON, W., 1953, Report on survey of the limestone deposits of the southwest division of W.A. within a radius of 50 miles from Bunbury: Western Australia Geological Survey, Annual Report 1950, p. 77–79.

JOHNSTON, T. E., & ASSOCIATES, 1986, Report on vacuum drilling of the Kalbarri Lime Prospect E 70/181 and E 70/182, Menchetti Corporation Pty Ltd: Western Australia Geological Survey, M-Series Open File, Item 5954 (unpublished)

KENNEWELL, P. J., 1974, Herbert, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 20p.

KENNEWELL, P. J., 1975, Madley, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 13p.

KENNEWELL, P. J., 1977, Westwood, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 14p.

KERANS, C., 1985, Petrology of Devonian and Carboniferous carbonates of the Canning and Bonaparte Basins, Western Australia: Western Australian Mining and Petroleum Research Institute, Report 12, 223p.

KERANS, C., HURLEY, N. F., and PLAYFORD, P. E., 1986, Marine diagenesis in Devonian reef complexes of the Canning Basin, Western Australia, *in* Reef diagenesis *edited by* J. H. SCHROEDER and B. H. PURSER: Berlin, Springer Verlag, p. 357–380.

KOJAN, C. J., 1994, The geology and mineral resources of the proposed Dampier Archipelago National Park: Western Australia Geological Survey, Record 1994/2.

KOJAN, C. J., HASSAN, L. Y., and FREEMAN, M. J., 1995, The geology and high-grade limestone resource of the proposed Cape Range National Park extension: Department of Minerals and Energy, Land Access Report-EV 100.

KRIEWALDT, M., 1964, Dampier and Barrow Island, Western Australia: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 13p.

KRIEWALDT, M., and RYAN, G. R., 1967, Pyramid, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 39p.

KUKLA, G. J., 1977, Pleistocene land–sea correlations — 1. Europe: Earth Science Reviews, 13, p. 307–374.

LANDVISION, 1996, Managing the basic raw materials of Perth and outer metropolitan region — a report prepared for the Extractive Industries Committee of the Chamber of Commerce and Industry of Western Australia: Landvision, Report, p. 34–50.

LAWS, R., 1981, The petroleum geology of the onshore Bonaparte Basin: APEA Journal, v. 21, pt 1, p. 5–15.

LAYTON AND ASSOCIATES, 1975, Report on drilling for limestone north of Australind, Western Australia for Laporte Australia Ltd: Western Australia Geological Survey, M-Series Open File, Item 3290 (unpublished).

LEIGHTON, M. W., and PENDEXTER, C., 1962, Carbonate rock types, *in* Classification of carbonate rocks *edited by* W. E. HAMM: American Association of Petroleum Geologists, Memoir 1, p. 33–49.

LOGAN, B. W., 1968, Quaternary shorelines research in Australia and New Zealand: Australian Journal of Science, v. 31, no. 3, p. 110.

LORD, J. H., 1953a, Report on testing of a limestone deposit three miles north-west of Capel, South-West Division: Western Australia Geological Survey, Annual Report 1950, p. 77.

LORD, J. H., 1953b, Report on further testing of a limestone deposit three miles north-west of Capel, South-West Division: Western Australia Geological Survey, Annual Progress Report 1951, p. 58.

LORD, J. H., & ASSOCIATES PTY. LTD., 1983, Geological examination and sampling of M.C. 70/20549 and M.C. 70/20550 for limestone: Western Australia Geological Survey, M-Series Open File, Item 3200 (unpublished).

LOUGHBROUGH, R., 1994, European burnt lime — environment shows promise for a mature market: Industrial Minerals, no. 320, May 1994, p. 27–37.

LOUTHEAN, R., 1995, Loongana to double lime output: Gold Mining Journal, July 1995, p. 42.

LOW, G. H., 1965, Port Hedland, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 28p.

LOW, G. H., LAKE, R. W., and WILDE, S. A., 1978, Perth, W.A. Sheet SH 50-14 and part of Sheet 50-13: Western Australia Geological Survey, 1:250 000 Geological Series.

LOW, G. H., LOWRY, D. C., LAKE, R.W., WILDE, S. A., and HIRSCHBERG, K-J. B., 1980, Pinjarra, W.A. Sheet SI 50-2: Western Australia Geological Survey 1:250 000 Geological Series.

LOWRY, D. C., 1967, Busselton and Augusta, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes. 22p.

LOWRY, D. C., 1968, Tertiary stratigraphic units in the Eucla Basin in Western Australia: Western Australia Geological Survey, Annual Report, 1967, p. 36–40.

LOWRY, D. C., 1970a, Geology of the Western Australian part of the Eucla Basin: Western Australia Geological Survey, Bulletin 122.

LOWRY, D. C., 1970b, Culver, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 14p.

LOWRY, D. C., 1970c, Naretha, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 12p.

LOWRY, D. C., 1970d, Loongana, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 12p.

LOWRY, D. C., 1970e, Jubilee, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 12p.

LOWRY, D. C., 1970f, Forrest, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 13p.

LOWRY, D. C., 1971, Eucla–Noonaera, W.A. Sheet SH 52-14 and part of SH 52-2: Western Australia Geological Survey, 1:250 000 Geological Series.

LOWRY, D. C., 1972, Madura–Burnabbie, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 14p.

LOWRY, D. C., 1974, Dongara–Hill River, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 33p.

LOWRY, D. C., LOW, G. H., PLAYFORD, P. E., and DEDMAN, R., 1973 Dongara–Hill River, W.A. parts of Sheets SH 50-5 and SH 50-9: Western Australia Geological Survey 1:250 000 Geological Series.

LUDBROOK, N. H., 1958a, The Eucla Basin in South Australia: Geological Society of Australia, Journal, v. 5, pt. 2, p. 127–135.

LUDBROOK, N. H., 1958b, The stratigraphic sequence in the western portion of the Eucla Basin: Royal Society of Western Australia, Journal, v. 41, p. 108–114.

LUDBROOK, N. H., 1960, Exoil Pty Ltd, Eyre No. 1 and Gambanga No. 1 Wells subsurface stratigraphy and micropalaeontological study: South Australia Department of Mines, Palaeontology Report 11/60 (unpublished).

LUDBROOK, N. H., 1963, Correlation of the Tertiary rocks of South Australia: Royal Society of South Australia, Transactions, 87, p. 5–15.

MacLEOD, W. N., de la HUNTY, L. E., JONES, W. R., and HALLIGAN, R., 1963, A preliminary report on the Hamersley Iron Province, North-West Division: Western Australia Geological Survey, Annual Report 1962, p. 44–54.

MacLEOD, W. N., and de la HUNTY, L. E., 1966, Roy Hill, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 27p.

McEWEN, R. C., and WHITEHEAD, R. C., 1964, Report on Garden Island drilling programme and Cockburn Sound sampling including compilation of limesand reserves, Garden Island: Western Australia Geological Survey, M-Series Open File, Item 3226 (unpublished).

McHAFFIE, I. W., and BUCKLEY, R. W., 1995, Industrial minerals and rocks of Victoria: Department of Agriculture, Energy and Minerals, Victoria, Australia, Geological Survey Report 102, p. 115–140.

McLAREN, N., 1977, Final report for limestone exploration in the Temporary Reserve 6340H Cape Cuvier, Western Australia, Dampier Mining Company Ltd: Western Australia Geological Survey, M-Series Open File, Item 465 (unpublished).

McMATH, J. C., 1952, Limestone resources — Perth and environs: Western Australia Geological Survey, Map sheets 1–3.

McWHAE, J. R. H., PLAYFORD, P. E., LINDNER, A. W., GLENISTER, B. F., and BALME, B. E., 1958, The stratigraphy of Western Australia: Geological Society of Australia, Journal, v. 4, pt 2.

MAITLAND, A. G., 1919, Petroleum prospects in the Nullarbor Plains – Eucla Division: Western Australia Geological Survey, Annual Report 1918, p. 7–11.

MILES, K. R., 1945a, Preliminary report on limestone prospects — Commonwealth land south of Fremantle: Western Australia Geological Survey, Annual Report 1944, p. 107–110.

MILES, K. R., 1945b, Notes on sampling Douro Rd limestone quarry, South Fremantle: Western Australia Geological Survey, Annual Report 1944, p. 110.

MORGAN, K. H., and PEERS, R., 1973, Esperance–Mondrain Island, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 23p.

MORY, A. J., 1990, Ord Basin, *in* Geology and mineral resources of Western Australia: Western Australia Geological Survey, Memoir 3, p. 415–425.

MORY, A. J., 1995, Mingenew–Dongara, W.A. Sheet 1939 and part of Sheet 1839: Western Australia Geological Survey, 1:100 000 Geological Series.

MORY, A. J., and BEERE G. M., 1985, Palaeozoic stratigraphy of the Ord Basin, Western Australia and Northern Territory: Western Australia Geological Survey, Report 14, Professional Papers, p. 36–45.

MORY, A. J., and BEERE, G. M., 1986, Revised stratigraphic nomenclature for the onshore Bonaparte and Ord Basins, W.A.: Western Australia Geological Survey, Record 1986/5.

MORY, A. J., and BEERE G. M., 1988, Geology of the onshore Bonaparte and Ord Basins in Western Australia: Western Australia Geological Survey, Bulletin 134.

MUHLING, P. C., BRAKEL, A. T., and MONCRIEFF, J. S., 1984, Mount Barker–Albany, W.A. Sheet SI 50-11 and part of SH 50-15: Western Australia Geological Survey, 1:250 000 Geological Series.

MUHLING, P. C., and BRAKEL, A. T., 1985, Mount Barker–Albany, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 21p.

NOLDART, A. J., and WYATT, J. D., 1962, The geology of portion of the Pilbara Goldfield, covering the Marble Bar and Nullagine 4-mile map sheets: Western Australia Geological Survey, Bulletin 115.

O'DRISCOLL, M., 1988, Burnt lime/dolime — seeking markets green: Industrial Minerals, no. 248, May 1988, p. 23–51.

OPIK, A. A., 1967, The Ordian stage of the Cambrian and its Australian Metadoxididae: Australia BMR, Bulletin 92, p. 133–165.

PASSMORE, J. R., 1967, The geology, hydrology, and contamination of shallow coastal aquifers in the Rockingham District, Western Australia: University of Western Australia, PhD thesis (unpublished).

PASSMORE, J. R., 1970, Shallow coastal aquifers in the Rockingham District, Western Australia: Water Research Foundation of Australia, Bulletin 18, p. 83.

PLAYFORD, P. E., 1980, Devonian 'Great Barrier Reef' of the Canning Basin, Western Australia: American Association of Petroleum Geologists, Bulletin, v. 64, p. 814–840.

PLAYFORD, P. E., 1981, Devonian reef complexes of the Canning Basin, Western Australia: Geological Society of Australia, Fifth Australian Geological Convention, Field Excursion Guidebook, 64p.

PLAYFORD, P. E., 1984, Platform-margin and marginal-slope relationships in Devonian reef complexes of the Canning Basin, *in* The Canning Basin, W.A. *edited by* P. G. PURCELL: Geological Society of Australia and Petroleum Exploration Society of Australia; Canning Basin Symposium, Perth, W.A., 1984, Proceedings, p. 189–214.

PLAYFORD, P. E., COCKBAIN, A. E., and LOW, G. H., 1976a, Geology of the Perth Basin, Western Australia: Western Australia Geological Survey, Bulletin 124.

PLAYFORD, P. E., COCKBAIN, A. E., DRUCE, E. C., and WRAY, J. L., 1976b, Devonian stromatolites from the Canning Basin, Western Australia, *in* Stromatolites *edited by* M. R. WALTER; Developments in Sedimentology: Elsevier, v. 20, p. 543–563.

PLAYFORD, P. E., COPE, R. N., COCKBAIN, A. E., LOW, G. H., and LOWRY, D. C., 1975, Phanerozoic, *in* The geology of Western Australia: Western Australia Geological Survey, Memoir 2, p. 223–433.

PLAYFORD, P. E., HORWITZ, R. C., PEERS, R., and BAXTER, J. L., 1970, Geraldton, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 39p.

PLAYFORD, P. E., HURLEY, N. F., KEARNS, C., and MIDDLETON, M. F., 1989, Reefal platform development, Devonian of the Canning Basin, Western Australia, *in* Controls on carbonate platform and basin development *edited by* P. D. CREVELLO, J. L. WILSON, J. F. SARG, and J. F. READ: Society of Economic Paleontologists and Mineralogists, Special Publication 44, p. 187–202.

PLAYFORD, P. E., and LOW, G. H., 1972, Definitions of some new and revised rock units in the Perth Basin: Western Australia Geological Survey, Annual Report 1971, p. 44–46.

PLAYFORD, P. E., and LOWRY, D. C., 1966, Devonian reef complexes of the Canning Basin, Western Australia: Western Australia Geological Survey, Bulletin 118, 150p.

PLAYFORD, P. E., WILLMOTT, S. P., JOHNSTONE, D., HORWITZ, R. C., and BAXTER, J. L., 1971, Geraldton–Houtman Abrolhos, W.A. Sheet SH 50-1 and part of SH 49-4: Western Australia Geological Survey, 1:250 000 Geological Series.

POWER, T., 1985, Limestone specifications — limiting constraints on the market: Industrial Minerals, no. 217, October 1985, p. 65–91.

PRESTON, W. A., ABEYSINGHE, P. B., and BLOCKLEY, J. G., 1994, Western Australian long-term limestone requirements: Western Australia Geological Survey, Mineral Resources Report no. 1994/2.

PURCELL, P. G., (editor), 1984, The Canning Basin, W.A.: Geological Society of Australia and Petroleum Exploration Society of Australia; Canning Basin Symposium, Perth, W.A., 1984, 582p.

RANKINE, G., 1995, Technical and surrender report for E20/226 'Governess', Report for Posgold (Murchison) Pty Ltd: Western Australia Geological Survey, M-Series Open File, Item 8227 (unpublished).

RIGBY, 1986, Late Devonian sponges of Western Australia: Western Australia Geological Survey, Report 18, 59p.

ROBERTS, H. G., HALLIGAN, R., and PLAYFORD, P. E., 1968, Mount Ramsay, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 24p.

RYAN, G. R., 1966, Roebourne, W.A., Western Australia: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 26p.

RYAN, G. R., KRIEWALDT, M., and BACK, W., 1965, Roebourne, W.A. Sheet SF 50-3: Western Australia Geological Survey, 1:250 000 Geological Series.

SEHNKE, E. D., 1995, Bauxite — a global review: Industrial Minerals, no. 335, August 1995, p. 39–51.

SIMPSON, E. S., 1948, Minerals of Western Australia, Volume 1: Perth, Western Australia, Government Printer.

SWAN PORTLAND, 1971, Quinns Rock – Wabling Hill limestone and limesand exploration: Western Australia Geological Survey, M-Series Open File, Item 2479 (unpublished).

TEICHERT, C., 1949, Discovery of Devonian and Carboniferous rocks in the North-West Basin, Western Australia: Australian Journal of Science, v. 12, p. 62–65.

TEICHERT, C., 1950, Late Quaternary changes of sea level at Rottnest Island, Western Australia: Royal Society of Victoria, Proceedings, v. 59, p. 63–79.

THOM, R., CHIN, R. J., and HICKMAN, A. H., 1984, Newdegate, W.A., Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 24p.

THOM, R., LIPPLE, S. L., and SANDERS, C. C., 1977, Ravensthorpe, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 40p.

THOMAS, D., 1993, Limestone Quarrying at a Nullabor 'Whistle Stop': Australian Journal of Mining, July 1993, p. 50–51.

THOMAS, G. A., 1959, The Lower Carboniferous Laurel Formation of the Fitzroy Basin: Australia BMR, Report 38, p. 21–36.

THORNE, A. M., SEYMOUR, D. B., TYLER, I. M., and HUNTER, W. M., 1991, Turee Creek, W.A. Sheet SF 50-15: Western Australia Geological Survey, 1:250 000 Geological Series.

THORNE, A. M., TYLER, I. M., BLOCKLEY, J. G., and BLIGHT, D. F., 1996, Mount Bruce, W.A. Sheet SF 50-11 (2nd edition): Western Australia Geological Survey, 1:250 000 Geological Series.

TINGEY, R. J., 1985, Sandstone, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 37p.

TOWNER, R. R., 1977, Crossland, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 19p.

TOWNER, R. R., and GIBSON, D. L., 1983, Geology of the onshore Canning Basin, Western Australia: Australia BMR, Bulletin 235, 51p.

TOWNSEND, D. B., 1996, Basic raw materials of the Shark Bay World Heritage Area: Western Australia Geological Survey, Record 1996/9.

TRASK, F., 1980, Second annual report on TR 7050H, Lenkane Exploration Pty Ltd, Western Australia, final report: Western Australia Geological Survey, M-Series Open File, Item 2599 (unpublished).

TRAVES, D. M., 1955, The geology of the Ord–Victoria region, Northern Australia: Australia BMR, Bulletin 27.

TUCKER, M. E., WRIGHT, V. P., and DICKSON, J. A. D., 1990, Carbonate sedimentology: Oxford, Blackwell Scientific Publications, p. 18–22.

UNIVERSAL MILLING, 1976, MC 2443H drillhole summary: Western Australia Geological Survey, M-Series Open File, Item 2184 (unpublished).

van de GRAAFF, W. J. E., 1974a, Mason, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 24p.

van de GRAAFF, W. J. E, 1974b, Warri, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 21p.

van de GRAAFF, W. J. E., DENMAN, P. D., HOCKING, R. M., and BAXTER, J. L., 1980, Yanrey–Ningaloo, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 24p.

van de GRAAFF, W. J. E., DENMAN, P. D., and HOCKING, R. M., 1982, Onslow, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes. 27p.

van de GRAAFF, W. J. E., HOCKING, R. M., and BUTCHER, B. P., 1983, Yaringa, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 23p.

VEEH, H. H., 1966, Th^{230}/U^{238} and U^{234}/U^{238} ages of Pleistocene high sea level stand: Journal of Geophysical Research, v. 71, p. 3379–3386.

VEEVERS, J. J., and ROBERTS, J., 1968, Upper Palaeozoic rocks, Bonaparte Gulf Basin of Northwestern Australia: Australia BMR, Bulletin 97.

VIDAL, J. R., 1994, $CaCO_3$ fillers — market trends and developments: Industrial Minerals, no. 326, November 1994, p. 63–65.

WALLACE, M. W., 1987, Sedimentology and diagenesis of Upper Devonian carbonates, Canning Basin, Western Australia: University of Tasmania, PhD thesis (unpublished).

WELLS, A. J., 1959, Paterson Range — 4 mile Geological Series: Australia BMR, Explanatory Notes SF 51-6.

WILDE, S. A., and LOW, G. H., 1978, Perth, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes. 36p.

WILDE, S. A., and LOW, G. H., 1980, Pinjarra, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 31p.

WILDE, S. A., and WALKER, I. W., 1984, Pemberton–Irwin Inlet, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 37p.

WILLIAMS, I. R., 1968, Yarraloola, W.A.: Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 30p.

WILLIAMS, I. R., 1989, Balfour Downs, W.A., (2nd edition): Western Australia Geological Survey, 1:250 000 Geological Series Explanatory Notes, 38p.

WILLIAMS, I. R., RYAN, G. R., and HALLIGAN, R., 1972, Yarraloola, W.A. Sheet SF 50-6: Western Australia Geological Survey, 1:250 000 Geological Series.

WITT, W. K., 1996, Ravensthorpe, W.A. Sheet 2930: Western Australia Geological Survey, 1:100 000 Geological Series.

WOODWARD, H. P., 1906, Wagin district: Western Australia Geological Survey, Annual Report 1905, p. 14.

WOODWARD, H. P., 1907, Wagin: W.A. Geological Survey, Annual Report 1906, p. 21.

WOODWARD, H. P., 1912, Limestone deposits at Pinjarra: Western Australia Geological Survey, Bulletin 48, p. 82.

WOODWARD, H. P., 1915a, The foraminiferal sand deposits of Dongara: Western Australia Geological Survey, Annual Report 1915, p. 112–114.

WOODWARD, H. P., 1915b, The limestone deposits near Denmark: Western Australia Geological Survey, Annual Report 1915, p. 112.

WYATT, J. D., 1961, Reconnaissance survey of commercial lime deposits within a 15 mile radius of Albany, S.W. Division: Western Australia Geological Survey, Annual Report 1960, p. 95–96.

Appendix 1

Sample locations and assays in the Perth Metropolitan Region

Sample location no.	Longitude	Latitude	$\%CaCO_3$ maximum	$\%CaCO_3$ minimum	No. of samples	$\%CaCO_3$ Average
1	31°15'20"	115°27'30"	87.3	85	2	86.2
2	31°16'41"	115°27'06"	83	83	1	83
3	31°17'05"	115°26'36"	75.9	75.9	1	75.9
4	31°16'32"	115°29'21"	89.9	60	2	75
5	31°17'44"	115°30'40"	80.9	80.9	1	80.9
6	31°19'27"	115°31'21"	65.3	65.3	1	65.3
7	31°19'46"	115°30'35"	70.2	69.1	2	69.7
8	31°20'35"	115°30'18"	92	90.2	2	91.1
9	31°19'05"	115°35'05"	60.5	60.5	1	60.5
10	31°21'47"	115°35'59"	92.6	83.1	4	86.6
11	31°22'14"	115°35'58"	84.1	84.1	1	84.1
12	31°22'32"	115°37'10"	73.4	73.4	1	73.4
13	31°23'11"	115°36'18"	53.3	53.3	1	53.3
14	31°24'14"	115°36'43"	89.2	89.2	1	89.2
15	31°26'11"	115°35'38"	69.8	69.8	1	69.8
16	31°25'58"	115°38'08"	62.5	57.7	2	60.1
17	31°24'55"	115°39'26"	84.3	84.3	1	84.3
18	31°24'46"	115°39'35"	77.4	72	2	74.7
19	31°24'35"	115°41'18"	65	62.5	2	63.8
20	31°24'55"	115°41'58"	73	73	1	73
21	31°26'18"	115°42'23"	71.4	66.4	2	68.9
22	31°26'38"	115°42'29"	81.2	72	3	76.1
23	31°26'06"	115°40'12"	85.7	82.7	2	84.2
24	31°26'35"	115°39'37"	90.5	87	2	88.8
25	31°27'06"	115°40'42"	85	76.6	2	80.8
26	31°29'51"	115°39'24"	80	79.8	2	79.9
27	31°29'36"	115°41'51"	79.5	73.9	2	76.7
28	31°30'18"	115°42'14"	72	72	1	72
29	31°30'54"	115°43'10"	81.6	62.5	2	72.1
30	31°31'43"	115°43'01"	87.7	87.7	1	87.7
31	31°31'44"	115°42'38"	83.1	83.1	1	83.1
32	31°31'52"	115°42'20"	93	93	1	93
33	31°31'47"	115°40'59"	83	83	1	83
34	31°32'16"	115°42'08"	98	98	1	98
35	31°32'38"	115°42'23"	88	88	1	88
36	31°31'44"	115°37'05"	76	76	1	76
37	31°31'57"	115°37'25"	71	66	2	68.5
38	31°32'16"	115°38'03"	73	73	1	73
39	31°32'48"	115°38'14"	51.9	51.9	1	51.9
40	31°32'47"	115°37'33"	58	58	1	58
41	31°32'45"	115°37'15"	54	54	1	54
42	31°32'56"	115°37'31"	84	84	1	84
43	31°33'06"	115°37'26"	91	91	1	91
44	31°33'05"	115°37'34"	83	83	1	83
45	31°33'14"	115°37'27"	86	75	2	80.5
46	31°33'16"	115°37'57"	78	78	1	78
47	31°33'26"	115°37'43"	78	78	1	78
48	31°33'32"	115°37'44"	63	63	1	63
49	31°33'04"	115°38'44"	63	46	2	54.5
50	31°33'40"	115°39'57"	68	61	2	64.5
51	31°33'44"	115°41'23"	68	55.9	3	63
52	31°33'35"	115°41'36"	86	86	1	86
53	31°33'42"	115°44'07"	84	84	1	84
54	31°33'21"	115°44'45"	81	81	1	81
55	31°34'14"	115°44'14"	89	89	1	89
56	31°34'31"	115°44'11"	80.9	80	4	82.2

Appendix 1 (continued)

Sample location no.	*Longitude*	*Latitude*	*%CaCO$_3$ maximum*	*%CaCO$_3$ minimum*	*No. of samples*	*%CaCO$_3$ Average*
57	31°34'27"	115°43'13"	89	89	1	89
58	31°34'04"	115°41'09"	87	87	1	87
59	31°35'12"	115°38'41"	81	81	1	81
60	31°35'06"	115°39'47"	38	38	1	38
61	31°35'12"	115°40'06"	24	24	1	24
62	31°35'36"	115°41'54"	83.4	83.4	1	83.4
63	31°35'47"	115°40'32"	66	66	1	66
64	31°36'00"	115°39'57"	73	71	2	72
65	31°36'47"	115°41'07"	67	67	1	67
66	31°36'47"	115°41'31"	58	58	1	58
67	31°37'03"	115°40'41"	70	70	1	70
68	31°37'03"	115°41'40"	56	56	1	56
69	31°37'21"	115°40'46"	71	71	1	71
70	31°37'31"	115°40'23"	84	84	1	84
71	31°37'44"	115°40'19"	81	81	1	81
72	31°37'43"	115°40'05"	86	86	1	86
73	31°37'47"	115°40'04"	83	83	1	83
74	31°37'48"	115°40'13"	75	73	2	74
75	31°37'45"	115°40'26"	83	83	1	83
76	31°37'41"	115°40'32"	86	86	1	86
77	31°37'54"	115°40'38"	68	68	1	68
78	31°37'40"	115°41'10"	56	55.5	3	55.5
79	31°37'32"	115°41'20"	41	41	1	41
80	31°37'40"	115°42'19"	73	66	2	69.5
81	31°37'12"	115°44'12"	83.4	83.4	1	83.4
82	31°38'45"	115°43'38"	68	68	1	68
83	31°38'42"	115°44'12"	87	87	1	87
84	31°40'17"	115°43'21"	65	65	1	65
85	31°40'16"	115°43'30"	79.4	79.4	1	79.4
86	31°40'22"	115°44'00"	69	69	1	69
87	31°40'36"	115°44'07"	86	80.6	2	83.3
88	31°40'49"	115°41'50"	84	84	1	84
89	31°41'15"	115°41'55"	93	93	1	93
90	31°42'02"	115°42'36"	79	79	1	79
91	31°42'27"	115°42'35"	61	58	2	59.5
92	31°42'38"	115°42'35"	60	60	1	60
93	31°42'52"	115°42'25"	58	58	1	58
94	31°42'45"	115°43'57"	84.4	84.4	1	84.4
95	31°42'27"	115°44'27"	65.9	65.9	1	65.9
96	31°42'39"	115°44'24"	66.7	66.7	1	66.7
97	31°43'26"	115°44'34"	86	79.5	4	82.7
98	31°43'36"	115°44'54"	86	86	1	86
99	31°43'48"	115°44'13"	90	73.3	2	81.7
100	31°43'59"	115°44'00"	80.3	73.9	2	79.8
101	31°44'38"	115°44'56"	78.9	58.7	3	68.5
102	31°33'22"	115°45'31"	92	92	1	92
103	31°36'36"	115°45'04"	78	78	1	78
104	31°36'32"	115°45'28"	84.6	60	3	72.9
105	31°37'36"	115°45'44"	85.8	36.9	4	67.4
106	31°38'12"	115°45'39"	81.9	81.9	1	81.9
107	31°38'23"	115°45'34"	83.9	79.1	2	81.5
108	31°38'26"	115°45'45"	85	85	1	85
109	31°38'44"	115°45'29"	82.9	82.9	1	82.9
110	31°39'24"	115°46'28"	80.8	80.8	1	80.8
111	31°39'48"	115°46'45"	87	78.9	2	83
112	31°39'56"	115°46'04"	75.8	75.8	1	75.8
113	31°40'10"	115°45'54"	93	83.4	2	88.2
114	31°40'14"	115°46'13"	80.8	80.8	1	80.8
115	31°40'10"	115°46'29"	80	80	1	80
116	31°40'36"	115°46'42"	80	80	1	80
117	31°40'57"	115°46'36"	76.9	76.9	1	76.9
118	31°41'04"	115°46'31"	85	85	1	85
119	31°41'08"	115°46'23"	70.8	70.8	1	70.8
120	31°41'18"	115°46'13"	78.9	54.5	4	69.2
121	31°42'11"	115°46'00"	68	68	1	68
122	31°39'43"	115°59'09"	91	91	1	91
123	31°40'04"	115°59'55"	86	86	1	86

Appendix 1 (continued)

Sample location no.	*Longitude*	*Latitude*	*%CaCO$_3$ maximum*	*%CaCO$_3$ minimum*	*No. of samples*	*%CaCO$_3$ Average*
124	31°40'14"	115°59'56"	93	93	1	93
125	31°42'22"	115°59'14"	83	83	1	83
126	31°43'56"	115°46'30"	93	73	2	83
127	31°43'51"	115°45'25"	72	65.9	4	69.2
128	31°44'00"	115°45'18"	73.9	58.9	5	65.6
129	31°44'17"	115°45'06"	72.5	67.5	2	70
130	31°44'31"	115°45'30"	73.3	73.3	1	73.3
131	31°44'46"	115°45'08"	64.4	61.9	4	63.2
132	31°44'57"	115°45'08"	76.9	68.2	7	73.5
133	31°45'02"	115°45'15"	82.6	80.7	2	81.7
134	31°45'49"	115°45'01"	67.5	67.5	1	67.5
135	31°46'11"	115°43'59"	88	88	1	88
136	31°45'28"	115°46'09"	51.4	38.5	2	45
137	31°45'36"	115°45'59"	68.9	47	4	58.1
138	31°45'48"	115°46'12"	70.1	46.4	3	61.6
139	31°45'42"	115°46'33"	72.6	60.7	4	68.1
140	31°45'52"	115°47'06"	64.5	59.8	4	62.3
141	31°46'00"	115°47'14"	55.9	55.9	1	55.9
142	31°48'04"	115°44'06"	84.7	84.7	1	84.7
143	31°49'07"	115°44'30"	21	21	1	21
144	31°50'10"	115°45'49"	56.4	52	2	54.2
145	31°54'43"	115°46'41"	66	66	1	66
146	31°54'58"	115°46'09"	59	59	1	59
147	31°56'27"	115°46'34"	82	82	1	82
148	31°56'45"	115°45'37"	56.9	56.9	1	56.9
149	32°01'09"	115°45'02"	86	86	1	86
150	32°01'20"	115°45'57"	67	67	1	67
151	32°03'22"	115°45'58"	66.9	68	2	67.5
152	32°04'17"	115°45'46"	73.9	71.9	2	72.9
153	32°04'30"	115°45'22"	76.9	75.8	2	76.4
					27	[(a)] 91.4
154	32°05'52"	115°45'52"	80.8	57.2	6	70.5
155	32°05'59"	115°45'32"	78.9	78.9	1	78.9
156	32°06'38"	115°45'38"	75.0	75.0	1	[(a)] 75
157	32°06'54"	115°45'38"	64.6	64.6	1	64.6
158	32°07'06"	115°45'38"	80.0	80.0	1	[(a)] 80
159	32°07'08"	115°46'23"	60.9	60.9	1	60.9
160	32°07'18"	115°46'24"	58.9	58.9	1	58.9
161	32°07'32"	115°46'17"	86.1	74.9	3	86.1
162	32°07'49"	115°46'05"	84.6	84.6	1	84.6
163	32°08'05"	115°45'59"	84.1	48.4	3	70.9
164	32°07'49"	115°47'14"	84.8	82.1	2	83.5
165	32°08'08"	115°47'22"	80.8	80.8	1	80.8
166	32°08'24"	115°45'42"	90.0	90.0	1	[(a)] 90
167	32°08'33"	115°46'05"	78.9	41.9	2	60.4
168	32°08'36"	115°46'57"	98	98	1	98
169	32°08'52"	115°47'31"	86.9	82.9	3	86.4
170	32°08'48"	115°45'52"	84.1	84.1	1	84.1
171	32°09'00"	115°45'52"	87.0	87.0	1	[(a)] 87
172	32°09'15"	115°46'12"	61.5	46.9	6	53.5
173	32°09'12"	115°46'21"	49	35.7	2	42.4
174	32°09'28"	115°46'00"	63.9	38.6	4	51.9
175	32°09'18"	115°47'23"	68	68	1	68
176	32°09'24"	115°47'48"	88.9	79.4	3	85.1
177	32°09'26"	115°48'01"	84.1	84.1	1	84.1
178	32°09'48"	115°48'08"	83	79.6	2	81.3
179	32°09'55"	115°47'50"	85	80	3	81.8
180	32°10'01"	115°47'35"	84.9	79.8	2	82.4
181	32°09'49"	115°47'31"	76.4	76.4	1	76.4
182	32°09'48"	115°46'30"	41.5	41.5	1	41.5
183	32°10'06"	115°46'16"	85.8	85.8	1	85.8
184	32°10'23"	115°46'48"	–	–	10	48.8
185	32°10'35"	115°46'23"	93	93	1	93
186	32°10'25"	115°47'54"	97	82.5	2	89.8
187	32°10'37"	115°48'50"	80.5	66.2	5	72.9
188	32°10'51"	115°48'24"	76	76	1	76
189	32°10'46"	115°48'16"	83	83	1	83

Appendix 1 (continued)

Sample location no.	*Longitude*	*Latitude*	*%$CaCO_3$ maximum*	*%$CaCO_3$ minimum*	*No. of samples*	*%$CaCO_3$ Average*
190	32°10'49"	115°48'06"	73.9	73.9	1	73.9
191	32°11'01"	115°47'58"	80	71.9	2	76
192	32°11'19"	115°48'08"	82.1	75.8	2	79
193	32°11'17"	115°47'42"	91	69.3	3	82.8
194	32°11'29"	115°47'35"	85	70	2	77.5
195	32°11'17"	115°46'40"	92	92	1	92
196	32°11'39"	115°46'50"	63	50.9	2	57
197	32°12'00"	115°46'42"	86	86	1	86
198	32°11'41"	115°48'06"	85	85	1	85
199	32°11'47"	115°48'15"	76.2	65.5	2	70
200	32°11'53"	115°48'09"	69.6	69.6	1	69.6
201	32°12'22"	115°48'15"	86	77.5	2	81.8
202	32°12'33"	115°48'25"	79.3	79.3	1	79.3
203	32°12'34"	115°48'39"	70.8	58.2	2	64.5
204	32°13'31"	115°47'17"	79.4	42	2	60.7
205	32°13'42"	115°47'14"	83	28.2	2	55.6
206	32°14'33"	115°47'29"	58	58	1	58
207	32°14'29"	115°49'33"	73	73	1	73
208	32°15'06"	115°46'35"	69	69	1	69
209	32°15'07"	115°47'23"	84	84	1	84
210	32°15'20"	115°49'28"	79	30	2	54.5
211	32°15'31"	115°45'20"	61	61	1	61
212	32°15'59"	115°46'09"	50	50	1	50
213	32°15'57"	115°47'00"	64	64	1	64
214	32°16'06"	115°45'50"	47	47	1	47
215	32°16'28"	115°45'48"	37	37	1	37
216	32°16'18"	115°45'10"	41	41	1	41
217	32°16'42"	115°45'25"	41	41	1	41
218	32°16'42"	115°44'55"	58	58	1	58
219	32°16'14"	115°41'24"	85	85	1	85
220	32°16'06"	115°41'04"	80	80	1	80
221	32°16'23"	115°41'12"	90	90	1	90
222	32°17'27"	115°42'07"	80	80	1	80
223	32°18'32"	115°43'29"	90	90	1	90
224	32°17'37"	115°46'18"	50.5	50.5	1	50.5
225	32°17'08"	115°47'51"	87	72	2	79.5
226	32°16'56"	115°48'54"	91	91	1	91
227	32°17'44"	115°48'58"	76.8	62.9	2	69.9
228	32°18'16"	115°49'19"	89	89	1	89
229	32°17'51"	115°48'09"	87	87	1	87
230	32°18'07"	115°47'44"	65	65	1	65
231	32°18'40"	115°46'10"	33.3	33.3	1	33.3
232	32°19'31"	115°44'39"	72	72	1	72
233	32°20'02"	115°45'14"	53	53	1	53
234	32°19'57"	115°46'16"	98	98	1	98
235	32°19'54"	115°46'16"	96	96	1	96
236	32°19'41"	115°46'15"	47	47	1	47
237	32°19'37"	115°46'26"	58	43	2	50.5
238	32°19'37"	115°46'33"	89	89	1	89
239	32°19'38"	115°46'43"	68	68	1	68
240	32°19'41"	115°46'50"	71	71	1	71
241	32°19'48"	115°46'59"	88	51	2	69.5
242	32°19'33"	115°47'27"	88	88	1	88
243	32°19'45"	115°48'08"	78	72.3	2	75.2
244	32°20'10"	115°47'29"	88	88	1	88
245	32°20'12"	115°47'10"	68	68	1	68
246	32°20'27"	115°45'11"	58	58	1	58
247	32°20'56"	115°44'50"	51	51	1	51
248	32°21'09"	115°45'12"	42.7	42.7	1	42.7
249	32°20'58"	115°47'22"	88	68	3	76.3
250	32°22'37"	115°46'48"	88	88	1	88
251	32°22'30"	115°45'46"	51	51	1	51
252	32°22'21"	115°43'36"	88	88	1	88
253	32°23'08"	115°46'15"	63	63	1	63
254	32°23'08"	115°46'29"	83	83	1	83
255	32°23'11"	115°46'53"	75.5	75.5	1	75.5
256	32°23'22"	115°46'16"	49.2	49.2	1	49.2

Appendix 1 (continued)

Sample location no.	*Longitude*	*Latitude*	*%$CaCO_3$ maximum*	*%$CaCO_3$ minimum*	*No. of samples*	*%$CaCO_3$ Average*
257	32°23'53"	115°46'02"	60.1	60.1	1	60.1
258	32°24'01"	115°46'03"	51.7	51.7	1	51.7
259	32°24'12"	115°46'18"	30.3	30.3	1	30.3
260	32°24'40"	115°46'14"	78	78	1	78
261	32°25'25"	115°45'45"	78.9	78.9	1	78.9
262	32°25'56"	115°45'39"	61.8	61.8	1	61.8
263	32°26'05"	115°45'54"	78.9	78.9	1	78.9
264	32°26'09"	115°46'00"	73.9	63.4	2	68.7
265	32°26'16"	115°46'07"	80.8	79.4	3	77.6
266	32°26'29"	115°46'00"	81.9	72.6	3	77.8
267	32°26'51"	115°45'34"	48.7	48.7	1	48.7
268	32°27'27"	115°46'00"	82.2	71.4	4	78.8
269	32°27'26"	115°46'07"	71.8	67.4	3	69.8
270	32°27'29"	115°46'12"	64	50	3	57.5
271	32°28'03"	115°46'05"	62.4	58	3	59.5
272	32°28'00"	115°45'59"	62.4	50	4	57.2
273	32°28'03"	115°45'51"	82.2	60	3	73.9
274	32°28'01"	115°45'38"	83.6	68.2	3	77.3
275	32°28'09"	115°45'13"	74.9	74.9	1	74.9
276	32°28'25"	115°45'24"	76.9	76.9	1	76.9
277	32°28'53"	115°45'18"	83.9	83.9	1	83.9
278	32°28'55"	115°45'21"	83	54.6	3	70.5
279	32°29'13"	115°45'25"	78	71.8	2	74.9
280	32°29'54"	115°44'38"	77.3	77.3	1	77.3
281	32°29'54"	115°45'13"	80	80	1	80
282	32°29'39"	115°45'33"	60.2	60.2	1	60.2
283	32°29'44"	115°45'35"	93	76.9	5	83.5
284	32°29'50"	115°45'31"	83.6	65.7	13	61.6

NOTE: (a) total carbonates

Appendix 2

Index of limestone and limesand localities in Western Australia

H

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N

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P

Q

R

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V

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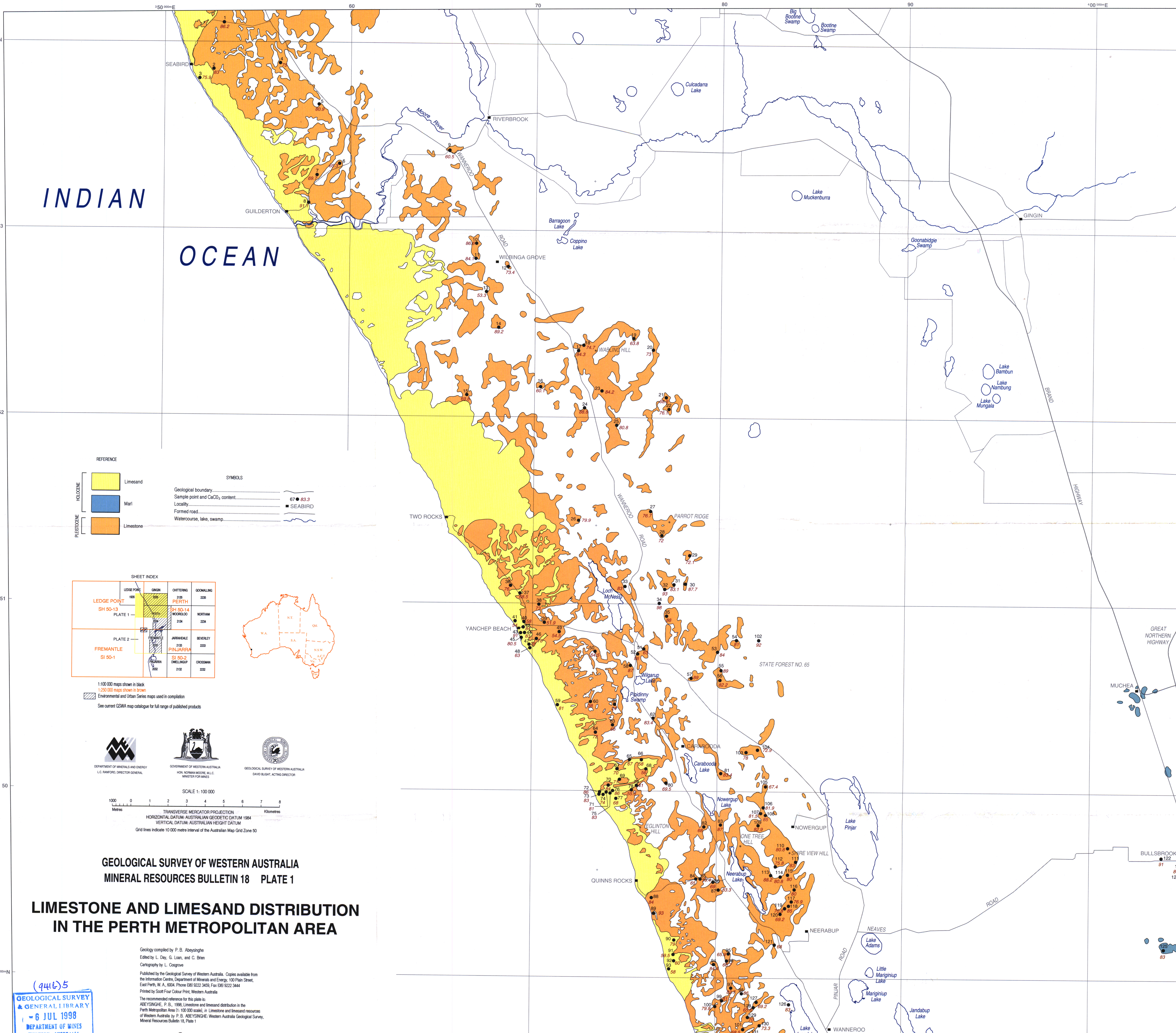
Y

Z



REFERENCE

HOLOCENE
- Limesand
- Marl

PLEISTOCENE
- Limestone

SYMBOLS

Geological boundary
Sample point and $CaCO_3$ content — 67 ● 83.3
Locality — ■ SEABIRD
Formed road
Watercourse, lake, swamp

SHEET INDEX

LEDGE POINT SH 50-13 — LEDGE POINT 1935
GINGIN 2035
CHITTERING 2135
GOOMALLING 2235
PERTH SH 50-14 — PERTH 2034
WOOROLOO 2134
NORTHAM 2234
PLATE 1
PLATE 2
FREMANTLE SI 50-1 — FREMANTLE 2033
JARRAHDALE 2133
BEVERLEY 2233
PINJARRA SI 50-2 — PINJARRA 2032
DWELLINGUP 2132
CROSSMAN 2232

W.A. N.T. Qld. S.A. N.S.W. A.C.T. Vic. Tas.

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GOVERNMENT OF WESTERN AUSTRALIA
HON. NORMAN MOORE, M.L.C.
MINISTER FOR MINES

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
DAVID BLIGHT, ACTING DIRECTOR

SCALE 1: 100 000

1000 Metres 0 1 2 3 4 5 6 7 8 Kilometres

TRANSVERSE MERCATOR PROJECTION
HORIZONTAL DATUM: AUSTRALIAN GEODETIC DATUM 1984
VERTICAL DATUM: AUSTRALIAN HEIGHT DATUM
Grid lines indicate 10 000 metre interval of the Australian Map Grid Zone 50

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
MINERAL RESOURCES BULLETIN 18 PLATE 1

LIMESTONE AND LIMESAND DISTRIBUTION IN THE PERTH METROPOLITAN AREA

Geology compiled by P. B. Abeysinghe
Edited by L. Day, G. Loan, and C. Brien
Cartography by L. Cosgrove

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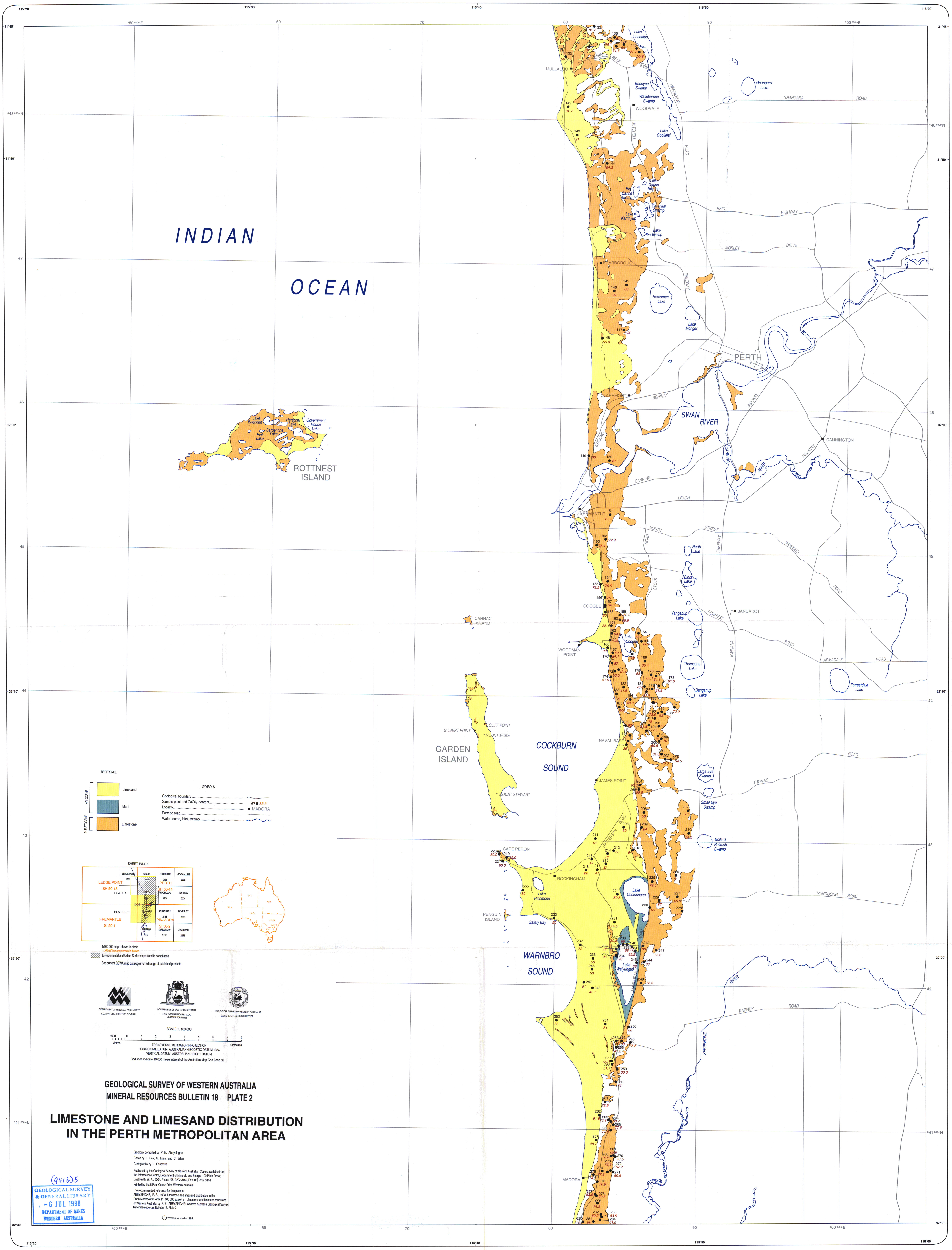

GEOLOGICAL SURVEY OF WESTERN AUSTRALIA
MINERAL RESOURCES BULLETIN 18 PLATE 2

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